The future of offshore wind turbine foundation installation

Scaling offshore wind turbine foundation installation from 2010 to 2030

Offshore and Dredging Engineering

O.J. Ordelman

Delft University of Technology

TU Delft

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by

O.J. Ordelman

at the Delft University of Technology,

Student number:	4491726	
Defence:	17 December 2024	
Thesis committee:	Dr. Ir. P. van der Male,	TU Delft, supervisor
	Dr. Ir. B. Ummels,	TU Delft
	Ir. S. Raymackers,	DEME
	Ir. N. Loosveldt,	DEME

Preface

This thesis report is the final step in completing my Master in Offshore and Dredging Engineering at the Delft University of Technology and the final step in obtaining the degree of Master of Science. One of my primary goals before starting this research was to gain a deeper understanding of the entire offshore wind sector. After several months of hard work, I am proud to say that this goal has been achieved. It has been a challenging yet incredibly interesting experience.

I would like to thank my supervisors, Pim van der Male and Bart Ummels from Delft University of Technology for their excellent guidance and continual support during this project. Also special thanks are due to Sylvie Raymackers, Nicolas Loosveldt, and Bas Nekeman from DEME who have introduced me to the company and provided me with invaluable insights and expertise throughout the process. Also, I would like all the interviewees who participated in my study. Without their contributions, completing this thesis would not have been possible.

Obbe Ordelman Amsterdam, December 10, 2024

Summary

The demand for renewable energy is rising, and offshore wind energy is at the core of the sustainable development. The offshore wind sector has grown in a rapid pace, driven by the need to reduce carbon emissions, and to meet the strict climate goals set for 2030 and 2050. This growth is marked by increasing turbine sizes, installations in deeper waters, and expanding project scales, presenting both opportunities and challenges.

This thesis investigates the evolution of offshore wind turbine foundation installation practices from 2010 to 2030. As the offshore wind industry has grown in a rapid pace to meet global renewable energy goals, the challenges created by scaling turbine sizes, deeper water installations, and stricter environmental regulations, have increased. This research provides a comprehensive analysis of how the sector has evolved, and furthermore it identifies key technological and logistical advancements, and explores the implications of these changes on the future of foundation installation.

Chapters three and four form a foundation for the rest of the research. Chapter three provides an overview of the primary foundation type used in the offshore wind sector, including monopiles, jackets, suction buckets, gravity based foundations, tripods, and floating foundations. By examining their advantages and limitations, the chapter creates an basic understanding of the different factors that influence the choice for a foundation type. Chapter four build on this by exploring the different installation procedures of each foundation type. Together, these chapters create a basis for analyzing the evolution and evaluating future trends of the foundation installation sector.

In the subsequent chapter, the evolution of the offshore wind foundation installation sector from 2010 to 2024 is examined, highlighting the industry's response to scaling turbine sizes and deeper water projects. The chapter analyzes the developments of the offshore wind market, foundation types, installation vessel, and installation equipment across three time periods: [2010-2015], [2015-2020],[2020-2024].

Chapter six explores the implications of further scaling offshore wind turbine on the foundation installation sector. As turbine sizes have grown significantly, with capacities now exceeding 14-15 MW, the chapter examines how this scaling affects foundation design, installation methods, and logistical requirements. Key challenges include handling larger monopiles, adapting installation vessels and equipments, and addressing supply chain constraints. The chapter also highlights the environmental impacts of scaling, such as noise mitigation and seabed disturbance, and the regulatory measures driving innovation. By analyzing these factors, the chapter provides critical insights into how the industry must adapt to support the sustained continued growth of the foundation installation sector.

Chapter seven focuses on innovations in the fast evolving offshore wind sector, and examines the drivers, challenges, and success factors for technological advancements. The chapter highlights key developments, such as hybrid installation methods, advanced noise mitigation systems. It discusses the criteria that are contributing to the success of of an innovation, cost effectiveness, scalability, regulatory compliance, and risk management.

Chapter eight analyzes the limitations of the different foundation types, taking into account the entire installation process. It examines key variables, as water depth, seabed conditions, turbine sizes, and supply and logistics. The chapter highlights how these factors influence the selection of foundation types.

Chapter nine provides a forward-looking analysis of the foundations installation sector, where it looks into trends, challenges, and potential innovations for the period up to 2030. The chapter discusses how scaling turbine capacities and deeper water locations will drive the developments of technological advancements. By addressing the technical, logistical, and environmental aspects, Chapter 9 provides a road-map for the industry's growth and its ability to the ambitious renewable energy targets.

Finally, the thesis is concluded by summarizing the key findings of the research. It is emphasized how the evolution of foundation installation practices, driven by turbine scaling trends, technological advancements, and stricter environmental regulations, has shaped the offshore wind industry. The historical developments, current challenges, and future opportunities, are combined and highlight the importance of innovations, collaboration, and adaptability for the sector's sustained continued growth.

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Introduction

1.1. Rising demand for renewable energy

The global transition towards renewable energy is driven by the need to mitigate climate change. The EU has set the goal for climate neutrality in 2050 and has committed to a reduction of CO2 emissions by 55% before 2030. Offshore wind energy, is at the core of this strategy due to its significant potential to generate clean, sustainable power. In 2020, the European Commission published a comprehensive strategy for offshore renewable energy, setting a target of achieving 60 GW of installed offshore wind capacity by 2030, to meet the the strict climate goals set for 2030 and 2050 [1].

In 2022, 23% of the total energy consumed was produced by renewable energy sources, and this figure needs to increase to the target of 42.5% by 2030, emphasizing the need for rapid deployment of renewable energy sources [2]. This growth demands a considerable expansion in offshore wind capacity. By 2050, the offshore wind capacity needs to grow 25-fold, emphasizing the scale of the challenge the industry is facing.

1.2. Growth offshore wind

The offshore wind sector has experienced significant growth since its inception, as can be seen by the increasing number of wind farms deployed across Europe, and the yearly installed capacity of offshore wind, given in Figure 1.1. The first offshore wind farm was installed in 1991, off the coast of Vindeby Denmark. The installation existed out of eleven turbines, with a rated capacity of 0.45 MW, combining to a total installed capacity of 4.95 MW for the entire farm [3]. Appendix B provides a detailed overview of wind farms installed to date, capturing key metrics such as installed capacity, turbine capacity, number of turbines, water depths, and distance to shore. Figure 1.1 shows the annually installed offshore wind capacity. The complexity of the installations increases, as turbine sizes increase and wind farms are being installed in deeper waters and further from shore, as can be seen in Figure 1.4.

Figure 1.1 shows a gradual increase in annually installed offshore wind capacity from 2000 to 2023, with notable surges in 2015 due to large-scale projects in Germany and the UK [4]. In 2016 there was a dip in the yearly installed offshore wind capacity, due to delays in interconnections and changes to market support mechanisms, particularly in the Netherlands and UK [5][6]. Recent challenges, such as the COVID-19 pandemic and supply chain issues, affected capacity growth between 2020 and 2022 [7]. Nonetheless, the sector has demonstrated resilience and continued to expand.

The cumulative offshore wind capacity has grown steadily, and since each year some capacity has

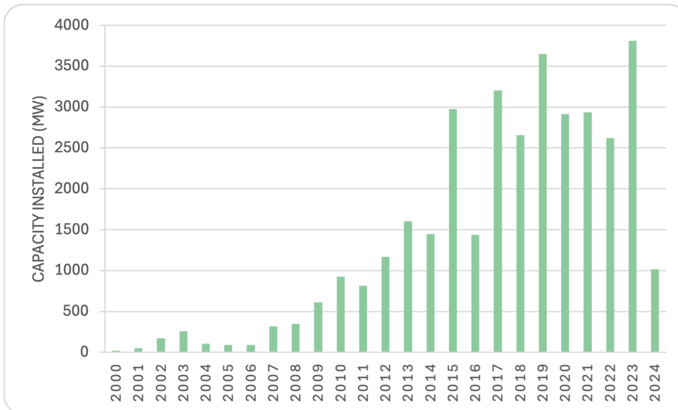


Figure 1.1: Annually installed offshore wind power 2000 to 2024

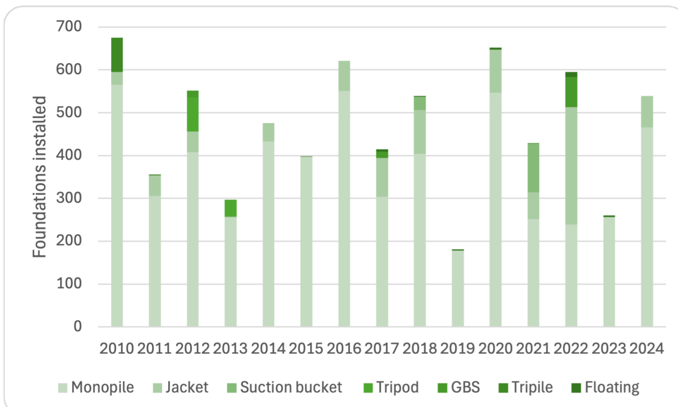


Figure 1.2: Annually installed foundations

been added, bringing the total installed capacity to approximately 35 GW by 2024 1.3. While this shows impressive progress, it still falls short of the EU's 2030 target, emphasizing the need for accelerated deployment over the coming years.

1.3. Depth and distance to shore

Offshore wind farms are moving further from shore and into deeper waters to make use of higher wind speeds often encountered further offshore, which directly increases the potential energy capture. However, this shift brings additional engineering challenges, as increased distances require longer export cables, and deeper installations involve more complex foundation designs. Figure 1.4 illustrates the trend towards greater distances from shore and increasing water depths, which in turn increase the cost and logistical complexity of installation. Some years show significant dips in the average distance to shore, for instance in the years from 2021, this is mainly because in these years, some offshore wind farms have been developed relatively close to shore, in countries like France, the UK, and the Netherlands. Additionally, in recent years new markets have started

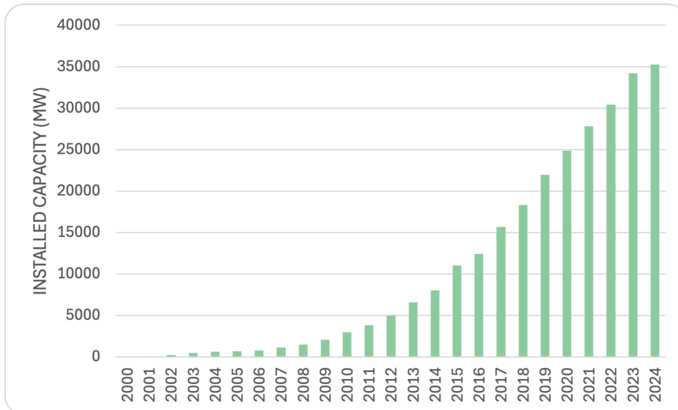


Figure 1.3: Cumulative installed offshore wind capacity

to develop more offshore wind farms, as Japan, the US, and Taiwan, also with several installations relatively close to shore.

Most offshore wind farms today are bottom-fixed, with economic viability typically limited to depths of around 60 meters [8]. Beyond this, floating offshore wind technologies might become more competitive. Floating wind projects, although currently in their early stages, are set to play a critical role in the future of offshore energy, particularly in deeper waters. By 2023, Europe had four operational floating wind farms, with an average water depth of 170 meters, and a combined capacity of 176 MW [8]. New projects are already on the horizon with project A05 off the coast of south Brittany, with a capacity of 270 MW, with an average depth of 90m [9]. One of the next big challenges to overcome for floating offshore wind is the scalability of the production of the foundations [8].

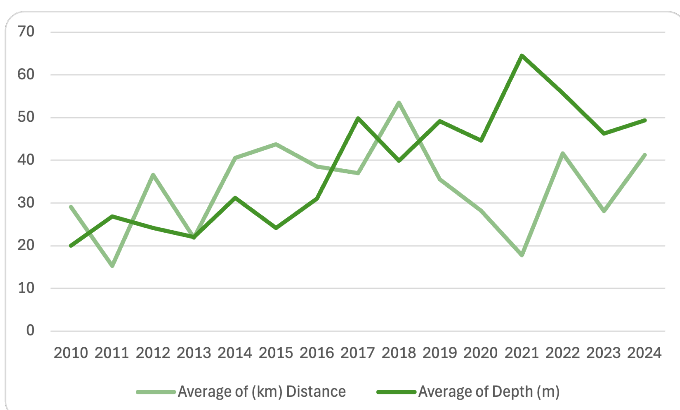


Figure 1.4: Average yearly depth and distance to shore of foundations installed between 2010 and 2024

1.4. Scaling challenges and opportunities

The growth of offshore wind is not without its challenges. The industry is facing a shortage of installation vessels, which is projected to intensify in the next years, potentially delaying up to 50 GW of planned capacity by 2030 [10][11]. Additionally, scaling wind turbines to larger sizes requires innovative approaches to foundation design, transportation, and installation. Figure 1.5 shows the yearly growth of offshore wind turbines in terms of their capacity to give perspective on the size of more recent installations and the increase in turbine capacities over the years. Figure 1.6 gives a graphical representation of the growth of offshore wind turbines and their expected future growth, in terms of rated power and actual size of the structure.

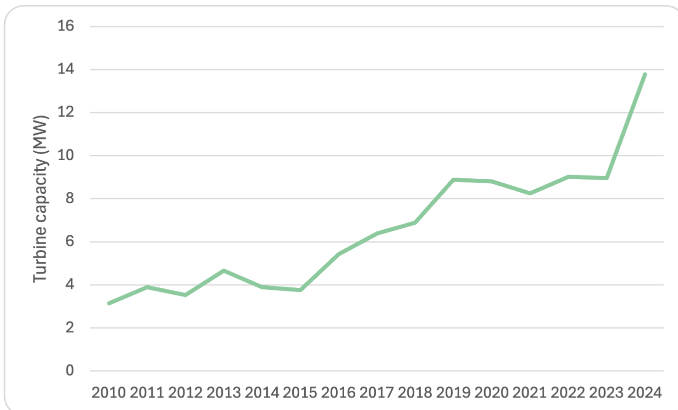


Figure 1.5: Average offshore wind turbine capacity

Figure 1.6: Growth of offshore wind turbines over the years [12]

1.5. Scope of research

This research focuses on how the offshore wind foundation installation sector has evolved from 2010 to 2024, and how it will likely develop up to 2030. One goal of this research is to investigate the challenges and opportunities that come with the scaling of the industry, to meet the growing demand for renewable energy. The research explores how the installation process has changed over the years to support larger turbines, deeper water locations.

The research focuses on the main foundation types used for offshore wind turbines, as monopiles, jacket foundations, gravity-based foundations, suction bucket foundations, and floating foundations. These foundation types are analyzed in terms of their design, and their installation procedures. The study focuses on the role of technological advancements, such as innovations in installation equipment and in installation vessels. The focus of the study is on the installation of the primary structure of the foundations, but it also quickly touches upon the installation of secondary foundation parts, such as jacket piles, and transition pieces.

The geographical focus of the research is on Europe, since the largest developments have taken place here, but the analysis also includes emerging markets, including the APAC region and North America.

Environmental and regulatory considerations are also discussed during the research. Primary issues, such as noise pollution, seabed disturbance, and compliance with regulations are discussed to understand how they influence the selection, design, and installation of foundations, and how it will influence the future of the installation sector. Furthermore, the research considers current noise-mitigation strategies, and how they have evolved to comply with the strict noise regulations, even with the installation of larger foundations.

This study focuses on the analysis of the installation and the scaling of offshore wind turbine foundations. Although costs are an integral part of the scaling efforts in the offshore wind sector, this study does not include financial considerations.

1.6. Objectives and research questions

This research analyzes the evolution and future directions of the offshore wind foundation installation sector from 2010 to 2030, focusing on the drivers, challenges, and technological advancements within the fast-developing sector. As offshore wind energy capacity grows and installations extend to deeper waters, with larger turbines, the installation faces both opportunities and technical limitations. This research aims to provide a comprehensive understanding of how foundation types and installation methods have changed and adapted over the years, and what the future of the installation sector may look like. To achieve these objectives, the research will be addressing the following research questions:

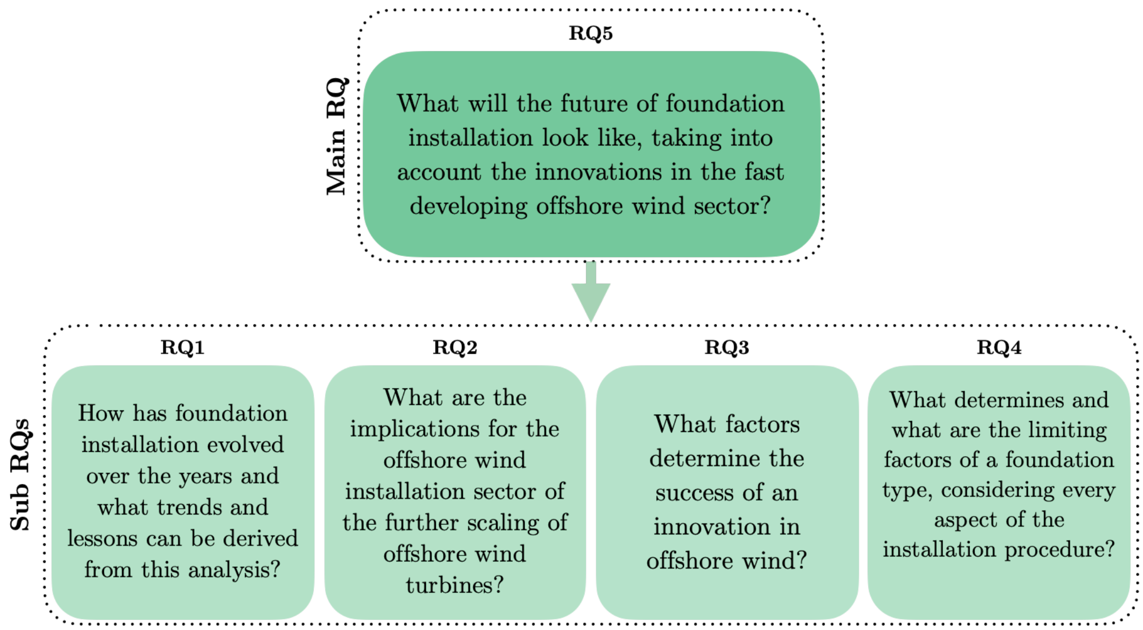


Figure 1.7: Research questions

2
Method

This chapter presents the methods used in the research. The primary objective of this chapter is to show how data will be collected and analyzed to answer the following research questions:

1. How has foundation installation evolved over the years and what trends and lessons can be derived from this analysis?
2. What are the implications for the offshore wind installation sector of the further scaling of offshore wind turbines?
3. What factors determine the success of an innovation in offshore wind?
4. What determines and what are the limiting factors of a foundation type, considering every aspect of the installation procedure?
5. What will the future of foundation installation look like, taking into account the innovations in the fast developing offshore wind sector?

This research uses a 'mixed methods' approach, combining both qualitative and quantitative methods to answer the research question about the evolution and the future of the offshore wind foundation installation sector. In Figure 2.1 it is shown what data methods are used at which chapter. Furthermore, it shows which chapter answers what research question. Qualitative methods, such as interviews and a literature review, will provide insights into the sector and help to identify key trends, challenges, and opportunities. Quantitative methods will be used to see how the sector has evolved, by analyzing data, findings trends, and create future projections.

2.1. Research strategy

The goal of this research is to understand both the historical and the future developments in the offshore wind foundation installation sector. The strategy involves:

1. An historical analysis of foundations and their installation practices from 2010 to 2024.
2. A visual and numerical analysis of previously installed offshore wind farms, and the entire installation procedure.
3. An evaluation of innovations and their success factors.
4. Analysis of the limiting factors of each foundation type.
5. A future vision for the foundation installation sector.

One of the goals of this research is to create an overview of the offshore wind turbine foundation installation sector. Companies in the foundation installation sector are hesitant to share information with the outside world, and rather keep data to themselves to ensure competitors cannot take advantage of any data the company gathered during its own projects. Due to this lack of information sharing, and due to the lack of an overview of what foundation installation entails, a database of all previously installed wind farms is created. The database contains visual and numerical information about previously installed offshore wind farms and the foundation installation phase.

2.2. Data Collection Methods:

The data-gathering process consists of several steps.

Literature review

Prior to the research, an extensive literature review has been performed, of which parts have been included in the research. In the literature review, a theoretical foundation and a part of the historical context for the research were made.

Interviews

Interviews will be conducted to gather insights from stakeholders in the offshore wind industry. These interviews will provide additional data, such as expert opinions, practical experiences, and perspectives on future developments. The interviewees will include experts in the field of offshore wind, but from different parts within the industry. The different stakeholders include:

- Offshore wind farm developers
- Foundation manufacturers
- Installation contractors
- Installation equipment specialists
- Researchers and academics in the field of offshore wind

The goal is to speak with experts from all different sections within the offshore wind sector. The information gathered during the interviews will be used throughout the report, to get better insights into certain topics, and certain developments in the offshore wind sector. The information gathered during the interviews will mainly be used for the following topics:

- implications of further scaling offshore wind turbines
- Innovations in offshore wind
- Limitations of foundations
- The future of foundation installation

Within the corresponding chapters to these topics, quotes from the interviews will be used to further highlight certain statements.

Interview protocol

The interviews will be semi-structured to allow for flexibility in exploring different themes while ensuring that all relevant topics are covered. An interview guide will be prepared in advance of conducting the interviews, including questions based on the formulated research questions. The questions are formulated around the research questions, and roughly focus on:

- Evolution of offshore wind turbines and especially developments in the field of foundations and their installation.
- Technological developments in foundation installation.
- Implications of scaling offshore wind turbines.
- Limiting factors for foundations
- Innovations in the offshore wind sector
- Predictions for future trends in foundation installation

The interviews will be conducted either in person, or online, depending on the availability and the location of interviewee. All interviews will be recorded (with consent) and transcribed automatically via Microsoft teams, so the information of the interviews can be used for further analysis.

Database

A visual and numerical database is created to support the analysis of the evolution of the foundation installation sector. The visual part of the database consists of visual material of the installation procedure of each previously installed offshore wind farm. The material will be analyzed to gather valuable insights into the evolution of the foundation installation sector and to extract trends, technological advancements, and innovations. Besides the visual database, a numerical database will be created to be able to numerically analyze developments and trends. Due to the size of the databases, they are not added in to the report. For additional information on the databases, or to request access to the databases, the author can be contacted.

2.3. Data Analysis

Qualitative analysis

The data from interviews and the literature review will be analyzed to identify key patterns, themes, and insights related to the research questions.

Quantitative analysis

1. Data will be gathered from industry reports, databases, and scientific studies to identify historical trends in offshore wind foundation installation. This includes analysis of foundation types, installation depths, turbine sizes, and installation timelines.
2. Statistical methods will be applied to assess trends over time and to predict future developments.
3. Scenario analysis: Different future scenarios will be developed by combining insights from interviews with the data.

2.4. Ethical Considerations

The interview participants will be fully informed about the purpose of the research, and how the data will be used. The data gathered during the interviews will be anonymous to protect the privacy of the participants. Furthermore, approval will be requested before recording the interviews.

2.5. Limitations

- The number of interview participants may be restricted by time constraints and accessibility of interviewees, which could impact the overall findings.
- Data availability: Access to data and reports can be very limited in the industry, which could constrain the depth of the quantitative analysis.

2.6. Structure of the report

The following sections of this report will explore how the offshore wind foundation installation industry has evolved from 2010 to 2024 and examine the technological, economic, and environmental implications of further scaling turbine and foundation sizes. By investigating the trends, challenges, and innovations shaping the sector, this research aims to provide a comprehensive overview of the future of offshore wind foundation installation, contributing to the sector's ability to meet its ambitious growth targets. A graphical representation of the structure of the report is given in Figure 2.1.

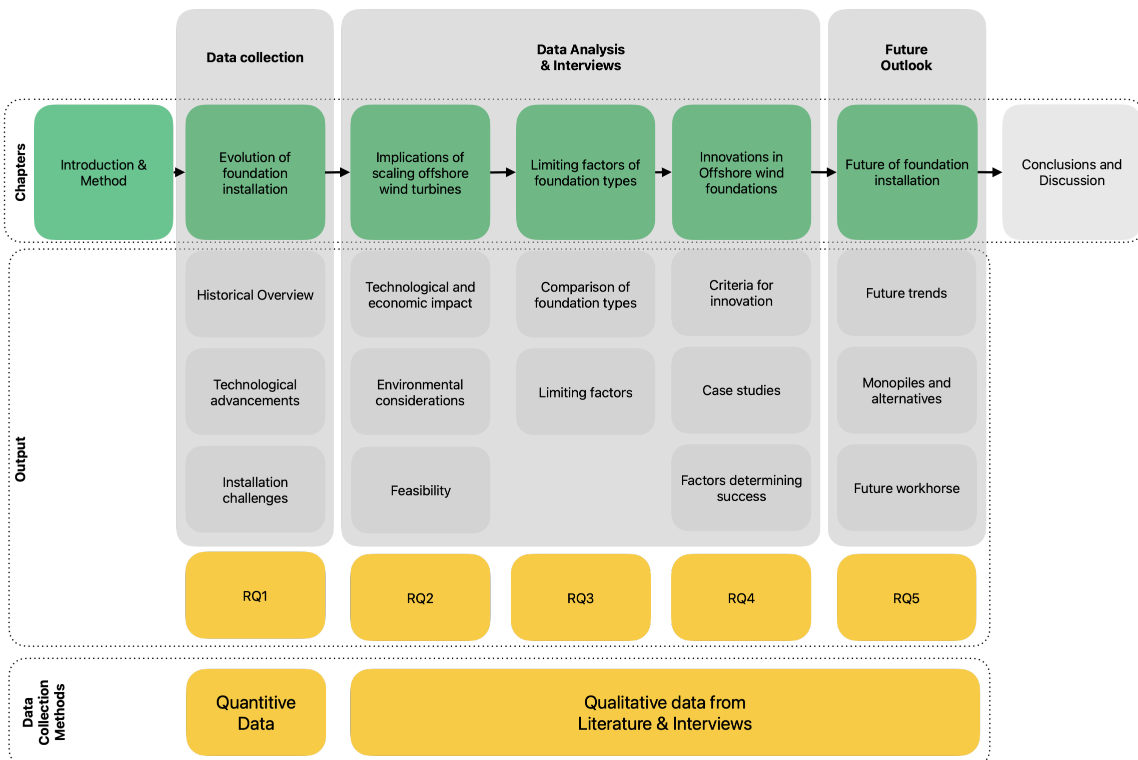


Figure 2.1: Structure of the research

3 Foundations

Several different types of foundations for offshore wind turbines exist and have been used throughout the years. The different foundation types can be categorized into two main categories. Bottom fixed foundations, shown in Figure 3.3, and floating foundations, shown in Figure 3.6. The most used foundation type is the monopile, with a market share of over 80%, with respect to other foundation types. Each foundation type has been developed to overcome specific challenges with for instance the movement to larger turbines and to deeper waters. Each foundation type has its own advantages and disadvantages, and the selection of a suitable foundation type is influenced by several factors such as water depth, seabed conditions, turbine size, environmental impact, and cost.

This chapter provides an in-depth review of the main foundation types currently used for offshore wind farms. Within each foundation type, the advantages and disadvantages are discussed and summarized in a table. The chapter focuses on monopiles, jackets, gravity-based foundations, suction bucket foundations, tripods, and floating foundations. This chapter provides a solid foundation for the upcoming chapters, which go more into depth and will provide answers to the research questions.

The chapter focuses on the main foundation types currently used. For each foundation type a short description is provided to give some context about what all the foundation types look like, what their limitations are, and what factors play a role in the selection of a foundation type. In Chapter 4, a detailed analysis of the entire installation procedure for each foundation type will be given.

The chapter is divided into several sections, as shown in the Figure. The first Section 3.1, gives an overview of the different foundation types, with a comparative table that gives an overview of several characteristics of the foundation types that have been installed in the previous five years. In each of the subsequent Sections ([3.2 to 3.7), a different foundation type will be presented. Within each of these sections, the foundation type will first be introduced, after which a short discussion is given about the advantages and disadvantages of the foundation type.

3.1. Foundation overview

The choice of a foundation type depends on several factors, including cost, water depth, and soil composition. Foundation selection for offshore wind turbines plays an important role in the overall concept selection for offshore wind farms. The foundation and its installation contribute a substantial part to the overall cost of the wind farm [13]. Due to the size of the wind farms, the seabed conditions vary within a wind farm. This means that ideally a custom foundation design is chosen per wind turbine location. This is however not feasible due to economic restrictions. To minimize the costs, it is desirable to reduce the number of different foundation types to a minimum since producing one type of foundation in mass will reduce the production price and therefore the overall cost of the project. From an economic perspective, it is desirable to choose a suitable foundation type with the lowest overall cost. This overall cost mostly consists of manufacturing costs, transportation costs, installation costs, and decommissioning costs.
In Table 3.1, a comparative overview of all the foundation types installed in the last 5 years is presented with some of their key metrics. This table should give a quick overview of recent foundation types, and provide some insight into where the current offshore wind foundations stand.

Foundation type	**Deployed at wind farms**	**Foundations installed**	**Turbine Capacity (MW)**	**Depth range (m)**	**Weight (T)**	**Cost**
Monopile	33	1805	8-15	20-57	600-2100	$
Jacket	8	540	8-14	30-56	1000-2000	$$
Gravity based	1	71	7	25-30	5000	$$$
Suction bucket	1	114	10	42-58	2000-2250	$$$
Floating	5	21	2-9.5	>60	2000-3000[1]	$$$$$

Table 3.1: Comparative overview of foundation types installed in the past 5 years

Figure 3.1: Life cycle of a foundation

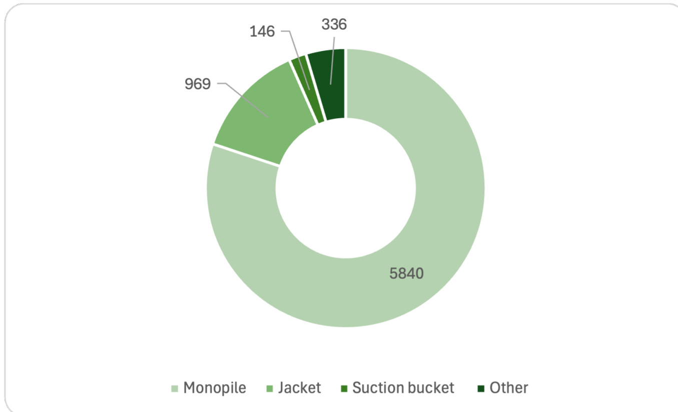


Figure 3.2: Number of foundations installed for the most used foundation types

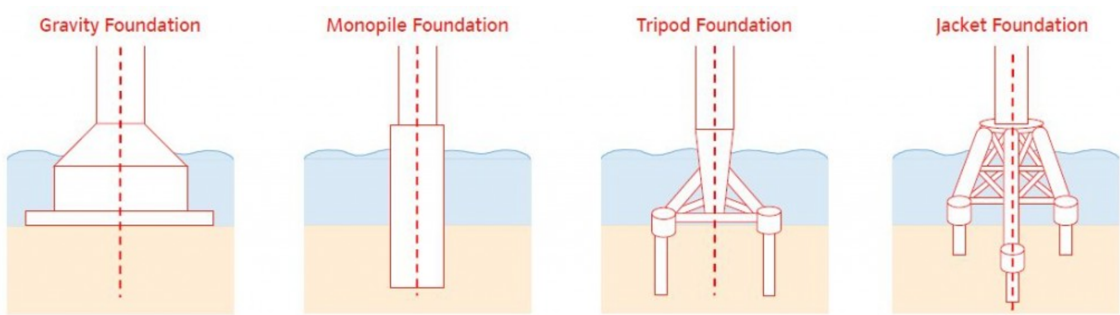


Figure 3.3: Schematic representation of offshore bottom-founded foundation types [14]

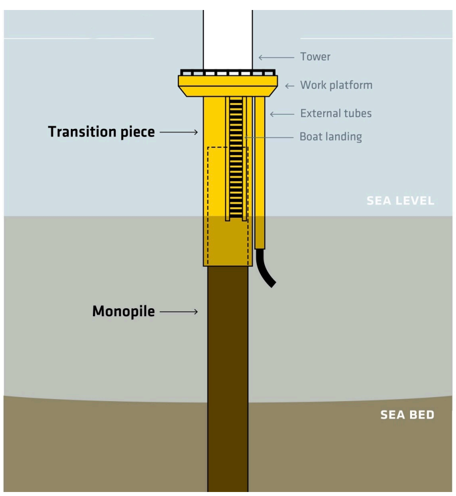
3.2. Monopiles

Monopiles are the most commonly used foundation type, as shown in Figure 3.2, and they have usually been installed in relatively shallow water depths of up to 40 meters. However, current installations do exceed this number. They are the most simple foundation type and consist of a large hollow steel cylinder, which is driven directly into the seabed. Installation is relatively straightforward, requiring fewer components and less specialized equipment than other foundation types.

Monopiles are most effective in uniform seabed conditions such as sand or gravel, where they provide excellent stability. In the history of the offshore wind sector, the 'death' of the monopiles has often been predicted, due to perceived water depth limitations beyond which the foundation type was deemed uneconomical. However, these depth boundaries have been pushed further, and it is still not quite clear at what water depths monopiles really become uneconomical [15]. Of course, this foundation type has its own downsides and challenges, which include their increased dimensions and weight to sustain the increased loads of the larger turbines. The diameter and wall thickness of monopiles have grown over the years to support larger turbines, which in turn raises manufacturing and transportation costs. The evolution of the monopile, combined with the other foundation types is discussed in more detail in Chapter 5.

Traditionally the entire foundation consisted of two parts; the primary monopile, and the transition piece, to which the turbine tower is connected. The transition piece (TP) is shown in Figure 3.4a, and is positioned between the monopile and the turbine tower, and the secondary steel, such as the boat landing, maintenance platform, cable entry points, and corrosion protection systems [16]. The transition piece is usually connected to the monopile with a grouted or a bolted connection [17]. The grouted connection was first used to be able to compensate for the not precise enough installation of the monopile into the seabed, where the incorrect inclination of the pile could be rectified by perfectly leveling the transition piece before grouting the annulus between the transition piece and the monopile [18]. The bolted connection relies on large bolts for the interface connection, and the continuous movement to larger turbines results in higher interface loads and bolt loads, which results in the bolted connection nearing its end [19].

The push for cost reduction and simplification has led to the development of TP-less monopiles, which eliminate the need for a separate TP altogether [19]. For this design the monopile and the transition piece are incorporated in one structure, removing the need to install the transition piece offshore, and therefore reducing the number of offshore lifting operations, and improving installation efficiency [17]. Furthermore, the TP-less monopile removes the bolted or grouted connection between the transition piece and the monopile and removes a flange, reducing the maintenance operations and maintenance costs [19]. The TP-less monopile is, however, longer and therefore heavier than its equivalent monopile without a transition piece, requiring vessels with larger capacity cranes. Kurstjens and Erents [19] mentioned that a TP-less monopile is 250 - 300 tonnes heavier than a 'traditional' monopile (without its transition piece). Furthermore, the secondary steel previously attached to the transition piece now has to be directly attached to the monopile separately [19].



(a) Schematic representation of a monopile with a transition piece [20]

(b) TP-less monopile produced by Sif [21]

Figure 3.4: Transition piece (TP) and TP-less monopile

Advantages	Disadvantages
Simple design	Installation noise
Scalable for mass production	Slenderness issues
Relative low cost	Large diameters needed for deeper waters
Proven concept	

Table 3.2: Advantages and disadvantages of monopile foundations

3.3. Jacket foundations

Jacket foundations consist of a lattice framework composed of tubular steel members, with three of four legs anchored into the seabed with anchor piles. They are particularly suited for intermediate water depths of 30 to 80 meters and can support larger turbines (up to 15 MW) [22]. Jackets are the second most used foundation type after monopiles as can be seen in Figure 3.2.

Jacket foundations are however more expensive than an equivalent monopile, due to their complex design and manufacturing cost. The multiple components of jacket foundations have to be welded together, introducing more work, and more possible failure points which increases the quality checks during and after the manufacturing process. The installation of a jacket is also more complex than monopiles due to the need for pre-piling and the mating of the multiple components.

Advantages include reduced hydrodynamic loading, making them more suited for locations where wave and current loading is higher. Disadvantages primarily involve higher manufacturing and maintenance costs, as well as greater logistical challenges during installation due to the multi-stage installation campaign, which is discussed in more detail in Chapter 5.

Advantages	Disadvantages
Suitable for deeper water	Higher fabrication and installation cost
Adaptability to seabed conditions	Higher maintenance requirements
Reduced hydrodynamic loading	

Table 3.3: Advantages and disadvantages of jacket foundations

3.4. Gravity based foundations

Gravity-based foundations, often called GBF or GBS (gravity-based structure) shown in Figure 3.3, rely on their own weight to provide stability. They are most suited for clay, sandy soil, and rock seabed conditions [15]. These structures are typically built onshore and transported or floated out to the installation site, where they are submerged and anchored by ballast. Installation requires significant preparation work before the foundation can be installed offshore, such as levelling the seabed to ensure stability, which increases the overall project cost. GBS are inherently heavy, due to the nature of the foundation type, and therefore require installation by heavy lift vessels. However recent projects have demonstrated advancements in buoyant transportation methods, which reduce the need for heavy-lift vessels.

Advantages	Disadvantages
No need for piling	High material and transportation costs
Suitable for rocky or poor soil conditions	Requires extensive seabed preparation
Long term stability	Limited depth capability

Table 3.4: Advantages and disadvantages of a GBS

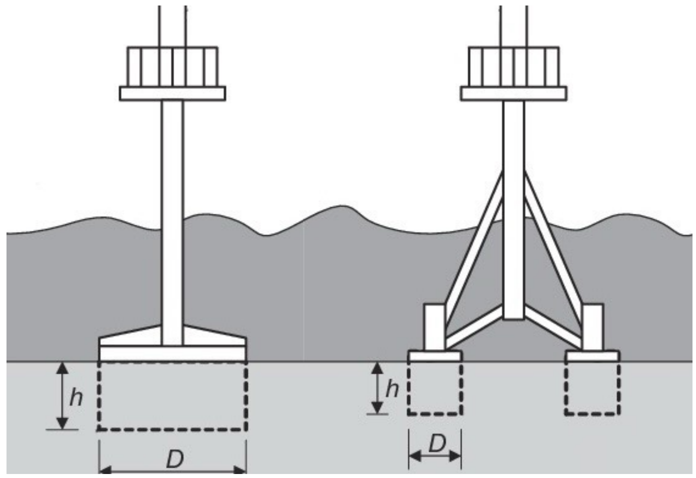


Figure 3.5: Schematic representation of a monopod and suction bucket jacket foundation [25]

3.5. Suction bucket foundations

Suction bucket foundations, shown in Figure 3.5, consist of a large inverted steel bucket that is installed by creating a vacuum within the bucket, anchoring it to the seabed. The foundation type has been used only at four offshore wind farms, with the total number of foundations installed being 146, making that the experience with the foundation type can be considered as limited with regards to the experience with monopile foundations [23]. The installation process is highly dependent on soil type and soil strength, which introduces installation and stability risks [24]. This foundation type is often referred to as a low-noise alternative, since it does not rely on the use of impact hammers during the installation phase, reducing environmental impact [24]. Another additional positive effect of suction bucket foundations is that the suction process can be reversed at the end of the structure's life cycle, making decommissioning of the entire foundation possible, whereas other foundation types are partially decommissioned or require advanced technologies for the entire removal of the structure. Besides the positive attributes of the foundation type, the foundation type has a large surface area in contact with the soil, introducing more risk [23].

3.6. Tripod foundations

Tripod foundations consist of three tubular steel legs that extend from a central pile, forming a stable base that can support the turbine tower, shown in Figure 3.3. The central pile transfers the vertical loads from the turbine to the three legs, which also provide lateral stability by distributing the horizontal loads, such as those caused by wind and waves, across a larger area of the seabed.

Advantages	Disadvantages
Fast and quiet installation	Limited experience
Relative straightforward decommissioning	High soil dependence
	Large footprint

Table 3.5: Advantages and disadvantages of suction bucket foundations

Tripod foundations have been installed in water depths of 30 meters, and they offer an alternative for the jacket or monopile foundations, although the foundation type has only been installed 2 times since 2010, namely at the Borkum one and Global Tech one offshore wind farms in 2012 and 2013. Tripods can be used for water depths of up to 60 meters [15]. The depth limitations of monopiles were however pushed further, making the foundation type somewhat redundant.

The structure of the tripod makes for a stable foundation, which makes it especially suitable for deeper waters or areas where monopiles might struggle to maintain stability. Tripod foundations are made from steel, and the steel members are fabricated and welded into the required triangular geometry onshore before being transported to the installation site.

Advantages	Disadvantages
High stability	More expensive than jackets
Relative simple construction	Heavy structure

Table 3.6: Advantages and disadvantages of tripod foundations

3.7. Floating foundations

Floating foundations are a relatively new foundation type, which is not deployed as often as the other foundation types, with only 176 MW operational capacity in Europe [8]. The structure is not anchored directly to the seabed as with traditional (bottom-fixed) foundation types. The foundation is however anchored to the seabed using mooring lines and anchors. Floating foundations are ideal for deep water applications since they are not limited to a certain water depth. Three main types of floating foundations exist, shown in Figure 3.6.

While the LCOE (Levelized Cost of Energy) for floating foundations remains higher than bottom-fixed options, advances in mooring systems and modular designs are expected to significantly lower costs by 2030 [26]. The LCOE of Floating offshore wind projects is estimated to be roughly three times higher than that of bottom-fixed offshore wind projects in 2023. However, a drop in the LCOE of floating wind turbines is forecasted at 74% by 2030 and 82% by 2050, reaching 78 EUR/MWh by 2030 and 43 EUR/MWh by 2050 [27]. This reduction will depend on several factors, such as technological advancements, standardization and economies of scale [27]. Mooring of floating foundations in water depths below 100 meters is a challenging task and can therefore be very expensive. A Spar type requires a minimum water depth of 80 meters even for relatively small turbines, due to their large draft. This number is expected to increase even further for larger turbines [28]. TLP and Semi-submersible foundations can be used in more shallow waters, but are less cost-effective at the moment due to their construction cost [28].

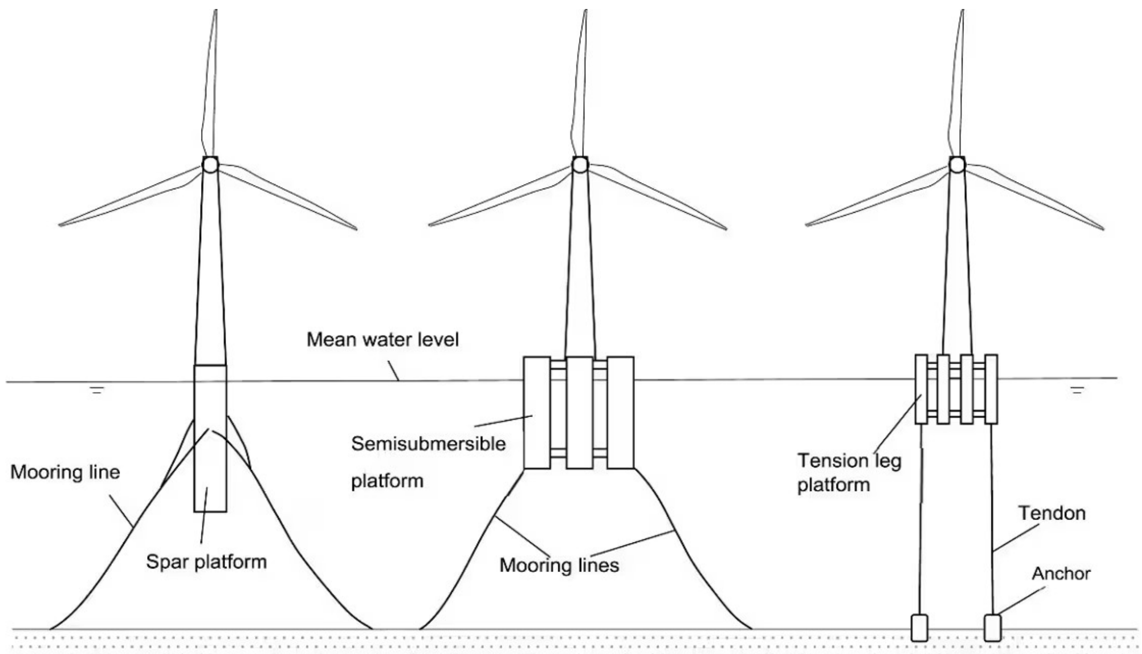


Figure 3.6: Schematic representation of three main floating offshore wind turbine foundation types [22]

Advantages	Disadvantages
Deep water capability	High initial cost
Reduced seabed impact	Limited experience
Onshore assembly	Dynamic maintenance challenges
Scalable for large turbines	Complex structures
Opens up more possible locations	Anchors and mooring lines that can disrupt the sealife

Table 3.7: Advantages and disadvantages of floating foundations

4 Foundation installation

The installation of offshore wind turbine foundations is a complex process consisting of several steps. These steps are different for each foundation type, and tailored to the logistical, and engineering needs of the foundation type. Each foundation type has specific installation requirements, based on its design and the conditions of the installation site, such as water depth, seabed composition, distance to a port, and location-specific environmental regulations.

The goal of this chapter is to provide an understanding of what the installation procedure of each of the different foundation types really entails. The chapter aims to provide an overview of all the aspects of the foundation installation sequence, from the installation methods, and the vessels used, to the equipment used during the installation.

This chapter provides extensive background information about the installation processes of each foundation type, which is needed for the following chapters, to be able to answer the research questions. The chapter provides graphical examples of each of the installation steps, and of the equipment under used during the operation, to give some context to the reader when talking about the different components and equipment types.

The focus of the chapter will be on providing an understanding of the different phases of the foundation installation procedures and does not go into depth in terms of how the different installation steps, or vessel and equipment used, changed over the years. The evolution and the changes in installation will be thoroughly discussed in Chapter 5.

The structure of the chapter follows the installation steps of the different foundation types. Each section treats the installation procedure of one foundation type, as shown in the Figure. Each of the sections starts with a graphical overview of the installation steps specific to that foundation type. This structure gives some guidance for the reader to be able to quickly see and understand the differences in installation steps between the several foundation types.

4.1. Monopile installation

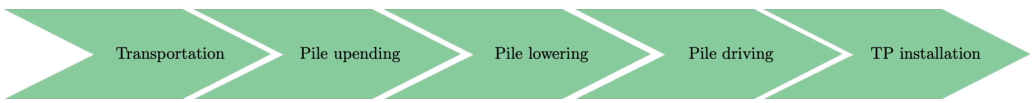


Figure 4.1: Installation steps of a monopile

This section is copied from the literature review done prior to this research.
As briefly mentioned in the introduction, the installation process of a monopile consists of several steps. The installation steps of a monopile are shown in Figure 4.1. In the following section, these different process steps are thoroughly reviewed and discussed.

4.1.1. Transportation

Before a monopile can be installed at the offshore installation location, it has to be transported to the installation site. A monopile can be transported to the offshore site in several ways. The foundation can be transported on a transportation vessel, on the installation vessel itself, or can be floated out to the installation location [29]. The first method mentioned is called a 'feeder' method, where a feeder vessel supplies and delivers the foundations to the offshore location. The foundations have to be lifted from the transportation vessel by the installation vessel before the foundation can be installed. The second method mentioned is called a 'Shuttling method', where the installation vessel sails back and forth between the offshore site, and the port to pick up and transport the foundations on deck. The foundations are transported in a horizontal position on the deck of the installation vessel. With this method, the foundations are already on board the installation vessel, and therefore no difficult offshore lifting procedure including two moving vessels is needed. Another transportation possibility for monopiles is the floating delivery of a pile. With this method, the installation vessel remains at the offshore installation location, and the piles are transported in a floating manner, with plugs on each open end of the foundation pile to enable a water-tight, floating structure. The foundations are towed one at a time, by towing tugs. This method is mainly used for installations where sheerleg vessels are used for the installation, since these vessels have a fixed crane, limiting the ability to lift foundations from a transportation vessel.

4.1.2. Upending process

Monopiles are mostly transported horizontally to the offshore location, by either a transportation vessel or by the installation vessel. After the transportation, the piles have to be up-righted before they can be lowered to the seabed. This so-called upending sequence can be done either by an upending tool, by a crane, or by a pile gripper frame [29]. Figure 4.2 shows an upending tool of IQIP, the tool is inserted in the pile while the pile is in a horizontal position, after which it can be raised and brought to an upright position to be installed.

Figure 4.2: Upending tool by IQIP [30]

4.1.3. Pile lowering

After the pile is upright, the pile has to be lowered to the seabed. A gripper frame, fixed to the vessel, controls the horizontal movements of the pile during the lowering process. Different types of pile grippers exist, which have seen a development throughout the years, discussed in further detail in Section 5.4. When a jack-up vessel is used, which has no relative motion with respect to the seabed, a fixed pile gripper can be used. Figure 4.3 gives a representation of a fixed pile gripper.

The introduction of floating installation vessels introduces, however new problems with regard to the installation of a monopile. A ship that is afloat during the installation, will move relative to the seabed, due to the wind and wave forces acting on the ship, transferring the motions to the monopile. This can lead to the inaccurate installation of the pile. A Motion compensated gripper is used to overcome this problem, instead of a fixed frame gripper. The gripper keeps the pile vertical by compensating the motions of the vessels and it prevents uncontrolled oscillations and motions of the monopile during the lowering and piling process. The gripper can also be used during the upending procedure of the pile. Figure 4.4 shows a motion-compensated gripper frame developed by Huisman and installed on the Orion, a floating heavy lift installation vessel by DEME.

Another additional issue with the introduction of floating mono-hull installation vessels is the lifting of equipment and the insertion of equipment in the foundation piles. Since the vessel is moving

Figure 4.3: Fixed pile gripper frame installed on jack-up vessel Innovation by DEME [31]

Figure 4.4: Motion compensated monopile gripper frame installed on Orion [32]

due to wave and wind forces acting on the vessel, a free-hanging lifting tool will be able to swing freely when it is hanging overboard, before it is inserted in the foundation pile, creating possible dangerous scenarios where the tool can swing into the foundation pile. To overcome the issue of a free-moving lifting tool, hanging overboard trying to attach to the foundation pile, an outrigger frame was designed, where the lifting tool can be lowered, after which the tool can be safely inserted into the pile. An example of an outrigger is shown in Figure 4.5. The Figure shows a zoomed-in version of the structure shown in Figure 4.4, where the outrigger can be seen on the right side below the monopile. The frame-like structure is designed to safely insert the lifting tool in the foundation.

Figure 4.5: Outrigger frame installed on Orion [32]

4.1.4. Pile driving

After the lowering process, the piles have to be driven into the seabed to a certain target installation depth. This target depth is determined by the seabed consistency, the water depth, and the loads acting on the foundation [33]. Over the years, several installation techniques have been applied to drive the foundation piles into the seabed. The dominant method to drive a foundation pile into the seabed is by impact hammering, or impact piling. During the hammering process, the hammer delivers a short duration of blows at the pile head, forcing the pile into the seabed. One of the disadvantages of impact hammering is the high levels of noise generated during the process, which carries through the water, the seabed, and the air [34]. The noise produced and several noise mitigation measures deployed during the installation of monopiles are discussed in further detail in Section 4.1.5. In the next Sections, several categories of equipment used to drive monopiles into the seabed are discussed.

Hydraulic hammer

Hydraulic hammers are the most commonly used in monopile installation. They can deliver repetitive blows to the top of a monopile, driving the pile into the seabed. The size of the hammers evolved over the years, following the size increase of the foundations, to be able to deliver the increased force required to drive the larger piles into the soil. Hydraulic hammers use hydraulic pressure to lift the hammer drive inside the hammer, after which a valve will open to release the hydraulic pressure and enable the hammer drive to drop to generate the force required to drive monopiles into the seabed. They offer precise control over driving force and energy, making them suitable for a wide range of soil conditions and pile sizes [35]. IQIP is one of the leading companies in the field of hydraulic hammers, and Figure 4.6 shows the largest hydro hammer of IQIP, the IQ6. The hammer can deliver repetitive blows of 5500 kJ at the pile head and is therefore suited for the installation of the largest monopiles [36].

Vibro hammers

Vibro-hammers are another pile-driving method. They use vibration instead of impact to drive monopiles into the seabed. They transmit high-frequency vibrations through the pile, to reduce soil resistance, which leads to easier soil penetration [37]. During the installation of XXL monopiles,

Figure 4.6: IQ6 by IQIP [36]

vibro-hammers are mainly used for their capability to control the pile in the first part of the pile installation, to avoid pile run and ensure a good installation [37]. Figure 4.7 shows a vibro hammer of CAPE, this tool can also be used for the up-ending of the pile, removing the need to change equipment and thus decreasing installation time [37].

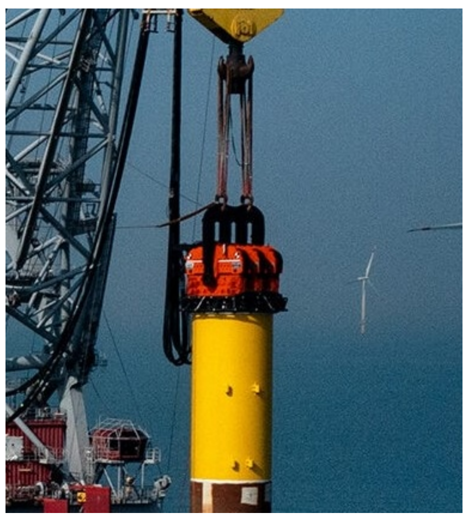


Figure 4.7: CAPE-VLT-640 vibro lifting tool [38]

Drilled foundations

When soil conditions are encountered that are not suitable for driving the foundation piles into the seabed with impact hammering, or vibro-driving, drilling offers a solution so foundations can even be installed in locations with rocky seabeds, opening up more possible installation locations, for instance of the coast of France. Drilling can also offer a solution when pile refusal is encountered during the driving process with an impact hammer.

The two main drilling methods applied in the offshore wind sector, are relief drilling and socket drilling. Relief drilling operations begin with driving the foundation into the seabed, and when the foundation experiences pile refusal, due to the encounter of dense soil layers, specialized drilling equipment, shown in Figure 4.8 can be lowered in the foundation pile to alleviate the pile resistance [39]. Socket drilling is applied when pile driving is entirely unfeasible, such as in rocky seabeds. This method involves the drilling of a borehole to create space for the monopile. After the drilling operation, the foundation pile is lowered into the hole, and the gap between the soil and the pile will be grouted.

An example of a socket drill for offshore wind foundations, is the offshore foundation drill (OFD), by Herrenknecht. The OFD 7700, shown in Figure 4.9 has a drilling diameter of 7.7 meters, and was used to drill the foundations for the Saint Nazaire and the Noirmoutier offshore wind farms [40].

Figure 4.8: LD 5000 drill, for relief drilling foundation piles [39]

The drilling operation in locations with challenging marine conditions, and the need for a safe installation, introduced the need to develop an innovative drill and pile installation aid [42]. DEME developed the MODIGA, shown in Figure 4.10, which shields the drilling and installation operations from harsh conditions, optimizing operational efficiency [43].

4.1.5. Noise pollution

During the installation of the foundation piles of offshore wind farms, a lot of noise is produced. Kikuchi [45] found that the underwater noise created during the installation could reach 210 dB.
Several countries have set specific requirements for the maximum sound levels allowed during offshore operations. The German government set the maximum allowed sound exposure level at 160 dB and the maximum allowed sound peak pressure level at 190 dB, both measured at 750 m from the pile [46]. In the Netherlands, the regulations have changed from allowing pile driving during a specific period of the year to specific sound-level criteria [47]. In the UK an EIA, a separate environmental impact assessment must be made for each project [47].

Several possibilities exist to minimize the effect of the noise pollution. The noise production can

Figure 4.9: OFD 7700 offshore foundation drill by Herrenknecht [41]

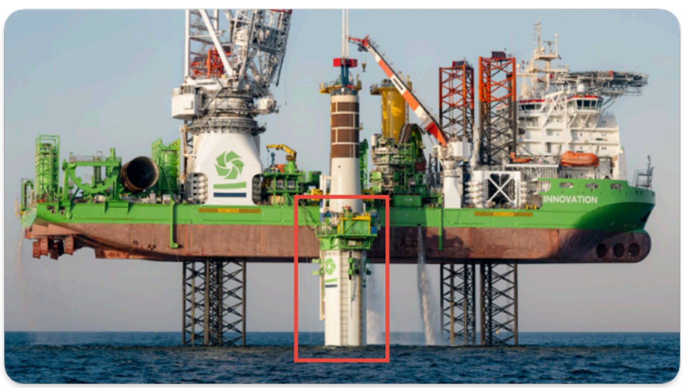
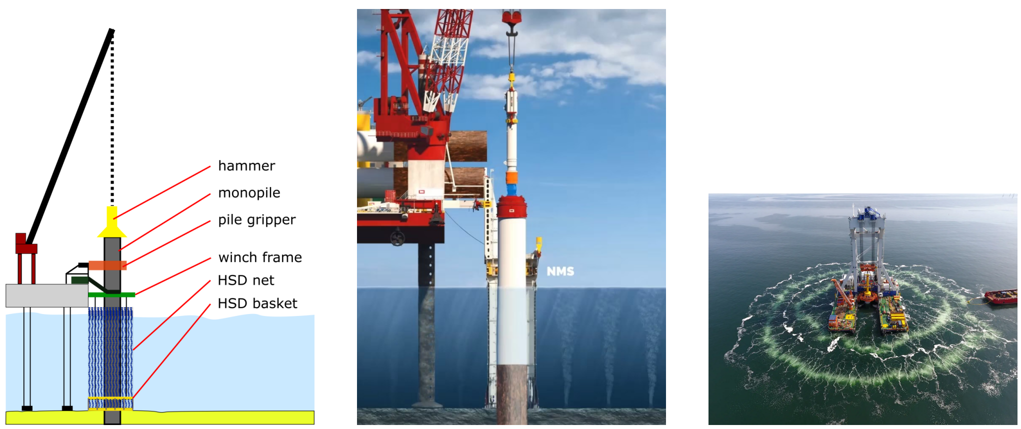


Figure 4.10: MODIGA monopile drilling and installation aid [44]

be brought to a minimum or the sound propagation could be halted or minimized. To reduce the sound produced during installation, different pile driving methods are being developed. One of the most promising new pile driving methods is vibro piling, mentioned in Section 4.1.4. GBM Works is working on a solution called 'vibrojetting', which utilizes jetting to reduce soil resistance in combination with vibropiling to minimize noise production during pile installation [48].

Noise Mitigation

To reduce the noise emission and mitigate the effects of the noise pollution several noise mitigation measures are deployed during the installation process. Tsouvalas [47] described available noise mitigation measures and strategies in great detail. Figure 4.11 gives an overview most widely used noise mitigation systems. In Figure 4.11a a representation of a hydro sound dampener is given. A hydro-sound dampener consists of a net lined with foam and air elements to be able to reflect and absorb underwater noise created during the pile-driving process. The net is deployed around the monopile. In Figure 4.11b the NMS screen of IQIP can be seen. Simply put, it is a double-walled steel structure filled with air and creates a barrier between different media and materials to reduce sound propagation. In Figure 4.11c a double bubble curtain is shown. A Bubble curtain consists of a large perforated hose, which lies on the seabed around the installation site. Air is pumped through the hoses, and bubbles surface from the perforated hose, changing the density of the water and thus breaking down sound waves [49].



(a) HSD [50] **(b)** IQIP screen [51] **(c)** Big bubble curtain [52]

Figure 4.11: Noise mitigation systems

4.2. Jacket installation

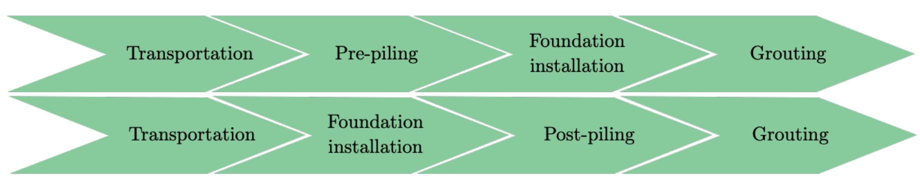


Figure 4.12: Jacket installation sequences for pre and post-piling methods

The installation of a jacket foundation also consists of different steps but differs from a monopile foundation in terms of installation methods and installation equipment needed. The different installation steps of a jacket foundation are shown in Figure 4.12. Jackets are comprised of a lattice structure with three or four legs. Jackets are anchored to the seabed at each corner of the structure.

Two main anchoring methods are used for jackets, called pre-piling and post-piling [29]. In the following sections, the different steps of the two methods are described.

4.2.1. Transportation

The transportation of a jacket foundation to the offshore installation site can be done in several manners. Due to the dimensions of jackets, most installation vessels do not have the deck space to transport many foundations at a time. The different transportation methods for jackets are:

- Transportation by barge or transportation vessel
- Transportation on the deck of the installation vessel
- Suspended transportation in crane of the installation vessel

Several factors play a role in the selection of the transportation method. The cost, the capacity, and the trip duration, all play an important role in the selection of the transportation method. The shuttling method often applied for the installation of monopile foundations, is due to deck size limitation often not the most efficient transportation method [29]. Transportation by barge or transportation vessel is often the preferred method, a method similar to the 'feeder' concept for monopiles.

4.2.2. Jacket installation

Pre-piling method

Pre-piling is the operation where the piles used to anchor the jacket structure to the seabed are installed prior to lowering the jacket structure to its final location. With the pre-piling method, the first step in installing jacket foundations is driving anchor piles into the seabed, which usually is done with an impact hammer. These piles are called pin piles and are hollow piles similar in shape to a monopile but with smaller dimensions.

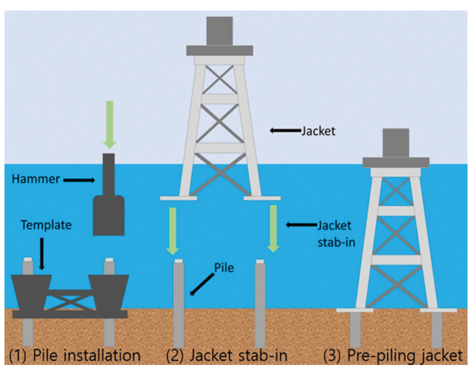
These pin piles are installed first, after which the jacket structure is lifted. Figure 4.14a gives a graphical representation of the installation process, where the pin piles are installed first, after which the jacket structure is lifted. Since the three or four pin-piles are installed first, tight tolerances must be achieved to ensure spacing and inclination corresponding with the spacing between the legs of the jacket structure. To achieve these tight tolerance levels, a pre-piling template is used, which makes sure the pre-piles are installed with the same orientation and spacing from each other as the jacket structure [53]. The most advanced pre-piling templates are self-levelling, which makes sure the pre-piles are installed upright, and within given tolerances. Figure 4.13 gives an example of a pre-piling template used for the adequate installation of the piles.

After the pre piles are installed, they are cleaned before the jacket structure is lifted in place on top of the pre-installed piles. After the pre-piles are installed and cleaned, the jacket can be lifted from the transportation vessel and lowered to the correct position on the pin-piles. As can be seen in Figure 4.14a, the jacket legs are equipped with location cones beneath the legs, to help the mating process. After the jacket reaches its correct position, the gap between the pre-pile and the leg of the jacket is filled with concrete and left to cure before the wind turbine is installed on top of the structure. The process of filling the gap with concrete is called grouting.

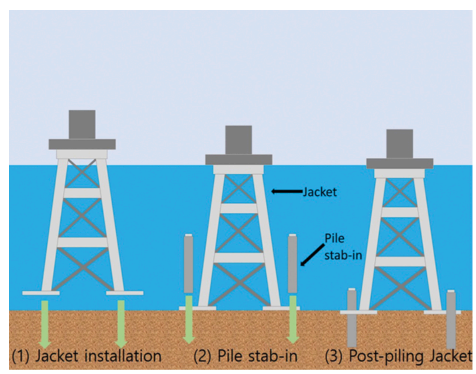
Figure 4.13: pre-piling template [53]

Post piling method

Another anchoring method used for jacket structures makes use of anchor piles which are installed after the structure is lowered to the seabed. These anchor piles differ in dimensions and shape from pre-piles since they are used to lock the structure in its place, similar to how a nail is used in woodworking for example. In Figure 4.14b, a graphical example is given of how this process works.



(a) Graphical representation of jacket pre-piling method



(b) Graphical representation of jacket post-piling method

Figure 4.14: Piling methods for jacket foundations [54]

Lifting of foundation

When the jackets are supplied by an external vessel, the jackets have to be lifted off the transportation vessel in the offshore environment. The transportation vessel will moor alongside the installation vessel.Similar to the lifting of a monopile, a specialized lifting tool is used to ensure a safe lifting operation. Figure 4.15 shows a flanged jacket lifting tool made by IQIP.

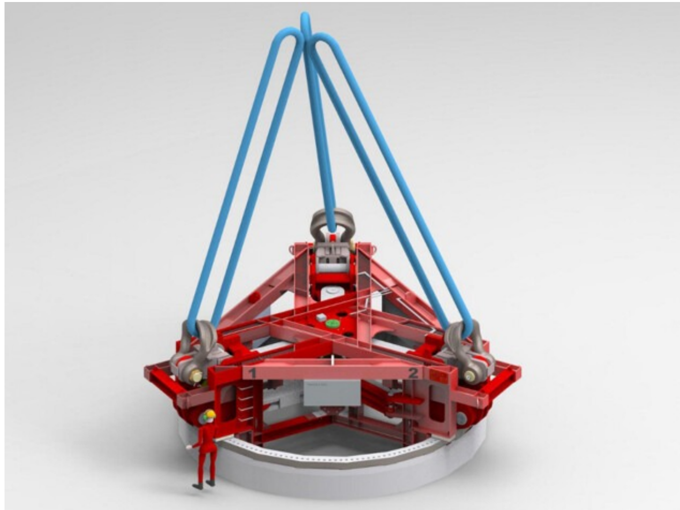


Figure 4.15: Flanged Jacket Lifting Tool [55]

4.3. Installation of gravity-based foundations

Figure 4.16: Installation process of gravity-based foundations

Gravity-based foundations use their weight to counteract the forces acting on the structure. Gravity-based foundations stand on the seabed and are heavy structures, with a large footprint. The installation of a GBS does not require any piles to be driven into the ground, and can therefore be seen as a relatively low noise installation process. The installation process consists of a few different steps, as shown in Figure 4.16.

For gravity-based foundations, the manufacturing method influences the transportation method, and therefore the manufacturing method is also taken into consideration.

Seabed preparation

Seabed preparation is a step that is not required for monopile or jacket foundations and is unique for gravity-based foundations [56]. It is therefore an extra step, which is a large disadvantage of the foundation type. The heavy structure rests on the seabed and must sit flat, to ensure the correct inclination of the turbine tower. It also relies on a large load-bearing capacity of the soil and therefore soil layers with a low load-bearing capacity, like loose sand, mud, clay, and silt, have to be removed to make sure the foundation will remain upright, and will not tip over [56]. The soil will be removed with dredging. When suitable soil layers have been reached, a rock bed is installed. The surface of the rock bed has to be horizontal, to again ensure the correct inclination of the foundation.

Manufacturing

Due to the nature of Gravity-based foundations, the structures are large and heavy. This influences the manufacturing possibilities since it is needed to manufacture the foundations in a location where they can be lifted, or where they directly can be transported to their offshore location. Three main manufacturing methods exist [56]:

- Manufacturing in a dry dock: The foundations are manufactured in a dry dock. Once they are finished, the dry dock is flooded, and the foundations will eventually be floated out to the offshore installation site.
- Manufacturing on floating pontoons: The foundations are constructed directly on a transportation barge. Some of the main advantages of this method are the reduced yard capacity needed, and the reduced number of lifting operations.
- Onshore manufacturing: The foundations are manufactured onshore in a port. The foundations have to be lifted from the quayside to a transportation vessel, which introduces an extra lifting step.

Figure 4.17: Float out of gravity based foundation for float and submerge method used at Blyth offshore wind farm [57]

Transportation

Due to the size and weight of the foundations, transportation and installation are challenging operations. The vessels deployed during the installation campaign often consist of barges which transport the foundations, and a crane vessel with a large lifting capacity [56]. Figure 4.19b shows the transportation barge with its corresponding tugs, and the lifting of the GBF of the barge at

Figure 4.18: Suspended transportation of gravity-based foundation for Thornton Bank wind farm [56]

Fécamp offshore wind farm. Several transportation methods exist, and they are dependent on the chosen manufacturing method. Therefore the transportation methods are classified according to the manufacturing methods:

- Dry dock manufacturing: When the foundations are manufactured in a dry dock, the foundations are flooded and float out of the dry dock. They will be lifted often by an HLV, due to their large weights, and transported suspended to the offshore installation site. Figure 4.18 shows the transportation of a foundation by the installation vessel, for Thornton bank.
- Floating pontoon manufacturing: Foundations that have been produced on a floating pontoon, are directly manufactured on their transportation vessel. The foundations sail out to the offshore site, on the pontoon, or barge on which they are produced, minimizing lifting operations, as can be seen in Figure 4.19a.
- Onshore manufacturing: Foundations that have been produced onshore have to be lifted from the quayside. Often an HLV vessel is used for the transportation and the installation, where the foundation is transported suspended, as in Figure 4.19a.

To solve the challenging installation of the heavy structures, a different installation concept has been introduced during the installation of the Blyth wind farm [58]. The installation method is called the ”Float and submerge” method. Figure 4.17 shows a floating gravity based foundation, leaving the manufacturing facility. This method reduces the lifting operations, which is beneficial with these large heavy structures, since the number of cranes capable of lifting these large structures, weighing 7500 tonnes, is limited. Figure 4.17 shows the foundations of the float and submerge installation process, floating out of the dry dock in which they were produced.

Installation

The foundation can be installed in two different ways, depending on the transportation method used. When the foundation is transported by the installation vessel, the foundation is already attached to the crane of the vessel, and can directly be lowered to the seabed. If the foundations are transported on a barge, or transportation vessel, the foundation has to be lifted off this vessel and can be lowered to the seabed afterwards, as shown in Figure 4.19. In the Figure, two different generations of gravity-based foundations are lifted from their transportation barge, after which they are lowered to the seabed, and placed on the prepared surface. The foundations in Figure 4.19a, were installed in 2012 at the Karehamn offshore wind farm by the Rambiz vessel and weighed around 1950 tonnes [59]. The foundations lifted in Figure 4.19b, were installed in 2017 at the Fécamp offshore wind farm and were lifted by the semi-submersible crane vessel Sleipnir of HEEREMA, and these foundations weighed 5000 tonnes [60].

(a) Offshore lifting of gravity-based foundation for Karehamn wind farm from transportation barge by Rambiz vessel [59]

(b) Lifting of gravity-based foundation at Fécamp offshore windfarm, from transportation barge by Sleipnir vessel [61]

Figure 4.19: Offshore lifting of two generations of gravity-based foundations

Ballasting and anti-scour protection

After the foundations have been placed on the levelled seabed, the foundations have to be ballasted. The ballast is required to reach the design weight of the foundation, to ensure the stability of the foundation. After the foundations have been ballasted, anti-scour protection is placed around the foundation in areas with high seabed mobility, and or strong currents [56]. The first generation of GBS foundations did not require the ballasting step, since these foundations were solid concrete structures. The second generation of structures required ballast in the holes in the slab of the foundation. The third-generation foundations were hollow and were filled from the top, as shown in Figure 4.20. For the float and submerge method, used at the Blyth offshore wind farm, the ballasting process starts when the foundation reaches its installation location. The ballasting process is used to lower the foundation to the seabed and overcome the buoyancy of the structure. The foundation 'sinks' in a controlled manner to the seabed, after which the ballasting and anti-scour protection procedure will continue in the same manner as for foundations that are lowered to the seabed in a conventional manner.

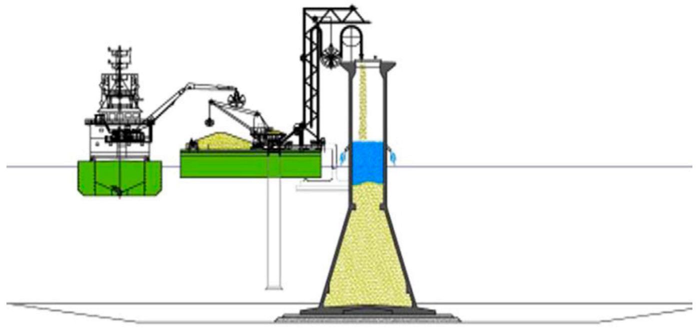


Figure 4.20: GBS ballasting [56]

4.4. Tripod installation

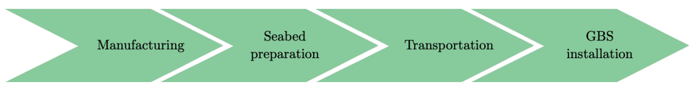


Figure 4.21: Installation steps of tripod foundations

Tripod foundations were tested for the first time in 2010 at the Alpha Ventus offshore wind farm. In this period, the depth boundary of monopiles was said to be around 20-25 meters, and therefore an alternative for deeper waters for future installations was needed. The Tripod was introduced as a suitable alternative foundation for deeper waters. The foundations are large, and consist of a three-legged structure with a centre pile, as can be seen in Figure 4.22a.

Transportation

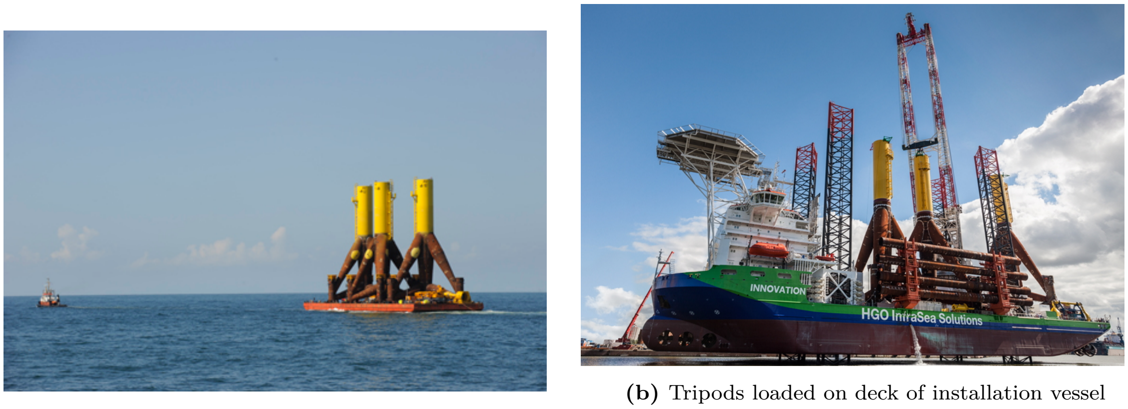
The foundations can be transported by barge, or by the installation vessel. However, due to the large footprint of the foundations, most of the installation vessels available around 2010 were not capable of transporting multiple foundations per trip. Figure 4.22a shows the transportation of three tripod foundations on a barge. These foundations were for the Alpha Ventus offshore wind farm, were 45 meters tall, and weighed 700 tonnes [62].

A second possible transportation method is the transportation on the deck of the installation vessel, as can be seen in Figure 4.22b, where three foundations, with their corresponding anchor piles, are transported on deck on the installation vessel. These foundations were installed at the Global Tech One offshore wind farm in 2012, with the at that moment in time, state-of-the-art vessel 'Innovation'.

Installation

Tripod foundations are heavy structures, that require high-capacity cranes for the installation procedure. The installation process consists of several steps, which are shown in Figure 4.21.

After the foundation is lowered to the seabed, the foundations need to be anchored. Three anchor piles are driven into the seabed with the use of an impact hammer, or by a combination of a vibratory hammer with impact hammers. Vibratory hammers are used for the initial penetration



(a) Transportation by barge of three tripod foundations to the offshore installation location [63]

(b) Tripods loaded on deck of installation vessel Innovation, with their anchor piles, for Global Tech one wind farm [64]

Figure 4.22: Transportation methods for tripod foundations

of the pin piles in the seabed, and after a stable depth has been reached, impact hammers will be used to install the pin piles to the final depth. Figure 4.23 shows a vibratory hammer attached to a pin pile, used to anchor a tripod foundation. The inclination of the structure is monitored and the correct inclination is achieved by hammering the three anchor piles in the seabed in alternating fashion.

Figure 4.23: Pin pile installation with vibratory hammer for a tripod foundation [65]

4.5. Installation of suction bucket foundations

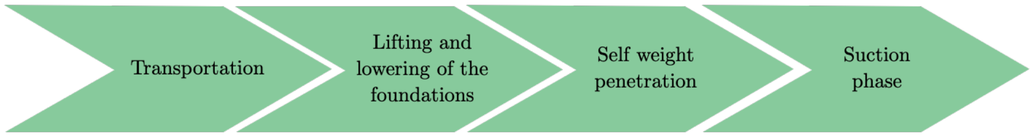


Figure 4.24: Installation steps of suction bucket foundations

Suction buckets can be described as up side down cups, that use a suction force to penetrate the seabed [13]. Suction bucket foundations have been used in the oil and gas industry since the 1980s, and they are used and known for their high installation efficiency and short construction time [23]. Since 2014 the foundation type has also been adopted in the offshore wind sector. The first test of suction bucket foundations took place with a pilot project at the Borkum Riffgrund one offshore wind farm in Germany, where one SBJ was installed besides 77 monopiles in 2014. For offshore wind turbines, the suction bucket technology is typically used in combination with jacket structures with three of four buckets attached to the legs of the jacket.

Transportation

SBJs are large structures, which influence the transportation possibilities [66]. Most of the installation vessels do not have the deck capacity to store and transport several foundations on deck. The foundations are typically transported in an upright position, but have a large footprint nevertheless. Transportation of the foundations can be done, either by a barge or transportation vessel or by the installation vessel itself. Figure 4.25 shows the transportation of an SBJ foundation by heavy lift vessel Asian Hercules 3, for the EOWDC offshore wind farm. The foundations were transported in a suspended manner, from the port to the offshore site, by the installation vessel. Figure 4.26 shows the transportation of SBJ foundations for the Seagreen offshore wind farm, where the foundations were supplied by barges, and lifted afterwards at the offshore location by the installation vessel.

Installation

The installation of a SBJ differs from the other foundation types, since the foundation has the ability to install itself, without the need to drive foundation piles into the seabed, as shown in Figure 4.24. The installation therefore does not require the use of an impact hammer, and therefore produces less noise, and can be seen as a low-noise alternative to monopiles, or 'traditional' jacket foundations. The installation consists of two main phases [13]:

- **Self-weight phase:** After the foundation is lowered to the seabed, the foundation will first sink into the soil due to its own weight. When the force due to the soil resistance becomes equal to the gravitational force on the foundation, the foundation will not sink any further. After the first phase, the second phase will be initiated.
- **Suction phase:** To further penetrate the soil, a suction force is applied under the buckets, creating an under pressure inside the bucket, which creates a downward force on the foundation, pushing the structure into the seabed. The inclination of the structure is measured, and controlled by changing the suction force in each of the three buckets.

Figure 4.25: Transportation of SBJ foundation for EOWDC wind farm [67]

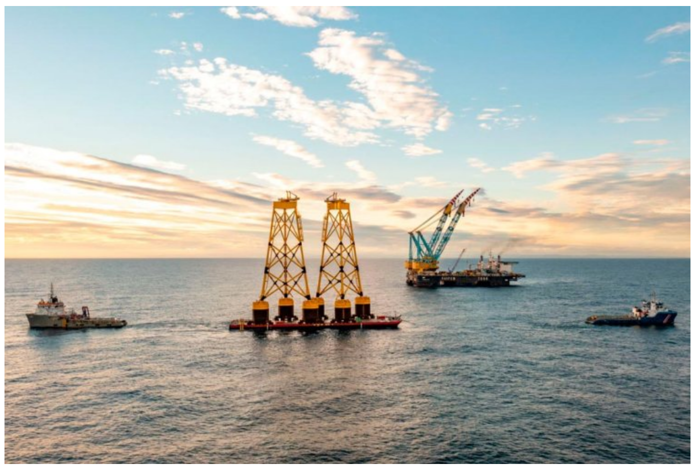


Figure 4.26: Transportation of 2 suction bucket jacket foundations on a barge, for Seagreen offshore wind farm [68]

4.6. Installation of floating foundations

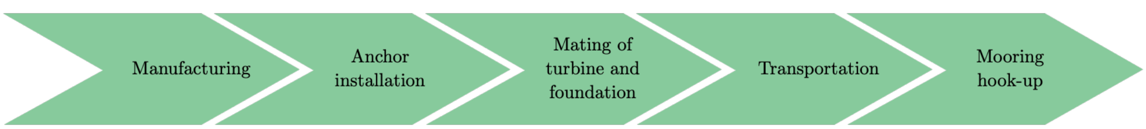


Figure 4.27: Installation steps of floating foundations

Floating foundations offer a promising solution for offshore wind farms in deeper waters, where traditional bottom fixed foundations become economically and technically unfeasible. The installation process of floating foundations is significantly different than the procedure of bottom fixed

Figure 4.28: Manufacturing of floating foundations for Hywind Tampen offshore wind farm [70]

foundations, shown in Figure 4.27. The installation of floating foundations is a process that consists of several stages, such as onshore fabrication, near-shore assembly, transportation, mooring system installation, and the connection of the floating structure to the pre-installed mooring lines [69]. This section discusses the key steps in the installation process and highlights some of the technical challenges associated with the foundation type.

Manufacturing and transport

Floating foundations are buoyant structures, shown in Figure 4.28. The foundations are manufactured onshore, and assembled near shore, enabling transportation of the entire structure to the offshore installation site by towing, rather than requiring expensive heavy lift vessels, and removing the need to mate the foundation and turbine in an offshore environment. The wet towing procedure of the complete turbine to the offshore installation site, where it will afterwards be connected with mooring lines to previously installed anchors, is shown in Figure 4.30. The towing operation is highly dependent on weather conditions, as the floating structure's stability and towing speed can be affected by wind and sea state [22].

Mooring installation

Before the floating foundation arrives at the offshore site, the mooring system must be installed. The mooring system consists of anchors that secure the floating foundation to the seabed and mooring lines that attach the structure to the anchors. Depending on the seabed conditions and foundation type, several anchor types can be used, including drag-embedded anchors, suction piles, driven piles, or gravity anchors. The selection of anchor type is critical to ensure long-term stability and is dependent on seabed conditions [73]. After the anchors are installed, the mooring lines are laid out from the seabed to the surface. The correct tensioning of these lines is critical to maintaining the platform's stability. For TLPs, vertical tensioned mooring lines (tendons) are used to provide additional stability, while semi-submersibles and SPARs rely on more horizontal mooring systems that allow greater flexibility, as shown in Figure 3.6.

Figure 4.29: Hywind Tampen turbine assembly [71]

Figure 4.30: Towing of a floating wind turbine to its installation site at Hywind Tampen offshore wind farm [72]

Foundation installation

Once the mooring system is in place, the floating structure is towed to the offshore location, where it is positioned and attached to the mooring lines. Tugs are used to precisely position the floating foundation at the installation site, and afterwards, the floating foundation is connected to the pre-installed mooring lines. This 'hook-up' process is critical and must be completed within optimal weather windows. After the initial connection, the mooring lines are tensioned to achieve the required stability to counteract the wind, wave, and operational forces.

Challenges

The installation of floating foundations is highly sensitive to bad weather conditions, particularly during the towing and hook-up phases [26]. Rough sea conditions can delay operations, as towing speeds are reduced and the dynamic motions of the platform increase. Installation windows must therefore be carefully selected, and real-time weather monitoring is essential to minimize downtime and associated costs.

It is expected that floating offshore wind will become economical from a water depth of 60 m, but other depths are also mentioned [74]. Liu [75] mentioned that mooring of floating offshore wind turbines in less than 100 m water depth is a challenging task and could be very expensive.

Furthermore, the effectiveness of the mooring system is dependent on the seabed conditions [76]. In locations with soft or variable seabeds, additional geotechnical investigations may be required to determine the appropriate anchor type. The selection of anchor type, such as drag-embedded anchors, driven pile anchors, gravity anchors, and suction piles, plays a critical role in ensuring the long-term stability of the floating foundation [26].

5
Evolution of foundation installation

The offshore wind industry has seen a significant growth since 2010, driven by growing demand for renewable energy sources. As wind turbines have become larger and moved further offshore, the methods used to install their foundations have evolved considerably. This chapter examines the developments in foundation installation, focusing on how the methods, foundations, vessels, and equipment have scaled to meet the demands of larger turbines and deeper waters.

The objective of this chapter is to provide a comprehensive analysis of the evolution of previously installed offshore wind farms from 2010 to 2024. During the analysis it will be explored how the market, the foundations, the vessels, and the equipment used for the installation have evolved over the years, and have shaped the foundation installation sector. One of the key problems that was identified during the literature study, performed prior to this research, is the lack of data sharing in the industry. Due to the lack of information, a visual analysis of the graphical material of installation campaigns of previously installed offshore wind farms was required to gather all the information needed to be able to analyze previous installations. Both a visual and a numerical database have been created. The visual analysis of each previous installation provided great insights and details about the evolution of the installation of foundations for offshore wind turbines, and created a clear picture of all different aspects of the installation phase. Additionally, the chapter will provide a future outlook of what future trends and innovations might shape the foundation installation market through 2030.

By looking at past installations and talking to field experts to gather information, key milestones and limitations within the foundation installation procedure will be identified. This chapter contributes to the overall research objective by addressing the research question:

How has foundation installation evolved over the years and what trends and lessons can be derived from this analysis?

The chapter continues on the discussion of foundation types and their installation methods presented in Chapters 3 and 4, and focuses on the evolution of the installation.

This chapter will primarily focus on bottom fixed foundations, such as monopiles and jackets, and all aspects of their installation procedures. The discussion around floating foundation installation, while important, will not be discussed in depth in this chapter, since this chapter focuses on the evolution, and floating foundations are still in the early stages of deployment. The analysis is furthermore limited to developments between 2010 and 2024 and gives some predictions for the 2024 to 2030 period, which will be discussed in greater detail in Chapter 9.

To obtain an in depth understanding of the evolution of the offshore wind foundation installation sector, all the different aspects of the foundation installation campaign have to be taken into account. For the analysis, all different aspects of the foundation installation have been sub divided and categorized in four main categories, as market developments, foundation developments, vessel developments, and equipment developments. The structure of the chapter follows these categories, and will be structured as shown in the Figure.

In Section 5.1 an overview of the developments of the offshore wind market is presented. This overview is followed by evolution of the foundations used, in Section 5.2. In Section 5.3, the development of installation vessels and their increasing capacity is analyzed, and focuses on the installation of the primary foundation structures. Section 5.4 highlights advancements in installation equipment, where the focus lies on the driving equipment.

5.1 Evolution of the offshore wind sector
5.2 Evolution of foundations
5.3 Evolution of installation vessels
5.4 Evolution of foundation installation equipment
5.5 Conclusion

By dividing the chapter into these four categories, the evolution of the foundation installation sector are followed over three time periods (2010-2015, 2015-2020, 2020-2024). In each time block, the evolution of the four categories is highlighted. The developments are subdivided in these time blocks to be able to follow the developments in a specific time period, in a chronological order. After the analysis, the findings for all the different categories are combined to form a conclusion about the evolution of the foundation installation sector.

5.1. Evolution of the offshore wind sector

The first offshore wind farm was installed in 1991, in Denmark off the coast of Vindeby. The wind farm consisted out of eleven 0.45 MW turbines, and it was installed in water depths of 2 to 5 meters. After the installation of this wind farm, the offshore wind sector has seen large developments in terms of the number of offshore wind farms installed per year, the size of wind farms, installation depths, and the size of offshore wind turbines. The first large-scale offshore wind farm was installed in 2002, in Germany. This was the Horns Rev 1 offshore wind farm, and consisted out of eighty 2

MW turbines, which brings the total capacity of the wind farm to 160 MW. Until 2010 this wind farm remained one of the largest in existence, with only two wind farms installed with a higher capacity. Around 2010, the yearly average size of offshore wind farms was finally on par with the size of the Horns Rev 1 wind farm built in 2002. In Figure D.2 the average yearly capacity of installed offshore wind farms can be seen. Besides the increase in overall capacity of offshore wind farms, the individual turbine capacity increased too, driven by the constant search for LCOE reductions, as came also forward in interview one:

> "The push towards bigger turbines is driven by the need for cost reduction. Larger turbines mean lower costs per megawatt, but it also means more stress on foundations and installations, pushing us to innovate constantly."

The developments of the offshore wind turbines and the size of the offshore installation have thus induced the need to scale the foundations, and thereby influenced the evolution of the vessels and equipment used in the sector. This section provides an overview of the evolution of the offshore wind sector, highlighting key technological, regulatory, and market drivers that have shaped its growth from 2010 to 2024.

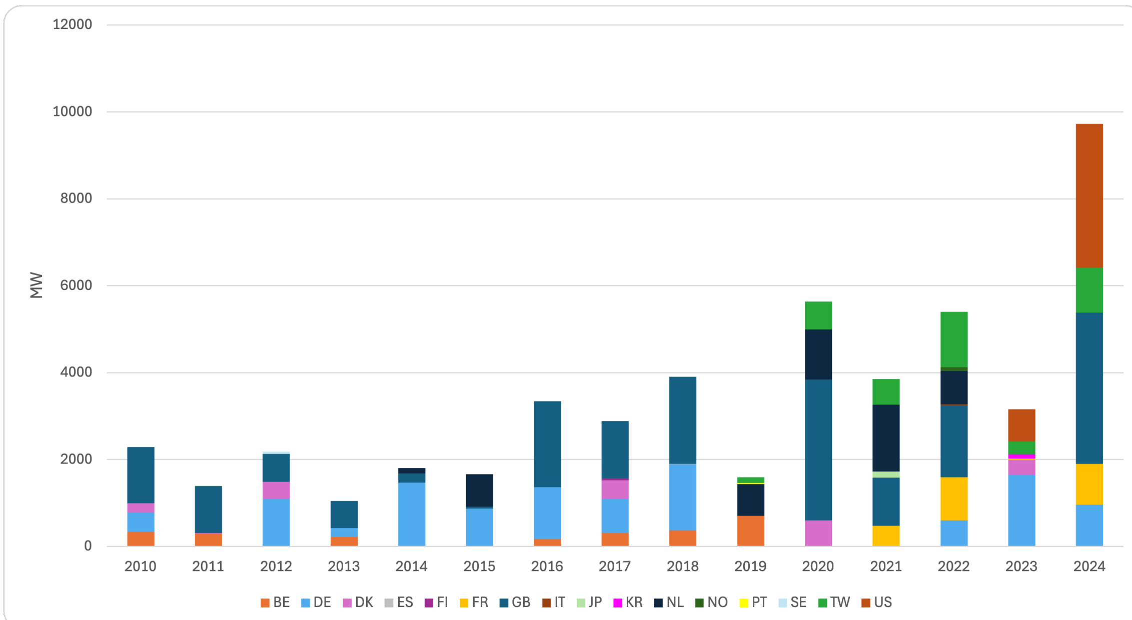


Figure 5.1: Yearly installed offshore wind capacity per country

5.1.1. Expansion and early growth: 2010 - 2015

Before 2010, less than 30 offshore wind farms had been installed, and the total installed offshore wind capacity amounted to approximately 2 GW. This figure increased significantly over this period, reaching over 10 GW installed capacity in 2015, as can be seen in Figure 1.3. The period from 2010 to 2015 has seen a rapid expansion of the offshore wind capacity in Europe, with GB, Germany, and Denmark leading developments, shown in Figure 5.1. These fast developments were primarily

driven by Europe's ambitious renewable energy targets. The European Union's 2020 'climate and energy package', which set targets for member states to achieve 20% energy from renewable sources by 2020 with respect to 1990 levels, was a major driver for growth during this period [77].
The offshore wind market did grow significantly in terms of installed capacity, number of offshore wind farms, and yearly installed capacity. The turbines that were installed during this period have seen a great increase in capacity, from around 2-4 MW turbines that were installed in 2010, to 3-6MW turbines being installed in 2015, as shown in Figure D.3. The average turbine size did not increase very much in the year between 2010 to 2015, as can be seen from the slowly increasing average in Figure D.3. The average turbine sizes did grow from 2.7 MW in 2010 to 4.3 MW in 2015.
Besides a growth in turbine size and number of wind farms, the overall sizes, in terms of capacity of the offshore wind farms increased as well, although not as significantly. The average offshore wind farm capacity grew from around 200 MW in 2010 to just over 250 MW in 2015. It must be noted that these averages also take into account the demonstrator project deployed over the years, which can influence the average wind farm capacity in a specific year. For instance in 2011, 3 out of 8 project were demonstrator projects, where the overall capacity of the project lied between 2 and 11 MW, reducing the yearly average of that year.
As a consequence of the growth of the offshore wind turbines, the foundations had to grow with the turbines and so did the installation sector. The installation of offshore wind turbines became a more specialized and challenging operation. The growth of the offshore wind turbines and the growth of the entire sector can clearly be seen in Figure D.3 and D.2. The growth of the offshore wind sector and the turbines installed, has been a significant driver of developments in foundation installation, which are discussed in great detail in Section 5.2.

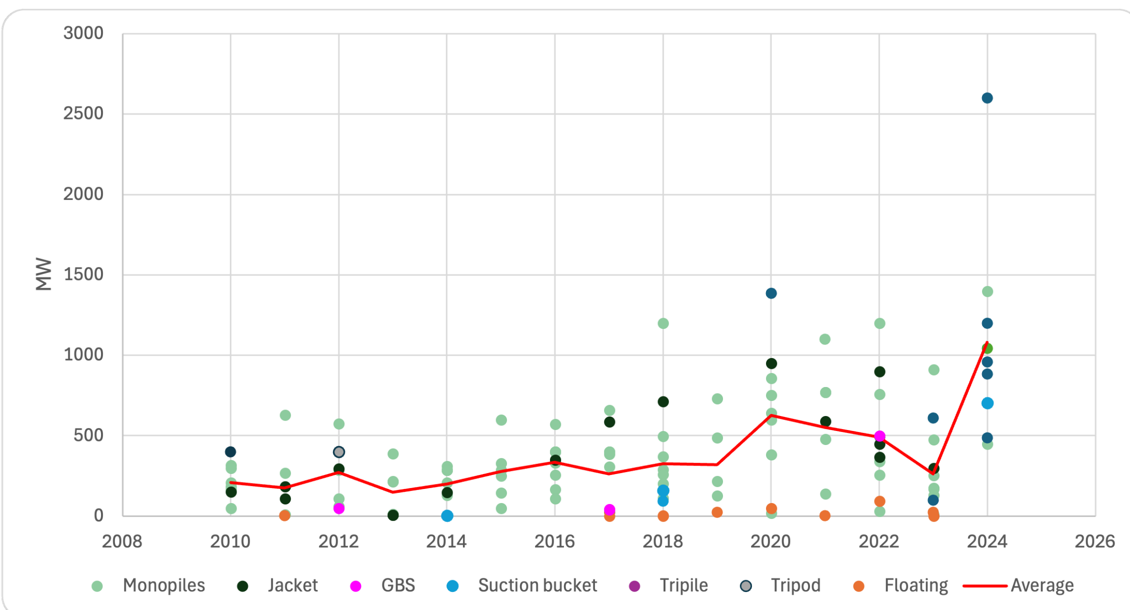


Figure 5.2: Capacity of installed offshore wind farms from 2010 to 2024 per foundation type and the overall yearly average

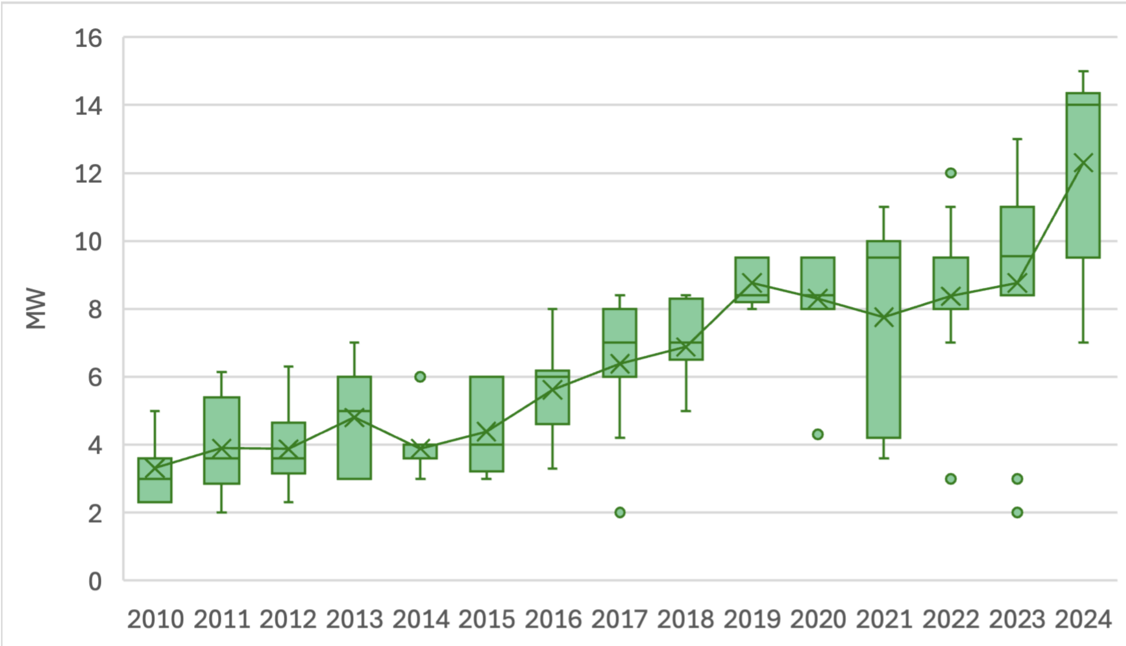


Figure 5.3: Yearly developments in offshore wind turbine capacity (MW) installed between 2010 and 2024

5.1.2. Scaling and technological advancements: 2015 - 2020

During the period from 2015 to 2020, the offshore wind market has seen a significant increase in average turbine capacity, from 4.3 MW in 2015 to over 8 MW in 2020. This contributed to the sharp increase in the annually installed offshore wind capacity from around 1.5 GW installed in 2014, to almost 3 GW installed in 2015, after which the annually installed capacity remained higher than in previous years, with more than 3.5 GW installed in 2019. The market moved away from the smaller turbines, and mainly focused on larger turbines, as can be seen from Figure D.3, which contributed significantly to the market growth. The turbine capacities increased, from the smallest turbine installed in 2015 with a capacity of 3 MW, to the largest turbine installed having a capacity of 9.5 MW in 2019. The average turbine capacities increased significantly as well, from 4,4 MW in 2015 to 8.9 MW in 2019.

Germany, and the UK dominated this period in terms of installed capacity, but several other countries as Belgium and the Netherlands also increased their offshore wind portfolio. Offshore wind became a cost competitive source of electricity, with the first subsidy free tender for the Hollandse Kust Zuid offshore wind farm in 2018. This period was marked by a decline in the levelized cost of electricity for offshore wind. By the end of 2020, some auctions even achieved prices as low as €50/MWh, a substantial drop from the €150-200/MWh range seen in 2010 [78]. This period marked the full transition from government-supported projects to market-driven deployments, with private investments playing an increasingly significant role.

5.1.3. Market developments from 2020 - 2024

By 2024 the offshore wind market has reached a total installed capacity of over 35 GW, with the continuing dominance of Europe through large scale projects as the 1.4GW Sofia offshore wind farm of which the foundations installation has begun in 2024. The focus still is on scaling turbines, and the current developments aim at increasing turbine capacity to 15+ MW. The offshore wind market is also expanding in Asia and the US, with several wind farms in development. In Figure 5.1, it can be seen that the projects in the US, like Vineyard in 2024, are a large contributor to the overall installed capacity in this year, but what remains important to note, is that these years are not the operational dates of the wind farms, but are marked in the year in which the foundation installation works did began. Most of the installations presented in the charts for 2024, are therefore not yet fully installed and operational, but rather have started foundation works.
The European green deal, launched in 2020, set the stage for further offshore wind growth by targeting climate neutrality by 2050 and increasing the renewable energy target of the EU, from 32 % to 42.5 % by 2030 [1].
The global market began to diversify during this period. Taiwan became a key player in Asia, with its government target of 5.5 GW of offshore wind by 2025, which attracted major European developers like Ørsted [79].

5.1.4. Future outlook: 2024-2030

Looking forward, the offshore wind market is expected to grow exponentially, driven by the ambitious renewable energy targets and continued drive to lower LCOE. Europe is expected to remain the largest market, with targets to have up to 60 GW of offshore wind capacity installed by 2030 [1].

A large part of the offshore wind developments will take place in the North Sea, and it will become a hub, with cross border projects and grid integration becoming a reality, with the Esbjerg cooperation, between Denmark, Germany, the Netherlands, and Belgium [80]. The four countries agreed to have a combined integrated installed offshore wind capacity of 65 GW in 2030, and 150 GW by 2050. The goal of the cooperation between the four countries, is the fast, and coordinated expansion of the offshore wind power in the North Sea [81].

Asia will also account for a large portion of the global capacity expansion, with targets of emerging markets as Japan, Taiwan and South Korea. Which also have ambitious offshore wind capacity goals. A relatively large portion of these installations will be floating wind projects, due to the large water depths encountered near shore. The US is aiming to achieve 30 GW by 2030, driven by federal targets and state level targets, particularly in New York and Massachusetts [82].

Despite the promising growth of the sector, several challenges remain present. Supply chain bottlenecks, as vessel shortages, are expected to constrain the pace of deployment [10].

5.1.5. Key drivers of developments of the offshore wind market

Environmental regulations have been a key factor in shaping the evolution of offshore wind development, particularly in Europe. Noise mitigation during pile driving, seabed disturbance, and impacts on marine life have become significant concerns as offshore wind farms expand, and move to deeper waters. Countries like Germany have introduced strict noise regulations, which have driven the adoption of noise mitigation and alternative driving technologies, like bubble curtains and vibratory pile driving.

5.2. Evolution of foundations

Over the past decade, the offshore wind industry has seen a rapid evolution of foundation types and installation methods. These changes have been driven by the scaling of turbine sizes, deeper installation sites, and environmental regulations. This section focuses on the developments of foundations, highlighting key advancements in installation techniques.

This section will examine these developments through the periods:

- 2010-2015: Expansion and scaling of offshore wind
- 2015-2020: Scaling for larger turbines and deeper waters
- 2020-2024: Technological innovation and regulatory adaptation
- 2024-2030: Future developments

5.2.1. Overview of foundation developments from 2010 to 2024

Before diving into each period, a quick comparison of the key foundation types that have been used since 2010 is given in table 5.1. The table gives a quick overview of the primary foundation types used over the years. It show the number of times a certain foundation type has been used in the period between 2010 and the present, together with important metrics, as installation depths, weight, and turbine capacities. From the table it quickly becomes clear what the favorable foundation type is, and which foundation types have been used less often. In Figure 5.4, the use of each foundation type throughout the years can be seen. It shows the dominance of the monopile, and the increase in use of jacket foundations in later years. In some year, as for instance in 2019, the number of installed foundations appear to be lower than in some industry reports. The year in which the first foundation was installed for the wind farm, has been used as the installation date for the entire wind farm, since this report focuses on the installation of the foundations. Therefore it would not make sense to use the date on which the wind farm came online, or was inaugurated.

Foundation type	**Number of windfarms**	**foundations installed**	**Depths (m)**	**Weight (T)**	**Turbines (MW)**
Monopile	93	5840	2-55	200-2100	3-15
Jacket	19	969	20-55	450-2000	4-14
Gravity based	4	102	10-40	2000-7500	2-7
Tripod	2	120	30-40	900	5
Tripile	1	80	40-45	500	5
Suction bucket	4	146	30-58	850-2000	4-10
Floating	12	34	40-300	2000-3000	3-10

Table 5.1: Comparative overview of key foundation types used from 2010 to 2024

Over the years, offshore wind farms have moved to deeper waters and, and turbines have grown in size. This is valid for each foundation type, however, not all foundation types have seen as large

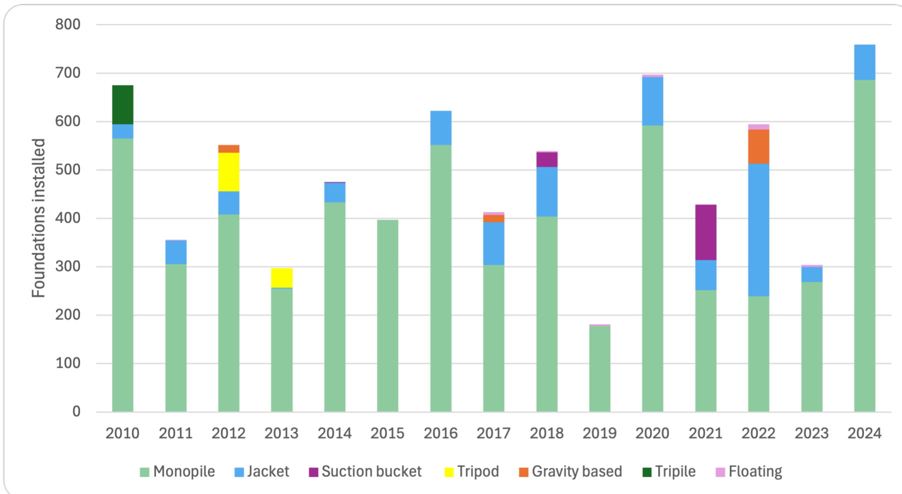


Figure 5.4: Number of foundations installed in each year

developments in each area. In Figures 5.5, 5.6, and 5.7, the yearly averages of all foundation types deployed during the period 2010 to 2024 are shown. A clear increase in average turbine capacity, foundation weight, and depth can be seen, albeit not a very large increase in some cases. Since some foundation types have not been installed in every year, the evolution can not be followed in great detail, as can be done for monopiles, since they are by far the most installed foundation type. From Figure 5.6, it can be seen that the increase in average turbine capacities is somewhat independent of foundation type used, and follow the same trend upwards. This can be related to the general increase in turbines developed over the years. All the foundation types have seen a slight increase in installation depths over the years, with depths of floating foundations up to 300 meters, which can be seen in Figure 5.7. More detailed figures of the developments of each foundation type can be found in Appendix D.

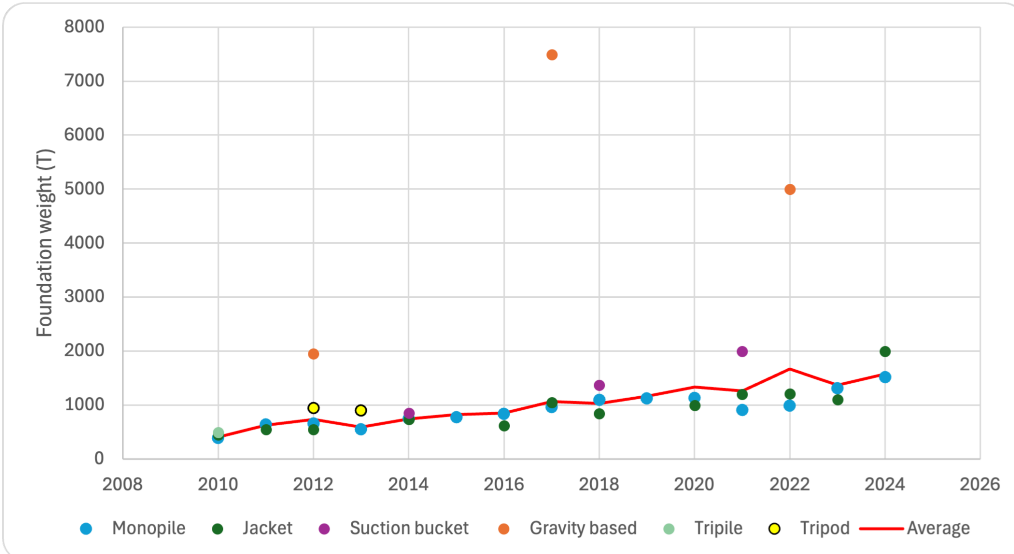


Figure 5.5: Yearly average weight per foundation type from 2010 to 2024

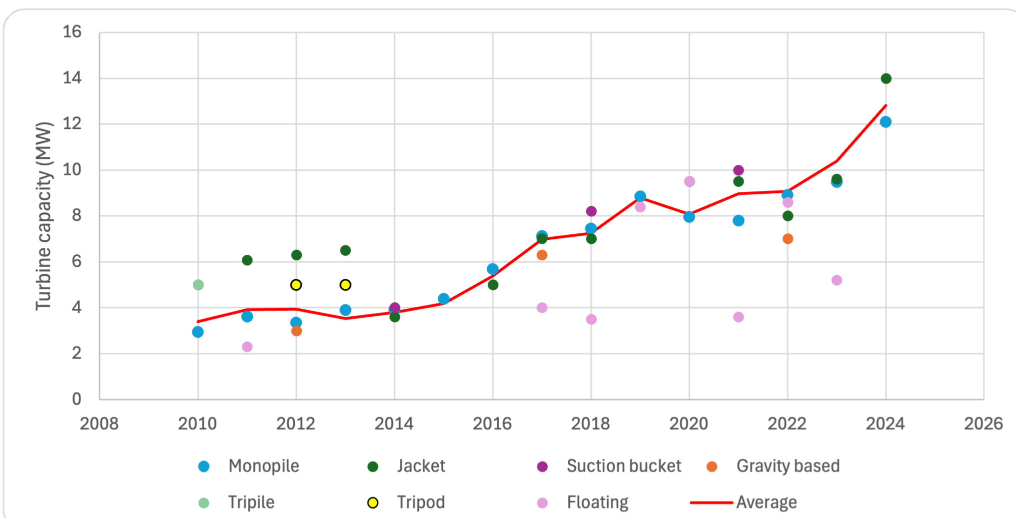


Figure 5.6: Average yearly turbine capacity of foundation types installed from 2010 to 2024

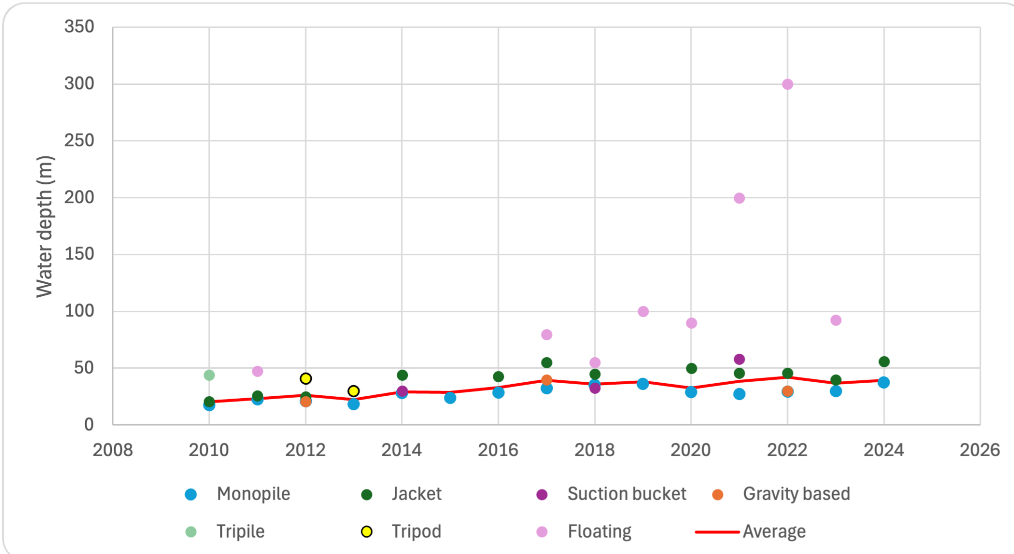


Figure 5.7: Average yearly water depths of offshore wind farms installed per foundation type from 2010 to 2024

5.2.2. 2010-2015: Expansion and scaling of offshore wind

During this period, the industry experienced rapid growth, driven largely by developments in Europe. Key countries like Germany, the UK, and Denmark led the expansion, with turbine sizes growing from 2,3 MW to 6 MW. The MOST USED foundation type was the monopile, which increased in size to accommodate the larger turbines.

Foundation type	foundations installed	Depths (m)	Weight (T)	Diameters (m)	Turbines (MW)
Monopile	1967	2-35	200-900	4-6.5	2.3-6
Jacket	169	20-45	450-750	-	3.6-7
GBS	16	10-20	1950	-	2.3-3
Tripod	120	30-40	900-950	-	5
Tripile	80	40-45	500	-	5
Suction bucket	1	30	850	-	4
Floating	2				

Table 5.2: Evolution of foundations between 2010 and 2015

Monopiles

The offshore wind industry saw its first significant scaling efforts between 2010 and 2015. Monopiles dominated this time period, due to their simplicity, cost effectiveness, and scalability, as can be seen from Figure 5.4. As Turbine capacities increased, so did the dimensions of monopiles. The diameter of monopiles grew from 4 to over 6 meters by the end of this period. Figure 5.8 gives a graphical representation of the size increase of monopiles over the years, and Figure 5.9c shows the increase in monopile diameters over the years. An example of an offshore wind farm utilizing these larger monopiles, is Borkum Riffgrund 1, where 76 foundation piles with a diameter of 6 meters were installed in 2014. Monopiles increased in dimensions, in weight, and their installation depths increased. In Table 5.2 an overview of the developments in monopile sizes is given.

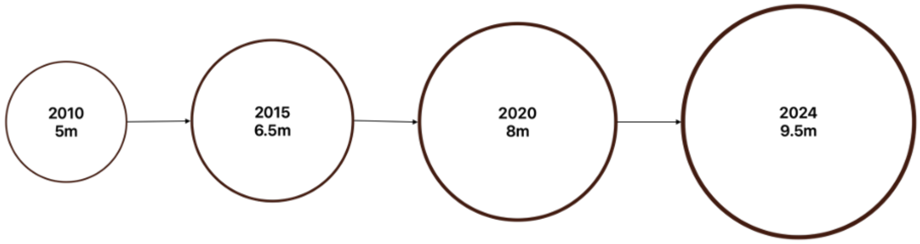
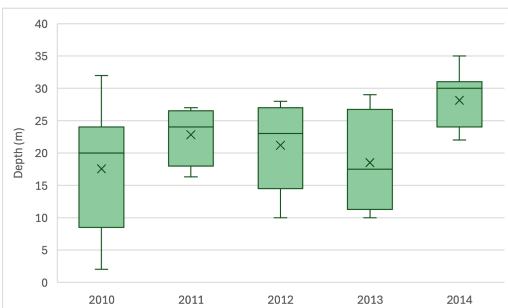
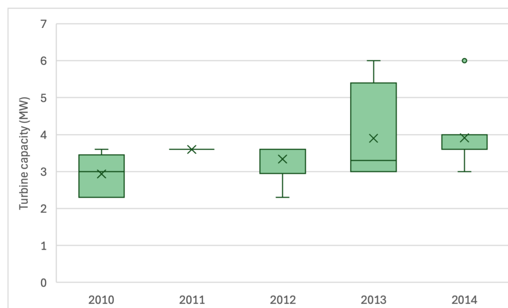


Figure 5.8: Average size evolution of monopile foundations from 2010 to 2024

In Section D.2 of Appendix E, more detailed figures of the yearly developments in terms of monopile characteristics are given. These Figures consist out of Boxplots of the developments in terms of installation depths, size and weight evolution.

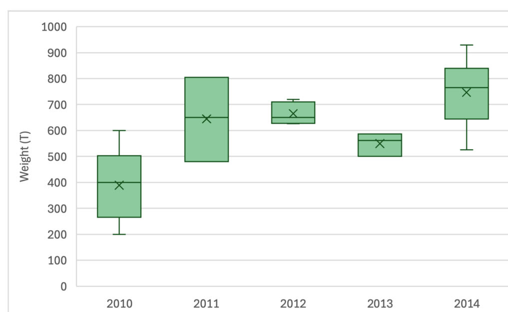


(a) Water depths



(b) Turbine capacities

(c) Monopile diameters



(d) Monopile weights

Figure 5.9: Evolution of monopiles installed from 2010 to 2015

As turbine sizes increased, especially with the deployment of larger turbines in deeper waters, the structural limits of monopiles were tested. Monopile foundations had to be made larger and thicker, which in turn increased their weight and required more advanced and powerful installation tools. Despite initial concerns that monopiles would soon be phased out due to water depth limitations, the foundation type showed its resilience, and was pushed even further and remained the preferred foundation type.

In the period between 2010 and 2015 the majority of the installed monopiles have been monopile with transition pieces, as can be seen in Figure 5.10. The TP-less monopiles was introduced for the first time in this period, and was only used for one offshore wind farm. The first project where a TP-less monopile was used was at the Eneco Luchterduinen offshore wind farm.

Figure 5.10: Transition piece type used between 2010 and 2015

Jackets

While monopiles dominate shallow to intermediate water depth installations, jacket foundations were designed for deeper water locations, and offered greater stability due to their wider construction. Jackets have been installed in water depths of 15 to 45 meters. The first jacket was installed in 2009, at the Alpha Ventus one offshore wind farm. This installation was a test for the offshore wind market in Germany, as this was the first German offshore wind project. The wind farm used large capacity turbines of 5 MW for that time period, in water depths of 30 meters. After the first successful installation, several other installation have used jacket foundations over the years. At the first offshore wind farm where jackets were used, the foundations were anchored by using the post piling method, as described in Figure 4.12, but after this installation this method has only been used once at a full scale offshore wind farm. In 2012, this method was applied once more at the Nordsee Ost offshore wind farm, but after this installation all installations preferred the pre-piling method. Early deployments in projects such as the Alpha Ventus offshore wind farm, showcased their potential for deeper installations, in water depths beyond 30 meters, as an alternative to monopiles. In Figure 5.11, the depth evolution of jacket foundations can be followed, but due to the lower deployment rate than monopiles, only a handful of installations can be presented and analyzed. The installation depths increased over the years, from 20 to 30 meters in 2010, to installation in water depths up to 45 meter in 2014.

Jackets also were more suitable for sites with higher wave and current loads due to their reduced hydrodynamic profile. However, their complex fabrication process, which included welding of the multiple sections, increased manufacturing costs and timelines, which worked in favor of the less complex monopile.

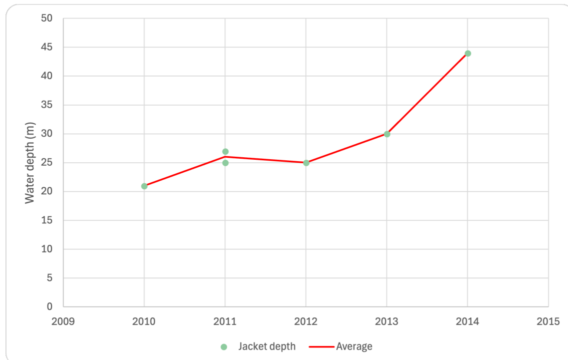


Figure 5.11: Water depths of jackets installed from 2010 to 2015

Other foundation types

Other foundation concepts have been developed and used for offshore wind farms, but these foundations have only been used a number of times, which makes it difficult to evaluate the evolution of the foundation concept in terms of installation methods used, weight developments, or other changes in the design. These foundation concepts can mainly be evaluated on the incentives why the foundation type was developed in the first place, and what the causes were of the abandonment of the foundation concept.

Tripod foundations have only been used a number of times. The first tripod foundation was installed in 2009, in Germany, at the Alpha Ventus offshore wind farm. Six tripod foundations were installed, besides the six jacket foundations, designed for 5 MW turbines. In 2012 and 2013 two more offshore wind farms moved towards tripod foundations, both again using 5 MW turbines. The tripod foundation concept was designed for deeper waters where monopiles were perceived unusable. In total, only 126 tripod foundations have ever been installed, divided over three installations. The foundation type was abandoned, because it was deemed less competitive in comparison with monopile or jacket foundations. The weight of tripod foundations was too high in comparison to that of jackets, and the manufacturing process was more complex than the manufacturing process of monopiles [83]. Tripod foundation have only been used for 5 MW turbines, and have been installed in water depths of 30 to 40 meters, and weigh 700 to 900 tonnes. At the Alpha Ventus offshore wind farm, 6 tripods were installed together with 6 jackets, both designed for the same turbine, in similar water depths. When comparing the two foundation types with each other, the weight of the jackets installed, was approximately half of the weight of the tripod foundation.

Tripile foundations were tested at the BARD offshore wind farm in 2012. These alternative foundations types were introduced to open the offshore wind market to deeper waters, where the monopile was thought not to be suitable. Due to pushed perceived boundaries of what depth were capable with monopile foundations, the tripod and tripile foundations disappeared from the market. The tripile foundation was only used for the BARD wind farm only, and not more often.

The foundation weighed just below 500 tonnes, and was designed for a 5 MW turbine in water depths of up to 44 meters. When we compare these values to a monopile designed for approximately the same conditions, the weight of the tripile foundation is significantly lower, up to almost two times.

Gravity based foundations were deployed only once in this time period, at the Karehamn offshore wind farm. Their reliance on seabed preparation and high weight made them suitable for specific seabed conditions, but they are limited to relatively shallow water depths due to the weight of the foundations. The foundation used for Karehamn offshore wind farm were designed for 3 MW turbines and were installed in water depths of 21 meters. And even for this relatively small turbine and shallow water location, the foundations weighed almost 2000 tonnes, emphasizing the immense weighed of the foundation type.

Suction bucket foundations were developed to offer an alternative to monopile foundations where seabed conditions, or noise limitations, did not allow for monopile foundations. The foundation type has been deployed at Borkum Riffgrund 1 offshore wind farm for the first time, where one test foundation was installed. The foundation weighed 750 t, and was transported to the offshore location and installed by the installation vessel Pacific Orca.

Key drivers

- Regulatory Support: European governments, particularly in Germany, the UK, and Denmark, provided significant subsidies and incentives for offshore wind development. This regulatory support helped push the rapid expansion of offshore wind farms, leading to an increased demand for innovative foundation solutions.
- Environmental Impact and Noise: Early environmental regulations around noise pollution during pile driving began to take shape. The German government, in particular, began with the implementations of rules requiring noise mitigation systems, such as bubble curtains, to protect marine ecosystems. These requirements drove research into alternative low noise foundations, and installation methods, such as suction bucket foundations, and vibratory pile driving.

Limitations and challenges

- The scaling of monopiles led to manufacturing bottlenecks, as production facilities were not initially designed to handle the increased steel requirements or the complex logistics of transporting the larger structures.
- As foundation increased, the need for larger installation vessels became more pressing. In the beginning of the period, around 2010, few installation vessels had the crane capacity and deck space required to transport and install the larger foundations.

5.2.3. Further scaling foundations [2015-2020]

As the industry moved beyond 2015, deeper water installations and larger turbines began to present new challenges. The period from 2015 to 2020 saw an increasing shift towards deeper installations, requiring more advanced foundation designs. Jacket foundations, gravity-based structures, and, in some cases, suction buckets were selected to meet the demands of deeper water installations, and more challenging conditions.

Foundation type	foundations installed	Depths (m)	Weight (T)	Diameters (m)	Turbines (MW)
Monopile	1835	7-40	350-1500	5-8.4	3-9.5
Jacket	260	40-55	600-1000	-	5-7
GBS	15	25-40	7500	-	4.2-8.4
Suction bucket	31	25-35	950-1800	-	8-8.4
Floating	11	40-120	10000	-	2-8.4

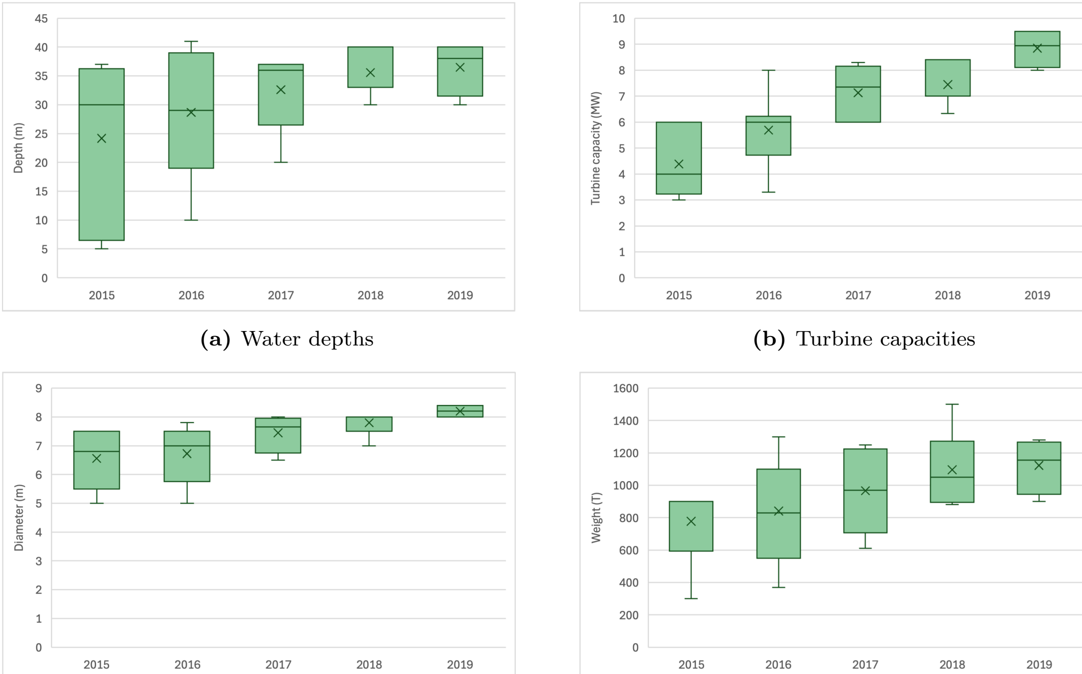
Table 5.3: Evolution of foundations between 2015 and 2020

Monopiles

Monopiles remained the foundation type of choice in this period, with a market share of over 80 % with respect to the other foundation types. Monopiles were predominantly used for water depths up to 40 meters, and the installation depths increased from an average installation depths of approximately 25 meters in 2015, to an average installation depth of over 35 meters in 2019, as shown in Figure 5.12a. Besides a movement to deeper waters, the offshore wind turbines also experienced a growth, with an increase in average turbine size from 4.4 MW in 2010 to 9 MW turbines just before 2020. As turbine sizes increased, the monopiles again needed to follow, and grow significantly in both diameter and length to provide the necessary structural support. By the end of this period, offshore wind projects were using 8 to 9.5 MW turbines with monopiles reaching diameters of up to 7 to 8.4 meters and weighed already more than 1000 tonnes, as can be seen in Figure 5.12b and 5.12c. Besides the increase in diameter and weight, not many changes have been made to the design of the foundation type. The biggest change in monopile design is arguably the movement away from grouted foundations, to bolted transition pieces, and eventually to TP-less foundations. The advantage of a TP-less design is the reduction in offshore operations. One negative effect of the movement to TP-less monopile designs, is the increase in weight of the structure. TP-less monopiles are 10 to 20 meters longer than monopiles with transition pieces, when comparing for the same location and load requirements. In Figure 5.13, the number of TP-less monopiles that have been installed between 2015 and 2020 is given together with the number of foundations that still used a transition piece. It can be concluded that the number of foundations with transition pieces remains higher in each year, with the TP-less monopile only being used at two wind farms.

Jackets

Jacket foundations have been installed in increasingly deeper waters over the years, as can be seen in Figure 5.14. In the early days of the offshore wind sector, it was thought that the depth limits of the monopile were around 30 meters, and that jackets would become the preferred foundation type for deeper waters. If we look back, and compare the figures of the number of installed jackets to the installed monopiles, we now know otherwise. Despite the advantages of jackets in deeper waters, the foundation type remained expensive to manufacture and install. The multi-stage installation process, requiring both piling and jacket lifting, and the complex fabrication process, made them less appealing compared to monopiles, even in intermediate water depths. The complex fabrication process increased the cost, and the depth boundaries of monopiles were pushed further and further, and it remained the most economical option. This has led to the somewhat low deployment numbers of jacket foundations in the offshore wind sector. In this time period, only 4 offshore wind



(a) Water depths

(b) Turbine capacities

(c) Monopile diameters

(d) Monopile weight

Figure 5.12: Evolution of monopiles installed from 2015 to 2020

farms were installed that made use of jacket foundations. The four offshore wind farms were located in water depths of around 40 to 55 meters, and made use of 5 and 7 MW turbines, and weighed between 600 and 800 tonnes. In Figure 5.14 the installation depths of the jackets are shown, but due to the low installation numbers, no clear trend or conclusion can be drawn from these figures. The installations took place in water depths between 40 and 55 meters, were designed for 7 MW turbines, and they weighed between 600 and 850 tonnes. In this period one alternative innovative type of jacket was tested at the Nissum Bredning offshore wind farm. The foundations consisted out of jackets, with a concrete transition piece, of which four foundation were installed. The goal of the foundation type was to lower cost.

One large change in the way jackets and their pre-piles were installed was introduced in this period. As mentioned in Section 4.2, the foundation type has two different piling methods that have been used throughout the years. The pre-piling, and the post-piling method. Innovations in piling techniques, such as the introduction of arguably one of the largest innovations in jacket piling technology, helped reduce installation times. A hanging pre-piling template under the deck of the jack up vessel Apollo, first deployed at Moray East offshore wind farm, removed the need to lift the pre-piling template on deck with the crane, reducing the number of offshore lifting operations, and increasing installation speeds.

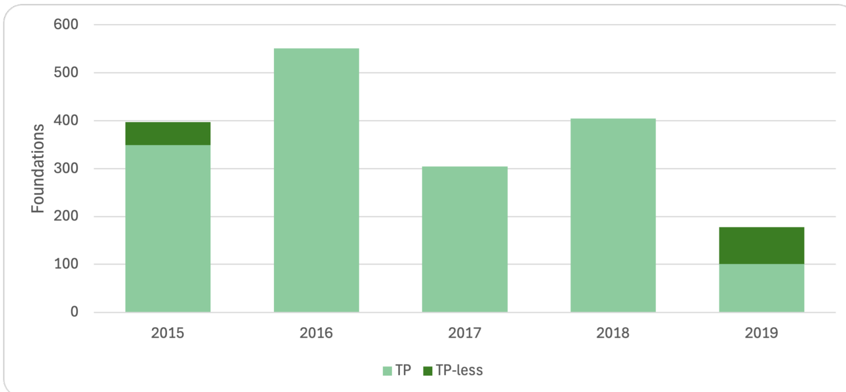


Figure 5.13: Transition pieces used between 2015 and 2020

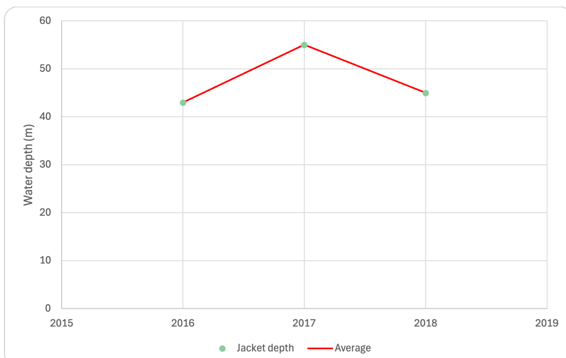


Figure 5.14: Depths of jacket foundations installed between 2015 and 2020

Suction bucket foundations

The foundation type was used at two more offshore wind farms in 2018, EOWDC and Borkum Riffgrund 2. Twenty 1400 tonnes SBJ foundations, designed for 8 MW turbines, were transported to, and installed at Borkum Riffgrund 2, by installation vessel Innovation. The vessel shuttled between the offshore location and the port, and transported one foundation per trip, due to the large footprint of the foundations. The Borkum Riffgrund 2 location is approximately 30 kilometers off the coast, and the foundations have been installed in water depths of around 30 meters.
At EOWDC OWF, 11 SBJ foundations, designed for 8.4 MW turbines, have been transported and installed by Asian Hercules 3 vessel, also in water depths of around 30 meters. For this installation, once again the shuttling method by the installation vessel was chosen as the preferred transportation method, since this location was only 2 kilometers off the coast. Due to the low number of installations that made use of this foundation type, no figures have been included, since no clear trends or conclusions can be drawn from a figure with only two data points.

GBF

Gravity based foundations have mainly been used in the early days of the offshore wind market, with most of the installations before 2010, and is not often used in recent years, as can be seen in

Figure 5.3. The foundation type has evolved over the years, and three main generations have been identified by Esteban *et al.* [56], which are shown in Figure 5.15. In the period between 2015 and 2020, gravity based foundations have not been used extensively, and all installations made use of the third generation of GBS in this period, shown at right in Figure 5.15. Only two offshore wind farms used the foundation type, both in 2017, and both times for small scale projects of 42 MW in total capacity. The foundations for the Blyth project were designed for 8.4 MW turbines, and water depths of around 40 meters, and had an ballasted weight of 7500 tonnes. Due to the movement to larger turbines and to deeper waters, these foundations increased significantly in weight with respect to previously installed gravity based foundations, weighing 'only' 2000 tonnes.

The installation methods of gravity based foundations did not change much over the years. One of the largest changes in installation methods for this foundation type, is the innovative float and submerge installation method introduced at the Blyth offshore wind farm. This installation method was introduced to remove the need for heavy lift vessels to transport and install the foundations, due to their significant weight, with the foundations used at the Blyth wind farm , weighing 7500 tonnes. The several manufacturing methods mentioned in 3.4, were not used in any chronological order, so cannot be really be labeled as a development, but rather as different possible manufacturing methods.

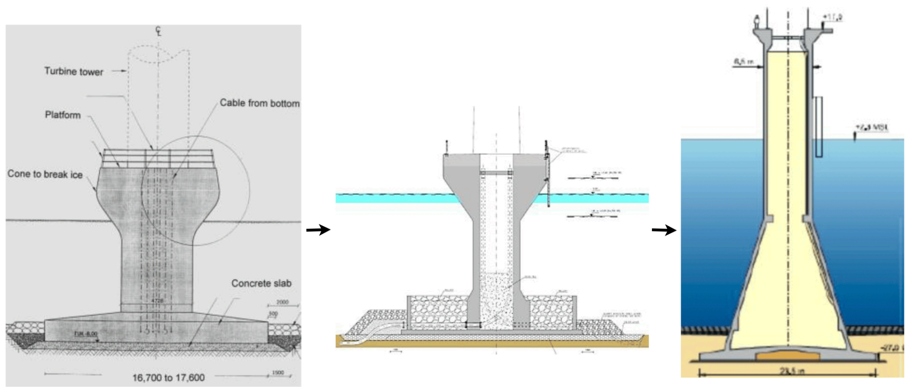


Figure 5.15: Three generations of gravity based foundations

Floating wind

One of the most revolutionary developments in offshore wind foundation technology is the movement to floating foundations. These foundations enable wind turbines to be deployed in water depths exceeding 60 meters, opening up vast new areas for wind energy development that were previously inaccessible due to seabed conditions or prohibitive costs of bottom fixed installations.

During the period between 2015 and 2020, twelve floating foundations have been installed, with most of the installations being small scale demonstrator projects. Floating foundations are still in the early stages of developments, with only two windfarm where multiple foundations have been deployed. At the Hywind Scotland Wind farm, five 6 MW turbines have been installed in water depths of 120 meters in 2017. And at the Windfloat Atlantic wind farm, three 8.4 MW wind turbines have been installed in water depths of around 100 meters. This shows the small scale of the projects in this period, with only 12 turbines installed in total in this period.

5.2.4. 2020-2024: Technological innovation and larger turbines

As the industry entered the 2020s, offshore wind turbines grew significantly larger, pushing the boundaries of foundation technology. The industry began to accommodate turbines of 12 MW and even up to 15 MW, which required new innovations in both monopile and jacket foundations. In Table 5.4 an overview of the developments in foundations between 2020 and 2024 is given. It can be seen that the monopile remains the most installed foundation type, but that almost twice the number of jacket foundations have been installed in between 2020 and 2024, in comparison to the previous period.

Foundation type	**foundations installed**	**Depths (m)**	**Weight (T)**	**Diameters (m)**	**Turbines (MW)**
Monopile	2038	4-54	500-2100	6.5-10	3-15
Jacket	540	30-55	1000-2000	-	8-14
Gravity based	71	25-30	5000	-	7
Suction bucket	114	40-58	2000	-	10
Floating	21	60-300	3000-5000	-	8-9.5

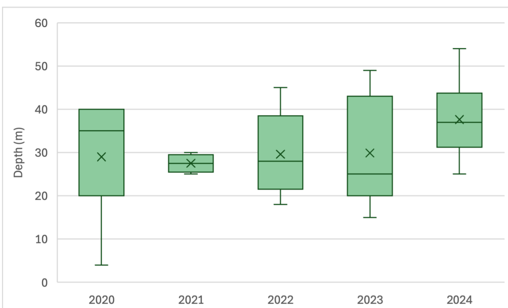
Table 5.4: Evolution of foundations from 2020 to 2024

Monopiles

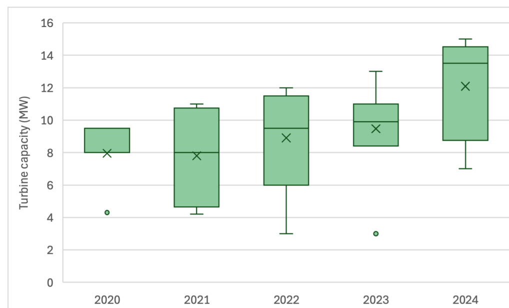
Figure 5.16 shows the evolution of monopile foundations in terms of water depths, turbine capacities, pile diameters, and weight, from 2020 to 2024. During this period monopiles grew even more in size, up to almost 10 meters in diameter. Turbine capacities ranged from some installations with 4 MW turbines in the beginning of the period, with some already nearing 10 MW, and increased to 10+ MW turbines becoming the norm and even to 15 MW turbines in 2024. As turbines approached 15 MW, the industry saw the introduction of monopiles with diameters of 9 to 10 meters, requiring larger scale, higher capacity lifting and installation technologies. These monopiles pose significant logistical challenges in terms of manufacturing, transportation, and installation.

Figure 5.17 shows the number of monopiles that have been installed between 2020 and 2024, with the type of transition piece that has been used. It can be seen that the number of installation with TP-less foundations is increasing with respect to the previous periods, but that the design remains less popular that the foundation with a separate transition piece. The movement to TP-less foundations can improve the installation efficiency and improve cost, but the foundations will be longer and up to 250 to 300 tonnes heavier than a 'standard' monopile (without its transition piece) [19].

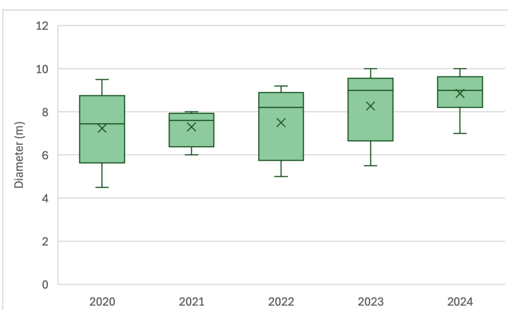
Figure 5.17: Transition pieces used from 2020 to 2024



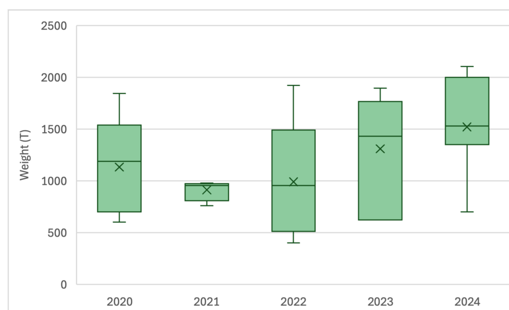
(a) Water depths



(b) Turbine capacities



(c) Monopile diameters



(d) Monopile weight

Figure 5.16: Characteristics of monopiles installed from 2020 to 2024

Jacket foundations

Jacket foundation gained more traction in recent years, which can be seen from the number of installed jacket foundations in this period, shown in table 5.4. Jacket foundations always had issues with manufacturing scalability, due to the complex process of welding the multiple components together. This introduces more potential weak points, increasing the inspection times. Recent improvements in manufacturing processes have mitigated these issues, increasing the mass manufacturing possibilities for jacket foundations [84]. As can be seen from Figure 5.18, the foundation type has been used several times after 2020, in water depths ranging from 30 to 55 meters, and were designed for turbines ranging from 8 to 9.5 MW. The Foundation also increased in weight in comparison to the previous period, and ranged from 1000 tonnes, to 1200 tonnes, with one exception. The foundations for the Hai Long two and three offshore wind farm, weighed 2000 tonnes. These jackets were designed for 14 MW turbines, explaining the weight increase.

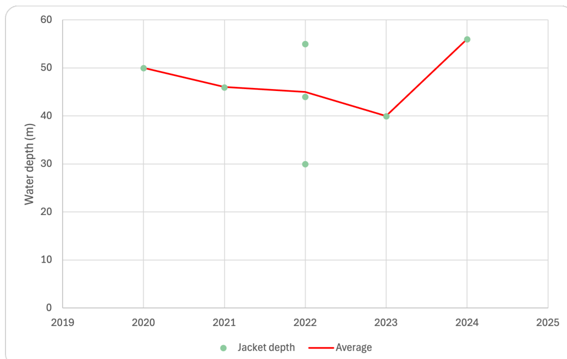


Figure 5.18: Jacket depth 2020-2024

Alternative foundation types

Suction bucket jacket foundations were selected once more as the preferred foundation type, in 2021. 114 2000 tonnes SBJs were installed at the Seagreen offshore wind farm, designed for 10MW turbines. This installation also set the record for the deepest bottom-fixed offshore wind installation, with a water depth of 58 meters. For this installation, barges were selected as the preferred transportation method for the foundations to the offshore installation location. Each barge carried 3 foundations per trip, and multiple barges were deployed. The foundation were installed by SSCV Saipem 7000. This installation showed the possibility of the large scale deployment of suction bucket jacket foundations.

Floating foundations entered commercial-scale deployment in the period between 2020 and 2024, with Hywind Tampen being the first large scale operational floating offshore wind farm. The project demonstrated the commercial viability of floating foundations in waters depths greater than 100 meters. Floating foundations offer the potential to unlock offshore wind potentials in deeper waters, where bottom fixed foundation are not possible.

The primary challenges for floating foundations remains their cost, and scalability. Floating foundations require advanced mooring systems that can withstand harsh ocean conditions. However, the benefits of deploying wind turbines in deep waters, where wind speeds are higher and more consistent, makes floating wind an attractive option for the future.

Gravity based foundations were deployed once in this period, at the Fécamp offshore wind farm in 2022. The installation used 7 MW turbines in a maximum water depth of 30 meters, and the foundations weighed 5000 tonnes. It can be said, that gravity based foundations are therefore more suited for relatively shallow water depths, and are also not really suited for the current or next generation offshore wind turbines, which will continue to grow in size. The larger loads encountered with the current wind turbines, requires even larger and heavier gravity based structures than the last two installed projects, surpassing the lifting capacity of most installation vessels. During interview 9, it was mentioned that studies for future wind farms with gravity based foundations have been performed, but that the weight of these foundations would be in excess of 10000 tonnes, significantly limiting the manufacturing, transportation and installation possibilities. It was mentioned that only two transportation vessels are currently in existence that would be able to transport such structures. Manufacturing facilities would have to be built near locations were the foundation type would be used, since long transportation ways would amount to an installation period of up to four years.

Tripod foundations have gained some interest in recent years in the form of a combined study performed by Sif and Smulders. The two companies worked on the revival of the foundation concept, to overcome the current challenges the offshore foundation market is facing [83]. With the constant growth of turbines, and the movement to even deeper waters, the question remains, what the limitations of monopiles will be, and what alternative solutions there are. Although monopiles might not encounter structural constraints, it might be the case that it will no longer be feasible to use and install monopile foundations, due to their dimensions for the future 20+ MW turbines. Therefore the two companies collaborated on the 'revival' of the tripod foundation, to serve as an alternative to monopiles. The study showed a potential decrease in weight of the foundation type, but came to the conclusion that the foundation type would still be heavier than a jacket foundation, designed for the same load characteristics [83]. The study concludes with the statement that tripod foundation will be a niche product, for specific projects that encounter challenging soil conditions, where monopiles cannot be used, or where factors like ice loading excluded the use of jacket foundations [83].

5.3. Evolution of installation vessels

The vessels used for foundation installation have evolved over the years to meet the demands of larger turbines and larger foundation designs. This section answers the question how vessels have evolved over the years. It will look into previous installations and what vessels are used during the installation phase. To be able to track developments in terms of vessels, a timeline will created of all vessels that were deployed during previous installations. These vessel developments will be quantified in terms of capacity of the vessel, to be able to answer the question of what is possible at what moment in time. This will in terms lead to insights in what will be possible with the current ships in the next years and what cannot be accomplished with the current fleet.

By analyzing all previous installed offshore wind farms in the period from 2010 to the present, all installation vessels used during the installation of offshore wind turbine foundations have been identified. In Appendix E, a track-record of the vessels deployed during the foundation installation procedure can be found. This vessel track record resulted in a complete list of the vessels used for the installation of foundations at previously installed offshore wind farms. From this list, a vessel database is created, this database can be found in Appendix C. It consists of the vessels deployed during the installation of foundations, with their accompanying most interesting figures, as vessel type, lifting capacity, vessel dimensions, and deck capacity. In Appendix E, the deployment of specific vessels is also given and categorized per foundations type. It shows which vessels are responsible for the majority of the installations, and which foundation type they installed.

This section traces the vessel developments from 2010 to 2024, and projects future trends. Vessel evolution is categorized into three main periods based on significant advancements in technology and industry needs.

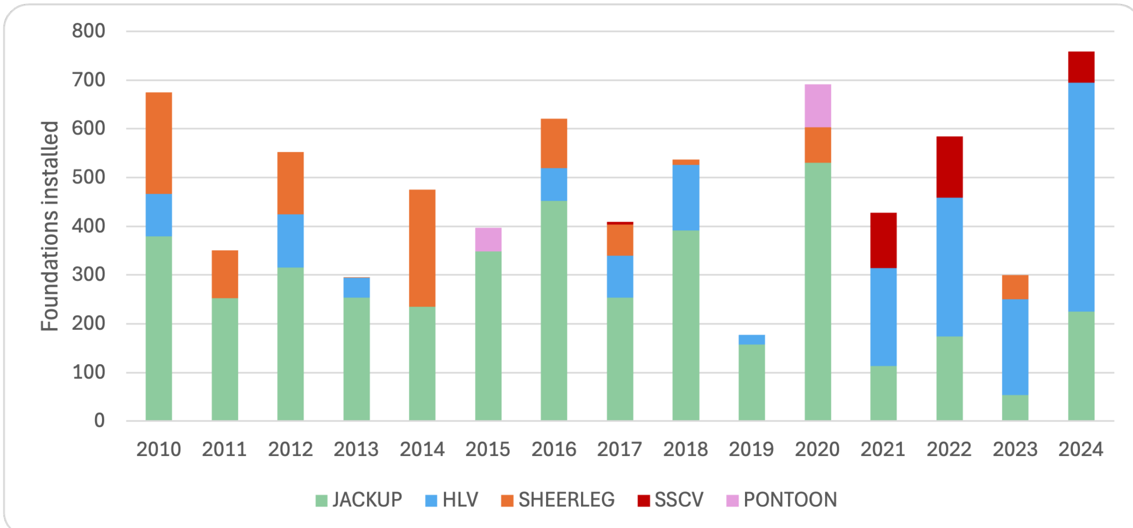


Figure 5.19: Foundations installed per vessel type in each year

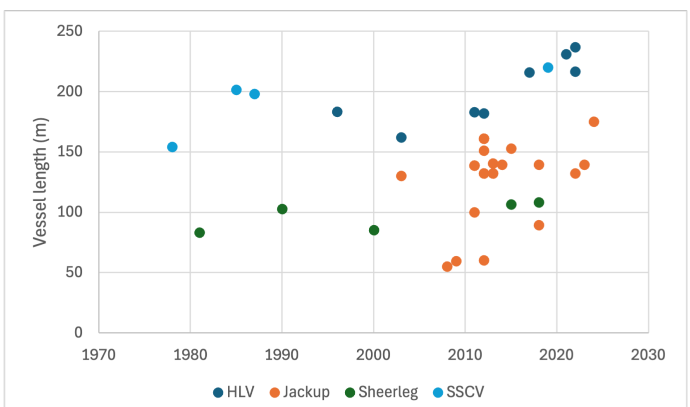


Figure 5.20: Length evolution of installation vessels in their respective launch year

5.3.1. Overview of vessel evolution

Figure 5.21, gives graphical representation of the evolution that the vessel used for the foundation installation have gone through. It Figures are scaled relatively to each other, to be able to make a visual comparison between previous and current installation vessels. The vessels have gone through a large evolution, in terms of vessel type, size, technologies, and crane capacities. In Table 5.5 the evolution of crane capacities is presented, which shows an increase over every period in terms of lifting capacities and foundation weights.

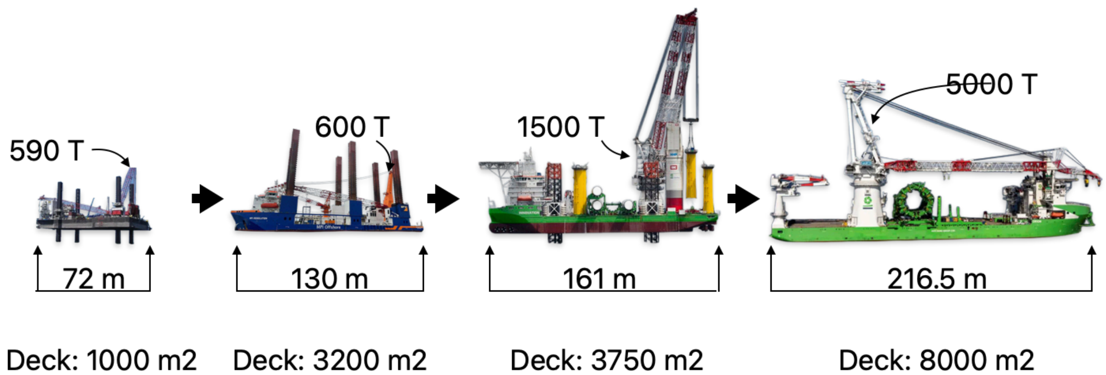


Figure 5.21: Evolution of installation vessels deployed for the installation of foundations

Year	Foundation weights (T)[1]	Crane capacities (T)
2010 - 2015	200-950	1200 - 2000
2015 - 2020	300-1800	1800- 4000
2020 - 2024	600-2100	3500 - 5500

Table 5.5: Evolution of crane capacities used for foundation installation, with the evolution of foundation weights

Vessel evolution drivers

The vessels deployed for the installation of offshore wind turbine foundations have evolved over the years, to be able to lift and handle the increasingly large foundations. The growing scale of offshore wind turbines, and thereby their foundations, has been one of the main drivers behind the development of installation vessels. The foundations installed in 2010 weighed around 500 tonnes, and increased gradually in weight over the years, to 750 tonnes in 2015, and to 1000 to 1500 tonnes in 2020, as can be seen from Figure 5.22. This increase in foundation weight, combined with the movement to deeper waters, created a demand for vessels with higher lifting capacities, and larger deck spaces.

However, technological advancements were not only driven by the increasing size of turbines but also by the need for cost optimization. Offshore installation vessels are accountable for a significant part of the total installation cost of a wind farm, with daily vessel rates contributing heavily to overall costs. Efficiency improvements, such as lowering the installation times, reducing downtime, and the larger deck spaces to carry more foundations per trip, have been key in reducing project costs per megawatt installed.

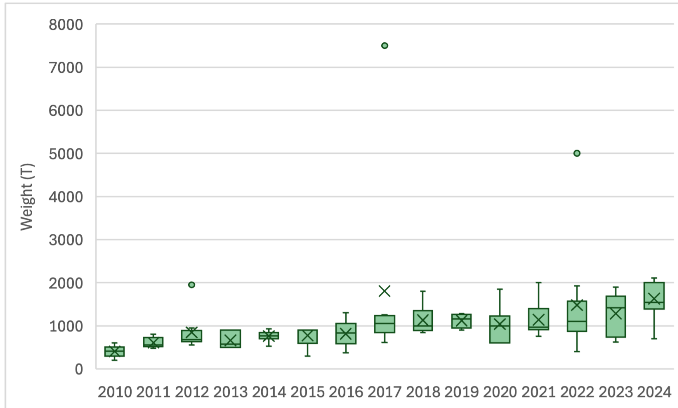


Figure 5.22: Weight of foundations installed per year, excluding floating foundations

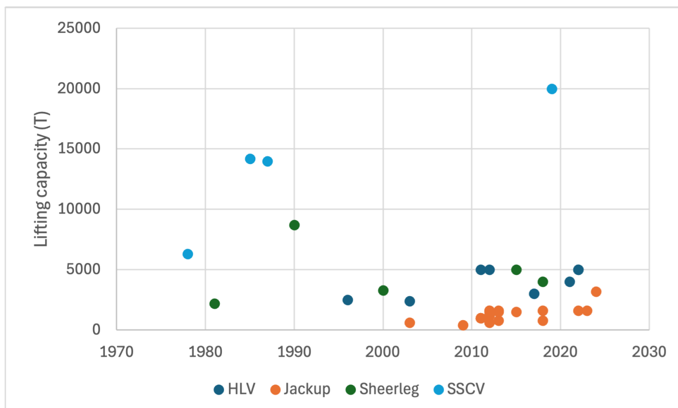


Figure 5.23: Lifting capacity of installation vessels with their respective launch date

5.3.2. Vessel developments from 2010-2015

The period from 2010 to 2015 marked a significant shift in the design and capability of installation vessels, largely due to the increasing scale of the turbines and their foundations. As offshore wind turbines scaled up from 5 MW to 8 MW, and water depths increased beyond 30 meters, the industry could no longer rely on previously used vessels. This period saw the development of more specialized vessels, that were specifically designed for the unique demands of the offshore wind foundation installation market.

In this period, key advancements included the introduction specifically designed jackup vessels for the installation of large wind turbines and their foundations. These vessels were equipped with larger cranes with lifting capacities ranging from 1000 to 1600 tonnes, allowing vessels to handle the increasing weight and size of the foundations. In the beginning of this period, foundations weighed between 300 tonnes, but by the end of this period, the offshore wind industry had successfully scaled turbine capacities to 6 MW, with monopiles reaching diameters of up to 7 meters and weights of 700 tonnes. This growth in turbine and foundation size necessitated the growth in vessel design and

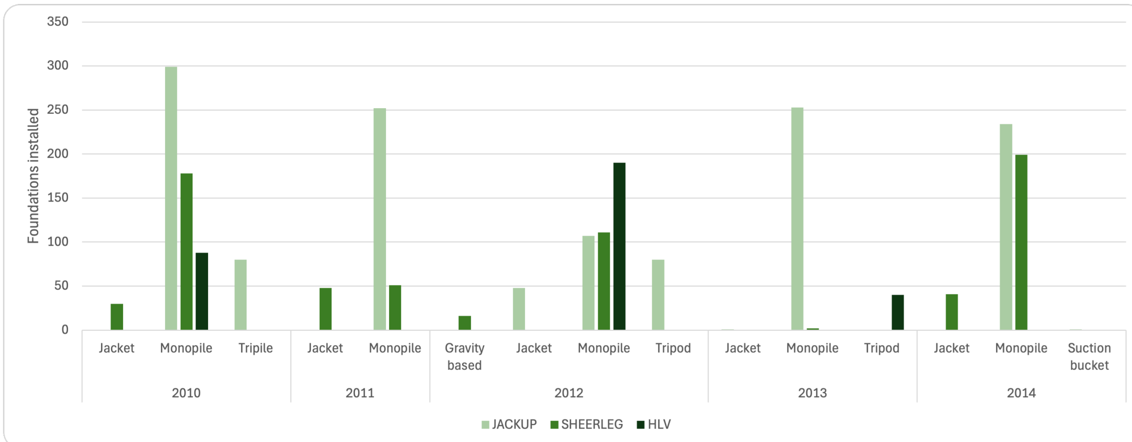


Figure 5.24: Vessel types used for the installation of foundations from 2010 to 2015

capacity. Figure 5.23 shows the vessels used for previous offshore foundation installation campaigns, with their lifting capacity, and their respective launch year.

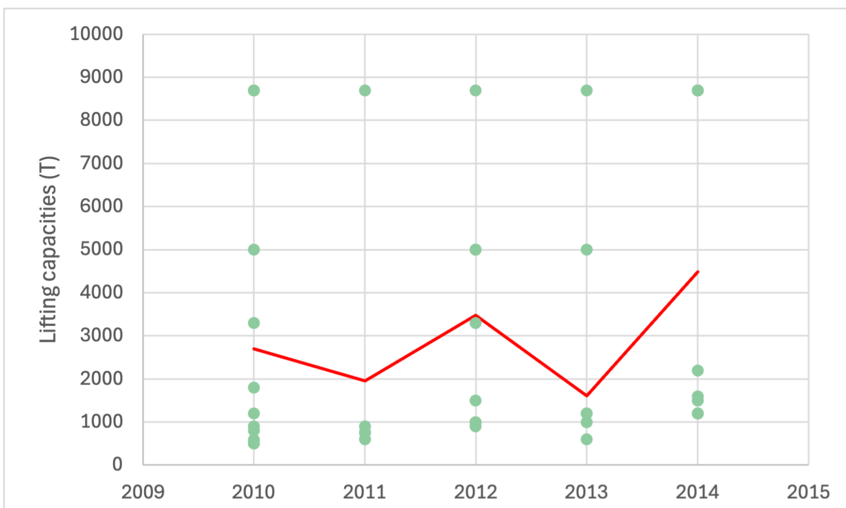


Figure 5.25: Lifting capacity of installation vessel used per year with the yearly average lifting capacity between 2010 and 2015

Notable vessels of this period include the Innovation of DEME and Van Oord's Aeolus, which became two of the most used vessels for foundation installations projects. With lifting heights larger than 120 meters and deck spaces capable of transporting multiple components and foundations per trip, these vessels significantly increased the efficiency and speed of the projects. In Figure 5.25, the average yearly lifting capacity of the vessel used for the installation of foundations can be seen. Several installation vessels, as the Innovation and the Aeolus entered the market between 2012-2013, which explains the dip in average lifting capacity in Figure 5.25. The years just these vessels were taken into use, the sector relied on high capacity sheerleg for the installation since the previously used jackup vessels were not capable of lifting the foundations anymore. Figure 5.24 shows the vessel types that have been used in this period, and it can clearly be seen that after 2012, when several new jackup vessels with high lifting capacities had been launched, the jackups dominated the foundation installation market. In Figure 5.26 it can be seen that most of the installations between 2010 and 2015 have been performed etiher by high capacity cranes, i.e. 5000 and 8700 tonnes, or either by vessels with crane capacities of 1500 or 1600 tonnes. This corresponds with the high use of a few vessels, like the innovation, the Aeolus, and the sheerleg vessel Svanen.

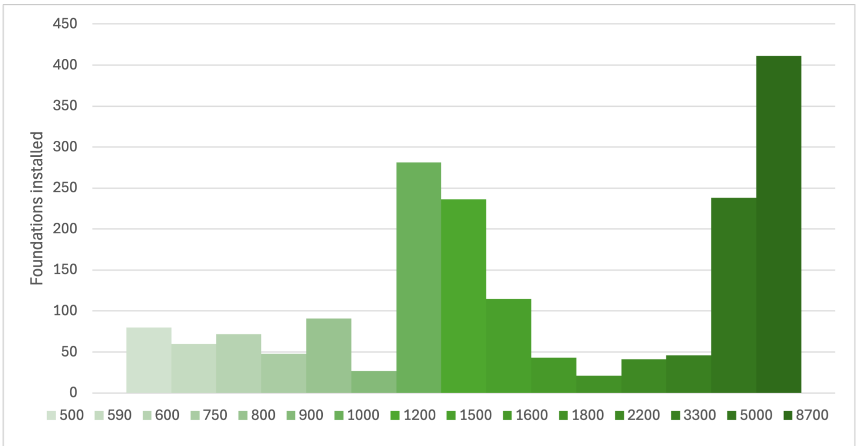


Figure 5.26: Number of foundations installed per lifting capacity from 2010 to 2015

Key developments between 2010 and 2015:

- Purpose built wind installation vessels: Several wind specific installation vessels entered the market around 2012, addressing the limitations of the previously used vessels. These vessels were equipped with larger deck spaces, and cranes with larger lifting capacities, of up to 1600 tonnes. Notable vessels of this period are the innovation of DEME, and the Aeolus of van Oord. These vessels were launched around 2012 and were specifically designed for offshore wind, with lifting capacities of 1500 and 1600 tonnes, and deck spaces of around 3000 to 4000 square meters.
- Multi functional vessels: To improve project efficiency, vessel designers began to focus on the design of vessels that were capable of performing multiple aspects of the installation campaign, as transportation of foundations and components, and the installation, reducing the number of vessel required.

5.3.3. Vessel developments from 2015-2020

The period from 2015 to 2020 was characterized by the further scaling of offshore wind farms, with the yearly average turbine size increasing from 4 MW in 2015 to almost 10 MW in 2020, and monopile foundations growing in diameter and weight. The average weight of foundations therefore increased even more, and exceeded 1000 tonnes, and even reaching up to 1200 tonnes by the end of this period, with some foundations even exceeding 1500 tonnes. In Figure 5.29 the lifting capacities of the installation vessel that were used for the installation of foundations are shown. It can ben seen that the average lifting capacity did rise slightly from 2015 to 2017, from 1500 to 3000 tonnes. This can be related to the multiple deployment of the Svanen sheerleg in 2016 and 2017, with its high lifting capacity of 8700 tonnes. Furthermore it can be noted that most of the installation are carried out by jackup vessels, as can be seen from Figure 5.27. Jackup platforms were phased out in this period, due to their limited lifting capacity in combination with the rising foundation weights. In this period the jackup vessel was favored for most of the installations, Figure 5.28 even shows that the majority of the installations was performed by only several vessels, like the Innovation and the Aeolus with lifting capacities of 1500 and 1600 tonnes, which corresponds with Figure 5.30, where it can be seen that most of the installations in the period between 2015 and 2020 have been installed with vessels with crane capacities of 1500 and 1600 tonnes, emphasizing the highly dependence of the industry in this period on only several vessels.

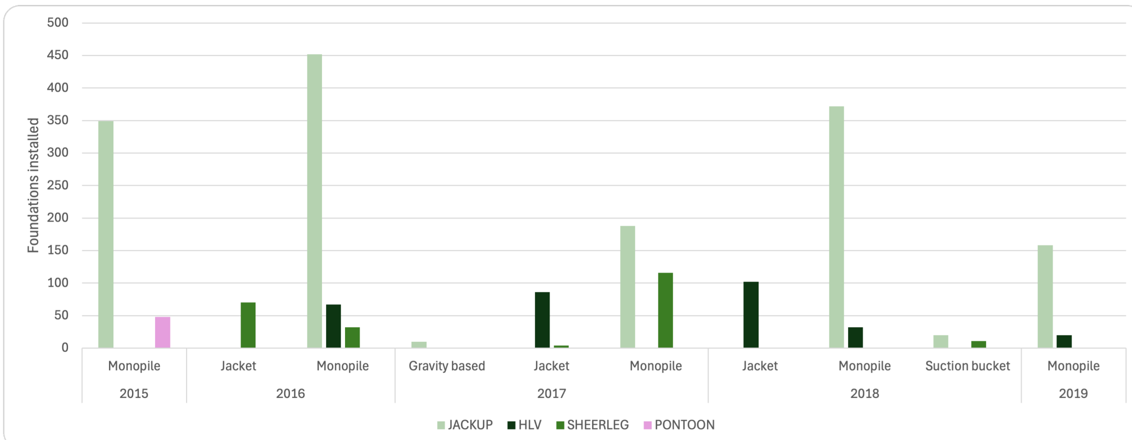


Figure 5.27: Vessel types used for the installation of foundations from 2015 to 2020

5.3.4. Current installation vessels 2020-2024

The evolution of installation vessels accelerated further after 2020, as turbine capacities grew even further. These larger turbines and deeper water installations, often exceeding 40 meters, placed even greater demands on the installation vessels in terms of both lifting capacity, water depth capabilities, and operational efficiency.

After 2020, the foundation weight exceeded the capabilities of most jackup vessels, and where jackup vessels previously dominated the installation market, they phased out, as can be seen from Figure 5.31. After 2020, the market share of foundations installed by HLV's, SSCV, and in some cases sheerleg vessels increases. The market shift to the use of these alternative vessels, due to the excessive weight of foundations, which makes the previously 'loved' jackup vessel somewhat redundant for the installation of the newest, highest capacity turbines and their foundations. Figure 5.32 also shows that the average lifting capacity of the vessels used, is higher in the period after 2020, in comparison to the two previous periods, due to the deployment of higher capacity cranes.

One of the most significant advancements during this period is the development of floating monohull installation vessels, such as DEME's Orion. In 2022 the first floating installation of a foundation

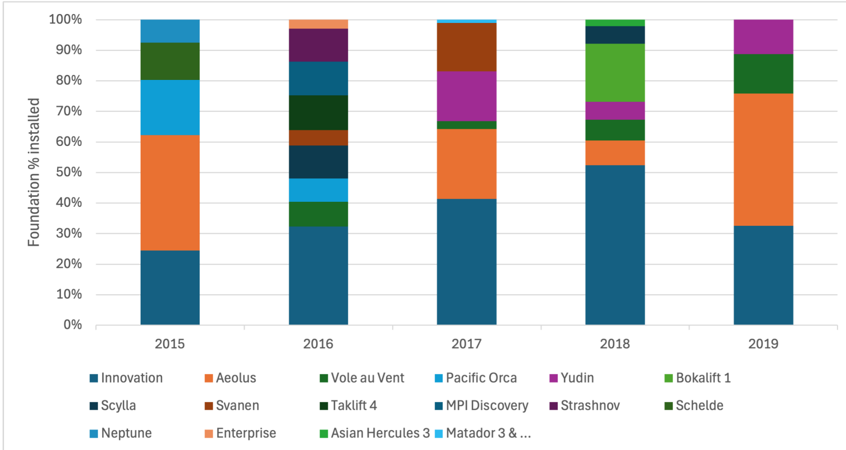


Figure 5.28: Vessels with their contribution to the installation of foundations from 2015 to 2020

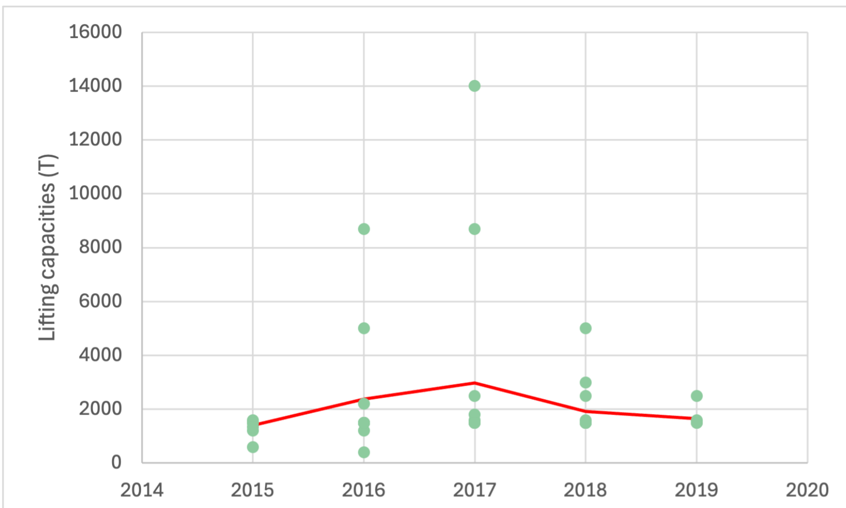


Figure 5.29: Lifting capacity of installation vessel used per year with the yearly average lifting capacity from 2015 to 2020

took place. The current state of the art installation vessels are characterized by the need to be able to install foundations and turbines for 15+ MW turbines, which can be deducted from the crane capacities of the latest installation vessels, reaching 5000 tonnes. The introduction of these floating installation vessels removes the depth limitations seen with leg lengths of jackup vessels.

Another key development is the increased deck space on next-generation vessels, allowing them to transport more components per trip, reducing the number of offshore lifts and transportation delays.This is particularly important as foundation sizes continue to grow, with monopiles exceeding

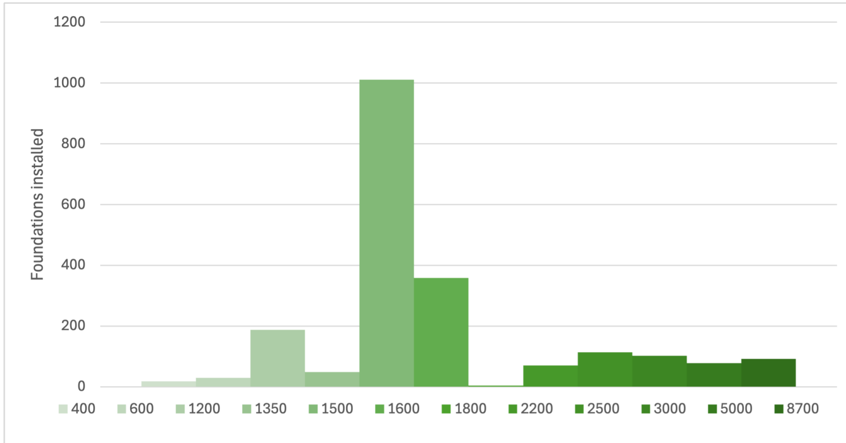


Figure 5.30: Number of foundations installed per lifting capacity from 2015 to 2020

9 to 10 meters in diameter and the current largest foundations weighing more than 2000 tonnes. Vessels such as the Orion, les Alizes, and the Bokalift 1 and 2 are designed to meet these demands with even larger cranes, advanced stability systems, and greater deck spaces.

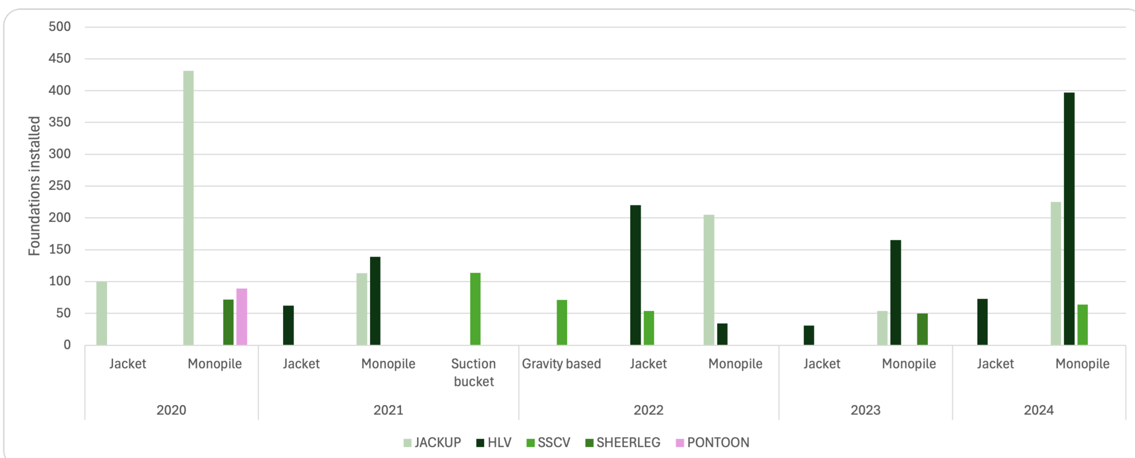


Figure 5.31: Vessel types used for the installation of foundations from 2020 to 2024

Recent installation even see a shift to the use of SSCV's for the installation of foundations. Heerema recently installed the He Dreiht offshore wind farm, with the Thialf where it deployed the specially designed T-NMS-10000 noise mitigation system, shown in Figure 5.56. This noise mitigation system shows the immense structures installation companies are willing to develop and deploy to be able to keep installing monopile foundations.

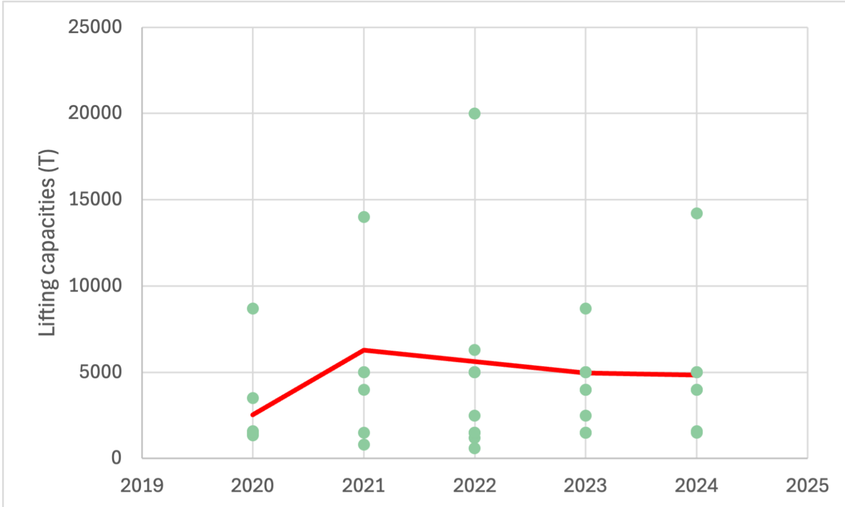


Figure 5.32: Lifting capacity of installation vessel used per year with the yearly average lifting capacity from 2020 to 2024

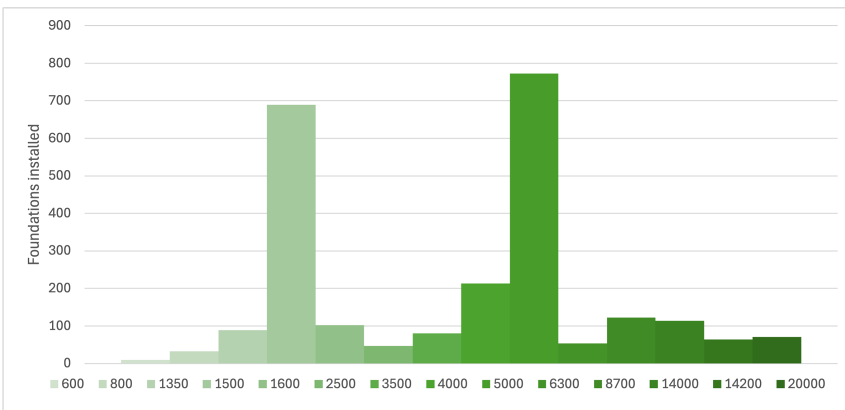


Figure 5.33: Number of foundations installed per lifting capacity from 2020 to 2024

Key developments expected in 2020 to 2024:

- Floating mono-hull installation vessels: Turbine sizes continue to grow, and so have the installation vessels. From larger jack-up vessels with even more deck space, greater lifting capacity, and larger jacking heights, to floating mono-hull installation vessels like DEME's Orion. The Orion is commissioned in 2022 and has a 5000 tonnes crane, and a free deck space of 8000 m2.

- Motion compensated pile gripper, which stabilizes foundations during their installation, enabling installation while on DP, and allowing work to continue in sea states that would have previously caused delays.

- Larger deck space, allowing multiple components or foundations to be transported and installed in fewer trips, further optimizing installation time and costs.

5.3.5. Future outlook 2024-2030

Looking ahead, turbines are expected to reach capacities of 20+ MW by 2030, with even larger foundations, weighing more than 3000 tonnes. The offshore wind industry will require vessels with even larger lifting capacities, deck space, and operational flexibility to meet these challenges. The monopile is thought to remain the foundation type of choice, however it will lose some market share to other foundation types. Future monopiles might become too large and heavy to handle, but foundation solutions like the slip joint interface can gain market share in this case, since it has the ability to reduce the length of the foundation pile, and thereby its weight.

Another future trend is the development of hybrid vessels, capable of handling both multiple foundation types, future proofing the vessel. As deeper water sites become more prevalent, and turbines keep increasing in capacity, vessels will need to be versatile, able to manage the unique challenges of each installation type.

The advancements in vessel design over the next decade will focus on increasing installation speed, increased foundation weights, and on further optimizing the installation process. These vessels will be designed to minimize downtime caused by weather conditions, further driving down the levelized cost of energy (LCOE) for offshore wind projects.

As the offshore wind industry continues to expand, several challenges related to vessel capacity and availability are emerging. It is anticipated that a shortage of specialized installation vessels could become a bottleneck for future offshore wind projects. With turbine capacities expected to exceed 20 MW and foundations continuing to scale in size, vessels with lifting capacities above 3000 tonnes will be in high demand. Industry estimates suggest that by 2030, over 50 GW of offshore wind capacity could be at risk of delays due to insufficient vessel availability [11].

Vessel capabilities

From Figure 5.34, the limitations of current vessels can seen. In the figure, each dot corresponds to a vessel, with its respective crane capacity, at the launch date of the vessel. A range of possible foundation weight is given, which shows an increase in foundation weights over previous and upcoming years. Between 2010 and 2015 several offshore installation vessels have been launched, with similar specifications. The lifting capacities of these jack-up vessels range from 1400 to 1600 tonnes, which means that these vessels are not capable of installing the current average foundation, simply by exceeding the lifting capacities. The vessels with the higher lifting capacities are heavy lift vessels, with lifting capacities up to 5000 tonnes. The Figure shows that these vessels can be used for future foundations, since the foundation weights up to 2030 will remain under their lifting capabilities. When looking at Figure E.3, and Figure 5.28, it can be seen that only a number of vessels was responsible for the majority of installation between 2013 and 2019.

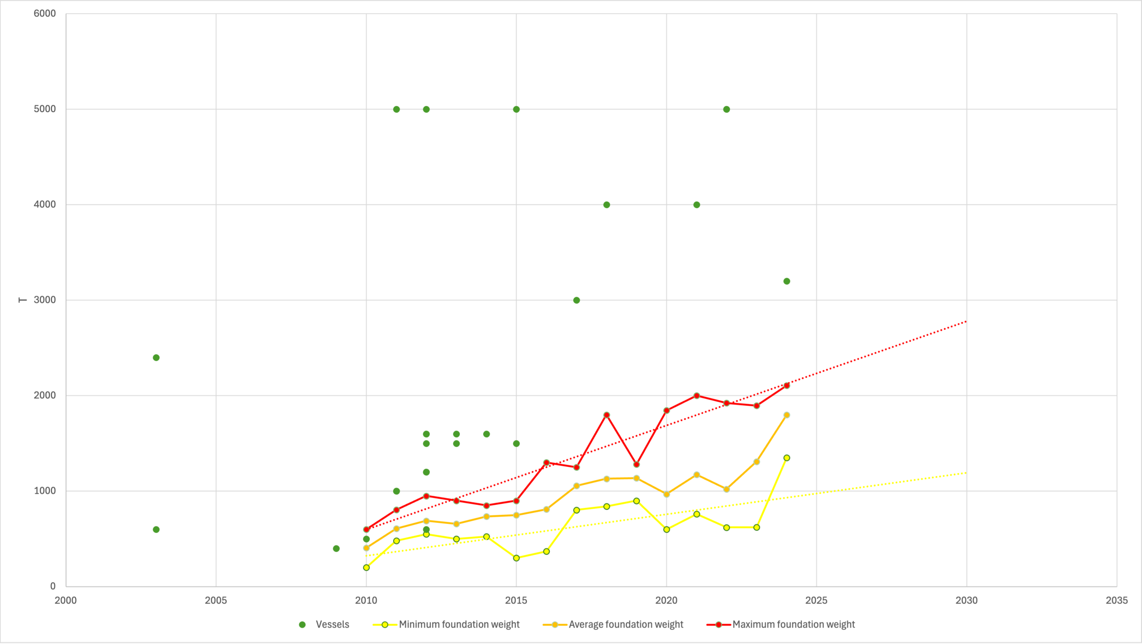


Figure 5.34: Lifting capacities of vessels launched with the evolution of foundation weights

5.4. Evolution of foundation installation equipment

As the offshore sector and the offshore wind turbines have grown in size, and installations have moved into deeper waters, the demands on the equipment used during the installation sequence of foundations for offshore wind turbines have increased significantly. The evolution of pile driving equipment, noise mitigation systems, and other tools related to the installation of foundations have been driven by the need to handle larger, heavier foundations, reduce installation time, and minimize environmental impacts. During each phase of the installation different types of equipment is used to perform several very specific tasks. The equipment that is used during the installation phase, can be categorized in four main categories:

- Driving equipment
- Pile handling equipment
- Frames and grippers
- Noise Mitigation equipment

This chapter explores the advancements in these key equipment categories over time, focusing on specific phases and milestones in the industry's developments.

5.4.1. 2010-2015: Growth in scale and introduction of specialized tools

The offshore wind industry saw rapid advancements in equipment used for the installation, between 2010 and 2015 due to the increased size and installation challenges of wind turbine foundations. As foundations scaled up to accommodate higher capacity turbines, installation equipment evolved to

Year	Monopile diameter (m)	Hammer capacity (kJ)
2010 - 2015	5-7	1200 - 2000
2015 - 2020	5-8.5	1800- 4000
2020 - 2024	7-10	3500 - 5500

Table 5.6: Evolution of driving equipment used for monopile installation

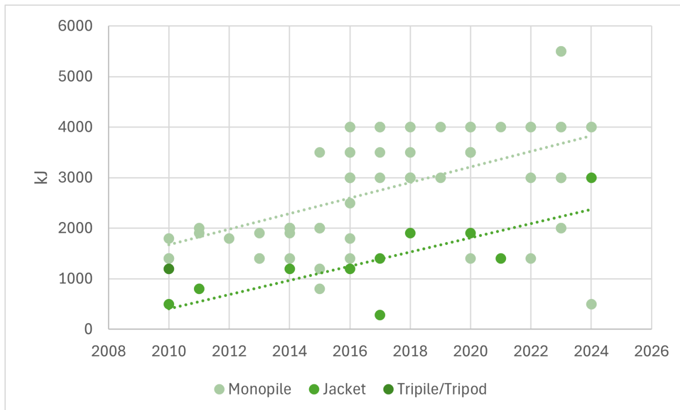


Figure 5.35: Size of impact hammers used per foundation type in each year

meet these new demands. This period was marked by the introduction of high-capacity hydraulic impact hammers and the development of specialized equipment aimed at improving installation efficiency and addressing environmental concerns.

Driving equipment

During this period, the offshore industry saw the installation of larger turbines, requiring significantly larger foundations. As turbine capacities did rise from 4 to 6 MW, and monopiles grew in diameter as shown in Figure 5.8, from 4 to 6 by 2015. The industry responded with more powerful hydraulic impact hammers, such as the IHC S-2000, capable of delivering up to 2000 kJ of energy, respectively. These hammer were designed specifically for offshore wind, a shift from the reliance on the hammers coming from the oil and gas industry [35]. Figure 5.35, shows the increase in impact hammer sizes used over the years.

In this period alternative pile driving technologies emerged in the offshore wind sector, besides impact hammering. Vibratory pile installation was used in 2012 at a large scale offshore wind farm for the first time. This technology offers an alternative to traditional impact hammers by using vibrations to drive piles into the seabed. During the period from 2010 to 2015, only two offshore wind farms made use of vibratory technology to install foundations for offshore wind farms. At the Riffgat offshore wind farm, 30 foundation piles were driven into the seabed with the use of a vibratory tool, which is explained in more detail in Section 4.1.4. The vibratory method was not selected to drive the foundation piles to target depth, and therefore did not show if it would be capable of doing so. The foundations were driven to their final depth with the use of a impact hammer, due to the requirement of a blow count for the load bearing capacity validation of the foundation piles [85]. During the installation with the vibratory tool no noise mitigation measures were required, due to the low noise levels produced during the vibratory operation. The other wind farm that used the vibratory technology was the global tech one offshore wind farm, where 240 piles of eighty tripod foundations had to be installed into the seabed. The foundations were driven by the vibratory tool and an impact hammer in an alternating fashion, to be able to precisely control the inclination of the foundation [86]. Dieseko, a company specialized in vibratory equipment, supplied the vibratory lifting tool shown in Figure 5.38.

After these two project, the technology was not directly widely adopted by the industry. A combination of regulatory hurdles, the lack of knowledge about the performance of piles installed with vibratory technology, and the absence of a large enough need for the technology to be widely adopted in the offshore wind foundation installation sector, since compliance with noise regulations was still possible with noise mitigation techniques, made that the technology was not quickly adopted by the industry [87], [88].

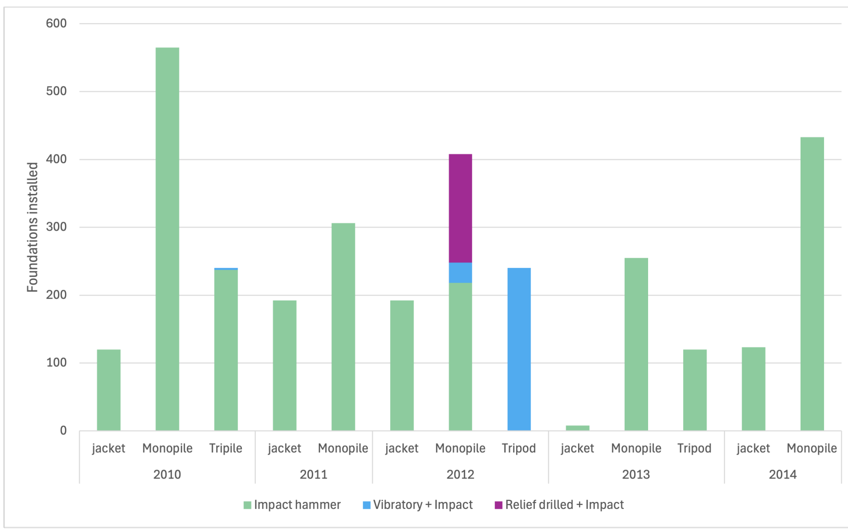


Figure 5.36: Driving methods used from 2010 to 2015

Figure 5.37: CAPE's Quad Kong vibratory tool [89]

Figure 5.38: Dieseko's 300MU vibratory tool for the installation of piles for Tripod foundations [86]

Another pile installation technique was used for the first time in 2012 at the Gwynt y Môr offshore wind farm. Due to the seabed conditions, impact hammering until target depth was not possible, and a drill was used to install monopile foundations in the rocky seabed off the coast of north Wales. The drill used was the LD 5000, shown in Figure 5.39. The drill was specially designed by LDD, to fit through the 4.6 meter diameter neck of the foundation pile and was able to expand in the pile to perform its under-reaming drilling operation below the foundation pile. The company developed a pile installation method called 'Drive-Drill-Drive' (3D), which uses the combination of impact hammering and drilling to save time and cost of the operation [90]. In this manner, the foundation can first be driven into the seabed with the use of an impact hammer until the pile cannot be driven further with the impact hammer, after when the hammer can be lifted of the pile, and the drill can be inserted in the pile to start the relief drilling operation, and finally the pile will be driven into the seabed to target depth.

Figure 5.39: LD 5000 drill [90]

Pile handling equipment

The evolution of handling equipment is somewhat hard to follow, since most equipment upgrades were new iterations with higher load capacities of older models. In Figure 5.40, the lifting capacities of the flanged pile upending tool and the upending tools used are given, and the Figure shows a steady increase in capacity over the years. Basic upending tools were used, as the IQIP internal lifting tool, shown in Figure 5.41. Furthermore, flanged lifting tools were introduced to lift monopile foundations with a bolted monopile-transition piece interface, as shown in Figure 5.42. As turbines and their foundations continued to grow in size, these tools faced limitations in capacity. Additionally, with the growth of the sector, the search and the need for optimization only got bigger. For monopile foundations, relatively simple fixed pile grippers were used, as the pile gripper shown in Figure 5.43, and the installations were also less accurate than today's standards.

Another development during this period is the introduction of the hanging pre piling template under the deck of the vessel Goliath introduced at the Trianel Borkum one offshore wind farm (previously know as Borkum West II) in 2013 [91]. Figure 5.44 shows the Goliath with the pre-piling template hanging under the deck of the vessel. The template can be lifted against the hull to allow the vessel to sail to its next location.

Some of the key technologies of this period included:

- Relatively basic Upending Tools: Early designs were manually operated.
- Basic pile retaining arms.

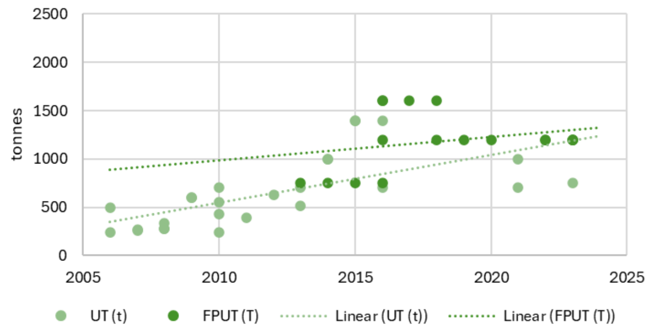


Figure 5.40: Flanged and non-flanged pile up ending tools

Noise mitigation: The rise of environmental protections

Environmental awareness became a hot topic, especially around the impacts of underwater noise on marine life. In response to regulations, like implemented in Germany in 2008, the industry improved, developed and implemented more noise mitigation measures such as double bubble curtains and hydro sound dampeners. Small single bubble curtains increased in size and evolved to 'big' bubble curtains, and eventually to double big bubble curtains. The first offshore wind farm where a big bubble screen was at the Trianel borkum one (Borkum west II) offshore wind farm in 2012 [96]. These systems could reduce the sounds levels by 11-15 dB SEL and 8-13 dB PSL, and became a standard practice of offshore wind installations in regions with strict environmental regulations [96]. Besides bubble screens, several other noise mitigation technologies were developed. In 2012, the IHC NMS, shown in Figure 5.45, was first used at the Riffgat offshore wind farm. This wind farm was also the first wind farm where vibratory piling technology was used to drive monopiles in to the seabed, which significantly reduced the sound levels of the installation [87]. At Riffgat only the first part of the piles were installed with vibro piling, after which the IHC NMS was placed around the pile and the piles were driven to final depth by impact hammering, which reduced the sound levels by approximately 17 dB SEL [96].

Another development was the hydro sound dampener (HSD), which was first used at a commercial scale for the London Array offshore wind farm [96]. An example of the system is presented in Figure 4.11a. The system reduces underwater noise by surrounding the monopile with a net of foam and air-filled elements, absorbing and scattering the sound waves. The system was able to reduce sound levels up to 18 dB [96].

5.4.2. High capacity equipment and Scaling technologies: 2015-2020

Driving equipment

Turbine capacities grew from 6 to 10 MW, and foundation weights increased to almost 1500 tonnes. The equipment used for foundation installation had continue to evolve, to accommodate these larger

Figure 5.41: Internal lifting tool by IQIP [92]

Figure 5.42: Flanged pile upending tool by IQIP [93]

structures. Both IQIP and Menck developed larger hydraulic hammers, as the S-3500, the S-4000, and the MHU 3500S, with higher power capacities ranging from 3500 up to 4000 kJ.

Vibratory hammers have not been quickly adopted by the offshore wind industry after the implementation at the Riffgat and Global Tech one offshore wind farms. The technology was only again selected for a project in 2019. The CAPE VLT-320, was used to install 20 monopiles of 8.4 meters in diameter at the Formosa 1 wind farm in Taiwan. The technology was selected due to its ability to reduce the risk of pile run, present by the increasing weights of foundation piles, and the challenging soil conditions encountered at the location of the offshore wind farm [97].

Between the installation at the Riffgat offshore wind farm, and the installation in 2019 at the Formosa one offshore wind farm, the technology has however been tested several times to improve the knowledge about the technology, and the performance of piles installed with vibration motions [98].

Figure 5.43: Pile gripper frame on Aelus vessel [94]

Figure 5.44: Pre piling template hanging under the deck of vessel Goliath [95]

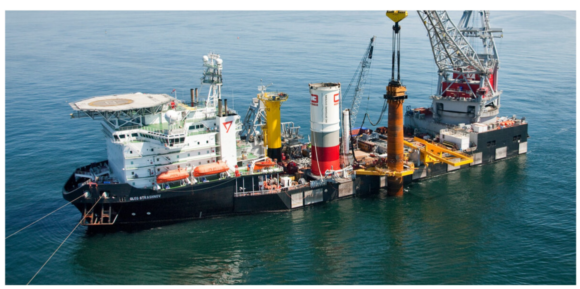


Figure 5.45: Integrated monopile installer by IQIP

Between 2015 and 2020, one offshore wind farm had to use drilling for the installation of foundations. In 2017 relief drilling was required to install the piles for 84 jacket foundations in Scotland, at

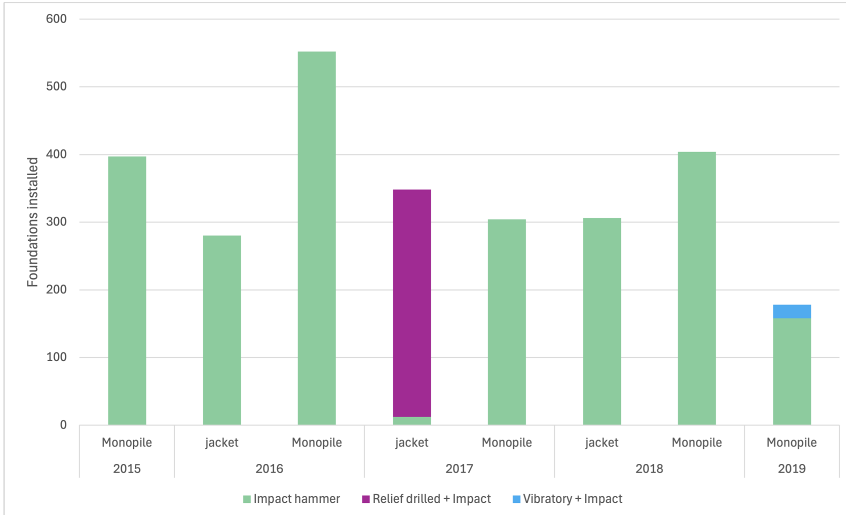


Figure 5.46: Driving methods used from 2015 - 2020

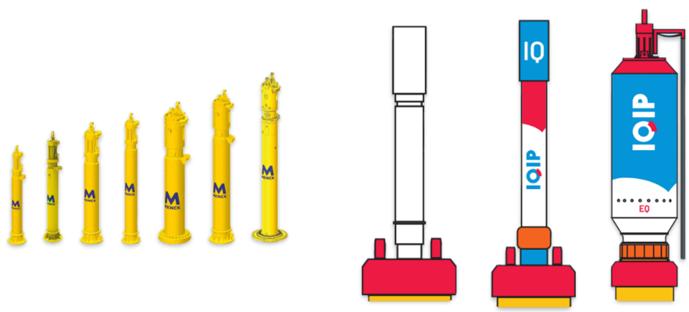


Figure 5.47: Different driving equipment for foundation piles

the Beatrice offshore wind farm. The foundation piles were supposed to be installed by impact hammering, but early refusal was a possibility, and therefore a drilling rig for relief drilling was supplied by BAUER [99]. The drill used, was the Dive Drill DDC40 by BAUER.

Pile handling equipment

From 2015 to 2020 the offshore wind sector saw rapid scaling in terms of number of installations, turbines, and also in foundation sizes. Diameters increased from 5 to over 8 meters and weights surpassed 1500 tonnes. One of the developments during this time period was the further development of upending tools, that increased safety and smoother operations, even as the size and weight of the monopiles increased. Another key development in this period was the development of the combi lifting tool of IQIP. The tool, shown in Figure 5.49, was used for the first time during the installation of the Borkum Riffgrund 2 offshore wind farm, in 2018. The tool ensures safer operations, by replacing the traditional crane hook with a 'quick connector' that is compatible with a variety of different tools of IQIP. The implementation of the tool requires fewer human interactions when changing tools in the offshore environment, and therefore increases the safety[100]. Furthermore, gripper frames evolved and improved their precision. For example, DEME installed a new pendulum design fixed pile gripper frame on the Innovation vessel, shown in Figure 5.48, which reduced the installation time and increased precision [101]. The new pile gripper was first used at the Seamade offshore wind farm.

Figure 5.48: Pendulum design monopile gripper for the vessel Innovation [101]

For the installation of pin piles for the Moray East offshore wind farm, DEME developed an advanced pre-piling template for the Apollo vessel, shown in Figure 5.50. The patented pre-piling template was designed to be integrated within the legs of the jackup vessel Apollo [102].

Figure 5.49: Combi lifting spread by IQIP [103]

Noise mitigation

Noise mitigation techniques continued to evolve, with double big bubble curtains and noise reduction sleeves being introduced to further reduce underwater noise pollution. These systems were more effective in deeper waters, addressing the increasing regulatory focus on marine protection.

Figure 5.50: Under-deck hanging pre-piling template for the Apollo vessel by DEME [104]

During the Borssele 3 and 4 offshore wind farm, the AdBm technology, showed in Figure 5.51 was deployed at a commercial offshore wind project for the first time. The technology showed the possibility to reduce noise levels by 8 dB when using the system as a stand-alone noise mitigation measure, but could reduce noise levels up to 20 dB when combined with a single big bubble curtain [105].

Figure 5.51: AdBm noise mitigation technology [106]

5.4.3. 2020-2024: High capacity equipment and emerging technologies

The period after 2020 saw a continued push for larger-scale foundation installations, driven again by the increasing size of offshore turbines, now exceeding 14 MW, with pile diameters larger than 10 meters in diameter. This has pushed the limits of traditional installation equipment, leading to the development of new, high-capacity tools and also sparked the exploration of more environmentally sustainable technologies.

Driving equipment: Meeting the demands of XXL monopiles

As offshore wind turbines continue to grow towards and beyond 15 MW turbines, the foundations continue to increase in size too, from 7 to 10 meters in diameter. Yearly average monopile capacities range from 8 to 10+ MW. Monopiles with diameter of more than 10 meters, weighing over 2000 tonnes have already been used, for instance at Moray West offshore wind farm. To install these massive foundations, even more powerful driving equipment is and has to be developed. An example of the state of the art hydro hammer of IQIP, is the IQ series hammers. The series consists, until now, of the IQ2, IQ4, and IQ6, each capable of delivering 3000 kJ, 4000 kJ, and 5500 kJ respectively. Figure 5.35 again shows an increase in the hammer size used in this time period. The figure also shows that sometimes a lower capacity hammer is used in recent years, as for instance in 2020, where a 1400 kJ hammer was used for the installation of monopiles. These cases are mostly due to the installation of lower capacity turbines, and therefore smaller foundations. This specific example was of wind farm Fryslan, where 4,3 MW turbines have been installed. A variety of driving methods has been used from 2020 to 2024, as shown in Figure 5.52.

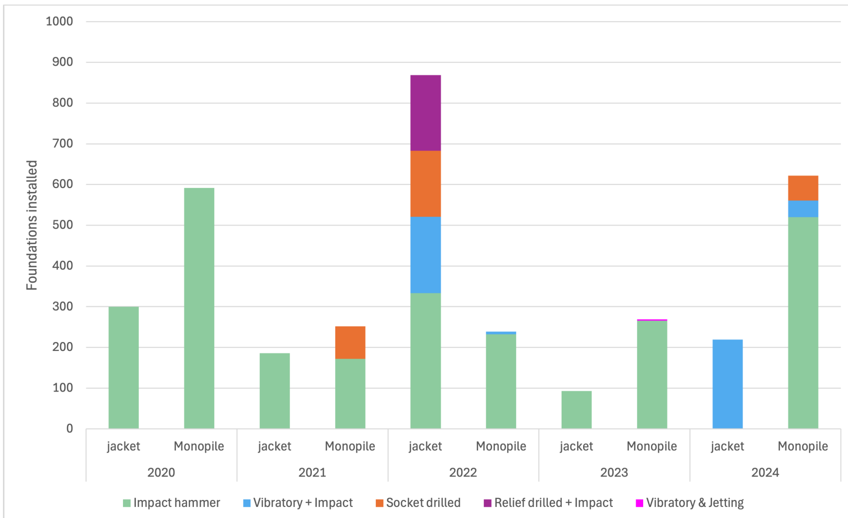


Figure 5.52: Driving methods used from 2020 to 2024

Although the vibro piling method was first deployed in 2012, it was not widely adopted by the industry, and was not used much in the offshore wind sector after this installation. The vibro technology recently gained more interest, and was used for several projects, due to its ability to remove the possibility of the issue of 'pile run', present at the large foundation piles [107].

The technology was tested at the Kaskasi 2 offshore wind farm in 2022, with the initial goal of driving all 38 foundations to target depth. In the end, only seven piles have been installed with the vibratory technology, and these foundations have also not been driven to target depth [108]. The remained of the scope, was awarded to DEME, and the 31 monopiles have been installed by the Blue Tern vessel in combination with the Neptune [109]. The installation was part of the VISSKA project, where the goal was to develop forecasting models aimed at predicting the behavior of foundation pile installed with vibratory technology [110].

At the Formosa 2 offshore wind farm, the CAPE VLT-320 has been deployed to lift and drive pin piles for jacket foundations off the coast of japan. At the Moray West offshore wind farm, 41 foundations have been installed with the vibratory technology of CAPE. The work was divided between DEME's Orion, which installed 29 monopiles and Boskalis's Bokalift 2, which installed 12 monopiles with the vibratory technology [107]. Both companies used the CAPE VLT-640 in quad configurations.

At the Hai Long 2 & 3 offshore wind farms, the CAPE VLT-640 in a single configuration was used to drive pin piles for the jacket foundation into the seabed [111]. The vibratory hammer of CAPE, the CAPE VLT is a a combination of a vibratory hammer and certified lifting tool in one [38]. In 2024 the vibratory technology of Dieseko is used to drive the foundations for 64 wind turbines at the Calvados offshore wind farm [112].

For all of the projects where vibratory technology has been deployed, the technology was used to partially drive the foundations into the seabed, and the foundations were driven to their final depth with the use of an impact hammer. The reason for this approach, where two different driving technologies must be deployed, is due to the ability of the vibratory tool to remove the possibility of a pile run, present at the heavier foundation piles in combination with the seabed compositions [107]. The reason why in the end impact hammering is used in all cases to drive the piles to their target depth, is due to concerns about the bearing capacity of vibrated piles, and due to the fact that a specific blow count is required to obtain the bearing capacity validation [113].

Figure 5.53: Cape VLT range

Five offshore wind farms resorted to using drilling technology to install foundations into the seabed in the period from 2020 to 2024. One installation in Scotland, and four offshore wind farms in France made use of drilling technology to install foundations into the rocky seabed off the French coast. In 2021 the OFD 7700 offshore drill developed by Herrenknecht was used at the St Nazaire offshore wind farm. This drilling operation is different to the earlier drilling operations where relief drilling was applied besides impact hammering. For the installation of the Saint Nazaire wind farm, Herrenknecht developed a full face drill specially designed for the installation of large diameter monopile foundations [40]. The OFD 7700, shown in Figure 4.9, is used to drill boreholes, and is used in combination with the MODIGA, a monopile drilling, installation and grouting system, shown in Figure 4.10. The location of the Saint Nazaire wind farm posed challenging rocky seabed conditions, which is why socket drilling was applied [40].

In 2022 the piles for jackets foundations for the Saint-Brieuc offshore wind farm were installed with drilling operations. 186 piles were installed for the 62 three legged jacket foundations. The drilling operations took place from the Aeolus vessel by van Oord, and three drills were deployed simultaneously, as shown in Figure 5.54. This method increased the efficiency, and furthermore the risk of collapsing boreholes was removed by the fully cased method [114].

During the installation of the Calvados offshore wind farm in France, socket drilling is applied, with drilling equipment supplied by LDD. In 2022, drilling was used for the installation of piles for jacket foundations for the Neart na Gaoithe offshore wind farm. In 2024 the OFD 7700 was used for the second time in combination with the MODIGA, at the Îles d'Yeu et Noirmoutier offshore

Figure 5.54: Simultaneous drilling operations for the Saint-Brieuc offshore wind farm in 2022[114]

wind farm, to install 61 monopiles, measuring 7 meters in diameter, in the rocky seabed off the coast of France.

One of the latest innovations in driving technology is the use of jetting technology to reduce soil resistance. The technology combines jetting with vibratory motions, to further reduce soil resistance, to be able to drive foundation piles in the ground without the need of an impact hammer. The first full scale pilot was performed by Ørsted in 2024, and was aimed at reducing sound, and to drive the foundation piles to target depth, as has been proven difficult when only using vibratory technology [115]. The technology reduced sound up to 34 dB [116], and this technology can lead to more efficient installations of monopiles. Another company working on a similar technology, is GBM Works. They have signed a contract to test their equipment at the Hollandse Kust west VI offshore site, where it will be used to install three monopiles [117].

Pile handling equipment

The period from 2020 onward has seen the offshore wind industry tackle the immense challenge of installing even larger monopiles exceeding 10 meters in diameter and with weights exceeding 2000 tonnes. At the same time, the industry has shifted toward using floating installation vessels for deeper water projects, introducing new challenges. Unlike jack-up vessels, floating vessels constantly move due to wave and wind forces, which complicates pile handling operations.

With the introduction of floating mono-hull installation vessels like DEME's Orion, a new challenge appeared. The movement of the vessel by waves and wind forces, had to be compensated. To solve this issue, the motion compensated pile gripper was developed, shown in Figure 5.55, to ensure accurate monopile installation, even in harsh conditions [32]. This advanced gripper can stabilize monopiles during installation by compensating for vessel movements, making sure that the monopile remains vertical during installation. This innovation has significantly lowered the risk of in accurate installation and damage, while it also improves installation accuracy [118]. Another development during this period is the use of outrigger frames for floating vessels. These frames provide a stable platform for inserting lifting tools in monopiles, solving the problem of free swinging tools caused by the vessel motions. For instance, outrigger frames used on the Orion have improved the safety and the efficiency by ensuring smooth and accurate pile handling, even in challenging conditions [32].

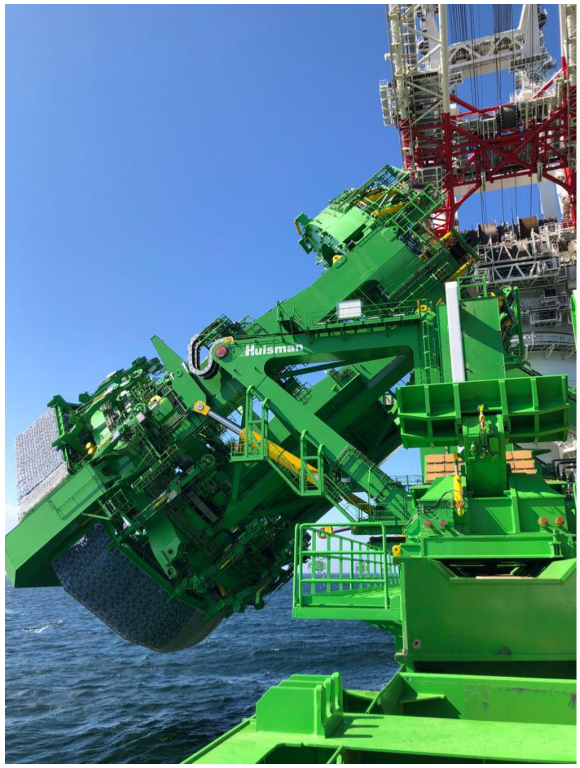


Figure 5.55: Motion compensated pile gripper on the Orion vessel by DEME [119]

Noise mitigation

Noise mitigation systems have continued to improve and evolve, often multiple systems are deployed simultaneously, for projects with strict noise regulations as in Germany. An example of a state of the art noise mitigation system is the T-NMS-10000, shown in Figure 5.56. It was used for the first time in the summer of 2024, by Heerema, at the He Dreiht offshore wind farm. The system is developed in collaboration with IQIP, and it was able to reduce the noise levels of the installation by 15 dB. The T-NMS-10000 is a sub-sea noise barrier for monopiles, and is capable of handling monopiles of 10 meters in diameter, and it has got a footprint of 45 meters and weighs just under 2500 tonnes. This shows the immense structures needed to reduce noise levels produced during the installation of current monopiles [120].

5.5. Conclusion

The offshore wind sector has undergone a significant evolution in the period from 2010 to 2024. As turbines increased in capacity and dimensions, and offshore wind farms moved to deeper waters, the foundation designs and installation techniques also needed to evolve and adapt to accommodate the higher structural demands of the turbines.

The objective of this chapter was to provide a detailed analysis of the evolution of previously installed offshore wind farms from 2010 to 2024. During this analysis, the changes over the years

Figure 5.56: T-NMS-10000 noise mitigation system by IQIP [121]

are followed in chronological order, to evaluate the evolution of the foundation installation sector. The evolution of several different areas of the offshore wind sector, such as the market developments, the developments in foundations, the evolution of installation vessels, and the evolution of the equipment used during the installation has been analyzed. This breakdown makes it possible to draw conclusions about the different areas and provide insight into how the sector has evolved. One of the other key problems that was addressed, was the issue of the lack of data sharing in the industry. Companies are reluctant to share data with the public since this can possibly harm the position of a company during tendering processes. By addressing these issues, the chapter provides an answer to the research question:

How has foundation installation evolved over the years and what trends and lessons can be derived from this analysis?

The offshore wind market has undergone large developments in terms of installed capacity and the size of the turbines used, from 2010 to 2024. The average turbine sizes increased from 3 MW, 4.5 MW in 2015, to 9 MW in 2020, and to almost 14 MW in 2024, and the total installed capacity of 35 GW in 2024. Several countries are responsible for the majority of the number of installations, such as Germany, the UK, and the Netherlands. The average size of the wind farms installed increased slightly over the years, from 200 MW in 2010, 250 MW in 2015, to 600 MW in 2020, and to over 1 GW in 2024. From 2020 to 2024 new countries entered the offshore wind market, such as Taiwan, France, and the US. These countries have set goals for themselves in the form of offshore wind energy targets, such as the 5.5 GW target of Taiwan for 2025.

Another key area of development in the offshore wind sector is the evolution of the foundations used for offshore wind turbines. The continuous search for lower cost has driven the movement to larger turbines, and to deeper waters, driving the evolution and use of different foundation types. Several different foundation types have been tested and used over the years, to find the most optimal, cost-effective solution. Between 2010 and 2015, several different foundation types have been tested, such as the tripod and the tripile foundations. These foundation types were developed as an alternative to the simple monopile design, for deeper water installations, since the monopile was thought to be feasible up to water depths of 30 meters. However, the limitations of the monopile kept being pushed further and further, and the foundation type remains the most used foundation type until today. The monopile, with its market share of over 80%, is the most used foundation type, and it has seen large developments in terms of size and weight over the years. The average diameter of the foundation type increased from 5 meters in 2010 to 6.5 meters in 2015, to 8 meters in 2020, and to 9.5 meters in 2024. In recent years, the jacket foundation has gained some more interest, because the question of how deep monopile installations can go again arises. Besides recent interests in jacket foundations, other alternative foundation types as suction bucket jacket foundations have also gained interest. Stricter noise regulations and difficult seabed composition drive technological advancements in foundation types, to provide a stable platform for the turbines, and comply with location-specific regulations.

Floating foundations have also gained more interest since the first pilot installations. Currently, two offshore wind farms are in existence, where multiple floating foundations have been deployed. These low deployment numbers, make it however difficult to follow the evolution of the foundation type.

In 2003 the first offshore wind-specific installation vessel, the MPI Resolution, was launched. After this first launch, the vessels evolved in size and lifting capacity from 600 tonnes, to jackup vessels with 1600 tonnes crane capacities. In the period between 2010 and 2015 several jackup vessels with crane capacities of 1500 to 1600 tonnes have been launched, to support the installation of offshore wind farms. The two most notable vessels of this period, are the Aeolus of van Oord, and the Innovation of DEME, with crane capacities of 1600 and 1500 tonnes respectively. Both these vessels are accountable for a large portion of the foundations installed for offshore wind farms between 2012 and 2019. This also shows the high dependence of the offshore wind sector, on only several installation contractors. From 2010 to 2020 the foundation installation market was dominated by jackup vessels, but after 2020 there was a shift towards heavy lift vessels and semi-submersible crane vessels. This movement away from the previously used jackup vessels can be attributed to the limiting lifting capacities of the jackup vessels, in comparison to the average foundation weights of the years after 2020. The jack-up vessels are not able to lift the current and future foundations, requiring vessels with higher-capacity cranes. This demand for a larger capacity crane has been filled by the use of heavy lift vessels, that can install monopile foundations while a float on DP. These 'new generation' installation vessels have crane capacities of up to 5000 tonnes, and large deck spaces to accommodate the transportation of multiple foundations per trip. An example of such a state-of-the-art vessel is the HLV Orion by DEME, which has a 5000 tonnes crane and a free deck space of 8000 square meters.

Another key area where developments have taken place is in the equipment used during the installation procedure. Due to the increase in foundation sizes and foundation weights, the equipment used for handling, lifting, and driving the foundations had to be scaled accordingly. The most used foundation type, the monopile, has to be driven into the seabed, which is typically done with the use of a hydraulic impact hammer. The force required to drive foundation piles into the seabed increases with pile dimensions, and therefore new, more powerful hydraulic equipment has been developed over the years. The hydraulic impact hammer has grown in power from 2000 kJ hammers to the largest hammer with a power rating of 5500 kJ. Besides developments in power ratings of impact hammers, alternative driving methods have also been developed and tested over the years, aimed at reducing the noise levels during the installation procedure. These technologies include vibratory piling and jetting. Vibratory pile installation was first used in 2012 at the Riffgat offshore wind farm, and aimed at reducing noise pollution during pile driving. The technology successfully reduced the noise of the installation but was sidelined after this first installation. One of the primary issues with such new technologies is the lack of a substantial track record, that shows the reliability of the technology and shows its ability to perform time after time. The risk-averse offshore wind sector shows that it prefers known, proven methods, of which the results can be predicted beforehand. The jetting technology is relatively new and has only been deployed once by Ørsted in 2024, but the technology showed great results and proved its ability to reduce noise levels up to 34 dB. Further development of the technology is needed to be able to comment on the future prospects of the innovative driving method. One thing that is certain, is the pressing noise limitations in areas with strict noise regulations, that require the deployment of several noise mitigation strategies at once, to remain under the thresholds. For Germany for instance, this results in the necessary deployment of noise mitigation measures as the 45 meter wide, 2500 tonnes weighing T-NMS-10000 of IQIP, when impact hammering is the selected driving method.

6
Implications of further scaling offshore wind turbines

The offshore wind sector has developed in a rapid pace in terms of overall capacity installed, and also in terms of turbine capacity. The first foundation for an offshore wind turbine was installed in 1991, at the Vindeby offshore wind farm, and these turbines had a rated capacity of 0.45 MW. After this first installation the turbine sizes have evolved over the years, as described in Section 5.1. When looking at the largest turbine installed each year, the average size increase over the past ten years is approximately 8%. The growth of the turbines will continue over the next years, with the first 20+ MW turbines are already in development. The fast growth of the offshore wind industry and the trend towards larger turbines has introduced complex challenges across foundation design, vessel requirements, logistics, and environmental impacts. From the evolution of foundations, to the first deployment of the first purposely built offshore wind installation vessels, to even larger vessels, the sector had to continually adapt to to accommodate the increasing demands driven by the increase in turbine sizes. As turbine sizes increase even more, driven by the goal to reduce the Levelized Cost of Electricity (LCOE), the impacts on foundations, vessels, and logistics will become more and more noticeable.

The goal of this chapter is to provide an in depth analysis of the implications of the further scaling of future offshore wind turbines. The scaling efforts impact several key areas in the industry, such as foundations, vessels and equipment, logistics, and the supply chain. This chapter will look into the effects on each of the different areas, and by understanding these implications, the chapter provides insights into how the industry can adapt for future larger turbines and more complex installations.

This chapter contributes to the overall research objective, by addressing the following research question:

What are the implications for the offshore wind installation sector of the further scaling of offshore wind turbines?

The chapter follows from the previous chapter about the evolution of the foundation installation presented in Chapter 5, and continues with a forward facing vision on the implications that will arise with future larger turbines. The chapter focuses on the specific challenges that come with these larger turbines and their accompanying larger foundations.

The Chapter focuses on the challenges that arise with further scaling offshore wind turbine sizes, by looking at several key areas. For the chapter, information from literature is combined with information gathered during interviews held with experts in the field of offshore wind, and the foundation installation sector. The different areas that are influenced by the increasing turbine sizes, are extracted from the information of the interviews, and supplemented with information found in the literature.

To create an total image of the consequences of larger turbines, all the areas that are affected must be analyzed. The chapter is divided into several sections, each addressing one area impacted by the further scaling of turbines, as shown in the Figure.

6.1 Overview of turbine scaling trends (2010-2030)
6.2 Impact on foundation design
6.3 Vessel and equipment requirements for larger turbines
6.4 Logistical and supply chain implications
6.5 Cost implications and economic impact of scaling
6.6 Environmental and regulatory implications of scaling
6.7 Future outlook and trends
6.8 Conclusion

In Section 6.1, the chapter begin with providing an overview of scaling trends from 2010 to 2030. First, the historical growth of offshore wind turbines and previous developments in presented, and afterwards, future projections for offshore wind turbines are presented and discussed, to provide context and background for the rest of the chapter. In each of the Sections from 6.2 to 6.7, a different area that will be affected by the scaling efforts is discussed.

6.1. Overview of turbine scaling trends (2010-2030)

6.1.1. Historical growth of turbine sizes

Offshore wind turbines have grown from using 0,45 MW turbines in 1993 at Vindeby offshore wind farm, to turbine capacities typically ranging between 2 and 5 MW in 2010, to eventually using 14,7 MW turbines used in 2024 at the Moray west offshore wind farm. This growth is not just limited to turbine capacity, Figure 6.1 gives a graphical representation of how the offshore wind turbines have evolved over the years in terms of capacity, hub height, and rotor diameter. Rotor diameters have grown from around 100 meters for early offshore models to over 200 meters for the latest designs. Hub heights, now often exceeding 150 meters, allow for better wind resource capture at greater altitudes. These larger turbines capture more energy per unit and reduce the number of turbines needed per wind farm, to obtain the same overall capacity of the wind farm, which contributes to the reduction of LCOE and supports the scaling of the offshore wind sector. A report published in 2016 predicted that 11 MW turbines would be possible by 2030. The turbines in 2024 already exceed 14 MW, which emphasizes the fast movement of the industry, that was even faster than researchers imagined a few years ago [122]. The tip height of offshore wind turbines in 2013 was approximately 150 meters, and these turbines had a rotor diameter of 120 meters 6.1. When we compare this to one of the current largest turbines used, the 14.7 MW turbines used at Moray West offshore wind farm, with a rotor diameter of 222 meters, with an maximum tip height of over 300 meters [123], the large increase in size is emphasized. These larger turbines allow for better wind resource capture at greater altitudes, where winds are usually higher, contributing to the reduction of LCOE. However, these advantages come with new challenges, as was emphasized during interview one: "Costs for vessels and hammers are rising, which means the industry must innovate to stay economically viable. The push for larger turbines is as much about efficiency as it is about reducing costs." The increase in turbine size has an effect on the foundation design, and installation procedure of the turbines and their foundations.

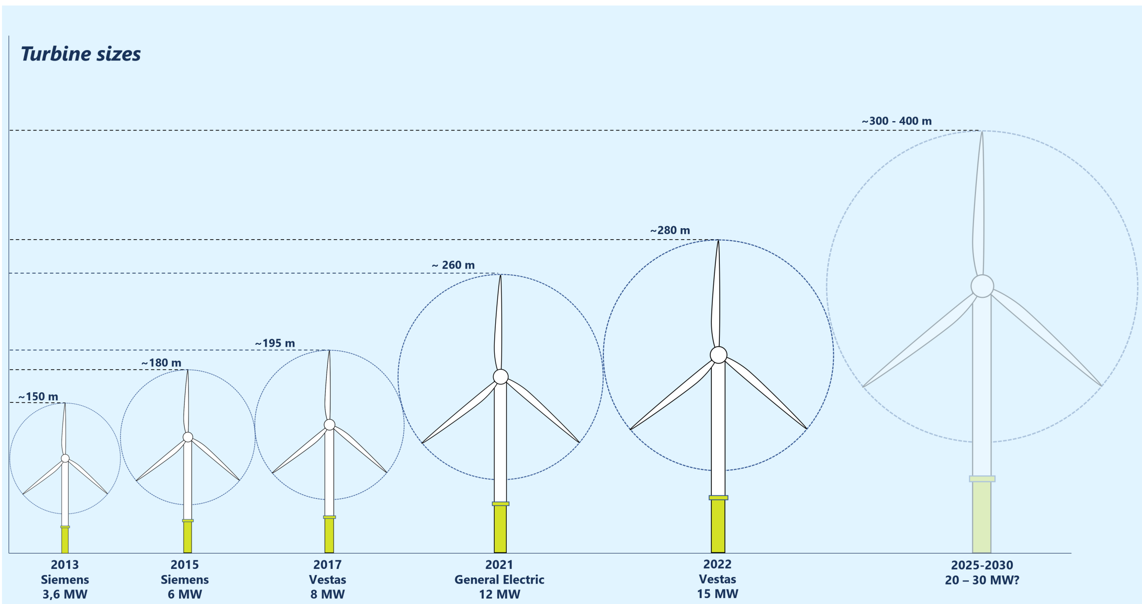


Figure 6.1: Advancements of offshore wind turbines [124]

6.2. Impact on foundation design

The further scaling of wind turbines places significant new demands on the foundations that support them. Larger turbines generate greater loads due to their increased weight, larger rotor diameters, and the higher wind forces acting on them. Consequently, foundations need to be designed to withstand the higher loads. The weight of the tower, nacelle, and rotor, combined with larger wind forces acting on the blades, results in much larger overturning moments and axial forces at the base of the turbine. These forces must be resisted by the foundation, which necessitates either larger foundations or more different foundation designs. The industry must continuously adapt to accommodate these new engineering demands. Transitioning from 5 MW turbines to 15+ MW turbines requires a large increase in the foundation load bearings capacity, and this led to a large increase in the foundation dimensions, as discussed in Section 5.2. As turbine capacities increased, monopile dimensions had to follow, as emphasized during the interviews "The push for larger wind turbines is driving the development of larger foundations. These foundations are getting heavier and more complex, requiring bigger ships and cranes for installation." This has forced Sif, a company that manufactures monopile foundations for offshore wind turbines, to innovate in terms of both fabrication techniques and the logistics of handling larger, heavier structures.

> "We are now producing monopiles of up to 11 meters in diameter and more than 100 meters in length. These dimensions would have been unimaginable a few years ago."

A good example of the fast developing sizes of foundations, is the evolution of their factory. Their adaptation to the scale developments, can clearly be seen when looking at their facilities. They scaled their factories accordingly to the demand for a certain foundation dimension. When standing in front of their office, the development of their production halls instantly becomes clear due to the size differences between the different generations of production halls, emphasizing the fast development of the foundation sizes.

When taking a closer look at monopile foundations as an example, the growth of foundations becomes clear right away. The foundations for 6 MW turbines in water depths of 30 meters, were around 7 to 8 meters in diameter and weighed up to 800 to 1000 tonnes. Modern XL, XXL, or even XXXL monopiles can exceed 10 meters in diameter and weigh over 2000 tonnes. Interviewee three mentioned that this scaling efforts will present significant challenges in the future in terms of manufacturing, transport, and installation. These two examples can obviously not directly be compared to each other, since the current offshore wind farms are installed in deeper waters, due to the lack of available shallow water locations, and due to the search for stronger wind speeds, but it sketches an image of the size increase of currently used monopiles in comparison to the foundation piles used 10 years ago. During interview five, it was discussed that besides just scaling the foundations, the design of the foundation has changed over the year, from relatively thick piles originating from design codes adapted from the oil and gas industry, to even more slender structures. "We are now making monopiles of 11 meters, and they are still 100 mm thick. You can see that the design code of monopiles, which was based on oil and gas principles, was ultra-conservative."

Scaling turbines from current sizes of sometimes 15 MW to 20+ MW in the future, poses new demands on foundation sizes. The primary challenge is not only the size and weight of monopiles but also the depth and distance to shore. Larger turbines require deeper foundations and vessels capable of handling these heavy loads, which necessitates increased collaboration between developers and installation contractors to ensure the availability of suitable equipment, as was underscored during the interviews: "One of the things I always emphasize is the importance of collaboration between designers, contractors, and installation companies. The growing complexity of projects means that working in silos doesn't work anymore. We need to ensure that designs are both installation- and operation-friendly from the start."

Monopiles are to this date the preferred and most used foundation type, due to its simplicity and cost effectiveness. However, the increasing diameter and weight of monopiles are pushing the limits of existing installation technology. Monopiles are getting larger not just in diameter but in length, as deeper water projects emerge. The designs have to account for both water depth and turbine size. During interview four it was mentioned that in response to the scaling challenges, jackets and other alternatives might become more attractive for deeper waters or sites where monopiles reach practical or economic limits. *"As turbines grow larger, I believe we'll see more focus on innovative foundation types and installation methods. Whether it's using monopiles or alternative designs, the key will be finding solutions that balance cost, efficiency, and environmental impact."*

6.3. Vessel and equipment requirements for larger turbines

Lifting capacity

Due to the increased size of offshore wind turbines and their foundations, the equipment and vessels used during the installation sequence had to scale accordingly. As turbines an foundations increase in size and weight, the vessels required for the installation must be equipped with higher capacity cranes, have large deck spaces, and more sophisticated handling equipment. Turbine sizes can reach up to 20 MW in the near future, which requires substantial vessels and lifting capacities. This scaling trend has been ongoing, and the industry has to keep up. As monopiles get larger, the logistical challenges increase as, transporting these huge structures, handling them at the port, and ensuring they can be installed efficiently at sea.

“The challenge with scaling is not just about handling larger monopiles; it’s also about coordinating the logistics of larger vessels and tools to ensure smooth installation.”

Current installation vessels are being pushed to their operational limits by the increasing size of turbines and their components. The installation of larger turbines and their foundations requires large installation vessels with high capacity cranes. Many jackup vessels that have been deployed for the previous and current installations, are nearing, or already exceeded, their operational limits. The current jack up vessel with the highest capacity crane is 1600 tonnes, and is therefore not able to install all current monopile sizes, with weights exceeding 2000 tonnes, which is a challenge that will become even more noticeable in the future, as was emphasized by interviewee three: *“As monopiles get larger, we’re seeing length limits become a challenge, both in terms of fabrication and installation. It comes down to what vessels are available and what kind of setup you need.”*

Over the past 4 to 5 years, a trend can be seen in the movement away from jackup vessels to heavy lift vessels for the installation of foundations, which can be related to the increased foundation weights and the inadequate crane capacities of the current jackup vessel fleet. In addition to increased lifting capacities, vessels also need larger deck spaces to transport the larger monopiles, jackets, and turbine components. The number of vessels capable of transporting, and handling the loads of the current and future foundation from ports to the offshore locations is limited. This creates potential bottlenecks in the supply chain, particularly as the demand for offshore wind installations continues to grow. The current state of the art installation vessels have therefore increased free deck space, as the Orion has a free deck space of 8000 m2, and a maximum pay load of 30.000 tonnes, capable of transporting multiple ’XXL’ foundations at a time.

The current movement is to state of the art installation vessels, equipped with high capacity cranes, and large free deck space. The Orion of DEME, is such a vessel, and is able to lift 5000 tonnes to heights of 175 meters. These vessels are also designed to operate in deeper waters, due to the DP3 system, combined with motion compensated equipment, that enables the vessel to install foundations while afloat without the need to deploy anchors. In an interview with Boskalis, it was mentioned that during the build phase of their current largest heavy lift vessel, they were already talking about plans for the next, larger vessel, emphasizing the implications of the fast developing offshore wind sector. *“We are already working on concepts for new vessels, like the BOKALIFT 3, which will have even bigger capacity to handle 20 MW turbines and their foundations. This is part of staying competitive in a fast-growing market.”*

Transporting larger components from ports to offshore installation sites requires specialized vessels and logistical planning, which is another significant challenge. Specialized vessels are required to transport over-sized monopiles and jackets, and the limited availability of these vessels can create bottlenecks in the installation process. The number of vessels capable of transporting and installing the current and future foundations is limited. This results in longer lead times and increased transportation cost, which can delay project timelines and affect the overall cost-effectiveness of offshore wind projects, and therefore influence the growth of the offshore wind market. The logistical challenges encountered with the current foundations, become only more noticeable when foundations get even larger. If the supply chain is in place, and foundations and components can be delivered, the transportation of these large structures remains highly dependent on vessel availability and infrastructure, which can in terms cause delays in the planning of the future projects where even larger turbines and foundations have to be installed.

Equipment

As installation vessels adapt to handle larger foundations, installation equipment and techniques must also evolve. The need for larger and more efficient installation vessels is accompanied by the requirement for specialized equipment to mange the installation of larger foundations. Motion compensated grippers were introduced to enable foundation installation while afloat, enabling installations in increasingly deeper waters. In addition to these developments, innovations in pile driving technologies are also being explored to reduce noise pollution and improve installation times of the ever increasing foundation sizes, as was emphasized during the interviews:

"Noise is one of the biggest challenges we face, especially as monopiles get larger. We've developed noise mitigation tools that help keep sound levels within acceptable limits during installation."

Environmental regulations demand quieter installation processes, certainly now the foundations are increasing in size, and requiring more powerful driving equipment. As an example: The current largest hammer in the world, the IQ6 designed by IQIP, can deliver 5500 kJ, but during the interviews it was mentioned that the company is even continuing to push for even larger stronger models, which will even create more noise during the installation.

This scaling of turbines from 15 to 20 MW and beyond, requires the design of new installation equipment capable of handling these larger monopiles. This increase in diameter necessitates the use of higher capacity driving equipment, as well as more robust noise mitigation measures to comply with stricter environmental regulations. Alternative driving methods, that are aimed at reducing installation noise can offer solutions for the noise limitations of future installations, however these methods are not yet widely adopted in the risk averse offshore wind sector. These methods lack large track records, introducing risks since their ability to deliver good results time after time is unknown.

Besides noise, lifting and handling equipment must be increased in capacity too. As turbines have scaled up, the tools to handle the larger monopiles had to be scaled up as well, to ensure the installation process remains efficient. Companies that design equipment, as TWD, have been developing new installation tools to meet the growing needs of the offshore wind industry. TWD has for instance developed new lifting tools and custom gripper frames that can handle the larger and heavier monopiles needed for the next generation turbines. One of the most significant innovations of the past few years, was the development of a motion compensated gripper frame, which provides the monopiles stability during installation, enabling the precize and efficient installation of monopiles while a float on DP, without the need to deploy any anchor. As was highlighted by the interviewee of TWD:

"We're constantly working on custom tools and vessels that can handle the increasing size of monopiles. It's not just about scaling up—it's about making the installation process more efficient and precise."

6.4. Logistical and supply chain implications

The scaling of turbines and foundations also presents substantial logistical challenges, particularly the supply chain and port infrastructure. Larger foundations and turbines require specialized handling, transportation, and storage, all of which can create bottlenecks in the offshore wind installation process. Interviewee two said that

"Larger foundations mean more complex installations, requiring specialized tools, bigger vessels, and more careful logistical planning."

During the several other interviews the need for optimized supply chains and port infrastructure capable of handling the larger components of offshore wind farms, was also emphasized. Specifically, experts highlighted that port infrastructure may become a limiting factor in future installations, as larger turbines demand larger storage areas and transport facilities, adding pressure on existing ports and logistics, as emphasized by an interviewee of Sif:

"As monopiles get larger, the logistical challenges increase, as well as transporting these huge structures, handling them at the port, and ensuring they can be installed efficiently at sea."

Port infrastructure limitations

The scaling of offshore wind turbines has created several bottleneck in the global supply chain. Larger foundations and turbine components require more advanced manufacturing and storage facilities that can handle the increased sizes and weights. Ports play a critical role in the offshore wind installation process, and scaling turbines and foundations have placed new demands on port infrastructure. Ports must be able to accommodate the storage and handling of larger foundations, which require larger quaysides, higher crane capacities, and more robust handling equipment. In some cases, ports are being redesigned or expanded to meet the demands of the offshore wind industry. For example, new heavy-lift quaysides are being constructed to handle the increased weight of turbine components, and larger storage areas are being allocated to accommodate the growing size of foundations [125]. However, the pace of these upgrades may not keep up with the scaling of turbines, leading to potential delays in the supply chain [126]. In the interviews it came forward that efficient logistics management and port handling will continue to play a pivotal role in supporting the scaling of offshore wind projects as the industry grows. Investments such as the €780 Million investment for the port of Esbjerg in Denmark and the £300 Million investment in the Ardersier Port in Moray Firth in Scotland, enable the handling of larger turbine components for the latest generation of offshore wind farms [125], [127]. Large Quay sides will be developed, with a high load bearing capacity.

Supply chain issues

The scaling of offshore wind turbines has exposed several bottlenecks in the global supply chain. Larger foundations and turbine components require more advanced manufacturing facilities that can handle increased sizes and weights. Steel production for foundations, for instance, has become a limiting factor, as suppliers struggle to meet the growing demand for large-diameter monopiles and jacket structures. Due to the highly specialized and specific equipment and due to the size of some of the equipment used in the offshore sector, this in some instances means that only a hand full of manufacturers exist for some components. To take an impact hammer as example, during the interview with IQIP, it was mentioned that these hammers rely on the use of an anvil that is currently only produces by a couple of manufacturers in the world. When the industry keeps scaling up, this reliability on one or two producers could be a potential risk and become a bottleneck in the future.

Additionally, the increased size of turbine components makes offshore installation more time-consuming, as larger foundations require more complex handling and positioning procedures. Delays in the availability of vessels, equipment, or components can have an cascading effect on project timelines, increasing costs and potentially delaying the wind farms.

During interviews with CAPE HOLLAND and Boskalis, the interviewees pointed out that transporting larger turbine components requires specialized vessels with high capacity cranes, which are often in short supply. As turbine sizes grow, the number of vessels capable of transporting and installing the ever increasing foundations, decreases, leading to longer lead times for securing the necessary vessel.

6.5. Cost implications and economic impact of scaling

The scaling of offshore wind turbines has both positive and negative effects on costs. On the one hand, larger turbines reduce the LCOE, however, they also increase the initial investment cost associated with the turbines. The installation cost of larger foundations needed, will also increase, as do vessel and equipment requirements and cost.

Cost drivers

During the interviews it was emphasized that while technological advancements will drive the future of offshore wind, economic and environmental factors will continue to shape the industry. Rising costs, particularly for vessels and hammers, will push the sector toward more cost-effective solutions, while stricter noise regulations will necessitate quieter installation methods.

The theme of cost reduction came up frequently during the interviews. Companies are focused on making installations more cost-effective while scaling up. The transition towards subsidy-free projects like Hollandse Kust Zuid exemplifies the trend toward minimizing expenses. According to interviewee nine, this has led to innovation in foundation designs, such as exploring alternative foundation types like suction buckets and floating platforms, but monopiles remain the dominant choice due to their relatively low cost and adaptability.

Economies of scale versus Increased complexity

While the upfront costs of installing larger turbines are higher, the interviewees frequently pointed out the long term economic benefits achieved through economies of scale. As turbines become larger, fewer turbines are required to generate the same amount of electricity, which can reduce the overall number of installations, thereby lowering costs related to project management, operations, and maintenance.

This has however a down side for the installation contractors, since they do not directly benefit from the increase in capacity per turbine. For them the scaling efforts mean constant new investments, to build capable vessels and upgrade equipment and technologies used, to guarantee their future position.

Fewer installations mean fewer trips for vessels and reduced logistics costs over time, which can balance out the higher initial costs. You can use these insights to argue that while the initial investment for larger turbines is significant, the potential for reduced operational costs in the long run is a key motivator behind the scaling trend.

Impact of technological innovations on costs

Several interviewees discussed how innovations in installation technologies are helping to mitigate the cost increases associated with larger turbines. For example, the development of floating vessels like Orion and the adoption of TP-less installation techniques allow for more efficient installation processes, reducing the time spent at sea and lowering the associated vessel costs.

6.6. Environmental and regulatory implications of scaling

Scaling offshore wind turbines and their foundations, also has significant consequences for the environment. Larger foundations require heavier equipment for the installation, which can have an impact on the marine ecosystems, in terms of noise pollution and seabed disturbance.

"Environmental concerns, especially noise, are becoming more important, particularly in countries like Germany. As foundation sizes increase, more noise reduction techniques are being developed, but we still need to strike the right balance between cost, efficiency, and environmental impact."

6.6.1. Regulatory changes and permitting

The offshore wind market is still growing, and so is the knowledge of the effects of offshore wind farms. Germany was the first country to impose noise restrictions during the installation phase of offshore wind farms, but more countries are following their example. In the early days of the offshore wind sector, not a lot was know about the effects on ecosystems and animals, and therefore regulations were not not in place or not as stringent. As turbine sizes and project scales continue to grow, collaboration between industry stakeholders and regulators will be essential to streamline permitting and ensure that environmental and social impacts are minimized.

6.6.2. Noise mitigation and seabed disturbance

The installation of larger turbines and foundations has notable environmental implications. Larger foundations result in greater seabed disturbance during installation, which can have an effect on marine ecosystems. During the interviews, several experts highlighted the environmental impacts associated with the installation of larger foundations, particularly regarding noise and seabed disturbance. For instance, interviewees two and four, discussed the increasing emphasis on noise mitigation measures during pile driving, as regulations on marine ecosystems, especially in regions like the North Sea, are becoming more strict. Technologies like bubble curtains are being deployed even more frequently to mitigate the underwater noise that can harm marine life during the installation of monopiles. The noise generated during the installation operation is currently one of the largest issues, and came forward in the interviews as possibly one of the biggest issues of the upcoming years. The noise can have negative effects on marine mammals sensitive to underwater noise. Larger foundations require more force to driven into the seabed, which creates even more noise. To address this issue, the industry is developing and deploying a range of noise mitigation measures, such as bubble curtains and hydro sound dampeners.

Besides noise concerns, the scaling of the offshore wind sector requires careful consideration of marine habitat impacts. Larger and more windfarms, with larger foundations may affect animal populations and migrations [128].

During the interviews, several interviewees, like interviewee three, highlighted how larger foundations result in greater seabed disturbance, particularly for monopiles and gravity based foundations. This has led to more frequent use of alternative foundation types and alternative driving methods, as suction buckets and vibratory pile installation, which can reduce the environmental impact. However, these alternatives are still in the experimental phase and face regulatory hurdles. Further scaling of offshore wind turbines increases environmental impact, but also drives the developments of innovative installation techniques aimed at mitigating these impacts. These innovations are however not just driven by the technical necessity, but are also responses to tightening environmental regulations in many offshore wind regions.

6.6.3. Regulatory challenges

As turbine sizes increase, experts noted that the regulatory landscape is changing to address the new challenges. Interviewee nine, for instance, pointed out that the push for standardization in foundation design helps reduce costs, but regulations often lag behind technological innovations. Delays in the approval of new designs, such as floating foundations or suction buckets, occur because existing regulations were created with traditional monopile and jacket foundations in mind.

6.6.4. Future environmental and regulatory trends

Lastly, many interviewees suggested that the future of offshore wind foundation installation will increasingly be shaped by environmental regulations aimed at reducing the carbon footprint of installation processes and minimizing the impact on marine ecosystems. For example, the use of vibro-hammers and floating foundations are seen as environmentally friendly alternatives that reduce the duration of pile driving, limiting noise pollution and seabed disturbance, as was mentioned by interviewees seven and eight.

6.7. Future outlook and trends

The scaling of offshore wind turbines and foundations presents both challenges and opportunities for the industry. Larger turbines offer the potential for lower LCOE and increased energy capture, making offshore wind more economically viable, but scaling also introduces significant technical, logistical, and environmental challenges that must be addressed through technological advancements and innovations. Future projections of the growth of offshore wind turbines say that offshore wind turbines will remain to grow. During interview nine it was even mentioned that 35 MW turbines would even be a possibility. Currently plans for developing 20+ MW turbines are already in motion. The Chinese manufacturer Dongfeng has even already rolled out a 26 MW turbine, and other companies as Siemens are also working on the 'next-generation' turbines with capacities exceeding 20 MW, which are expected to be deployed before 2030 [129]. Rotor diameters of these turbines will likely exceed 250 meters, and hub height will grow accordingly. Researchers at the Norwegian Institute of Energy Technology have found that 25 MW turbines appear to be the maximum size of offshore wind turbines [122]. Oggiano [122] however added to these findings, that they just as well could be proven wrong in 5 years time, emphasizing that it is actually unknown what the most installed turbine sizes in the future will really be. To future proof the offshore wind installation sector, the industry must continue to invest in next generation vessels, advanced installation techniques, and enhanced port infrastructure.

6.8. Conclusion

Offshore wind turbines have seen a large growth in capacity rating over the years, and turbine capacities will continue to grow in the upcoming years. Currently, the largest turbine installed is the 15 MW, but several companies are already working on 20+ MW turbines, as for instance Siemens, and 30+ MW turbines are also thought to be a possibility. The historical scaling of turbines has led to the constant adaptation of the foundation and installation sector, and the question arises what the implications will be, of further scaling offshore wind turbines.

The objective of this chapter was to analyze and discuss the consequences of the further scaling of offshore wind turbines. In this analysis, the scaling trends trends are presented, which present both opportunities and challenges for the installation sector. Larger turbines do offer the potential to lower the LCOE, but they also require significant advancements in foundation design, installation technology, logistics, and the supply chain. As the offshore wind sector moves to even larger turbines, the foundations and thereby the foundation installation sector has to grow with the turbines. The chapter follows the implications across several key areas as, foundation design, vessels and equipment, logistical, cost, and regulatory implications that follow from the further scaling of offshore wind turbines. The chapter highlights that logically the foundations be adapt and scale accordingly to the turbines, but that the movement to even larger foundations has a lot of implications. Foundations that are able to withstand the higher forces of larger turbines, are inherently larger and heavier. This has consequences for the entire transportation and installation sector. Larger and heavier foundations necessitate the use of vessels with larger crane capacities, and larger deck spaces. Larger turbines also impact the upfront investments, and the the larger foundations produce even more noise during the installation, requiring even more sophisticated mitigation strategies. By analyzing these implications, the chapter will provide an answer to the research question:

What are the implications for the offshore wind installation sector of the further scaling of offshore wind turbines?

One of the most logical consequences of the increasing turbine sizes, is the need for larger foundations that can withstand the larger forces accompanied with these larger turbines. As turbines continue to increase in size, the foundations have to follow. The fast developments of the sector put a lot of strain on the supply chain and manufacturing processes of the foundations. Foundation fabricators continuously have to scale up and increase their factory and manufacturing methods, to be able to accommodate larger foundations. Historical scaling efforts, show the same issues, but the monopile remained the foundation type of choice. As turbines get even larger, alternative foundation types, as jackets, might become more cost effective than monopiles due to the limitations of handling and installing even larger monopiles. Cost will always remain to drive the foundation selection, if several foundation types are feasible.

Due to the increased size of offshore wind turbines and their foundations, the equipment and vessels used during the installation sequence has to scale accordingly. Vessels have to be equipped with higher capacity cranes, have larger deck spaces, and require more sophisticated handling equipment. The jackup vessels that accounted for the majority of the installations, from 2012, are not even able to install the current largest foundations. This emphasizes the quick growth of the offshore wind sector, and the implications for vessel owners, of their costly investments. During one of the interviews this was underscored, by mentioning that plans for a new vessel were already being discussed when the previous vessel was not even launched. The equipment used during the installation procedure subsequently has to grow with the foundations, and no real issues are foreseen in this area. Everything needs to be scaled and becomes larger, but in one of the interviews it was even mentioned that designing equipment for 5000 tonnes foundations would not be an issue.

Besides scaling vessels and equipment, the increased size of turbines and their foundations also have large implications on the logistics and the supply chain. Larger foundations mean a more complex installation, requiring more careful logistical planning. A large area that will be impacted, are the ports that serve as hubs for the installation campaign of an offshore wind farm. Several reports predict a large issue with the supply chain, and ports must continue to invest in their infrastructure to be able to handle the future larger structures, since ports will play a pivotal role in the future of the offshore wind installation sector. Other supply chain issues become also become more pressing as the industry scales up even more. The industry is for instance heavily dependent on the steel supply, and in some cases on specific producers of highly specialized equipment and components needed for the manufacturing processes. This dependence on key producers can become a large concern in the future, and forms a potential risk.

The shift to even larger turbines is mainly driven by the goal to lower LCOE, and these economic benefits are only noticeable in the long term. The initial investment cost of these larger turbines and their foundations will be higher, and besides higher component cost, the installation will also be more costly, as vessels and equipment rates will also increase.

Larger foundations, when looking at monopiles, require more force to be driven into the seabed, and therefore produce more noise. In the interviews it came forward that environmental regulations concerning noise are expected to become more strict in more areas. This means that noise mitigation systems have to be improved in order to stay under noise limits. For current installations in Germany, almost all the stops have to be pulled out to remain under the limits. For the installation of the He Dreiht wind farm in 2024, a 45 meter wide, 2500 tonnes weighing noise mitigation system was deployed. This gives an understanding of the issues the industry is facing in terms of the size of noise mitigation systems for future larger turbines.

7
Innovations in offshore wind foundations

The offshore wind industry has seen a large growth since the first offshore wind farm, driven by the need for renewable energy. The rapid expansion of the offshore wind industry needs continuous innovation in foundation technology and installation methods. Innovations in the offshore wind sector and the foundation installation sector are essential for the future of offshore wind farms, particularly as the installations move to deeper waters, turbine sizes increase, and environmental regulations become stricter. Innovations are not only crucial for reducing costs and improving efficiency but innovations in noise mitigation systems and alternative driving technologies are also essential for reducing environmental impact, and assuring the feasibility of future large scale offshore wind projects.

This chapter explores the different phases of innovations in the offshore wind foundation installation sector, focusing on the factors that drive technological advancements, the challenges associated with innovation, and the characteristics that determine the success of new technologies. Innovations are essential for the future of the offshore wind sector, to sustain future growth with a low environmental impact, as was emphasized during interviews one, two, and five:

> *"The future of offshore wind relies on technologies that can address new challenges posed by deeper waters and harsher environments, which means we're constantly looking for solutions that weren't necessary just a few years ago."*
>
> *"Looking forward, there's a real need for technologies that can make the installation process faster and more cost-effective. If we don't innovate, projects will become more expensive and complex, which is not sustainable for the industry's growth."*
>
> *"The sector is evolving rapidly, and innovation is the only way to keep pace. As turbines get bigger and installations push farther offshore, the demands on foundation technology are growing."*

One of the key challenges of the next few years, that came forward during the interviews, are the noise limitations during the installation of foundation piles. A lot of the current innovations are therefore aimed at alternative driving methods, or improving noise mitigation systems. Innovating in the offshore wind sector, is however not as straight forward as might be in some other sectors. Installations of offshore wind turbines and their foundations are highly specialized and costly operations, leading to risk-aversity to avoid financial problems. Projects require extensive testing and track records before a technology gets adopted, but to obtain a substantial track record, the technology logically has to be used.

This chapter looks into the different phases that innovations go through, and discusses several challenges associated with each phase. To be able to asses and follow the progress of innovations, the TRL framework is used as guidance through the life span of an innovation, from its design, to its first tests, and eventually to full scale deployment. Furthermore, it explores the evolution of innovations within the offshore wind foundation installation sector, focusing on key advancements, challenges, and the factors influencing the successful adoption of new technologies, aiming to answer the research question:

What factors determine the success of an innovation in offshore wind?

The chapter is structured as shown in the Figure. In Section 7.1 the different phases a technology has to go through are described, as research, development and testing, and deployment and market adoption. In Section 7.2, the characteristics of a good innovation such as, scalability, adaptability, regulatory compliance, and environmental impact are discussed. In Section 7.3, A case example of an innovation in foundation installation sector is given, to provide insights in a real life situation, and to show the alignment with the characteristics presented in Section 7.2. In Section 7.4, a future perspective on how emerging trends and technologies are expected to shape the sector is given.

7.1: Different phases of innovations
7.2: Characteristics of a good innovation in the offshore wind sector
7.3: Case study
7.4: Future trends
7.5: Conclusion

7.1. Different phases of innovations

Innovations go through several phases before they achieve market penetration. What makes it so difficult to innovate in the offshore wind sector are factors as the risk-aversity of the sector, the high investment cost, and the fast pace of the developing sector. Technological innovations in the offshore wind sector can be assessed through the Technology Readiness Level (TRL) framework, which ranges from one to nine, and categorizes innovations on how ready they are for commercial deployment, and is used to assess the maturity of a technology. The TRL scale was originally developed by NASA, but it has since been adopted in many industries, including in the offshore wind sector, to help stakeholders understand how close a technology is to being deployed in real world conditions [130].

In the offshore wind sector, the TRL scale is used to evaluate and communicate the maturity of a technology, like new foundation types, installation methods, and other innovations. The TRL scale also makes it possible to compare innovations across projects and sectors.

The different levels can be linked to different phases of an innovations [131]. The different phases of innovations are given in Figure 7.1.

Figure 7.1: Key phases an innovation goes through

These three phases are discussed in the following Sections, and align with different levels of the TRL scale. For each phase, an example related to an innovation in the offshore wind sector is given, to provide some context about what the different levels imply.

7.1.1. Research (TRL 1-3)

In the early stages of an innovation, the focus is on basic research and concept development. The basic principles of the idea, formulation of the technology, and a proof of concept will be focus of in this phase of the innovation [131]. For example, floating foundations were once at this stage, where theoretical designs like spar buoys and semi submersibles were first proposed to address the challenges of deeper waters. At this stage, the focus is on feasibility, assessing how the designs might be implemented for offshore wind turbines beyond traditional bottom fixed foundations.
One of the main challenges in this phase is determining whether the design can solve specific industry problems, such as deeper installation requirements or reducing environmental impacts like noise. For instance, floating platforms must overcome the issue of stability while minimizing the complexity and cost of the anchoring systems used in deeper waters.

7.1.2. Development and testing (TRL 4-6)

The subsequent phase is the development and testing phase, innovations at TRL 4-6 move from theoretical research to practical testing. At this stage, prototypes are built and tested in controlled environments to evaluate their performance under realistic conditions. For instance, the first tests of the vibro jetting technology of GBM Works in 2020 is a good example of an innovation at this stage. In this phase, the technology was tested at a test location on shore, so not in a real world situation, and with a small diameter pile [132]. In this phase field testing under real world conditions becomes critical. The technology is currently in the next phase of development, and will be tested in October 2024 in a large scale offshore environment, where 3 test piles will be installed at the Hollandse Kust West VI offshore wind farm. The data gathered, combined with the drivability test and noise measurements will takes this technology to a TRL 7 [117].

7.1.3. Deployment and market adoption (TRL 7-9)

Once an innovation has proven its viability through testing, the innovation reaches the phase where the technology will be demonstrated with a prototype in a real life environment. This involves deploying the technology in small commercial projects to gauge its real world performance. Besides scaling regulatory approval is also an important part in this phase for an innovation [133]. One prominent example is the suction bucket foundation, which moved from the first pilot project at the Borkum Riffgrund one site, to full-scale deployment in projects like the Borkum Riffgrund 2 wind farm. Suction buckets allow for quicker and quieter installations compared to traditional pile-driven methods, particularly useful in areas with stringent noise regulations [23]. These technologies must undergo extensive field testing to validate their performance, scalability, and cost effectiveness. For suction buckets, the challenge at this phase was demonstrating its ability to be installed at a larger scale [23].

The final stage of the innovation life cycle is large scale deployment and standardization. The technology is mature, fully operational, deployed in commercial environments, and is becoming part of standard industry practice. Once the technology has been validated, industry adoption becomes the main focus point [134]. The focus at this level is on refining the technology, optimizing cost efficiency, and expanding its deployment. The monopile foundation has now reached this stage, as it is widely regarded as the industry standard for shallow to intermediate water depths. The focus at this stage is not just on proving that the technology works, but on optimizing it for cost efficiency, ease of installation, and integration with larger turbines.

For innovations at TRL 9, standardization becomes crucial. Industry-wide acceptance requires detailed standards for design, installation, and maintenance, ensuring that the technology can be applied consistently across various projects.

7.2. Characteristics of a good innovation in the offshore wind sector

Following from the different phases innovations go through before they achieve market deployment, it becomes clear that certain characteristics are crucial for an innovation to overcome the challenges associated with a certain phase. The success of an innovation in the offshore wind sector is not only based on the TRL level the technology is currently at, but depends on several other factors that are specific for the offshore wind sector. Innovations in the offshore wind sector face challenges with market acceptance, as was highlighted during interview two:

> *"The key to innovation success in offshore wind is balancing the technical aspect with market acceptance. Often, technically sound solutions fail to get adopted because companies aren't convinced the new technology will provide the improvements it promises. That's why innovation in this sector takes time."*

The offshore wind sector is risk averse and capital intensive, and for an innovation to be adopted in this sector, it must meet several key criteria to increase its chance for success. During the interviews several challenges that influence the adoption and the success of an innovation in the offshore wind sector came forward. The main points that were discussed are, cost reductions and the high investment cost in the offshore sector, risk-aversity, scalability of the technology, and environmental drivers.

> *"In the end, innovating in the offshore wind sector is a balancing act. We have to meet technical, regulatory, and market requirements simultaneously, which is challenging and time consuming."*

Furthermore innovations were said to be driven by necessity in the offshore wind sector. When combining these factors with the different phases of an innovation discussed in Section 7.1, several key factors for the success of an innovation in the offshore wind sector can be formulated. These success factors address the challenges that came forward during the interviews, and integrate the challenges that came forward during the different phases of an innovation. These factors influence the success of an innovation in the offshore wind sector:

- Solve a certain problem
- Improve installation efficiency
- Reduce costs
- Reduce risk
- Be scalable
- Minimize environmental impact

These characteristics define the success of an innovation in the fast evolving offshore wind sector, and are discussed in the following sections. Throughout the section, quotes extracted from the interviews are used to highlight the importance of the corresponding success factor. It is not said that an innovation cannot succeed when it does not comply with all the factors, but compliance with several factors, does increase the chance on market adoption, and deployment in the fast evolving offshore wind sector.

7.2.1. Problem solving ability and Necessity

A successful innovation must solve a specific problem or address a challenge in the offshore wind industry, as was mentioned in Section 7.1, at the research phase, corresponding to a TRL level of 1 to 3. In the offshore wind sector, these problems often include challenges such as increasing water depths, larger turbine sizes, complex seabed conditions, or environmental impacts. A successful innovation in the offshore wind sector must address a specific, existing challenge in the industry, such as reducing noise pollution, improving installation efficiency, solve issues related to deeper water locations, increasing turbines sizes, or other installation challenges. Innovations that solve long-term issues are particularly valued, as highlighted by interviewees six and five:

> *"It must meet a need. It must solve a real problem. And then it does not matter how you solve it, as long as it solves the problem."*

> *"If you can do things faster, smarter, cheaper, then you will innovate. But, if the innovation is not addressing a current need or isn't cost-competitive, it's often sidelined."*

In the interviews it also came forward that most of the innovations in the offshore wind sector have been of an incremental nature, and that the sector has not seen any large disruptive innovations. The innovations were optimizations and alterations, aimed at reducing installation times, reducing cost, and reducing risk.

Furthermore, it was mentioned that innovations in the offshore wind sector will remain to be driven by necessity. Innovations will be sparked, when a certain problem arises, that needs solving, as was emphasized by interviewee four: "I believe innovation will continue to be driven by necessity. As turbines get bigger, the stress on connections increases, which will push the industry to find new solutions. But we're already seeing developments, like using suction buckets to reduce environmental impacts in places like Germany." This shows that innovations follow after a certain problem arises, the new technology is developed after a need came forward to change the installation process to minimize environmental impact.

For example, the introduction of vibratory pile driving was aimed at mitigating the noise pollution caused by traditional impact piling. This problem became critical in regions where environmental regulations regarding under water noise were strict, as in Germany. By solving the issue of noise, vibratory pile driving enables projects to proceed, without the need of extensive noise mitigation measures in areas with strict noise regulations, where traditional impact hammering would have required the deployment of multiple noise mitigation measures to remain under the noise limits. This technology was first used in 2012, but afterwards was sidelined, because it was simply not necessary to use, and induced installation risks, since the installation method lacked a substantial track record. More recently, the technology gained traction, and was used for several installations by DEME and Boskalis [135]. The reason why the technology was selected, was however not to reduce installation noise, but to efficiently and safely install the piles, and mitigate the possibility of pile run [107], as discussed in Section 5.4. This example highlights the difficulty of innovating in the offshore wind sector, where the sector prefers trusted, known methods, and only adopts a new technology if really needed.

7.2.2. Cost effectiveness and efficiency

Often the success of a project and the success of an innovation is measured by its ability to bring down the cost, and reduce the levelized cost of electricity, and thus in the end improve the profits. Reducing the LCOE is therefore one of the most important factors for the success of an innovation. Innovations that can demonstrate significant savings in material cost, installation time, or operational costs are more likely to achieve widespread adoption. For instance, an innovation that reduces installation time, reduces the time a vessel spends offshore, which directly lowers the cost.

A good example of such a optimization is the adoption of XXL, or even XXXL monopiles. "We're often seeing innovations because the market needs them. For example, monopiles were scaled because jackets were too costly at shallower depths. This wasn't just an innovation for innovation's sake but a response to a real cost problem", as highlighted by interviewee five. In the end it all comes down to choosing the most cost-effective solution. Previously jacket foundation were even thought to replace monopile foundations beyond a certain depth, but the monopile remains the most cost-effective foundation, which is the reason for its wide spread use. *"In the past, jackets were considered for deeper waters, but monopiles have remained the most cost-effective option for many projects, which is why they're still so widely used. Innovations that can reduce costs compared to existing solutions are more likely to be adopted"*, as mentioned by interviewee four.

Innovations in the offshore wind market that are aimed at combining or optimizing several installation steps, or reduce installation times, lower the capital expenditures and can even mitigate weather related risks. Efficiency is therefore a critical aspect of an innovation in the foundation installation sector. The faster and more reliably a foundation can be installed, the more cost-effective a project becomes, as was emphasized by interviewee eight: "For a new technology like the Vibrojet to be accepted, it has to not only perform well but also provide a cost advantage. It's about proving that this method can do the job with fewer resources and potentially less environmental impact, which would make it a more attractive option for projects focused on cost-effectiveness and sustainability."

One example of an innovation that has improved installation efficiency was given by interviewee two, as the motion compensated pile gripper, which is used to stabilize monopiles during installation from floating vessels. These gripper frames compensate for vessel movements, ensuring monopile installation accuracy. By compensating for vessel movement due to wind and waves, these frames enabled the installation of monopiles by vessels while a float on DP, removing the need for a jack up vessel to lower its legs, or to deploy anchors, reducing installation times. This technology also allows for installation in more severe weather conditions, thereby reducing project delays and increasing operational efficiency. During the second interview, the interviewee mentioned that: "Keeping it as simple as possible was one of the biggest goals. Simplicity not only makes repairs easier but also keeps the system reliable and cost-effective."

7.2.3. Scalability and adaptability

The offshore wind market has evolved in a rapid pace since its inception. Offshore wind turbines have grown from 4 MW in 2010 to 6 MW around 2015, and to even some installations for 15 MW turbines in 2024. Especially in the last few years, the turbine sizes have increased in a rapid pace. Scalability is therefore a crucial element of a good innovation, to be able to keep up with the fast developments of the offshore wind sector, as was emphsized by interviewee two and five:

> *"We aim to keep the design of new equipment as simple as possible, so that it can be scaled up when necessary without becoming overly complex or costly. Simplicity in design makes it easier to adapt for larger projects."*

> *"The market will always push us towards scalable solutions. The initial concept might work for smaller applications, but if it doesn't scale to accommodate the next generation of turbines, it will quickly become obsolete."*

As turbines continue to grow in size, innovations must be compatible with the next generation of turbines. A successful innovation does not only have to address current technical challenges, but must also be future proof for larger turbines and installations in deeper waters. Innovations that cannot scale up as turbine sizes increase and can adapt to different conditions will quickly become obsolete, as highlighted by interviewee four:

> *"Adaptability is key as well. Each project brings unique challenges, so innovations must be flexible enough to adjust to different site conditions, water depths, and regulatory environments."*

Monopiles, for example, have been scaled in both size, installation depths, and in numbers over the years. As offshore wind turbines have grown in capacity and size, monopiles have scaled accordingly, with diameters and weights increasing significantly over the past years. This adaptability has made monopiles the foundation type of choice, even for the current deeper water installations up to 50 meters water depth. Even though the monopile was only thought to be feasible and economically viable up to a water depth of 30 meters around 2010.

Equipment used during the installation phase also has to be scalable to be able to install the future larger foundations. For some equipment and technologies this will be more difficult than for others, and for some, the increased weight will even benefit the technology. Vibro-jetting Is such an innovation that can add value to the installation process for larger and heavier foundations. In an interview with GBM Works, the company behind the vibro-jetting technology, it was said that: *"We actually believe that the bigger the pile, the better for us, because our technology becomes even more critical when more energy is required to install larger foundations."* Furthermore adaptability was also highlighted to be crucial for their innovation: *"Adaptability is also crucial. Since each installation site has its own challenges, we've designed the Vibrojet to be flexible enough to adjust to different conditions, whether that's softer soils or harder substrates. This adaptability helps ensure that we can use the technology across various projects without needing a completely new setup each time."*

7.2.4. Regulatory compliance and environmental impact

Regulatory hurdles can make or break an innovation. Regulatory bodies are prioritizing environmental impact in offshore projects more and more. Environmental regulations are becoming more strict, particularly regulations concerning noise pollution and seabed disturbance, have become major drivers for innovation. Technologies that can meet or exceed these regulatory requirements while maintaining installation efficiency are more likely to be widely adopted. Environmental concerns are now a large part of the R&D, as mentioned by interviewee two:

> *"Environmental regulations are a driving factor in our R&D. We focus on designs that reduce emissions and impact on marine life, which helps us gain faster regulatory approvals and attract environmentally conscious clients."*

Noise mitigation measures and alternative foundation types that can reduce under water noise levels to 'acceptable levels', foundations that limit seabed disturbance, innovations that are aimed at positively contributing to the ecosystem, and innovations in decommissioning and recycling are all good examples of technologies developed specifically to address regulatory requirements. Technologies such as vibro-piling and bubble curtains have been developed to minimize noise pollution during monopile installation. These innovations are driven not only by environmental concerns but also by regulatory requirements, like strict noise limits during installation phases, as was highlighted by interviewee six.

> *"Our R&D prioritizes minimizing environmental impact because compliance with these standards isn't optional. We're continuously developing methods like 'Blue Piling' to adhere to environmental guidelines, reducing underwater noise and vibrations."*

Environmental regulations have a significant influence on the success of foundation innovations. For instance, in countries like Germany and the UK, strict noise regulations during the pile-driving process have led to innovations like suction bucket foundations and vibratory piling. During the interviews, it was mentioned that innovations are believed to continue to be driven by necessity. As turbines get bigger, the environmental impact of the larger foundations increase, which will push the industry to find new solutions.

> *"we're already seeing developments, like using suction buckets to reduce environmental impacts in places like Germany."*

The regulatory environment plays a crucial role in the adoption of new technologies in offshore wind. Governments and policymakers can significantly influence innovation by setting strict environmental targets or by offering incentives for the development of sustainable technologies. Additionally, subsidy schemes and tenders often reward innovations that meet specific environmental and performance criteria, providing a market advantage for adopting those solutions.

7.2.5. Risk management and reliability

During the interviews, risk came forward as one of the most important topics. The offshore wind sector is known for its careful approach to adopting new technologies due to the high financial risks involved,as discussed during interview six.

> *"If an innovation increases the chance of delays or unforeseen costs, it's going to face resistance until it proves it can operate without adding risk."*

The offshore wind industry is very capital-intensive, and innovations that require significant investments or carry high financial risks are often slow to gain traction. Companies are risk-averse, especially when it comes to adopting new technologies that have not been fully tested at scale. Companies are often reluctant to invest in innovative solutions without extensive demonstration projects, which are costly and time-consuming. During interview 4, it came forward that innovation adoption is slow because of the 'chicken or the egg' problem. New technologies need proven success before the market accepts them, but achieving this proof requires the innovations to be used in real life situations, as was highlighted by interviewee four.

> *"Hands-on experience is crucial for reliability. Knowing how equipment performs in the field reduces unexpected issues, which is vital for risk management."*

Industry stakeholders prefer innovations that either incorporate risk management features, such as redundancies in design, or have proven success in rigorous testing environments. For instance, motion-compensated grippers, which minimize downtime caused by rough sea conditions, have been adopted because they reduce operational risks during installation, as discussed during interview one.

Due to the risk and reliability concerns, demonstrator projects are vital for the adoption of new technologies in the offshore wind sector, as mentioned by interviewee one:

> *"There's a big gap between research and what's actually applied on-site. Many ideas look promising in theory but are hard to implement practically, especially under offshore conditions where every variable matters."*

Furthermore, in interview two it was discussed that a major challenge for innovations is that even one-off prototypes have to work perfectly. There is no room for iterative testing like in other industries, so every project feels like a trial where reliability has to be guaranteed before the start of the project.

7.3. Case study

In this section a previous innovation in the offshore wind sector is discussed. The innovation will be analyzed, and during this analysis a comparison will be drawn to the previously discussed factors for success, to further underscore what determines the success or failure of an innovation. Some of the key areas of interest, identified during the interviews, where innovations have been implemented in the past in the foundation installation sector are:

- Innovations in foundations and different foundation types
- Pile driving methods

- Noise mitigation systems
- Installation methods

During the interviews it came forward that the foundation installation sector has gone through a substantial development since the first offshore wind farm, but that the developments happened in a gradual manner. No 'disruptive' innovation really changed the foundation installation phase, in such a way that had a large impact on the installation sector. Over the years improvements in technologies, methods and some innovations contributed to a steady improvement and optimization of the known existing installation procedures.

In the offshore wind industry innovation plays a crucial role in improving installation processes and addressing challenges such as environmental compliance, operational efficiency, and cost reduction. The innovation that has been selected is the vibratory pile driving method, since this technology is seemingly interesting. The technology was used for the first time in 2012, but was not selected after this first adoption, and in recent years the technology again gained interest. This adoption pattern of the technology makes for an interesting case to analyze, and provides valuable insights into the dynamics of innovation in the offshore wind sector.

First, the technology, and its adoption will be discussed, and afterwards, a reflection will be presented in Section 7.3.2, on the different success factors of innovations in the offshore wind sector, discussed in Section 7.2.

7.3.1. Vibratory pile installation

Vibro piling is an alternative driving method to install foundation piles in the soil by applying continuous vibrations, to reduce the friction between the soil and the pile, allowing it to penetrate the seabed without requiring traditional impact hammers, as further discussed in Section 4.1.4. Two of the main goals of this technology are to reduce the noise produced during the installation of offshore wind turbine foundations, and to reduce installation time [136]. Noise has become a critical concern in offshore wind construction due to its impact on marine ecosystems. Vibratory driving minimizes peak noise levels, aligning with increasingly stringent noise regulations [113]. Additionally, the faster penetration rates achieved with vibratory methods offer potential time and cost savings, especially in suitable soil conditions like loose sands or silts [113].

Despite these advantages, the technology has certain limitations. It is less effective in dense or layered soils, where penetration resistance can reduce efficiency [113]. Additionally, the long-term performance in terms of the load bearing capacity remains a concern. These uncertainties, coupled with limited operational experience, have hindered its adoption as a primary installation method.

The vibro-piling technology is already used in the offshore wind foundation installation sector, but is still not widely adopted by the industry.

First use, testing, and market adoption

The first full scale offshore wind farm that used vibratory technology, was the Riffgat wind farm in 2012. The monopiles were installed by the heavy lift vessel Strashnov, and the heaviest piles for the Riffgat offshore wind farm weighed 720 tonnes, and had a diameter of 6.2 meters [89]. The main reasons the driving technology was selected for the Riffgat project, was to reduce noise and comply with the noise regulations of Germany, where the offshore wind farm is located [137].

For the installation at Riffgat, the Super Quad Kong, a modular vibratory hammer was used, and the hammer was specially developed for the project [137]. The foundations were partially driven into the seabed, and have not been driven to target depth. The final 10 meters were driven by impact hammer, due to the fact that the owner of the wind farm required a specific 'blowcount', that indicates the bearing capacity of the pile as described in guidelines [87]. Therefore the technology could not show its potential to drive foundation piles to their target depth. After the project at Riffgat, CAPE developed a newer version of their technology, the CAPE VLT-320, a vibro lifting tool that removes the need to change from a lifting tool to the vibratory tool, and removing the need to let go of the foundation pile.

In the same year as the Riffgat offshore wind farm, the vibro driving technology was applied once more, at another wind farm in Germany. The vibro hammer used, the 300 MU of Dieseko, was used to lift and subsequently drive anchor piles for a tripod foundation into the seabed [86]. While these early applications highlighted the ability of the method to reduce noise and accelerate initial penetration, they also underscored its dependence on soil conditions. In loose and sandy soils, vibratory driving excelled, but in denser substrates, performance diminished significantly [88].

After these first two projects, the technology underwent further testing to evaluate its performance under varying conditions, and to asses the pile bearing capacity in comparison to piles driven by impact hammer. In 2014 a test was performed at Cuxhaven, where three piles were bench-marked against driven piles by impact hammer. The objective of the tests was to demonstrate the lateral bearing capacity of vibrated piles, to assess the reduction in noise levels, and to show the effect of the technology on the speed of the installation. These trials confirmed its efficiency in loose soils, with installation times up to three to four faster compared to traditional impact hammering [138]. However, challenges persisted in harder soils, confirming the limited adaptability of the technology across all seabed conditions.

The Kaskasi two Offshore Wind farm, part of the VISSKA research initiative, utilized vibratory driving to comply with noise regulations while exploring its potential for broader application [110]. This project demonstrated noise and efficiency benefits during the initial penetration phase, yet the final 10 meters were driven by impact hammer, due to the concern about the soil strength degradation by vibratory driving, and to achieve load bearing capacity validation, where the owner of the wind farm required a certain blow count as indication for the bearing capacity the the piles [85].

More recently the technology has been used at several offshore wind farms, around the world. The main reason for the selection of the technology is the ability of the vibro lifting tools to remove the risk for pile run, and to improve efficiency of the installation by not needing a separate upending tool [111]. As for instance at the Formosa 2 Offshore Wind Project in Taiwan, where vibratory driving was again combined with impact hammering in a hybrid approach to install pin piles for jacket foundations [97].

Despite these promising results, vibratory pile driving has faced significant barriers to market adoption. Technical limitations, particularly in harder soils, and uncertainties surrounding post-piling performance have limited its use and adoption [113]. The preference of the offshore wind sector for proven technologies with extensive track records also played a role, as impact hammering with advanced noise mitigation remained the dominant method.

Nevertheless, advancements in the technology, such as the development of the CAPE VLT-640, demonstrate its potential for scalability to larger monopiles, aligning with the industry's trend toward increasingly larger turbines [38]. Furthermore, ongoing field trials and research continue to address its limitations. The case of vibratory pile driving highlights the challenges of introducing innovation into the risk-averse and capital-intensive offshore wind industry, where the demand for proven reliability possibly outweighs the potential benefits of new technologies.

One of the biggest challenges of the technology is the design of foundation piles. The current foundation piles are designed for an installation method using impact hammering, and not vibro driving. Vibro driving might benefit from a reduction in wall thickness, where impact driving requires a strong pile to withstand the forces on the pile during the hammering process [113]. With optimized piles for this technology, the foundation piles will be easier to install with vibro technology, and another additional effect is a cost reduction of the foundation due to the reduced wall thickness, and therefore reduced material cost. The technology thereby however relies on a change in the design of the foundation type, limiting the ease of adoption and seamless integration in current processes.

7.3.2. Reflection on success factors

The vibratory pile driving case illustrates the combination of technical, economic, and regulatory factors that influence innovations in the offshore wind sector. By reflecting on the alignment of the case with the key success factors, discussed in Section 7.2, a better understanding of the innovation landscape within the offshore wind sector can be created.

Problem solving ability and necessity

One of the key selling points of vibratory pile driving is its ability to reduce installation noise. In noise-sensitive regions like the German North Sea, where regulations are strict, the method has demonstrated clear advantages. However, impact hammering, combined with advanced noise mitigation systems, remains an effective alternative, reducing the urgency for widespread adoption of the technology, especially for regions outside Germany, where noise regulations are less strict.

Cost effectiveness and efficiency

Economic considerations have also played a significant role in shaping the adoption of vibratory pile driving. While the method can reduce installation times, as shown at the Cuxhaven test site, the need for hybrid methods, where impact hammering must be used for the final penetration, increases the cost and negate the cost savings the technology could contribute.

Regulatory compliance and environmental impact

Environmental impact is an area where vibratory pile driving aligns well with industry trends. Its ability to significantly reduce peak noise levels makes it an attractive option for projects in areas with strict environmental regulations.

Scalability and adaptability

Scalability and adaptability are critical for any technology seeking to gain traction in the offshore wind industry. Vibratory pile driving has shown progress in scalability through innovations like the CAPE VLT-640, which can handle larger monopiles for modern turbines. However, its adaptability for different soil conditions remains a limitation. Optimizing pile designs, such as reducing wall thickness for vibratory installation, could improve adaptability while also lowering material costs. However, this means that the technology relies on the alteration of the design of the pile, which makes the implementation of the technology not best suited for existing methods and designs, as discussed in Section 7.2, possibly hindering its adoption.

Risk management and reliability

Finally, the risk aversity of the offshore wind sector poses a challenge to the adoption of new technologies like vibratory pile driving. Impact hammering has decades of proven success, whereas vibratory methods lack the extensive operational track record needed to overcome this preference for reliability. Addressing these issues through long-term monitoring, standardized guidelines, and more installations will be critical.

conclusion

This case example shows the difficulties that come with innovating in the risk averse offshore wind sector. The offshore wind sector is highly capital intensive, with small margins, halting the adoption of new technologies and innovation that can possibly introduce more risks. New technologies fail to get adopted due to the preference for known, proven installation methods. Market penetration requires an extensive track record, but to obtain a track record the technology has to be deployed and used, contributing to the difficult market penetration.

7.4. Future trends

Several trends in innovations will influence the future of the installation sector, as we look towards 2030 and beyond. As water depths and turbine sizes continue to increase, foundations will need to grow in size accordingly, to be able to withstand the even larger loads associated with the larger turbines, increasing the size and the weight of the foundations even more. The movement to deeper water locations, also contributes to an even further increase in weight. The size of the future foundations will create new challenges and issues for the installation phase, sparking new innovations in installation technologies, as discussed during the first interview:

> *"We are now at a point where the size and weight of monopiles are creating logistical challenges. We've already seen some monopiles exceeding 2000 tonnes, and companies are asking, 'How can we realistically install these?' This is driving innovation in installation technology, like floating installation methods and advanced gripper frames."*

Some of the key trends include:

- Larger turbines: As turbines continue to grow, with 20+ MW turbines expected by 2030, foundations will need to adapt to handle the increased loads and sizes of the foundations. This will drive innovations in both foundation designs and installation methods.
- Deeper water installations: Offshore wind farms will be installed in even deeper water depths than before, with bottom fixed foundations up to 60 to 70 meters in water depth. Floating foundations will likely not be installed in water depths where bottom fixed foundations are possible due to the much higher LCOE of the foundation type. Beyond the water depths of bottom fixed foundations, floating will become an option, albeit an expensive one in the near future. During the interviews it was mentioned that the break even point would be somewhere around 32-33 MW turbines.
- Environmental regulations: Environmental regulations will become more strict in even more areas, particularly regulations around noise pollution will drive innovations in alternative quieter installation methods and alternative foundation types.

7.5. Conclusion

Innovations in the fast evolving offshore wind sector are necessary for the sector to continue to grow and tackle issues that arise with further scaling. Innovations are aimed at solving several issues, but innovating in the offshore wind sector is not as straight forward as might be in some other sectors. The highly capital intensive sector, makes for a strategy where risk-aversity is one of the key priorities. Adopting new technologies and innovations, with a unknown performance, is therefore a large risk, posing significant hurdles for new technologies to be adapted by the industry.

The objective of this chapter was to analyze what makes innovations in the offshore wind sector different than 'regular' innovations, and what factors play a role in the adoption of an innovative technology in the fast evolving offshore wind sector. Furthermore, a goal was to find out what drives innovations, and why certain seemingly good innovations did not achieve market adoption in the sector. By tackling these objectives, the chapter will provide an answer to the research question:

What factors determine the success of an innovation in offshore wind?

The success of innovations in the offshore wind sector is determined by a combination of technical, economic, environmental, and regulatory factors. Innovations that are scalable, cost-effective, and environmentally friendly tend to gain the most traction within the industry. But market adoption remains really difficult in the risk-averse sector. Furthermore, successful demonstration projects play a crucial role in the adoption of technologies. The case study presented illustrates the importance of these factors in a real life situation.

Innovations go through several phases before they reach market adoption. By 'ranking' the innovations against the TRL framework, a unbiased comparison can be made between innovations in different areas in the sector, or even entirely different sectors. Innovating in the offshore wind sector can however be quite different than in other sectors.

The success of a new technology depends, or is influenced by several key success factors, as cost reductions, risk reductions, scalability, and regulatory compliance. These factors came forward during the interviews, as important, to be able to be adopted in the offshore wind market. However, even complying with all these factors, does not assure market penetration, due to the riks-aversity of the offshore wind sector. New technologies require a substantial track record to prove their performance time after time, as was emphasized by interviewee two:

> *"The key to innovation success in offshore wind is balancing the technical aspect with market acceptance. Often, technically sound solutions fail to get adopted because companies aren't convinced the new technology will provide the improvements it promises. That's why innovation in this sector takes time."*

For an innovation to be adopted in the market, it has to solve a certain problem. Innovations in the offshore wind sector are often driven by necessity, and will otherwise possibly fail to get adopted. Innovations that are not really needed, or show great improvements, can easily be sidelined.

One key factor for the success of a new technology is its ability to reduce costs. Lowering the LCOE of offshore wind, remains a key topic and innovations that show the ability to lower costs in an effective manner, are likely to be adopted, due to the financial incentive. New technologies can perform well, but if they do not reduce costs, what would be the point in adopting them.

The offshore wind sector is a fast developing sector, with installations moving to deeper waters and with the focus on scaling turbine capacities even further. Equipment, vessels, and other technologies all have to be scalable to be ready for tge future larger foundations. companies like CAPE HOLLAND, the developer of a vibro-lifting tool, focus on making their technology scalable and adaptable to several foundation sizes, emphasizing the need to prepare for the future in the fast evolving sector.

Regulatory hurdles can make or break an innovation. Innovations are nowadays often aimed at noise reduction strategies, since noise is thought to be one of the largest concerns the offshore wind sector is currently, and will be facing in the near future. This ties in with the statement that innovations will continue to be driven by necessity, and regulatory drivers. If noise regulations become more pressing, the need to innovate and reduce the noise levels during installation will automatically follow.

Risk mitigation or lowering risks is a key factor for the adoption of new technologies. The capital intensive sector is risk-averse, and prefers known methods, which halts the adoption of innovations. The adoption of new technologies is therefore highly dependent on the ability of a company to show the repeated performance of their technology, or give financial assurances that their technology will provide the promised success. Besides risk aversity, technologies that have been developed in a controlled environment or on paper, might sound promising, but do not take the scale and harsh environment into consideration of the offshore operations.

During the case study of the vibratory pile driving technology of CAPE HOLLAND, the success factors are related to a real life example. It is shown how the different factors influence the adoption of a new technology in the offshore wind market, and that innovating in this sector can be difficult.

8 Installation challenges and limitations per foundation type

The installation of offshore wind turbine foundations is a complex process that is significantly different for each foundation type. Each foundation type faces unique challenges and limitations at different stages of its life cycle, from design and manufacturing, to installation, operation and maintenance (O&M), to decommissioning. The high targets set by governments create future challenges, as the industry is facing more installations, deeper waters, and larger turbines.

This chapter aims to analyze the limiting factors affecting different foundation types. As the offshore wind sector continues to scale up, with turbines growing in size and installations moving to deeper waters, understanding these constraints is essential to ensuring the future viability of the offshore wind installation sector.

The most important limitations per foundation type are discussed, to be able to answer the research question:

What determines and what are the limiting factors of a foundation type, considering every aspect of the installation procedure?

The chapter is structured as shown in the Figure. In Section 8.1, first an overview of different factors that influence the choice of a certain foundation type are discussed, to provide some context for the different challenges and limitations of each foundation type, discussed during the interviews. After these factors, the different challenges that came forward during the interviews are given. From Sections 8.2 to 8.5, each Section tackles the challenges and limitations of a sepecifc foundation type.

8.1. Overview of factors influencing foundation type selection

The selection of an offshore wind foundation type is driven by several key factors that influence the feasibility, cost, and overall viability of a project. They vary depending on the site specific conditions of a wind farm and the specific requirements of the turbines that will be installed. Below, the primary factors that determine the choice of foundation type, are outlined.

- Water depth
- Seabed conditions
- Metocean conditions
- Turbine size
- Environmental impact
- Supply chain and manufacturing

Water depth

Water depth is one of the key factors that influences the choice for a foundation type. Not all foundation types are suited for all water depths, with most bottom fixed offshore wind farms installed in water depths below 40 meters. Some bottom fixed foundations have been installed in water depths of 50 to 60 meters, and several floating installations in even deeper waters. Throughout the history of the offshore wind sector, depth limitations have been an interesting topic, with several claims throughout the years predicting the end of the monopile foundation beyond a certain water depth. The end of the monopile has been predicted several times, but the industry adapted, and stretched the use of the foundation type to even deeper waters [17]. Now that the industry is currently moving to even deeper waters, the question remains, what will be the depth limits of bottom fixed foundations, and from which depth will floating foundation come into play.

Seabed conditions

Another important factor in selecting a foundation type, is the seabed composition. The soil composition, (sand, clay, or rock,) dictates which foundation type can be used, and can effectively be installed. Monopiles are suited for sandy or clay soils, where they can be driven into the seabed. However, they face challenges in rocky seabed conditions, where penetration can be limited, and drilling may be necessary.

Jackets offer more flexibility across different seabed types due to their multi legged design, which can provide a wider load distribution.

Gravity based foundations, rely on the bearing capacity of the soil for their stability, and are therefore highly dependent on the soil composition. The foundations stand directly on the seabed, and therefore require a relatively flat surface, and a soil composition with a high bearing capacity. They are therefore most suited for clay, sandy soils, and rocky seabed conditions. Seabed preparation is required prior to the installation, increasing the overall cost of the installation.

Foundations that use suction buckets, are also highly dependent on the soil composition. The suction buckets use negative pressure inside the buckets to penetrate the soil, and cannot be installed in locations where rocks are encountered. A large area of the foundation is in contact with the soil, creating possible risks.

For floating foundations, the seabed composition is important for the anchoring method. The soil composition will dictate the anchor selection, but the different floating foundation types will work with several anchor types, making seabed conditions a far less important factor when selecting a floating foundation type.

Metocean conditions

Metocean conditions, including wave heights, current velocities, and extreme weather, are of great importance during the selection and design of a foundation. Foundations must not only support the static loads of turbines, but also have to resist the dynamic forces induced by the wind and waves. For instance, jackets, with their open lattice structure, have a reduced surface area to the waves, which can the effects of wave loading. In contrast, monopiles, have a large surface area, and therefore face higher forces. Besides wind and wave forces, other environmental forces have to be taken into account as well. Ice loading, and seismic activity have to be considered in areas where these phenomena can occur. Gravity based foundations, can for instance be equipped with ice cones, so they can be used altered for use in regions where ice forming can occur.

Turbine size

One of the key drivers behind the growth of the foundations has been the development of larger offshore wind turbines. Turbine sizes have increased significantly from 2010 to 2024, and are expected to reach 20+ MW by 2030. In interview 9, the interviewee mentioned that even turbines of 35 MW will most likely become a reality in the future, but highlighted that it remains uncertain to what extend these foundation types will be installed. The possibility exists that the industry settles on a turbine size between 15 and 25 MW for the majority of the installations, standardizing the installation practices. An analogy made during interview five, was the movement to larger airplanes in the aviation sector, after which the industry came to the conclusion that deploying several smaller aircraft improved efficiency, making the 'jumbo' airplanes somewhat redundant.

Supply chain and logistics

Supply chain and logistical factors are becoming increasingly important, especially as offshore projects scale up in size and complexity. The manufacturing, transportation, and installation of larger foundations require coordinated logistics and a good infrastructure, including ports, high capacity cranes, and transportation and installation vessels. Foundations for instance, are limited in the number that can be transported simultaneously due to their size and weight, which can create a logistical bottleneck, that can delay installation timelines and increase the costs. Establishing localized manufacturing hubs close to installation sites can further streamline the supply chain and reduce logistical constraints, enhancing both efficiency and costs.

Government regulations

During the development of an offshore wind farm, a government can set certain rules for the design of an offshore wind farm. These can include restrictions in turbine size, foundation type, and about the environmental impact.

Noise regulations, for example, directly affect the installation methods for foundations, this is particularly noticeable when looking at monopiles, where traditional pile driving generates significant underwater noise. This potentially creates the need to shift to alternative quieter installation methods, or to totally different foundation types. Noise limitations have driven innovations in quieter installation techniques, and in noise mitigation strategies.

For example, the EU has stricter noise and environmental regulations than some other regions, influencing projects to adopt quieter and less invasive foundation types, or deploy extensive noise mitigation measures. This regulatory pressure has pushed several industry innovations, ensuring compliance, and minimizing environmental impact during the installation.

8.1.1. Foundation specific factors identified from the interviews

During the interviews several other factors were mentioned, relating to the challenges and limitations per foundation type. For each foundation type, several challenges have been discussed:

- For monopile foundations the challenges mentioned focused on the supply chain and logistical issues, cost, installation feasibility, and environmental concerns.
- For jacket foundations, the focus was on the fabrication limitations, and the cost of the foundation type.
- With floating foundations, the challenges discussed were mainly about the large scale deployment of floating foundations, the logistical issues, and the cost of the foundation type.
- Furthermore, it was discussed by interviewee nine, that gravity based foundations will be difficult to scale, and will run into logistical issues. The foundations for current and future larger wind turbines will become extremely heavy, weighing over 20000 tonnes, requiring a close by manufacturing facility, since long transportation is not an option.
- For the other, less used, foundation types, the question remains if they will be scalable, since they have not been used extensively and lack a track record

8.2. Limiting factors and challenges of monopile installation

Monopiles have traditionally been the most used foundation type, due to their relatively simple design and their cost-effectiveness. However, as turbine sizes increase, and water depths become larger, monopiles will need to continue to grow to ensure a sufficient load bearing capacity and structural stability. Monopile diameter needs to increase substantially with the growing turbine size to be able to handle the larger loads. Interviewee five even mentioned that some studies have already been performed that use 15.5 meter diameter piles. In the history of the offshore wind sector, the end of the monopile has been predicted multiple times [17]. The foundation type is however, still being used, and the preferred foundation type due to its costs and simplicity. The question arises, what will be or dictate the limit of the monopile, and will it retain its position as the preferred foundation type. As the industry moves to even deeper waters, monopiles will possibly reach their technical limits. During the several interviews it was mentioned that while monopiles can still be used in waters deeper than 60 or even 70 meters, but that monopiles will reach a limit, and alternative foundation types may soon become more practical:

"For the time being, monopiles can go to depths of more than 60 meters, but eventually, there will be a limit, and we'll need to consider other foundation types like jackets or suction buckets."

During the interviews, and in the literature, several challenges and limitations for future use of monopile foundations came forward. In the literature, the installation limitations mentioned, are often related to water depth limitations, but during the interviews it became clear that the installation limitations of monopiles do not depend on structural factors, but depend on other factors, such as economics, the feasibility of transportation, handling and installing these large structures, vessel availability, and environmental regulations.

8.2.1. Structural and manufacturing constraints

From an interview with Sif, a manufacturer of monopile foundations, it became clear that there are no structural limitations for using monopile foundations for even deeper waters. Furthermore, monopiles are fabricated out of steel, and the increasing demand for larger monopiles is putting pressure on the steel supply chain. Producing monopiles with increasing diameters, and wall thickness relies on the maximum plate thickness of steel producers and on specialized rolling equipment to fabricate the piles, currently only present at a few manufacturers globally [75]. The current fabrication technologies face challenges in terms of maximum allowable wall thickness, and maximum pile diameters due to manufacturing methods and machines used:

- Outer diameter: 10 - 14.5 m
- maximum D/t ratio: 160
- Maximum wall thickness: 150 mm
- Taper angle of cans < 4.5 deg

However, in the interview with Sif, it came forward that scaling up beyond these figures would be possible as well, if the market demands even larger foundations. The limit for ratio between diameter (D) and wall thickness (t), is governed by the handling of the foundation piles during manufacturing and transport. If this limit is exceeded, buckling can occur. But even these limits do not have to be a show stopper, since simple innovations, even like an inflatable balloon inside the foundation piles during the manufacturing process could be a solution to overcome this issue.

8.2.2. Installation limitations

Beyond water depth, the size and weight of monopiles present a practical limit. Monopiles are increasing in diameter and can weigh upwards of 2000 to even 3000 tonnes, which poses significant challenges for handling, transportation, and installation. Contractors are already facing significant challenges with monopiles larger than 3000 tonnes, which may require new methods or equipment to install these large structures, as came forward during interview three. There are physical limits to how large monopiles can be installed, particularly in deeper waters or challenging seabed conditions.

During the interviews it came forward, that while monopiles can still be scaled, there will come a point where jackets or other foundation types will become more practical. As monopiles increase in size and weight, the logistics of transporting them from the fabrication site to the offshore installation site become more complex. There are practical limits to how large these structures can be while still being transportable, as was highlighted by interviewee five: "Handling and transporting monopiles over 100 meters long is a logistical challenge. We're getting to a point where it becomes almost impossible to move these structures efficiently."

Vessel availability limitations

Monopiles require heavy lifting equipment and specialized vessel for installation. As turbine sizes increase, so do the dimensions of monopiles, making it more difficult to find vessels capable of handling the foundations. One of the biggest issues with further scaling turbines, and therefore their foundations, is the reduction in installation vessels capable of lifting and installing the larger and heavier foundations. A shortage in installation vessels is foreseen, related to the increased installation demands to reach set targets by several countries [11]. Several companies have published reports related to this topic, and in an recent paper of TWD, about the future of monopile installation, a installation vessel shortage of almost 50% with regards to the installation demand, will be expected by 2028 to 2029 [139]. The current largest capacity crane on a jack up vessel is 1600 tonnes, which cannot be used for the latest TP-less monopiles, weighing over 2000 tonnes [140]. There are even concerns about the ability of current high capacity installation vessels, like Boskalis' BOKALIFT 2, to handle the larger foundations in the not so distant future. For instance, 20 MW turbines and their foundations might be too large for such existing vessels, motivate plans for even larger ships by the end of this decade.

Equipment limitations

As monopiles grow larger, the energy needed to install them becomes a limiting factor. During an interview with IQIP, it was mentioned that hammers can be scaled up to provide the necessary energy, however there are limits to how much energy can be applied without causing environmental damage or exceeding vessel capacity:

> *"There's a limit to how much energy we can apply during installation, especially in sensitive environments. That's why we're developing more efficient installation techniques that use less energy."*

The representative from IQIP also noted that as monopiles get larger, there are also practical limits to how large vessels and equipment can get. While they continue to develop larger hammers and tools, there are physical constraints to how far monopiles can be scaled before alternative foundation types become necessary.

> *"At some point, we'll reach a limit where monopiles become too large for current equipment. We're already seeing projects explore jackets or floating foundations as alternative solutions."*

8.2.3. Logistical and infrastructural limitations

Port infrastructure plays a role in determining the feasibility of transporting these large structures. The size and weight of these structures, is moving beyond the capabilities of the current handling equipment, which makes transportation and handling of the foundations more challenging. New cradle systems have already been developed by Mammoet, to tackle the issue of handling the future large monopiles on shore [141]. Within the the transportation of the foundation piles to the offshore installation location, several other challenges and limitations arise. Specialized vessels with adequate deck space, sea fastening and lifting capacity are required to transport these massive structures from manufacturing yards to marshaling ports or offshore sites.

Noise regulation limitations

One of the biggest issues for the installation of monopiles is the noise created during the installation. During the interviews, the challenges induced by noise regulations were mentioned as one of the most significant issues of the upcoming years. As monopiles grow larger, the noise generated during installation increases, and many countries, especially in Europe, have implemented stricter regulations on allowable noise levels. Larger monopiles require larger hammers, which generate more noise during pile driving, leading to limitations with stricter environmental regulations. More regions are expected to introduce strict environmental regulations regarding underwater noise, as already implemented in countries like Germany, which can limit the possibilities of installing monopiles with conventional pile driving methods. In interview four it was mentioned that in regions with strict regulations, contractors currently have to pull out all the available measures to remain under the noise limits. Improved noise mitigation measures have shown to reduce noise below German noise limits. A good example of a project where new noise mitigation measure were tested, is the installation of the He Dreiht offshore wind farm, where Heerema in collaboration with IQIP showed a 24 dB noise reduction, by deploying a double big bubble curtain, pulse system, and the new T-NMS-10000 subsea noise barrier [116]. The T-NMS-10000 contributed by reducing the noise levels by up to 25 dB. The complexity and scale of the equipment needed to remain under the limits, can clearly be seen from the scale of this new 'state of the art' noise mitigation system, shown in Figure 5.56. Noise issue are therefore seen as one of the biggest hurdles to overcome in the next few years. This could limit the use of monopiles, since their installation methods might become too difficult, which makes jackets or other alternatives more attractive in certain markets, as for instance suction bucket foundations. Additionally, environmental considerations like seabed disturbance also impose limits on installation methods.

> *"Noise is becoming a bigger and bigger topic, and that's where suction bucket technology is very interesting, especially in countries like Germany with strict noise regulations."*

> *"As monopiles scale, the noise from pile driving increases, and this is something that's going to be a limiting factor unless innovations in quieter installation methods are adopted."*

> *"Noise is becoming a real challenge with stricter regulations in places like Germany. The larger the monopile, the more noise is generated during installation, and we have to find ways to minimize that."*

Alternative driving solutions as vibro piling, and vibro jetting also have proven to be a possible alternative for driving foundations piles into the seabed, to reduce noise levels during the installation. In an interview with CAPE HOLLAND, it was mentioned that:

> *"Noise regulations are getting stricter, especially in Europe. Vibro technology helps us stay within acceptable noise levels during installation."*

The jetting technology is tested by Ørsted at Gode Wind 3 offshore wind farm for the first time, showing a noise reduction of 34 dB [116]. These methods, however do not have a large track record yet, but can change the future of the offshore wind installations. An additional effect of using vibro-jetting technology, is the possible reduction in weight of the foundations as they can be designed lighter as they won't have to resist the hammering process of conventional pile driving [116].

IQIP is working on, and testing their EQ piling method, which increases the impact time, and also reduces the noise levels [142]. These innovations show that the noise regulations do not have to be a show stopper for installing larger monopiles in areas with strict environmental regulations.

8.2.4. Decommissioning

Decommissioning of monopile foundations involves the removal of the steel piles. Current decommissioning practice for foundation piles, is to cut the piles at or just below the seabed surface an leave the section below the seabed surface in place [143]. It is very likely that decommissioning and recycling regulations will become more strict in the future, possibly requiring the total removal of foundations after their operational period. In the interviews it came forward that decommissioning of an offshore wind farm and its foundations will become an important part of the overall project. It was even mentioned by interviewee 9, that the decommissioning contract might become governing with respect to the T&I contract and that the T&I contract will become a subsidiary of the decommissioning contract, due to the scale of the decommissioning operations. Vibratory pile removal can be one possible solution for the removal of foundation piles, as vibratory technology can be used for complete pile removal of piles up to 7.9 meters in diameter, resulting in possible pile removal of all monopiles that have to be decommissioned up to 2039 [144].

8.2.5. Future outlook

During the interview the majority of interviewees thought that monopiles will remain the most widely used foundation type for offshore wind projects. However, as turbines grow larger and installations move into deeper waters, the limitations related to size, vessel availability, noise pollution, and weather dependence, pose significant challenges. While technological innovations such as vibro piling and larger equipment and installation vessels offer potential solutions, these constraints must be addressed to enable monopiles to continue as a viable option for future large scale offshore wind projects. Without significant advancements in installation techniques or foundation design, the scalability of monopiles may become limited, requiring the industry to explore alternative foundation types in deeper waters or for larger turbines.

8.3. Limiting factors for jacket foundations

Jacket foundations are the second most used foundation type after monopiles. Unlike monopiles, jackets consist out of a multi legged lattice structure, which provides greater stability and load distribution. However, this introduces several challenges and limitations during the manufacturing and installation process. Their lattice structure, requires precision fabrication and welding of the multiple components in the structure, introducing more potential failure points, complicating and increasing cost of the design and manufacturing process, and leading to difficulties for mass production. This section will discuss the key factors that limit the installation of jacket foundations.

8.3.1. Cost and complexity

While jacket foundations offer advantages in deeper waters and for larger turbines, their installation and fabrication process is significantly more complex and presents several critical limiting factors.

Jacket foundations require pre-piling, which involves driving several pin piles into the seabed to create stable anchor points for the jacket structure, as discussed in 4.2. The need for pre-piling introduces additional time and logistical complexity into the installation process, as specialized equipment and multiple vessels are required. This dependency on multiple vessels, and the high costs of installation are limiting factors that play a role in the feasibility of jacket foundations in future large scale projects. The overall complexity of jacket installation, from pre-piling, placement, to grouting, results in longer installation times compared to monopiles [145]. This longer installation time directly translates to higher costs, particularly when considering the additional vessel and equipment requirements.

The cost of jacket foundations is also higher due to their more complex manufacturing process, which requires welding of the multiple components. The lattice structure of jacket foundations introduces significant fabrication challenges compared to monopiles. Jacket foundations generally require multiple steel tubular sections to be welded together, creating a high number of joints. This design makes jackets stiff, but manufacturing intensive, requiring precision welding and extensive quality checks at each joint. During interview 5 it was mentioned that the tipping point where after jackets become more cost effective than monopiles lies around 90 meters in Europe:

> *"The tipping point between a jacket and a monopile is currently around 90 meters in Europe. You have to believe my models, but a jacket is lighter yet requires more hours."*

When choosing a foundation type, the choice will almost always be for the most cost friendly solution, when multiple foundation concepts are viable options. So, if a jacket is more expensive than a monopile, and monopiles can be used at the specific location, the choice will always be for the cheaper monopile with simple design and its extensive track record. Besides cost, infrastructure and manufacturing capabilities will become even more pressing in the future if the offshore wind market want to continue to grow the yearly installed capacity over the upcoming years. Current jacket manufacturing is a costly and time consuming process, which is not advantageous with the future expected supply chain and infrastructural problems predicted [10].

8.3.2. Logistics and infrastructural challenges

Transporting jacket foundations from fabrication yards to feeder ports also presents logistical challenges due to the size of the structures. Jackets are typically larger than monopiles, requiring multiple transportation vessels.

Port infrastructure further restricts jacket handling, as only select ports are equipped to store and handle a large numbers of jacket foundations. Specialized cranes are required to lift jackets onto transportation vessels, furthermore, storage capacity can be a limiting factor, especially for high capacity wind farms that may require 100+ jackets. Ports in close proximity to offshore wind development sites, such as those along the North Sea coast, are being adapted with larger, reinforced quay walls, and large capacity cranes to accommodate larger and more offshore wind components, but infrastructure remains a bottleneck for projects located further offshore or in areas with limited port facilities [126].

8.3.3. Environmental impact and seabed disturbance

Environmental regulations, particularly around noise mitigation, affect jacket foundations differently depending on regional regulations. For instance, areas with strict noise regulations may require jackets as an alternative to monopiles if monopile installation methods cannot comply with noise regulations. Jackets typically generate less noise during the installation, which can make them the preferred choice in noise sensitive areas. As interviewee four mentioned, that jacket foundations might be preferred in comparison to monopiles, that require the implementation of extensive noise reduction strategies which adds additional costs and complexity, especially in regions where environmental regulations are strict.

8.3.4. Future outlook

The viability of jacket foundations in the future market is influenced by several factors, such as steel prices and regional manufacturing capabilities. Additionally, mass production and rapid large scale deployment remain issues, for future demands for large scale deployment and larger turbines and foundations. In some cases, manufacturing capacity in certain regions as for instance Asia, may drive down the cost, but this is often countered by higher transport expenses and potential quality control issues, as mentioned by interviewees two and five.

8.4. Limiting factors of floating foundations

Floating foundations represent a promising solution for offshore wind farms in deep water locations, particularly in locations where bottom fixed foundations, such as monopiles or jackets, become impractical or economically unfeasible. These foundations allow turbines to be installed in water depths exceeding 60 meters, and will most likely not be used in shallow waters, due to the costs, which are multiple times higher for floating wind compared to bottom fixed installations [27]. While floating foundations offer the possibility to open up completely new potential installation locations, their installation is more complex than that of bottom fixed foundations. During the interviews it was highlighted several times, that while floating foundations open up new markets, particularly for countries and regions that mainly have deep water locations, their adoption is limited by economic, logistical, and technical factors. This section will explore these key challenges and limitations of floating foundations.

8.4.1. Costs

Floating foundations face significant financial barriers due to their high investment and overall costs. The current LCOE of floating offshore wind is three times higher than when using bottom fixed foundations [146]. During the interviews, several interviewees mentioned the increased investments are required both for the construction and installation. Due to the large price difference with bottom fixed foundations, it is difficult for floating foundations to become a primary choice in the near future. The LCOE of floating foundations is expected to come down, but during the interviews it was stated that the break even point would be around using 32-34 MW turbines. Floating foundations are thus expected to be only economically viable with extremely large turbines, and in deep water locations.

8.4.2. Installation limitations

One of the most significant limiting factors for the installation of floating foundations is the complexity of the mooring and anchoring systems, and the complexity of their installation. These systems must be designed to secure the floating platform to the seabed while allowing for some degree of movement to accommodate waves, wind, and current forces acting on the structure. The design of the mooring system is highly dependent on the seabed conditions, and installing these systems in deep waters is both technically challenging and costly.

8.4.3. Logistical and infrastructural limitations

The turbines for floating foundations are typically mated to the foundation near shore or in a sheltered location, and afterwards towed to their final location, as shown in Figure 4.30, unlike bottom fixed foundations, for which the turbines are typically installed on top of the foundations at the offshore location. The towing process of the floating structure is highly weather dependent, and requires relatively long periods of stable weather conditions to ensure the safe transport of the floating structure to the installation site [26]. Bad weather can delay towing operations, which extends installation timelines. Additionally, the assembly of the floating platforms themselves is complex, often requiring specialized ports and infrastructure, as shown in Figure 4.28, which may not be available in all regions. During the several interviews, the challenge of constructing and assembling numerous large floating foundations within a port, as emphasized by interviewee two:

> *"If you want a bit of a wind park, you certainly need 50 turbines. How are you going to build 50 floaters in a port? How and where are you going to build them?"*

The supply chain infrastructure needed to manage and transport these massive structures is also underdeveloped, which could restrict future large scale deployment of floating foundations. Some of the floating foundations require large assembly locations with large depths of over 60 meters due to the size of the structures. In interview nine it came forward that in some studies, the future floating foundations for 20+ MW turbines have to be over 50 meters in width and have large draft as well. This also emphasizes the issue of transportation, because the question arises, which vessels would be suited to transport these immense structures, and what would transportation time frames look like in this situation. One of the benefits of the transportation method of floating foundations is the elimination of installation vessels with high capacity cranes, so no further strain is put on the vessel supply chain issues, that bottom-fixed foundations face.

Furthermore, the scarcity of essential materials, especially steel, shows the logistical and material difficulties that floating foundations face. It was noted that the large scale deployment of floating foundations could would not even be possible due to limited steel availability which even further drives up material costs, impacting project viability.

8.4.4. Limited Experience

Despite the growing interest in floating foundations, there is still limited experience with large scale deployment. While pilot projects such as Hywind Scotland and Kincardine have demonstrated the potential of floating wind farms, the lack of a long term track record creates uncertainty about the scalability and reliability of floating foundations. This limited experience introduces risks for the installation, but also for the entire life span of the wind farm, as there are fewer examples and almost no comparable installations. Furthermore, the current lack of a established supply chain for producing floating foundations also poses challenges, especially when scaling the production for future large scale commercial projects.

Operational and maintenance challenges

Floating foundations operate in environments with more significant wave and wind forces, which require additional maintenance compared to bottom fixed foundations, as emphasized to an interviewee. The constant movement impacts turbine performance, and components are subject to increased wear and tear. Floating foundations are subjected to constant dynamic loading due to wave and wind actions, leading to greater wear and tear on the structure, requiring more frequent inspections and maintenance. According to one interviewee, service intervals and maintenance needs for floating structures are likely to be more frequent due to these harsher conditions, which could increase operational costs. Maintenance operations for floating offshore wind turbines are difficult due to the dynamic behavior of the structure. An example of the complexity of the maintenance work for floating offshore wind farms, is the maintenance work for the Hywind Scotland offshore wind farm. This was the first floating wind farm, and its maintenance operation is also the first of its kind. The entire floating structures are towed back to sheltered areas to perform the maintenance tasks in the summer of 2024 [147]. After the maintenance operation the turbines will be towed back to their offshore location and will be installed once more. This example shows the limited experience with floating foundations, and the potential challenges that arise with their use.

8.4.5. Future outlook

Floating foundations open up new locations for offshore wind farms, where bottom fixed foundations are not feasible any more. Currently the technology is not yet deployed at a large scale, and therefore lacks a track record to show its potential for full scale wind farms.

Floating foundations offer a potential solution for locations that only have access to deep water locations. However, the installation of floating foundations remains considerably more complex than that of bottom fixed foundations, with significant limitations related to the mooring systems, towing logistics, and its high weather dependency. As the industry gains more experience with large scale deployment of floating wind farms, the price of floating foundations will come down, and with future even larger 30+ MW turbines floating wind farms in deep water locations might become a reality

8.5. Limiting factors of alternative foundation types

8.5.1. Suction bucket foundations

Suction bucket foundations use a negative pressure within an inverted bucket structure to drive the foundations into the seabed. This foundation type offers several advantages, including reduced noise pollution and a relative fast installation process, making it a promising option in regions with strict environmental regulations. However, the practical application of suction bucket foundations is limited by several key factors:

High soil dependence:

One of the primary limitations of suction bucket foundations is their high dependency on soil conditions. They require relatively soft, homogeneous soils for the suction installation process to work. In locations with rocky or uneven seabeds, the foundation type is less suited. Locations with high seabed mobility are also not beneficial, due to the shallow embedment of the foundation. This limits the range of locations where suction bucket foundations can be deployed.

Logistical and installation constraints:

Suction bucket jacket foundations have a large footprint, making transportation less efficient. For the transportation of 114 suction bucket jackets for the Seagreen offshore wind farm for example, it was calculated that 2473 vessel days were needed to transport the foundations from the factory to the marshaling port [148]. The overall supply chain for the installation of the wind farm spanned three continents, emphasizing the underdeveloped supply chain of the foundation type. The installation of these large structures relies, just as monopiles, on the availability of vessels with high capacity cranes, with the latest foundations for 10 MW turbines already weighing in excess of 2000 tonnes

[148].

Limited experience:

Suction bucket foundations are a relatively new technology in the offshore wind sector, and there is still limited commercial experience with their deployment. The lack of a long term and large track record creates uncertainty about their performance and installation process. This limited experience may steer developers away from using suction buckets in large scale projects until more operational data becomes available.

The market for suction bucket foundations also remains relatively small, and thus, there is limited support for their development on a large scale. This limitation also leads to a lack of standardization, making it harder to lower production and deployment costs through economies of scale.

8.5.2. Gravity based foundations:

Gravity based foundations are massive structures that rely on their weight to provide stability. Manufacturing these foundations requires significant quantities of concrete and steel, making them expensive and resource intensive to produce. Furthermore, these foundations require a flat and stable seabed, which introduces the need for seabed preparation, driving up the overall complexity and cost of the installation of the foundation type. The foundations are constrained by their heavy weight and logistical challenges during transport and installation. This section will explore the key challenges and limitations of gravity based foundations.

Logistical and transportation constraints

Gravity based foundations are suited for larger turbines, but the weight of the foundations does increase significantly. The heaviest gravity based offshore wind foundation previously installed weighed 7500 tonnes. During the interviews, un-ballasted weights in excess of 10000 tonnes were mentioned, for future installations in Finland.

In one of the interviews, the interviewee explained the regional feasibility for Gravity based foundations in the northern Baltic Sea area, noting that

“gravity based foundations can have a great future, but that depends on the constraint that the whole infrastructure gets in place. We can’t manufacture the foundation in Poland and transport it to North Finland, it just won’t work” Transporting these foundations is a complex task, often taking days for a single round trip, such as the transportation from Poland to Finland, which was mentioned to be a seven day return journey. When some delays are encountered, the installation of an entire wind farm can take several years: “it takes roughly four years to complete the installation if you come across a little bit of ice and harsh winter conditions.”

The size and weight of the foundations require specialized port facilities capable of handling large, heavy structures. The dependency on deep water ports with specific capabilities was also noted in one of the interviews, where it was mentioned that some ports do have the depth requirements, but the lack of adequate infrastructure in certain regions creates a barrier for using the foundation type, and can make it challenging to scale their deployment. Currently gravity based foundations are not a feasible option, due to these limitations, as was emphasized by interviewee nine:

> *”The business cases are dead at this point. So unless we start producing somewhere else and agree that the gravity based foundation is the foundation type to have in that region, then I think that will work”*

8.6. Conclusion

Throughout the life cycle of a foundation, several challenges and limitations impact their selection, design, installation, and decommissioning processes. Each foundation type faces specific constraints, as water depth, seabed conditions, manufacturing constraints, and environmental regulations.

The objective of this chapter is to give a detailed analysis of the challenges and limiting factors for each foundation type. Monopiles are the most common foundation type due to their cost effectiveness and simplicity. However, their future use is challenged by the need to accommodate larger turbines and deeper water sites. Jacket foundations provide greater stability than monopiles, but have a complex fabrication and installation process due to their multi legged structure, and anchoring method, resulting in manufacturing and logistical challenges. Suction bucket foundations offer advantages in specific soil conditions but face challenges and limitations due to the lack a large track record, and their high reliance on seabed conditions. Floating foundations open up whole new possible installation locations, but the foundation type is still in the early stages of commercial development. Furthermore, their fabrication and logistics remain complex and expensive and require significant advancements before the foundation type becomes economically viable at a large scale. By addressing these issues, the chapter provides an answer to the research question:

What determines and what are the limiting factors of a foundation type, considering every aspect of the installation procedure?

Monopile foundations are currently the most widely used foundation type, and the foundation type faces limitations in several key areas. In the past, the end of the monopile has been predicted several times, but it showed its resilience and remained the foundation type of choice. The monopile will not be limited for future installations by structural constraints. However, the future use of the foundation type depends on several other factors, as installation feasibility, logistical limitations, and environmental challenges faced during the installation procedure. The future of the foundation type is therefore not entirely predictable, since it depends on regulatory and environmental factors that are more difficult to control. Future monopiles faces challenges during the installation phase, since the higher loads and larger foundations are putting a lot of strain on the capabilities of the available installation vessels. If installation vessels are in high demand, and a shortage of capable vessels occurs, a shift towards alternative installation methods, or other lighter foundation types can be a possibility. Furthermore, noise limitations become even more pressing for future foundations, since more force is required to drive the foundation into the seabed. However, it is thought that the industry will find its ways around the noise limitations, with even better noise mitigation systems, or for instance with alternative driving methods. The installation methods will adapt, to be able to keep using the monopile. The monopile will remain the favorable foundation type, and the majority of the installation will be with monopiles.

Jacket foundations are the second most widely used foundation type, and gained more interest in recent years. the foundation type is however more difficult to manufacture that the simple monopile, due to the large number of components that have to be welded together. The jacket foundation therefore faces limitations in mass production, in future times where the number of installations will only increase. Furthermore, jacket foundations are more expensive that monopiles, with the current tipping around 90 meters water depths.

Floating foundations present opportunities for deep water installations, where traditional bottom fixed structures are not feasible. However, this technology is still in the early stages of commercialization, and face significant economical and logistical barriers. The LCOE of current floating offshore wind farms, is three times higher than bottom fixed foundations, which shows the large cost reductions needed for floating to become a economically viable option. Besides costs, the logistical challenges accompanied with floating foundations, make future large scale deployment of the foundation type somewhat difficult. For a decent sized wind farm, around 50 turbines are needed, and currently no installation has experience with the scale of such a project. The large structures are also material intensive and require a lot of steel, even so much that there would not even be enough steel in the world to produce all the floaters we need.

Suction bucket foundations also face challenges for future use. The foundation type is highly reliant on the seabed composition, and there is limited experience in installation the structures. Furthermore, the supply chain is not in order to produce large quantities of suction bucket foundations, which is highlighted by the supply chain issues for the Seagreen offshore wind farm, that spanned three continents. Gravity based foundations have only been used a number of times in recent years. The foundations rely on their large weight to withstand the forces acting on the structure. With increasing turbine sizes and therefore larger forces, the foundations have to become even more heavier. In a study for an offshore wind farm in Finland, the unballasted foundation weights amounted to over 12000 tonnes. These immense weights mean that only a handful of transportation vessels is in existence that would be able to transport the structures, highly limiting the installation and manufacturing possibilities. The foundations therefore have to be manufactured close to the installation location, and cannot be transported over long distances, since the installation would take several years to complete. If the foundation type will be used for future installations, it will most likely be for one specific region or area, where the infrastructure can be built specifically for gravity based foundations, as for instance in North Finland. If this is not the case, the business case of gravity based foundations is currently dead.

9 Future of foundation installation

Between 2010 and 2024, the offshore wind sector has seen significant technological advancements, with turbines growing both in size and capacity. This growth was driven by the increasing global demand for renewable energy and the ambitious targets set by multiple countries. If these countries want to meet these targets, the number of installed offshore wind farms, and the overall installed capacity has to continue to grow and expand at a rapid pace in future years. The EU for example, has set the goal to have 60 GW of offshore wind installed by 2030, which is a significant increase from the current capacity of 35 GW. The United States and several Asia-Pacific (APAC) countries have also set ambitious offshore wind targets, with the US aiming to have 30 GW installed offshore wind power by 2030 and The goal of Taiwan to have 5.5 GW installed in 2026. These targets emphasize the need for many foundations and foundation installation vessels in the near future.

The monopile is currently the most installed foundation type, but the end of its dominance has been predicted several times. The question remains what the future foundation type of choice will be, and how these foundations will be installed. The future of the foundation installation sector, and which foundation type will remain or become the 'workhorse' of the industry, are topics that are heavily discussed. The goal of this chapter is to provide a future vision for the foundation installation sector and highlight several factors that influence the future direction of the sector. This chapter will highlight several factors that can influence the future direction of the sector, and provide an answer to the research question:

What will the future of foundation installation look like, taking into account the innovations in the fast developing offshore wind sector?

In this chapter, the future of the offshore wind turbine foundation installation sector will be analyzed, and influences and drivers that can shape the future of the sector will be discussed. The different aspects that will be discussed came forward in the literature and in the interviews conducted with experts from the offshore wind sector.

The future of the foundation installation sector will be shaped by several key factors: technological innovation, lowering the LCOE, and regulatory and market pressures from government targets and tender requirements. The Chapter is divided in several Sections, as shown in the Figure, each tackling a specific driver for the future.

Section 9.1 discusses the role of targets and tenders in shaping the future of the sector. Section 9.2 discusses environmental and regulatory considerations, such as noise mitigation and initiatives to add positive environmental impact. Section 9.3 examines technological advancements, including turbine growth, and foundation design. Section 9.4 focuses on future vessels and equipment to address challenges posed by future larger turbines and deeper waters. Section 9.5 analyzes the economic and logistical challenges, such as vessel availability, supply chain bottlenecks, and port infrastructure requirements.

9.1. Targets and tenders

9.1.1. Targets

The growth of the offshore wind sector is heavily influenced by international and regional targets aimed at increasing renewable energy sources and reducing environmental impact. These targets set the scale for the offshore wind developments, and define the number of foundations that will need to be installed in the coming decades. The target has an impact on the foundation installation sector in several ways:

- The sheer volume of installations will require innovations that streamline the foundation installation processes, particularly through faster and more cost-effective installation methods. Monopiles are expected to remain dominant, but the number of alternative foundation types, as jackets and floating foundations will grow as well, as deeper water installations become necessary to meet the capacity targets.
- The US has got fewer shallow water locations, and encounter deeper waters closer to shore compared to Europe, which will spark the early adoption of floating foundation technologies. This market could accelerate the innovation in floating foundations, and thereby contribute in the reduction of the current high costs associated with floating foundations.
- For the APAC region, floating foundations will also be essential for reaching the targets set in these regions, which can also contribute to the faster development and cost reduction of floating foundations.

EU targets

The EU has set the target of having 60 GW of installed offshore wind capacity by 2030 and 300 GW by 2050 as part of its Green Deal and REPowerEU initiatives, aimed at being climate neutral by 2050 [149]. The cumulative installed offshore wind capacity in the EU was 19.38 GW in 2023, and these targets will require the installation of approximately 6 to 7 GW of offshore wind capacity annually between 2024 and 2030. The scale of this expansion means the installation of thousands of new foundations, pushing the boundaries of the current manufacturing and installation infrastructure.

US Offshore wind targets:

The United States, have set a target of deploying 30 GW of offshore wind capacity by 2030, and 110 GW by 2050. Several states, including New York, New Jersey, Maryland, and Massachusetts, have set their own targets, which combined will create a strong demand for offshore wind installations in the near future [82]. However, due to the greater water depths found closer to the US shoreline, a considerable portion of this capacity will likely be installed using floating foundations, increasing the knowledge, and sparking the development of floating offshore wind technologies. [150].

Asia-Pacific growth

Countries in the APAC region, have also announced ambitious offshore wind targets. South Korea, aims to install 14.2 GW of offshore wind capacity by 2030, of which a large portion will be in deep waters, requiring floating foundations. South Korea currently already has 6.7 GW of floating offshore wind in the permitting process. Japan has set a target of 10 GW by 2030, and 30 to 45 GW by 2040 [151]. Taiwan, with offshore wind farms already in operation, announced its allocation plan for a total of 15 GW of additional offshore wind installations, for the period from 2026 to 2035. Taiwan also has mostly deep water sites, which will also drive advancements in floating foundation technology [152][153].

9.1.2. The role of offshore wind tenders

Government tenders are a crucial mechanism for the offshore wind industry, since this is the way through which projects are awarded. The current tenders are structured in a way, to not only allocate capacity, but also to encourage innovation, and address environmental concerns [154]. Offshore wind tenders play therefore a crucial role in shaping the future market by allocating projects, dictating timelines, and in setting environmental and technical requirements. The Net Zero Industry Act, requires governments to include non-price criteria to at least 30% of their auctioned volume [154]. Offshore wind tenders normally favored projects with a low LCOE, where winning bids were determined based on the lowest energy prices. This pushed the development of larger offshore wind turbines, and increased the need for efficiency, also pushing innovation in foundation installation to reduce installation times and therefore costs. Winning tenders will however become increasingly dependent on non-price factors, sparking technological developments in areas as reducing environmental impact.

In certain markets, tenders incorporate factors to promote specific foundation technologies. For instance, France has issued tenders exclusively for floating wind projects, to spark the developments of deep water locations and floating technologies. By specifying that tender is specifically for floating wind, this encourages developers, manufacturers, and contractors to scale up their technologies for floating installations more rapidly. France, named the winner of the countries first large scale floating offshore wind farm tender in 2024 [155]. The AO5 tender, a 250 MW floating wind project off the coast of Brittany, requires the use of floating foundations [155]. These kind of tenders are needed to obtain a substantial track record for floating offshore wind, to be able to further drive down costs for floating wind farms.

9.2. Environmental and regulatory considerations

As the offshore wind industry grows and continues to scale up, environmental impacts and regulatory requirements are becoming critical topics that influence the installation of offshore wind turbine foundations, as was highlighted by interviewee three:

"As we scale up, cost efficiency and environmental regulations will drive innovation. Finding ways to reduce noise and improve the efficiency of installations will be key to the future of offshore wind." Governments and regulatory bodies are implementing more environmental regulations and guidelines aimed at minimizing the environmental impact of offshore wind projects, particularly in terms of underwater noise, seabed disturbance, and the protection of marine ecosystems, as was mentioned by interviewee one:

"Regulations around noise levels and seabed disturbance will get stricter, so the future of foundation installation will have to factor in those limits more than ever before." These evolving regulations, combined with the growing foundations, are creating the need for innovations in foundation installation technologies, as installations must not only meet technical and economic objectives, but also must comply with strict environmental standards.

This section explores the key environmental and regulatory challenges that will shape the future of the foundation installation market, including noise mitigation, seabed impact, and compliance with stricter environmental regulations. It also examines technological advancements in this area, and discusses how these technologies will influence the future of the foundation installation sector.

9.2.1. Noise during installation

One of the biggest issues of the upcoming years that came forward during the interviews, and one of the larger environmental concerns regarding the installation of offshore wind farms, is the noise generated during pile driving, particularly for monopile foundations. The high levels of underwater noise produced by the traditional driving method of impact piling, can disturb and harm marine life. Certain countries, as Poland in 2021, already have implemented stricter regulations concerning the marine life, and the expectation is that these regulations will only become more strict, and more widely adopted by other countries [156].

In Europe, several countries have implemented maximum allowable noise levels during pile driving, to protect marine life. Germany, for instance, has implemented strict noise limits of 160 dB SEL and 190 dB SPL at a distance of 750 meters from the installation site, in its Marine Protection Regulations [46]. The Netherlands and the UK have implemented similar regulations, which require developers to use noise mitigation measures during installation. The latest offshore wind farms installed in Germany deployed multiple noise mitigation measures, the more commonly used double big bubble curtain, besides a new noise mitigation technology developed in collaboration with IQIP. The immense structure of the IQIP T-NMS-10000, shown in Figure 5.56, deployed during the recent installation of monopiles at Deutsche Bucht wind farm, shows the immense lengths required to stay under the noise limits with the installation of current monopiles. For future, larger turbines, the noise mitigation measures will have to be improved even more, or alternative driving methods have to be adopted to remain under the noise limitations. Improved noise mitigation measures will most likely become more complex and more expensive, as was emphasized by interviewee two:

"Environmental concerns, especially noise, will have an increasing impact on the market. Noise

mitigation systems are getting more advanced, but as they become more efficient, they also become more expensive, which adds another layer of complexity to offshore wind projects." Developers are also moving towards innovative technologies that can reduce noise levels during the installation, to meet these regulatory requirements. Vibro-piling, is such a quieter alternative to traditional impact piling. This method uses high-frequency vibrations to drive piles into the seabed, generating significantly less noise than with conventional pile driving [157]. These pile driving methods are currently not widely adopted in the offshore wind installation market, but due to stricter regulations, and the growth of the foundations and thereby an increase in force required to install these larger structures, innovative lower noise pile driving methods become more interesting in terms of future. These pile driving methods are good scalable, according to CAPE, the company producing the CAPE VLT, a vibratory lifting tool [157].

Other innovative driving methods are also currently being tested, as the vibro-jetting technology of GBM Works, which is also aimed at reducing installation noise. It reduces the friction of the pile during installation, reducing the force required to drive the foundation pile into the seabed. When foundations are getting larger, more force will be required to drive the foundation into the seabed, so this technology makes it possible for future foundations to be installed with current impact hammer sizes, and or vibratory equipment [48].

9.2.2. Positive impact

Looking ahead, future regulatory trends are likely to include stricter requirements for contributing to a better marine ecosystem, where developers are required to implement technologies that have a positive effect on the marine environment instead of only mitigating the negative effects of installing offshore wind farms, like artificial reefs. [158]

9.3. Technological advancements

Further scaling the offshore wind sector and offshore wind turbines, will also require technological developments to meet future installation demands. As the offshore wind industry continues to grow, with turbines increasing in capacity and projects moving to deeper waters, currently used foundation sizes, installation techniques, and installation vessels must evolve as well. This section explores the key technological developments that influence the future of the installation sector, focusing on turbine growth and foundation developments.

9.3.1. Turbine growth and foundation design

The increase in wind turbine sizes has large implications on the foundation design. As turbines continue to grow in capacity from the 15 to 20+ MW range, the foundations need to be designed so they can accommodate the larger loads accompanied with the larger turbines. Foundations for offshore wind turbines with capacities of 15 MW have already been installed, and 20+ MW turbines are expected in the near future, requiring larger and stronger foundations capable of handling the increased loads.

Monopiles:

As turbine sizes increase, monopiles must also scale in size, and therefore also in weight. The latest generation of monopiles can reach diameters of 10 meters and weigh over 2000 tonnes, pushing the limits of the current installation capabilities. However, monopiles are thought to remain the

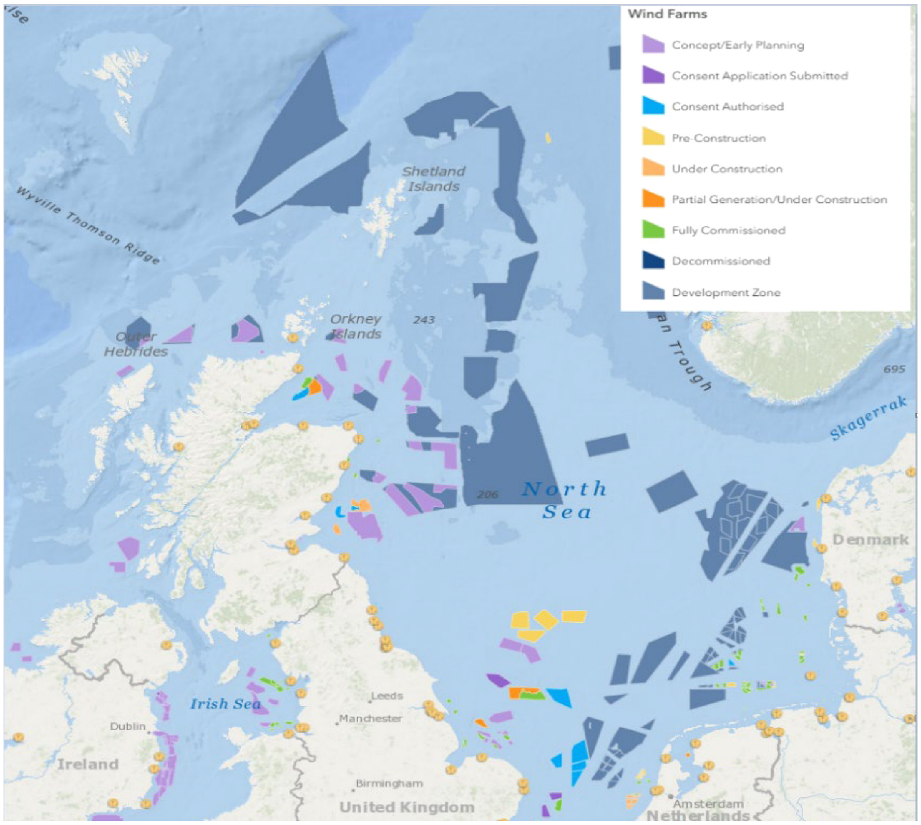


Figure 9.1: Wind farms and development areas in the North Sea [159]

foundation type of choice up to water depths of around 70 meters, as discussed during interview one. The 60 meter mark is mentioned multiple times during the interviews, and is connected to the water depths encountered in the North Sea, where a lot of the near future developments will occur, as can be seen on the map of development areas for Europe in Figure 9.1. The monopile has no structural limitations for its use in water depths up to 120 meters [75], however when looking at these large depths, floating foundations will come into play when this foundation type has successfully lowered its LCOE by deploying the foundation type more often, by the expected 74% reduction by 2030 [27]. In 2022 the LCOE of floating wind was three times higher than that of bottom fixed foundations, so these reductions are necessary to bring the costs of floating wind closer to the costs of traditional installations [27]. Besides floating foundations for deeper water locations, noise can become a show stopper for monopiles. When noise pollution becomes too large with bigger foundation piles, alternative foundation piles can become an alternative solution, as was discussed by interviewee five:

"If noise becomes a dis-qualifier, and you can't get the installation of a monopile under 160 dB, we will have to switch to jackets or other quieter alternatives."

Jacket Foundations:
As turbine sizes increase, jacket foundations also have to withstand the higher structural loads, and will increase in dimensions and weight. Jackets are more expensive that monopiles, and are also more expensive to produce. In recent years, jackets have been installed more frequently, and its market share increased over the last few years. To meet future offshore wind demand and targets set by countries, the offshore wind sector has to scale even more than it currently already has done. Since the production process of jackets is still not as automated and streamlined as that of monopiles, no real large scale manufacturing facilities exist for the production of jacket foundations. For the foundation to be more widely adopted in the future, the manufacturing processes will have to be streamlined, so the foundations can be mass produced, as was emphasized by interviewee four:

"If we could streamline the manufacturing process for jackets, they'd become more competitive. Right now, we rely on traditional methods, which are not optimized for the high volume and scale required in offshore wind."

9.3.2. Floating foundations

Floating foundations, are anchored to the seabed using mooring systems, are not restricted by water depth, making them ideal for wind farms located in waters deeper than 60 meters. Floating foundations will have their place in the future of offshore wind, albeit for deep water locations, as mentioned during interview 8:

"Floating wind technologies will be further developed, and as they become more economically viable, we'll see them being used in deeper waters that aren't currently being explored." This technology opens up installation regions where only deep water locations are available, as in some regions in the US. The future of floating foundations depends on future cost reductions and advancements in designs that allow for large-scale production of the foundation type. Targets specifically for floating offshore wind farms, will boost the developments of the technology, and will contribute to lowering the LCOE of the foundation type. By 2030, it is expected that floating wind projects will achieve a 74% reduction in LCOE, driven by improvements in material efficiency, manufacturing processes, and installation techniques [27]. The first large scale floating offshore wind farm is the Hywind Scotland project, which demonstrated the viability of floating foundations, with capacity factors of over 55%, which is significantly higher than many bottom fixed projects [160].

9.4. Future installation vessels and equipment

The fast growth of the offshore wind industry, and the increase in turbine sizes and the movement to deeper water locations, has brought significant challenges for installation vessels and equipment. The next generation of offshore wind projects, particularly those using 15+ MW turbines, will require advanced installation vessels and equipment, capable of handling larger, heavier structures and components. These innovations are critical for reducing installation times, minimizing costs, and to ensure that the industry can meet the ambitious targets set by governments worldwide. This section explores future directions in installation vessels and equipment, focusing on developments in vessels, lifting capacities, as well as specialized equipment.

9.4.1. Vessels

As turbines grow larger and offshore wind farms move to deeper waters, the demand for installation vessels with higher lifting capacities and larger deck spaces becomes more pressing. The installation of larger foundations, such as monopiles with diameters of 10 to 15 meters, requires vessels that can not only lift heavier loads but also operate safely and efficiently. Traditional jack-up vessels, which have been the workhorses of the offshore wind industry, are facing limitations when it comes to installing the latest generation of wind turbines and their associated foundations. These vessels are often restricted by their crane capacities and deck space, which are insufficient for handling the largest monopiles and turbine components. A large portion of the current fleet of installation vessels does not have the capacity to lift and install the future foundations. In the years between 2012 and 2020, the foundation installation sector relied heavily on the use of these jackup vessels with crane capacities of 1500-1600 tonnes, as the Aeolus and the Innovation, as can be seen in Figure E.3. With the average foundation weights increasing, the number of installations where these vessels can be deployed decreases. In the years after 2020, the market share of jackup vessels deployed for the installation of foundations decreased, as can be seen in Figure 9.2. This gap has been filled by the deployment of HLV's for the installation phase. An example of a state-of-the-art offshore wind installation vessel, is the Orion by DEME. This vessel has a lifting capacity of 5000 tonnes, 8000 m2 free deck space, and DP3 systems to handle larger foundations and deeper water installations. "The introduction of floating installation vessels and the use of tools like the motion-compensated gripper have changed the way we approach offshore installation. It allows us to handle larger monopiles with more precision, even in challenging sea conditions."

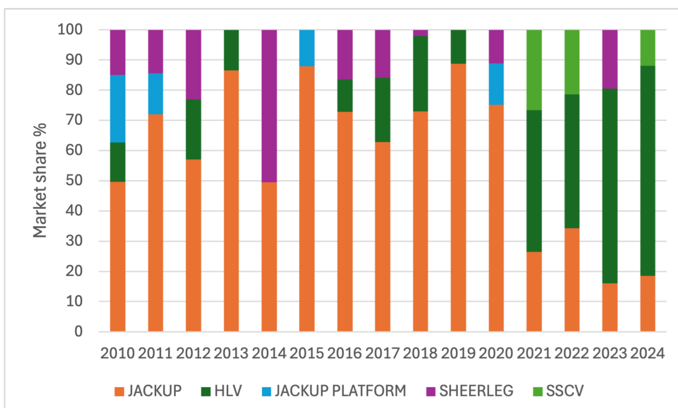


Figure 9.2: Share of total number of foundations installed per vessel type

9.4.2. Innovative equipment

One of the key components that enable vessels to install heavy components in harsh marine environments, are the equipment used during the installation. Innovations in lifting equipment, motion compensated systems, and other equipment are critical for foundations to be installed accurately and efficiently, even in challenging sea states. The introduction of floating installation of foundations using DP systems has created new challenges, in terms of relative vessel movements. Motion-compensated gripper systems have been developed to stabilize foundation components during the installation. These systems use real-time sensors and hydraulic actuators to adjust for vessel movement, allowing for more precise placement of foundations in rough seas. The development of motion compensated pile grippers, such as the one used on the Orion vessel, allows foundation to be installed while afloat, without the need to deploy any anchors. Furthermore, these systems allow installations to continue in sea states that would otherwise have caused delays, reducing overall installation times.

Noise pollution from traditional pile driving methods has become a major concern for the installation of foundations. Vibro-piling has gaining traction as an environmentally friendly installation technique, but is not yet widely adopted in the installation market.

9.5. Economics and logistics

The expansion of offshore wind capacity, driven by increasing turbine sizes and deeper water installations, comes with significant economic and logistical challenges. To meet the ambitious global targets for offshore wind, not only technological advancements but also cost-effective solutions and an efficient, reliable supply chain, are required. This section discusses the key economic and logistical challenges that will influence the future of the foundation installation sector, focusing on cost, supply chain, vessel availability, and port infrastructure limitations. These factors are critical to ensure that the offshore wind sector can scale, and targets are met.

9.5.1. Cost pressures and the drive to reduce LCOE

One of the largest economic drivers for the offshore wind industry is the continuous pressure to reduce the LCOE. The production of foundations, must scale rapidly to meet the growing demand for offshore wind farms. However, the manufacturing process for large foundations are resource-intensive, requiring significant material inputs, and specialized manufacturing facilities. Sif has just built a state-of-the-art new manufacturing facility aimed at the production of monopile foundations up to diameters of 11 meters, the will be able to produce 200 XXXL monopiles yearly [161].

9.5.2. Supply chain bottlenecks and material availability

As the offshore wind industry continues to scale, the supply chain for critical components, such as steel for monopiles, specialized vessels, and installation equipment, faces critical issues. Supply chain bottlenecks can lead to delays, increased costs, and logistical challenges, particularly in regions where the offshore wind industry is still in its early stages of development.

Steel is a critical material for the production of offshore wind foundations, and the global steel market has experienced significant price volatility in recent years [162]. As turbine sizes increase and require larger, heavier foundations, the demand for steel is expected to grow, potentially magnify the supply chain pressures.

Offshore wind projects often rely on a global supply chains for key components, including foundations, turbines, and installation equipment. However, the increasing complexity and scale of offshore wind farms have led to growing concerns about the resilience of these supply chains Additionally, the development of regional supply hubs, particularly in Europe and the United States, helps to reduce lead times and improves the efficiency of installations.

9.5.3. Vessel availability and logistical constraints

The availability of capable installation vessels is another critical logistical challenge for the offshore wind industry. As turbine sizes increase and projects move to deeper waters, the demand for vessels capable of handling the next generation foundations will possibly outpace the available vessel fleet. This vessel shortage can in the future create significant bottlenecks, where developers have to wait to secure appropriate vessels for their projects.

The global fleet of installation vessels is relatively limited, and many existing vessels are not equipped to handle the largest foundations or the deeper water depths. As a result, vessel shortages can become a major bottleneck in the offshore wind supply chain, since the number of yearly installations has to be increased over the next few years to reach offshore wind targets. To address this issue, several companies are investing in the development of next-generation installation vessels, with larger lifting capacities, increased deck space, and DP3 systems. However, the construction of these vessels requires significant lead times and large investment, meaning that vessel shortages are likely to remain a challenge in the near future. Furthermore, during interview nine it was highlighted that future investments in vessels might be postponed due to the uncertainty about the number of foundations that will have to be installed. When wind farms will keep on using 100+ turbines per wind farm, with the increasing turbine sizes, the wind farms will become too large from an investment point of view. Therefore it is likely that future wind farms will consist out of fewer turbines, requiring less vessel movements in the distant future. An example of an next generation jackup vessel is the 175-meter-long Boreas vessel of van Oord, which is expected to enter the market in 2025. This vessel is designed to install foundations and components for 20 MW turbines, and will be equipped with a crane of 3000 tonnes, with 126 meter long legs, enabling the vessel to operate in water depths of up to 70 meters [163].

9.5.4. Port infrastructure

The scaling of offshore wind projects also places significant demands on port infrastructure, which must accommodate larger vessels, heavier components, and more complex logistics. Many existing ports lack the infrastructure needed to support the next generation of offshore wind projects, particularly in terms of quay space, lifting equipment, and deep-water access. Upgrading port infrastructure is a capital-intensive process, and delays in port expansion can create bottlenecks in the offshore wind supply chain. In 2021, in a report of WindEurope, it is said that investment of €6.5bn are needed in ports, just to meet the offshore wind goals of 2030 [164]. In response to these challenges, the EU has announced investment programs to upgrade infrastructure and expand capacity to meet future offshore wind goals, in the Wind Power Package [165].

9.6. Conclusion

When looking at all previously installed offshore wind farms, the monopile was and is by far the most used foundation type. The foundation type had several favourable factors, such as its simplicity and cost-effectiveness, that contributed to its widespread adoption. But future larger even larger turbines and deeper water installations, pose significant challenges for the future use of the foundation type, leading to the question of what the future foundation type of choice will be.

The objective of this chapter was to discuss and analyze different factors that influence the future of the foundation installation sector. Furthermore, it aims to provide a future vision for the sector, focusing on future challenges, foundation types, and installation methods. The future of the foundation installation sector will be shaped and influenced by a number of different aspects, including regulatory, technological, environmental, economic, and logistical factors. As the industry continues its rapid expansion, to meet the renewable energy targets, the pressure on the foundation installation sector also continues to rise. Scaling installation technologies, equipment, and vessels to support larger turbines, deeper water locations, and stricter environmental regulations presents a variety of challenges, but also opens a lot of opportunities for innovations in the risk-averse offshore wind sector.

The chapter discusses the challenges that will most likely arise in the future and their consequences. The focus of the chapter was on the monopile foundation since this is the most used foundation type, and the most discussed foundation type in terms of its future use, or the deviation to alternatives for the monopile. The future of the foundations does depend on several factors, which tie into the limitations of each foundation type discussed in Chapter 8. By reaching this objective, the chapter will provide an answer to the research question:

What will the future of foundation installation look like, taking into account the innovations in the fast developing offshore wind sector?

The offshore wind sector is a fast-developing sector, with turbine sizes increasing in a fast pace, and installations moving to ever deeper waters. The future of the foundation installation will therefore be dependent on several key factors.

Several countries and governments have implemented ambitious targets for their installed offshore wind capacity in the future. The majority of the installations will take place in Europe, but Asia and the US market are also expected to grow, following the targets set, and the tenders rolled out by the countries. These targets and tenders will help roll out and shape the industry in all these different regions. However, the growth of the sectors is not only dependent on the implementation of a good tender structure and the implementation of targets. The sector is of course highly dependent on other factors such as an interesting investment opportunity. Without the incentive for investors, the growth of the sector will in the end also halt. Specific tenders aimed at a certain foundation type, such as floating wind, can spark the development of the foundation type, and help in creating a substantial track record, which is of great importance in the risk-averse sector. These projects will also in the end help to bring down the cost of the foundation type, by gaining experience and narrowing the financial gap between bottom fixed foundations and floating foundations.

Another key factor for future installations is and will be the environmental impact of the installation. More and more countries are and will be implementing strict regulations concerning environmental impacts as for instance noise. Noise will be one of the most important topics of the upcoming years, shaping the installation of monopiles. The monopile will remain as the preferred foundation type if it can adhere to future noise and other environmental standards. The regulations concerning noise limitations will spark innovations in even better noise mitigation systems, and alternative driving methods. The T-NMS-10000 of IQIP, used at the He Dreiht offshore wind farm shows the immense noise mitigation systems needed to comply with current noise regulations in Germany, highlighting the scale of future noise mitigation measures. Besides mitigating negative impacts, the focus will also be on adding positive value with the installations offshore. Tenders will again play an important role in this process, where the government can demand or favour projects or plans from developers that have implemented attributes like artificial reefs.

Technological advancements are very important for the future of the offshore wind foundation installation sector. Innovations in foundation designs, such as larger monopiles and jackets, and the development of floating foundations, are essential for the installation in future deeper water locations, and in accommodating the next generation of 20+ MW turbines. The introduction of floating foundations offers a solution for deep water locations where bottom-fixed foundations are not feasible, opening up new markets for offshore wind projects. However, industry-wide adoption of these technologies will require large cost reductions, through standardization, and the optimization of the foundations and their installation methods.

Vessels are obviously critical for the installation process, and current are seeing a shift from previously used jack-up vessels to higher capacity heavy lift vessels, as shown in Figure 9.2. The previously used vessels lack the capacity to install the current and future foundations, and the percentages of foundations installed with jackup vessels fell back after 2020. Future foundations will only become larger and heavier, with future larger turbines, and the movement to deeper water sites. It is difficult to say what the exact future most used vessel type will be, but it seems like floating installation on DP, with heavy lift vessels will be the way forward, at least for the upcoming years. These vessels currently do not have an extensive track record, but when time passes, the efficiencies and methods used with these vessels will likely only improve. Furthermore, the possibility exists that the foundations installed in the North Sea, for instance, will reach a plateau, similar to the analogy made with what happened in the aviation sector. 'Jumbo' aeroplanes were thought to be the way forward, but eventually, the sector came to the conclusion that deploying several smaller aircraft was more efficient. Equipment that is required for the installation procedure, will also play a large role in the adoption and continued use of XXL or even larger monopiles. The equipment can be scaled, and innovations like the motion-compensated pile gripper have already improved efficiency.

The expansion of the offshore wind capacity comes with significant economic and logistical challenges. The margins are small in the offshore wind sector, and there is and will remain the continuous search for a reduction in LCOE. This is also one of the primary drivers of the growth of the sector in terms of turbine and foundation sizes. The future growth of the sector is however presenting significant challenges for the supply chain. The future expected growth of the sector puts high strains on vessel availability, materials, and the local supply chain. Vessels are expected to be in short supply in the upcoming years, with the lack of an established large fleet that will be able to handle the future larger foundations. As turbine sizes increase, the sector will be dependent on only a handful of installation vessels capable of performing the installations. The construction of vessels takes several years, and it was noted that with the growth in turbine sizes, the possibility exists that future wind farms will consist of fewer turbines, possibly reducing the number of vessels required in the distant future and thus halting investments in vessels. Investments in ports will also have to continue to be able to keep up with the growing demands of the sector. Quayside improvements, larger storage areas, and high-capacity handling and lifting equipment are key to the future sustained growth of the sector.

10 Conclusion

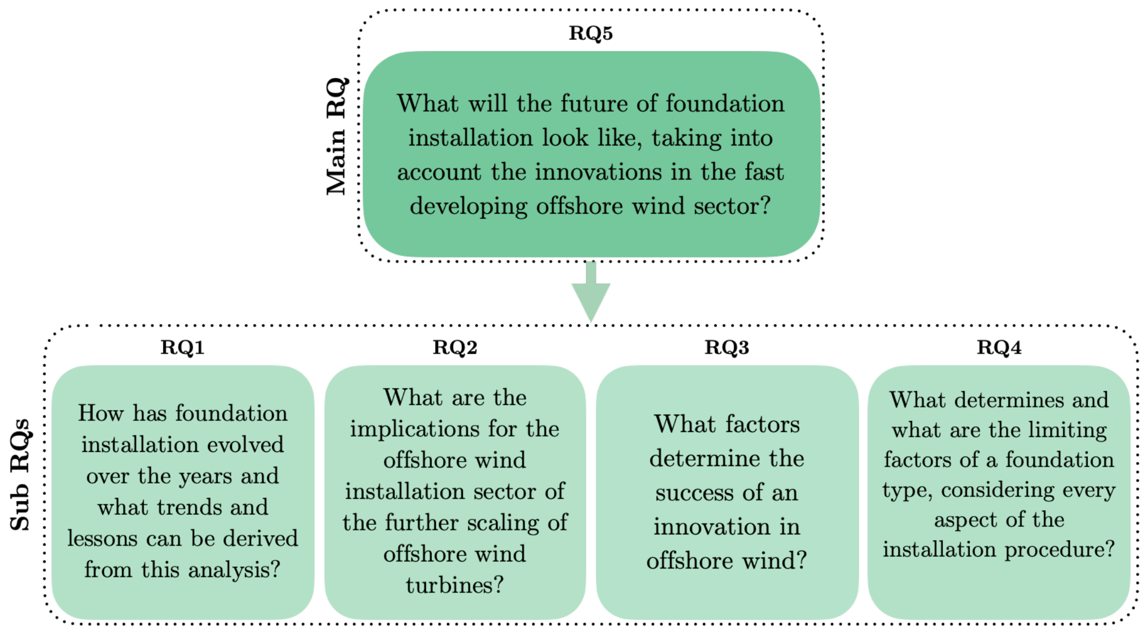


Figure 10.1: Research questions

First, the different sub-questions are handled, and afterwards, the main research question will be answered. For more detailed answers to the questions, see the conclusions of the previous chapters.

How has foundation installation evolved over the years and what trends and lessons can be derived from this analysis?

In the period after 2010, the offshore wind sector has grown at a rapid pace, not only in terms of installed capacity but also in terms of technological advancements and complexity of the installations. Monopiles dominated the foundation market due to their simplicity, cost-effectiveness, ease of installation, and due to extensive knowledge about the foundation type. However, as turbines have grown in size and projects have moved to deeper waters, other foundation types have been adopted more and more. The evolution of the entire sector was of a gradual kind, with incremental improvements and incremental scaling. The sector did develop at a fast pace, but no large advancements or innovations have had such an impact on the industry that the entire market changed. Installation depths and turbine sizes increased, leading to the development of new installation methods, installation vessels and equipment to handle the larger structures. The increase in turbine sizes and in water depths drive the foundation developments, which in turn influences the building of more specialized vessels and tools. Several foundation types have been tested and deployed over the years, but in terms of bottom fixed foundations, the monopile remained the foundation of choice. Floating foundations have been tested and deployed at a semi-large scale, which proved their viability and has shown that floating offers the potential to install wind turbines in water where bottom-fixed foundations are not viable any more. Furthermore, innovations in noise mitigation systems and low-noise alternative driving methods, have been developed to address the strict noise regulations in combination with the increasingly large foundations. The offshore wind sector has developed from 2010 to 2024 from a relatively young market, that relied on the use of equipment and vessels built for the oil and gas industry, to a fast-growing, highly specialized sector. Advances in vessels and equipment have enabled the growth of the sector, which is primarily driven by the search for a reduction to lower the LCOE of offshore wind turbines.

What are the implications for the offshore wind installation sector of the further scaling of offshore wind turbines?

The further scaling of offshore wind turbines has an impact on several key areas in the offshore wind foundation installation sector. As the offshore wind sector continues to grow, in terms of turbines and overall capacity, the infrastructure will have to scale accordingly. Larger foundations require large ports for storage, assembly, and transportation. High capacity installation vessels are also essential, to handle the next generation of turbines and foundations. The number of vessels capable of handling the future foundations is expected to be a large bottleneck for the industry in the years before 2030. As countries and governments want to meet their targets, more installations are needed and expected before 2030. The shortage in vessels, can possibly lead to delays and also to increased costs, which in terms will affect the financial viability of future projects. Furthermore, scaling also impacts the environment, as larger foundations require more force to be driven into the seabed, which will produce even more noise. The fast scaling efforts will increase the need to develop advanced noise mitigation strategies or alternative driving methods, to comply with stricter regulations on noise emissions. Therefore, further scaling offshore wind turbines creates the need for the industry to adopt and develop innovations in foundation design, but also in equipment, and installation techniques, to be able to comply with regulations, and to be able to handle the future larger structures.

What factors determine the success of an innovation in offshore wind?

The fast-developing offshore wind sector needs innovations and new technologies to be able to sustain its future growth. However, the sector is capital intensive, and the risk-adversity of the sector creates significant barriers to the adoption of new technologies. For a new technology to succeed, it must successfully demonstrate its reliability, cost-effectiveness, and regulatory compliance through a substantial real-life track record, to minimize the risks associated with adopting a new technology, for instance for the contractor using the technology. The main success factors for innovations in the fast-evolving offshore wind sector are:

- Problem-solving ability and necessity
- Cost-effectiveness and efficiency

- Scalability and adaptability
- Regulatory compliance and environmental impact
- Risk management and reliability

Demonstration projects are essential in showing the performance of a new technology and are therefore required for widespread market adoption. Nevertheless, market adoption remains challenging for new innovations. Regulatory hurdles can make or break an innovation. Innovations are nowadays often aimed at noise reduction strategies, since noise is thought to be one of the largest concerns the offshore wind sector is currently, and will be facing in the near future. This ties in with the statement that innovations will continue to be driven by necessity, and regulatory drivers. If noise regulations become more pressing, the need to innovate and reduce the noise levels during installation will automatically follow.

What determines and what are the limiting factors of a foundation type, considering every aspect of the installation procedure

Several limiting factors influence the foundation installation sector, including technical, logistical, environmental, and economic constraints. The increasing turbine sizes have large consequences for the foundation design and subsequently on their installation procedures. Larger and heavier foundations require high-capacity installation vessels, and make the installation procedure even more challenging and complex. Logistical challenges are also increasingly pressing in the future, as the installation process is constrained by the availability of specialized vessels, lifting equipment, and port infrastructure. The supply chain for large-diameter monopiles and jackets is complex, with fabrication yards, transportation logistics, and storage all being critical bottlenecks. Environmental regulations further limit installation methods. Compliance with regulations is also essential for a foundation type to remain a viable option. When noise limitations become even more strict, alternative driving methods and even more complex noise mitigation strategies have to be deployed. Furthermore, cost pressures are perhaps the most significant limiting factor. The industry is under constant pressure to reduce the LCOE, and the choice of a foundation type will therefore almost always be the most economically viable option.

What will the future of foundation installation look like, taking into account the innovations in the fast-developing offshore wind sector?

The future of the foundation installation sector is likely to remain to be driven by the continued scaling of turbines. Turbines up to 30 MW are expected to enter the market in the future, and possibly even larger turbines will be developed. It is however not sure if the industry will keep adopting the latest and largest turbines, or if there will be a certain sweet spot in terms of capacity, where the industry will settle.

Furthermore, environmental restrictions and regulations will play a large role in shaping the future of the foundation installation sector. Additionally, the offshore wind sector has to keep developing its supply chain, or otherwise, this could potentially halt or hinder the future growth of the sector. Besides focusing on an optimized supply chain, investments in the infrastructure of the sector will also play a large role, and future investment will also be required. The demand for specialized vessels will be high in the next few years, but the possibility exists that due to the capacity increase of individual turbines, wind farms in the more distant future will use fewer turbines since higher-capacity offshore wind farms are not wanted by developers. This outcome would result in highly expensive, large-capacity specialized installation vessels, that only install a few foundations for a wind farm. This scenario could halt the investments for future installation vessels.

11 Recommendations

11.1. Include financial analysis

One of the main drivers of the scaling in the offshore wind sector is the search for a reduction of LCOE. Many choices within the sector are based on costs, however, this research does not include a financial analysis or comparison of different foundation types and installation methods. Including such an analysis would make the overall conclusions more robust regarding the future outlook of the foundation installation sector. Future research should focus on developing a comprehensive cost model that integrates all aspects of the foundation installation process. This model should include metrics such as vessel time and equipment cost. By quantifying the different options and possibilities, the trade-offs between different technologies can be better evaluated.

11.2. Include analysis of efficiency improvements and installation times

Tracking the efficiency improvements of installation methods is very important in understanding how technological innovation impacts project timelines and costs. Future studies could compare installation times and efficiency metrics between earlier and modern practices. In this way effect of certain innovations and advancements in equipment can be evaluated. Such an analysis would provide valuable insights into the technological evolution, and could possibly also serve as a benchmark for future advancements and innovations.

11.3. Increase number of interviewees

The insights gathered from industry stakeholders have been key in finding details about the sector that have helped the research. The stakeholders have provided invaluable insights and perspectives on all the different aspects of the foundation installation sector. However, including more stakeholders would always be beneficial, since more viewpoints increase the validity of the findings. Future research should also try to include more perspectives from policymakers and environmental agencies, as well as stakeholders from emerging offshore wind markets in Asia and North America America. Engaging stakeholders from elsewhere than Europe is particularly important as these regions face different challenges, related to regulations, logistical constraints, and location-specific conditions.

11.4. Publish an open accessible industry database

One of the problems identified during the literature review, performed prior to this research, was the lack of data sharing across the industry. One of the goals of this research was to gather information about all aspects of the foundation installation campaign and to tackle the issue of the lack of widely available data on offshore wind projects. To help further research, it would be of great value to create an accessible, open data-sharing platform and database where information can be submitted, and shared across a free platform. During this research, an extensive visual and numerical database has been created, but an additional step could be to make the visual and numerical database editable, so information sharing could be enhanced. One issue with such an approach is sustaining the validity of the information when the platform is fully open, and monitoring would probably be accompanied by costs, resulting in a fee to use the database, foregoing the initial goal of making up-to-date, data publicly available. Another option could be to implement a peer-review system to validate submissions and maintain the reliability of the database.

11.4.1. Include evolution of market before 2010

One of the first limitations made to the scope of the research was the exclusion of projects that had been installed before to 2010. The choice for this approach was made, to limit the scope, and because the offshore wind sector was in its early stages of development before this period. The inclusion of this period could however complete the historical analysis, by including all previously installed offshore wind farms.

11.4.2. Expand the geographical scope

The focus of the research was on the installations performed in Europe and did not consider all projects performed outside of Europe, as for instance in China. The inclusion of all worldwide projects could lead to additional insights and could investigate how different logistics and supply chains in other parts of the world influence foundation installation. By analyzing such markets insights into the difficulties of an emerging, underdeveloped offshore wind infrastructure can lead to insights into factors that are of importance for the future growth of the offshore wind sector.

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A
Interview protocol

The interviews have been conducted both in person and online. The transcripts of the interviews have not been added to the report, due to the size of the files. The transcripts will be provided in an additional file. For additional information about the interviews, or for full transcripts of the interviews, the author of the report can be contacted via e-mail or LinkedIn.

A.1. Interview questions

The interviews have been conducted via a semi-structured approach, where questions were formulated in advance, but not all questions were asked and the interviewer was free to ask follow-up questions. Furthermore, the interview questions have been formulated around the research questions.

A.1.1. How has foundation installation evolved over the years and what trends and lessons can be derived from this analysis?

- How has the industry developed in terms of foundation installation?
- What were large milestones in the industry? In the field of installation and installation equipment?
- What were driving factors for technological developments?
- How have foundations developed or changed over the year, and what were driving factors behind this change?
- What were driving factors behind the developments of the sector?
- What have been the major changes in installation methods over the years?
- How have installation vessels evolved to meet the requirements of current offshore wind projects?
- What are the key trends and lessons learned from past projects?
- What are the current largest issues or challenges the industry has to overcome?
- What were in your eyes large turning points in the industry?
- What were large milestones for the industry in terms of foundation installation?
- What for role will environmental impact play in the next few years?

- How have government policies and regulations influenced the development and deployment of offshore wind farms?
- What do you believe are the primary drivers behind (technological) advancements in the offshore wind foundation installation sector?
- What role do economic factors, such as cost reduction and efficiency improvements, play in driving advancements?

A.1.2. What are the implications for the offshore wind installation sector of the further scaling of offshore wind turbines and their foundations?

- Do you think the industry is moving to fast towards even larger turbines?
- Would the industry benefit from standardizing current turbine sizes, before thinking about further scaling turbines?
- Wat do you think will be the limit in terms of capacity of offshore wind turbines?
- What will be the limiting factors?
- Do you think the turbine sizes will continue to rise?
- How is the scaling up of offshore wind turbines affecting foundation design and installation?
- What challenges and opportunities do larger turbines and foundations present?
- What are the implication for the equipment used during the installation phase?
- Or will the equipment just follow the turbine manufacturers?
- What will be the limits for the different foundation types?
- How do you think the industry will adapt to these challenges of larger foundations?
- How can it affect logistics and supply chain?
- What will be the limiting factors in this regard?

A.1.3. What determines and what are the limiting factors of a foundation type, considering every aspect of the installation procedure?

- What factors determine the choice of foundation type for a particular offshore wind project?
- How do site conditions, such as seabed composition and water depth, influence foundation selection?
- What are limitations of the offshore installation sector?
- What are the main technical and logistical challenges associated with the different foundation types?
- Can you discuss the key limiting factors for different foundation types?
- How will these limitations possibly shape the future of offshore wind installation?

- How do environmental regulations and impact assessments affect the choice of a foundation type?
- How do installation vessels and equipment capabilities limit the choice of a foundation type?

A.1.4. What determines a good innovation in offshore wind foundations and what factors determines the success of an innovation?

- What determines the success of an innovation?
- What criteria are important for the success of an innovation in the offshore wind sector?
- Why did certain innovations not 'survive', and why did others not succeed to penetrate the market, or faced difficulties with adoption? (Vibro-driving)
- Can you give an example of an innovation that did not succeed?
- How can you asses an innovation?
- What recent technological innovations have had the largest impact on foundation installation?
- What criteria do you use to assess the value and potential success of an innovation in offshore wind foundations?
- Can you provide examples of successful innovations, and the factors that contributed to their success?
- How do industry standards, regulatory compliance, and cost-effectiveness impact the adoption of new technologies?
- What role do pilot projects and field testing play in the assessment and adoption of new innovations?
- How important is collaboration between developers, researchers, and technology providers in driving successful innovation?
- What are the most successful innovations in the offshore wind sector, and why?

A.1.5. What will the future of foundation installation look like, taking into account the innovations in the fast-developing offshore wind sector?

- How do you envision and or see the future of offshore wind foundation installation sector?
- What trends do you think will shape the future of the offshore wind sector?
- Which emerging/new technologies do you believe will become standard practice by 2030?
- What are the key innovations you anticipate in the next decade?
- What are necessary innovation in your eyes?
- What are the largest challenges in the upcoming years, the industry has to deal with?
- What will be the boundary of the monopile, in terms of depth?
- Will there be a shift towards other foundation types?

- What for role will decommissioning play in the future?
- How do you see the role of floating offshore wind in the future?
- What will be required to make floating offshore wind more interesting?
- What future policy changes or regulations do you think will have the most impact on offshore wind foundation installations?
- Do you think offshore wind will remain to grow in terms of installed capacity and in terms of turbine size?
- What will be the maximum turbine size that will be used in the future?
- What major milestones or breakthroughs do you expect to see in the next decade?

A.1.6. General insights

- Are there any particular case studies or projects that you think offer valuable insights for my thesis?
- How important is collaboration between industry, academics, and governments, in driving advancements in offshore wind technology?
- What industry trends do you believe will shape the future of the offshore wind foundation installation sector?
- What policies or regulations do you think need to or will be implemented to support the growth of offshore wind foundations?

B
Offshore wind farms

	Year first foundation	Country	Wind farm Capacity (MW)	Foundation type	No. turbines	Turbine (MW)	Vessel lift & foundation install
Baltic 1	2010	DE	48,3	Monopile	21	2,3	Matador 3
BARD offshore 1	2010	DE	400	Tripile	80	5	Wind lift 1
Belwind phase 1	2010	BE	171	Monopile	56	3	Svanen
Belwind phase 2	2010	BE	165	Monopile	50	3,3	Svanen
Gunfleet sands	2010	GB	172,8	Monopile	48	3,6	Seacore
Horns rev 2	2010	DK	209,3	Monopile	91	2,3	Sea Jack
Ormonde	2010	GB	150	Jacket	30	5	Rambiz
Robin rigg	2010	GB	174	Monopile	60	3	MPI Resolution
Sheringham Shoal	2010	GB	317	Monopile	88	3,6	Strashnov & Svanen
Thanet	2010	GB	300	Monopile	100	3	Sea Jack
Walney phase 1	2010	GB	183,6	Monopile	51	2,3	Taklift 7
Avedore Holme	2011	DK	10,8	Monopile	3	3,6	
Lincs (UK)	2011	GB	270	Monopile	75	3,6	MPI Resolution
London Array (UK)	2011	GB	630	Monopile	177	3,6	Sea Worker & Svanen
SWAY scale test (NO)	2011	NO	2,6	Floating	1	2,6	
Thornton Bank phase 2	2011	BE	184,5	Jacket	30	6	Rambiz
Thornton Bank phase 3	2011	BE	110,7	Jacket	18	6,15	Rambiz
Walney phase 2	2011	GB	183,6	Monopile	51	3,6	Svanen
Windfloat 1	2011	PT	2	Floating	1	2	
Anholt	2012	DK	400	Monopile	111	3,6	Svanen
Global Tech 1	2012	DE	400	Tripod	80	5	Innovation
Gwynt y Môr	2012	GB	576	Monopile	160	3,6	Friedrich Ernestine & Yudin
Karehamn	2012	SE	48	Gravity based	16	3	Rambiz
Meerwind sud/ost	2012	DE	288	Monopile	80	3,6	Strashnov
Nordsee Ost	2012	DE	295	Jacket	48	6,3	Victoria Mathias
Riffgat	2012	DE	108	Monopile	30	3,6	Strashnov
Teesside	2012	GB	62,1	Monopile	27	2,3	Sea Jack

	Year first foundation	Country	Wind farm Capacity (MW)	Foundation type	No. turbines	Turbine (MW)	Vessel lift & foundation install
Belwind Alstom demo	2013	BE	6	Jacket	1	6	Pacific Osprey
Gunfleet Sands 3 Demo	2013	GB	12	Monopile	2	6	Svanen
Humber Gateway	2013	GB	219	Monopile	73	3	MPI Discovery
Methil Demo	2013	GB	7	Jacket	1	7	
Northwind	2013	BE	216	Monopile	72	3	Neptune
Trianel borkum 1	2013	DE	200	Tripod	40	5	Yudin
West of Duddon Sands	2013	GB	389	Monopile	108	3,6	Pacific Orca & Sea installer
Amrumbank West	2014	DE	288	Monopile	80	3,6	Svanen
Baltic 2 jackets	2014	DE	147,6	Jacket	41	3,6	Taklift 4
Baltic 2 Monopiles	2014	DE	140,4	Monopile	39	3,6	Svanen
Borkum Riffgrund I MP	2014	DE	308	Monopile	77	4	Pacific Orca
Borkum Riffgrund I SB	2014	DE	4	Suction bucket	1	4	Pacific Orca
Butendiek	2014	DE	288	Monopile	80	3,6	Svanen
DanTysk	2014	DE	288	Monopile	80	3,6	Seafox 5
Luchterduinen	2014	NL	129	Monopile	43	3	Aeolus
Westermost Rough	2014	GB	210	Monopile	35	6	Innovation
Gemini	2015	NL	600	Monopile	150	4	Aeolus & Pacific Osprey
Gode wind 1	2015	DE	330	Monopile	55	6	Innovation
Gode wind 2	2015	DE	252	Monopile	42	6	Innovation
Kentish Flats 2 Ext.	2015	GB	49,5	Monopile	30	3,3	Neptune
Sandbank	2015	DE	288	Monopile	72	4	Pacific Orca
Westermeerwind	2015	NL	144	Monopile	48	3	Schelde
Burbo bank ext.	2016	GB	258	Monopile	32	8	Svanen
Dudgeon east	2016	GB	402	Monopile	67	6	Strashnov
Galloper	2016	GB	353	Monopile	56	6,3	Innovation
Nobelwind	2016	BE	165	Monopile	50	3,3	Vole au Vent
Nordergrunde	2016	DE	110,7	Monopile	18	6	Victoria Mathias
Nordsee One	2016	DE	332	Monopile	54	6,15	Innovation
Race bank	2016	GB	573	Monopile	91	6	Innovation
Rampion	2016	GB	400	Monopile	117	3,45	Pacific Orca & MPI Discovery
Veja mate	2016	DE	402	Monopile	67	6	Scylla
Wikinger	2016	DE	350	Jacket	70	5	Taklift 4
Arkona	2017	DE	385	Monopile	60	6	Svanen
Beatrice	2017	GB	588	Jacket	84	7	Strashnov & Yudin
Blyth	2017	GB	41,5	Gravity based	5	8,4	
Floatgen demo	2017	FR	2	Floating	1	2	
Horns Rev 3	2017	DK	400	Monopile	49	8,3	Innovation
Hywind Scotland	2017	GB	30	Floating	5	6	Saipem 7000
Merkur offshore	2017	DE	400	Monopile	66	6	Innovation
Nissum bredning	2017	DK	28	Jacket	4	7	Matador 3
Pori tahkoluoto 2	2017	FI	42	Gravity based	10	4,2	Vole au Vent
Rentel	2017	BE	309	Monopile	42	7,35	Innovation
Walney Extension	2017	GB	659	Monopile	87	8	Aeolus & Svanen
Borkum Riffgrund 2 MP	2018	DE	290	Monopile	36	8	Vole au Vent
Borkum Riffgrund 2 SB	2018	DE	160	Suction bucket	20	8	Innovation
Deutsche bucht MP	2018	DE	260,4	Monopile	31	8,4	Scylla
East Anglia 1	2018	GB	714	jacket	102	7	Bokalift 1
Elisa elican	2018	ES	5	Floating	1	5	
EnBW Albatros	2018	DE	112	Monopile	16	7	Innovation
EOWDC	2018	GB	92,4	Suction bucket	11	8,4	Asian Hercules 3
Hohe See	2018	DE	497	Monopile	71	7	Pacific Osprey & Innovation
Hornsea one	2018	GB	1200	Monopile	174	7	Innovation
Kincardine pilot	2018	GB	2	Floating	1	2	
Norther	2018	BE	370	Monopile	44	8,4	Aeolus
Trianel Borkum 2	2018	DE	202,56	Monopile	32	6,33	Yudin

	Year first foundation	Country	Wind farm Capacity (MW)	Foundation type	No. turbines	Turbine (MW)	Vessel lift & foundation install
Borssele 3&4	2019	NL	731,5	Monopile	77	9,5	Aeolus
Formosa 1	2019	TW	128	Monopile	20	8	Yudin
Northwester 2	2019	BE	219	Monopile	23	9,5	Vole au Vent
Seamade	2019	BE	487	Monopile	58	8,4	Innovation
Windfloat Atlantic 1	2019	PT	25	Floating	3	8,4	
Borssele 1&2	2020	NL	752	Monopile	94	8	Innovation
Borssele 5	2020	NL	19	Monopile	2	9,5	Aeolus
Fryslan	2020	NL	382,7	Monopile	89	4,3	Sarens Soccerpitch
Hornsea two	2020	GB	1386	Monopile	165	8	Innovation & Pacific Orca
Kincardine	2020	GB	49,625	Floating	5	9,5	
Kriegers flak	2020	DK	600	Monopile	72	8,4	Svanen
Moray East	2020	GB	950	Jacket	100	9,5	Scylla
Triton Knoll	2020	GB	857	Monopile	90	9,5	Innovation & Strashnov
Yunlin	2020	TW	640	Monopile	80	8	Sapura 3500
Akita Noshiro	2021	JP	140	Monopile	33	4,2	Seajack Zaratan
Changfang & Xidao	2021	TW	382,7	Jacket	62	9,5	Bokalift 2
HKZ 1 & 2	2021	NL	770	Monopile	70	10	Strashnov
HKZ 3 & 4	2021	NL	770	Monopile	69	11	Strashnov
Saint-Nazaire	2021	FR	480	Monopile	80	6	Innovation
Seagreen	2021	GB	1100	Suction bucket	114	10	Saipem 7000
TetraSpar Demo	2021	NO	3,6	Floating	1	3,6	
Arcadis Ost 1	2022	DE	257	Monopile	27	9,5	Orion
Changua 1 and 2A	2022	TW	900	Jacket	111	8	Aegir
Dogger Bank phase A	2022	GB	1200	Monopile	95	12	Innovation
Fecamp	2022	FR	500	Gravity based	71	7	Sleipnir
Formosa 2	2022	TW	367	Jacket	47	8	Yudin
HKN	2022	NL	759	Monopile	69	11	Innovation
Hywind Tampen	2022	NO	94,6	Floating	11	8,6	
Kaskasi	2022	DE	342	Monopile	38	9	Blue tern + Neptune & Strashnov
Neart na Gaoithe	2022	GB	450	Jacket	54	8	Balder & Thialf
Saint Brieuc	2022	FR	496	Jacket	62	8	Borealis
Taranto (Beleolico)	2022	IT	30	Monopile	10	3	MPI Resolution
Batlic Eagle	2023	DE	476	Monopile	50	9,5	Svanen
Borkum Riffgrund 3	2023	DE	913	Monopile	83	11	Les Alizes
DemoSATH (BIMEP)	2023	ES	2	Floating	1	2	
Gode wind 3	2023	DE	253	Monopile	23	11	Les Alizes
Jeonnam	2023	KR	99	Monopile	10	9,9	
Nyuzen	2023	JP	9	Monopile	3	3	Blue wind
Provence grand large	2023	FR	25	Floating	3	8,4	
South Fork	2023	US	130	Monopile	12	11	Bokalift 2
Vesterhav nord	2023	DK	176	Monopile	21	8,4	Innovation
Vesterhav syd	2023	DK	168	Monopile	20	8,4	Innovation
Vineyard	2023	US	488	Monopile	47	13	Orion
Zhong Neng	2023	TW	882	Jacket	31	9,6	Green Jade
Calvados	2024	FR	450	Monopile	64	7	Vole au Vent
Coastal Virginia	2024	US	2600	Monopile	176	14	Orion
Dogger Bank phase B	2024	GB	1200	Monopile	95	13	Strashnov
Hai Long 2 & 3	2024	TW	1042	Jacket	73	14	Green Jade
He Dreiht	2024	DE	960	Monopile	64	15	Thialf
Îles d'Yeu et Noirmoutier	2024	FR	488	Monopile	61	8	Innovation
Moray West	2024	GB	882	Monopile	60	14,7	Orion & Bokalift 2
Revolution Wind	2024	US	704	Monopile	66	11	Bokalift 2
Sofia	2024	GB	1400	Monopile	100	14	Aeolus

C
Vessel database

Vessel type	**Year built**	**Vessel name**	**Length**	**Beam**	**Lifting capacity [mt]**	**Lifting height (m)**	**Deck m2**	**Load cap.**	**Anchor system**	**max depth**	**Leg length**
SSCV	1978	Balder	154	105	6300				DP3		
Sheerleg	1981	Taklift 4	83,2	36,9	2200						
SSCV	1985	Thialf	201,6	88,4	14200						
SSCV	1987	Saipem 7000	197,95		14000		9000	15000			
Sheerleg	1990	Svanen	102,75		8700		2500				
HLV	1996	Yudin	183,3	36	2500	78,04	2560	5000			
Sheerleg	2000	Rambiz conversion	85	44	3300			900			
HLV	2003	Saipem 3000 upgrade	162	38	2400						
Jackup	2003	MPI Resolution	130	38	600		3200		DP2		70,49
Jackup	2008	Seaworker	55	32							
Jackup	2009	Goliath	59,6		400		1100				
HLV	2011	Strashnov	183	47	5000	102	3700	8500	DP3		
Jackup	2011	Friedrich Ernestine	100		1000					45	
Jackup	2011	MPI Adventure	138,55	40,8	1000		3600		DP2		70,62
Jackup	2011	MPI discovery	138,55	40,8	1000		3600				73,56
Jackup	2011	Taillevent	138,55	40,8	1000		3600	6000	DP2		
HLV	2012	Borealis	182	46	5000		730		DP3		
Jackup	2012	Neptune	60,25	38	600		2000	1600			80
Jackup	2012	Brave Tern	132	45	1600	157,5	3600	9000		60	
Jackup	2012	Sea Installer	132	46	1600			6000			92,5
Jackup	2012	Seafox 5 (Blue Tern)	151	49,98	1200	127	3750	7000		65	
Jackup	2012	Pacific Orca	160,9		1200				DP2		
Jackup	2012	Pacific Osprey	160,9		1200		4300		DP2		
Jackup	2012	Innovation	161		1500		3750			65	
Jackup	2013	Bold Tern (2) upgraded	132	39	1600	157,5	3200	9000	DP2	60	
Jackup	2013	Vole au vent	140,4	41	1500		3535	6500	DP2	50	90
Jackup	2013	Bold Tern	132	39	800		3200	9500	DP2	60	
OIV	2014	Aeolus	139,4	44,46					DP2		
Jackup	2015	Scylla	152,6	50	1500		4600				
Sheerleg	2015	Asian Hercules 3	106,42	52	5000	120					
HLV	2017	Bokalift 1	216	43	3000		6300	15000	DP2		
Jackup	2018	Apollo	89,32	42	800		2000	4500	DP2		106,6
OIV	2018	Aeolus upgrade 1	139,4	44,46	1600				DP2	45	
Sheerleg	2018	Gulliver	108	49	4000	78,5					
SSCV	2019	Sleipnir	220	102	20000		12000	20000	DP3		
HLV	2021	Bokalift 2	231	49	4000	103	7500		DP2		
HLV	2022	les Alizes	236,8	52	5000	125	9300				
Jackup	2022	Bold Tern upgraded	132	39	1600		3200	9500	DP2	60	
OIV	2023	Aeolus upgrade 2 crane	139,4	44,46	1600				DP2		
OIV	2024	Boreas	175,1	63	3200		7150		DP2		

Table C.1: Vessel data

D

Foundation and equipment database

D.1. Market evolution

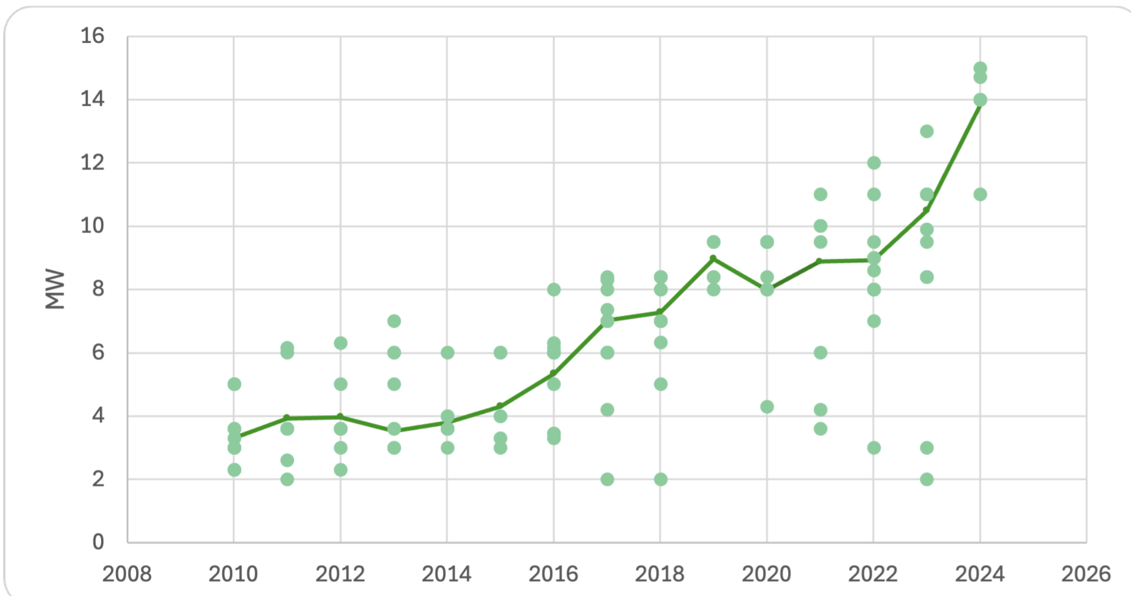

Figure D.1: Capacity (MW) of all offshore wind turbines installed between 2010 and 2024

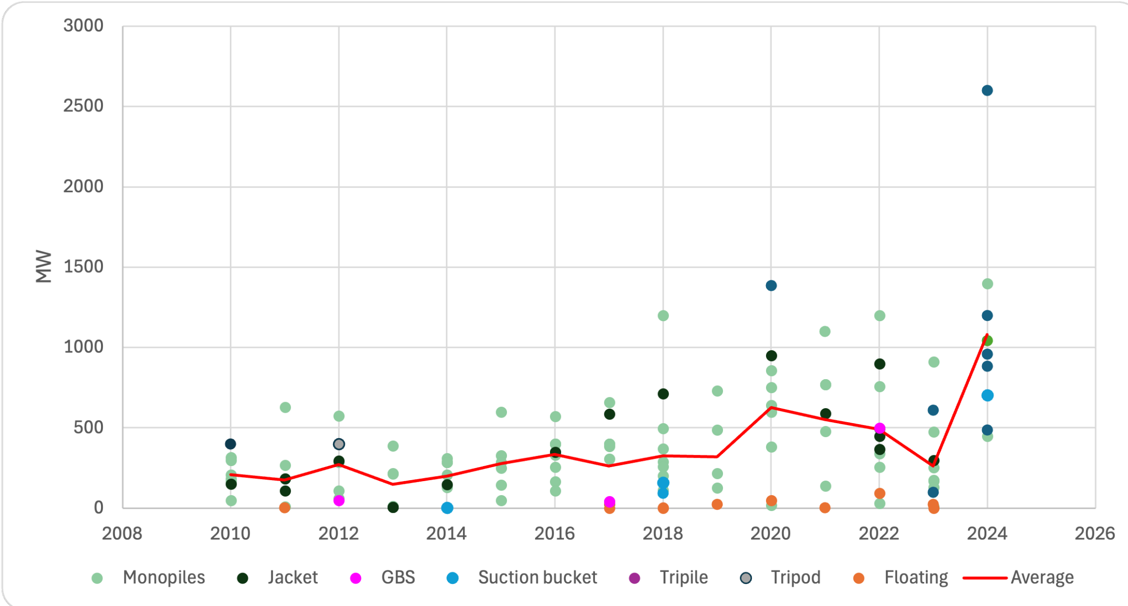

Figure D.2: Capacity of installed offshore wind farms from 2010 to 2024 per foundation type and the overall yearly average

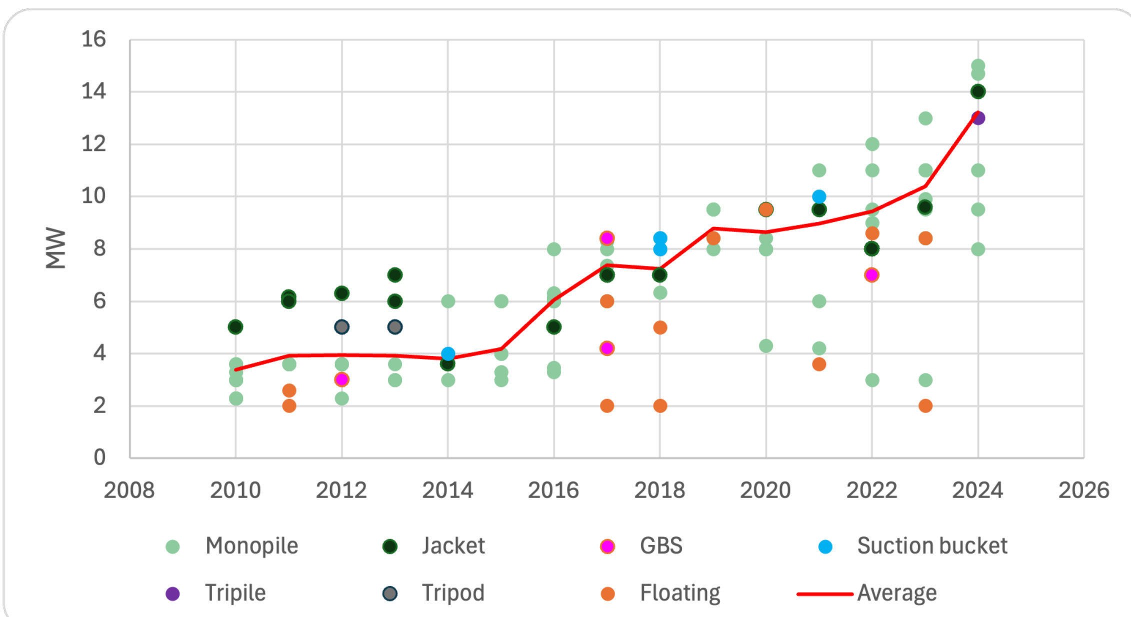

Figure D.3: Yearly developments in offshore wind turbine capacity (MW) installed between 2010 and 2024 per foundation type with the overall average

D.2. Monopile evolution

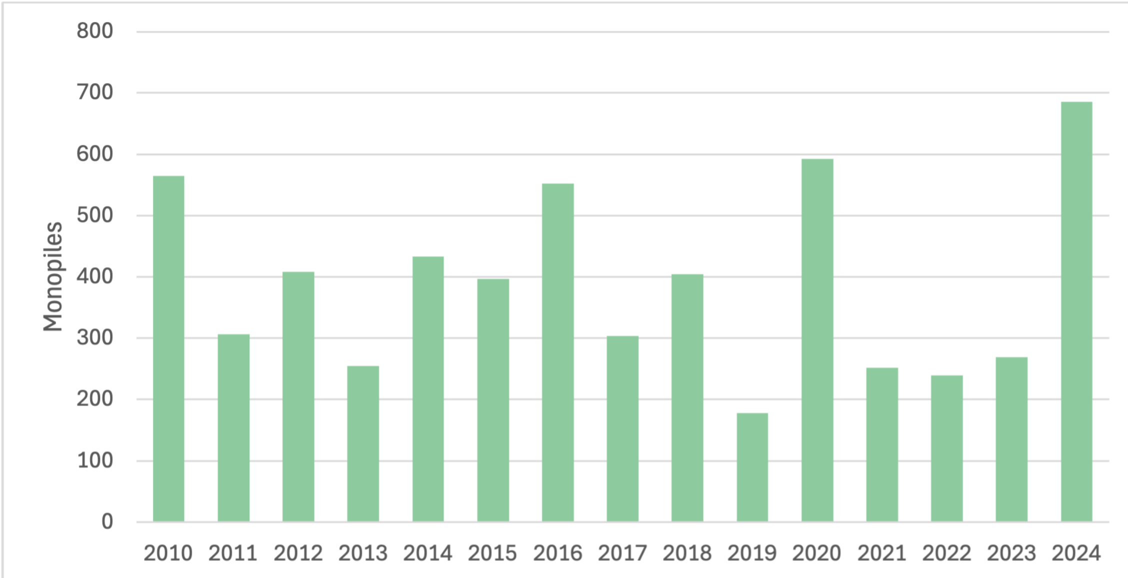

Figure D.4: Monopiles installed per year

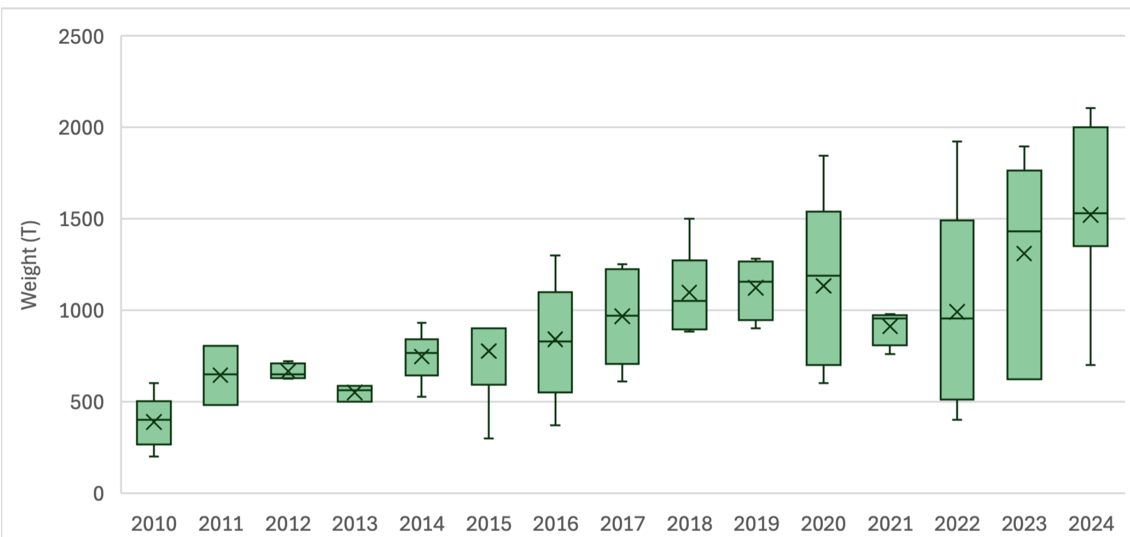

Figure D.5: Weight of monopile foundations used at offshore wind farms

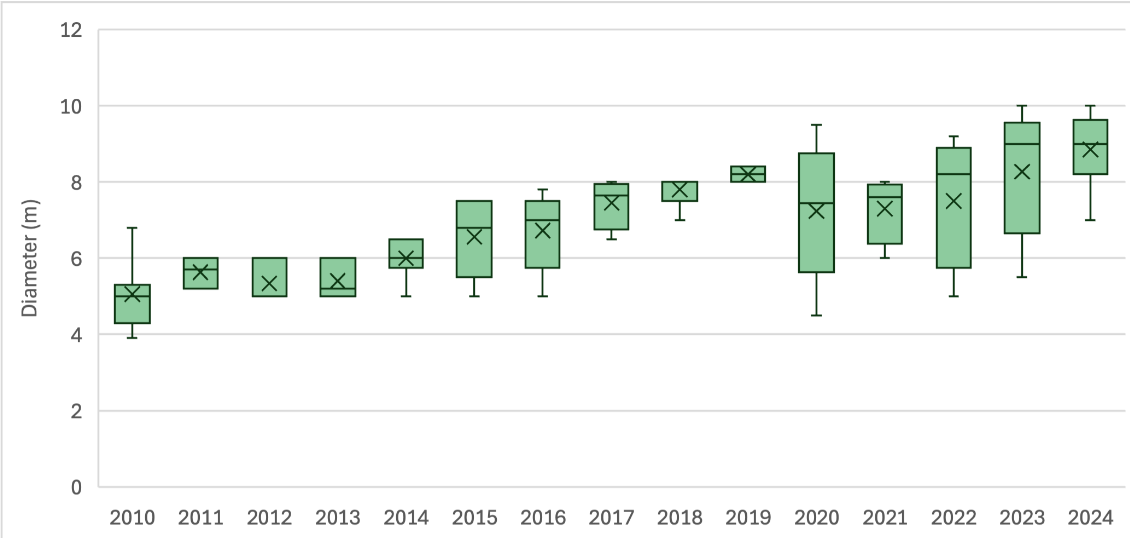

Figure D.6: Diameters of monopile foundations used at offshore wind farms

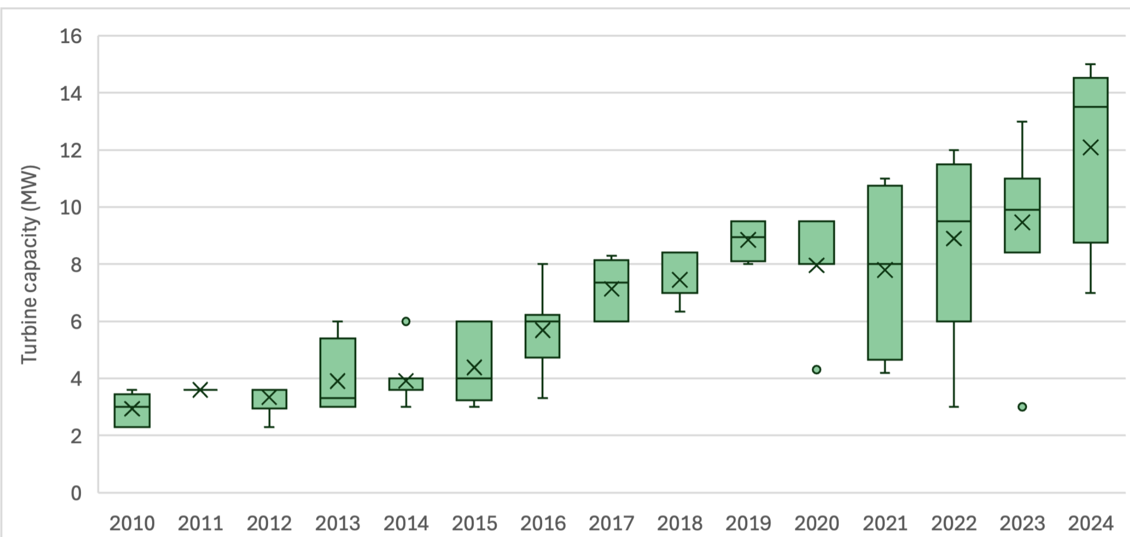

Figure D.7: Capacity evolution of offshore wind turbines that used monopile foundations

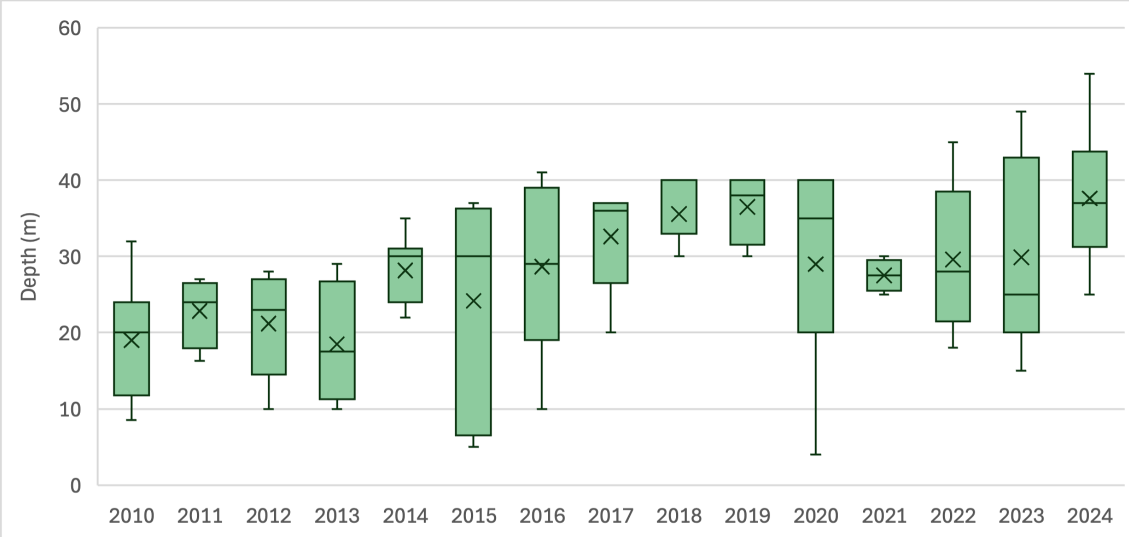

Figure D.8: Depths of offshore wind farms that used monopile foundations

D.3. Jackets evolution

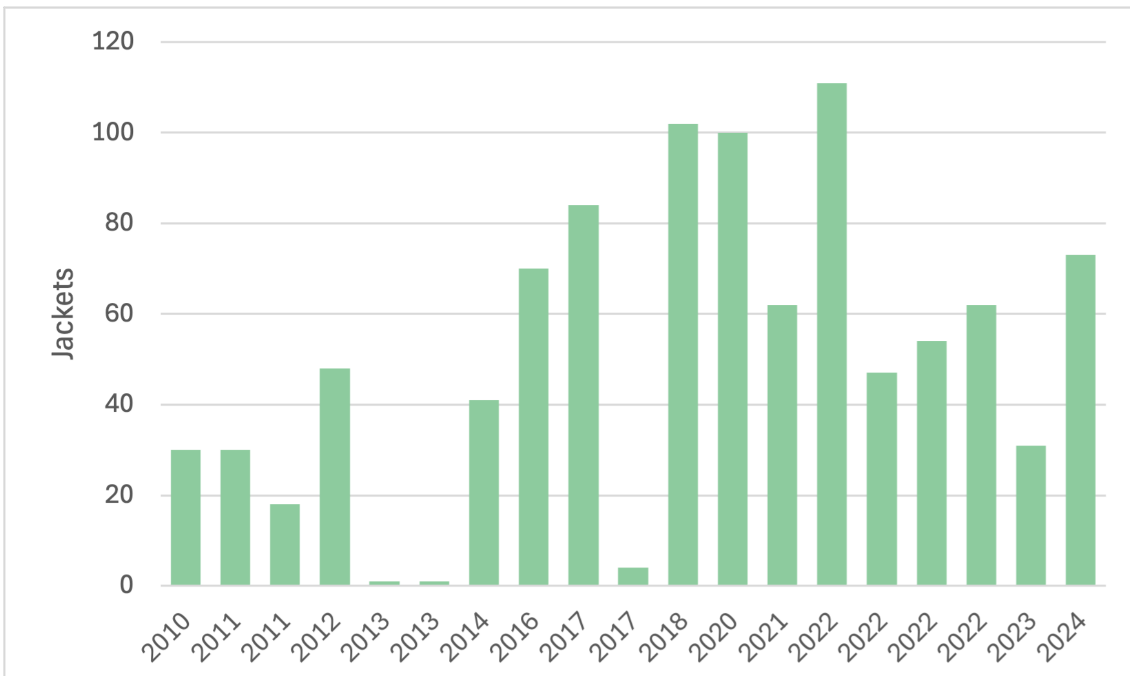

Figure D.9: Number of jacket foundations installed per year

Figure D.10: Number of jacket foundations per offshore wind farm that has been installed with jacket foundations

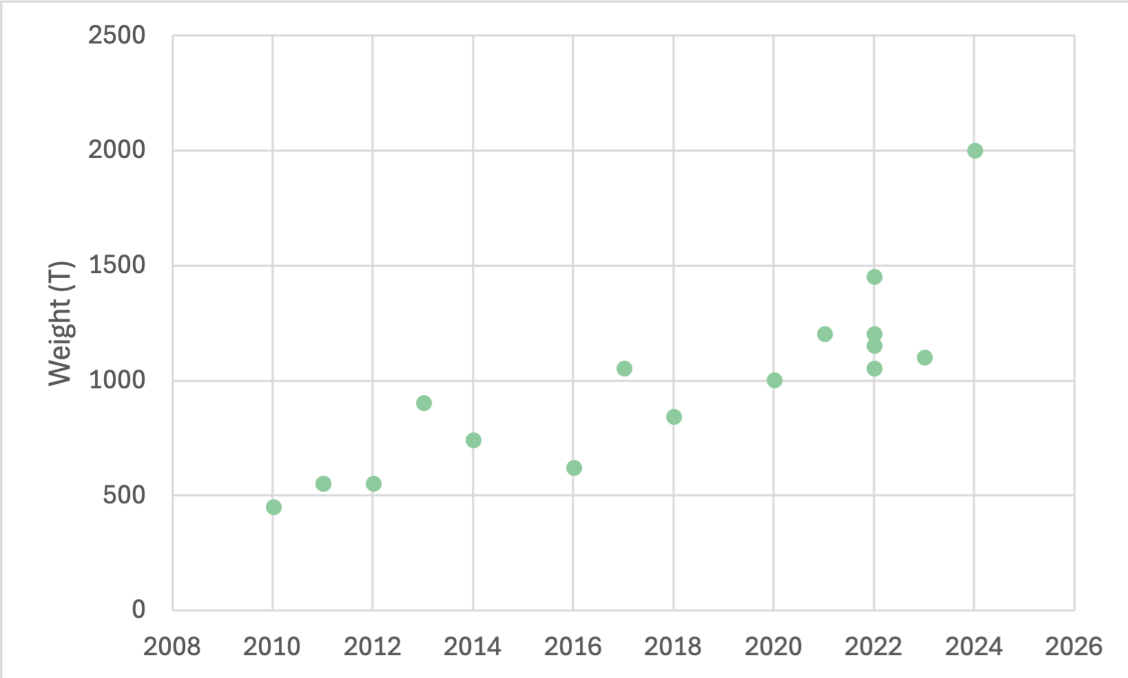

Figure D.11: Weight evolution of jacket foundations

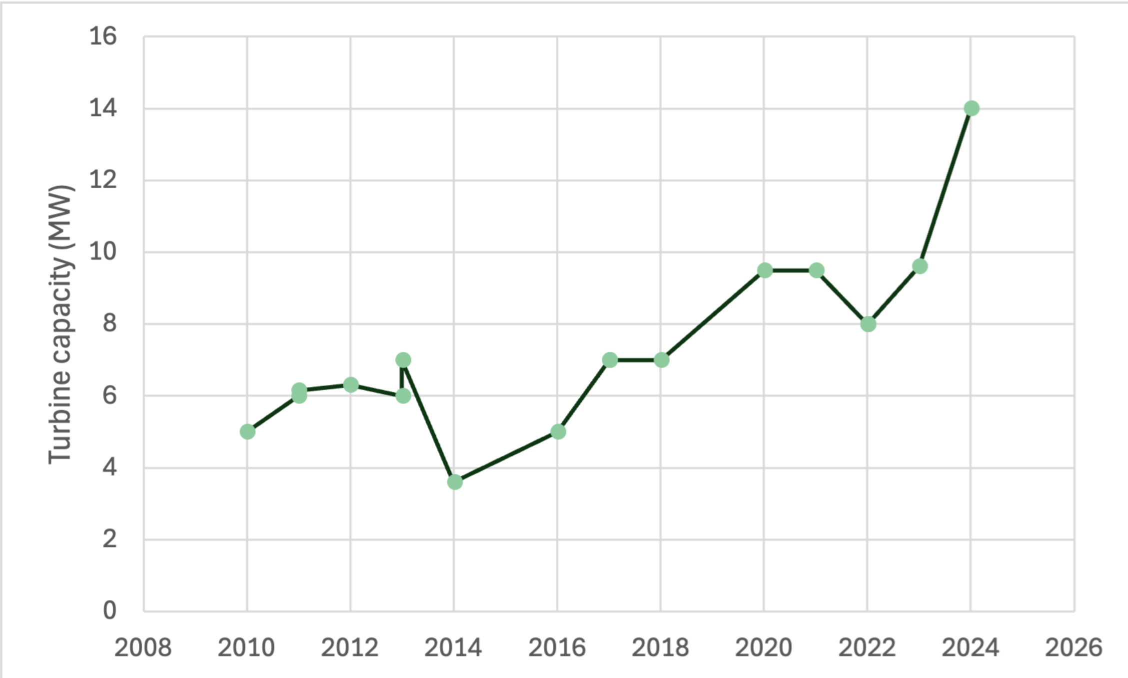

Figure D.12: Capacity evolution of offshore wind turbines that used jacket foundations

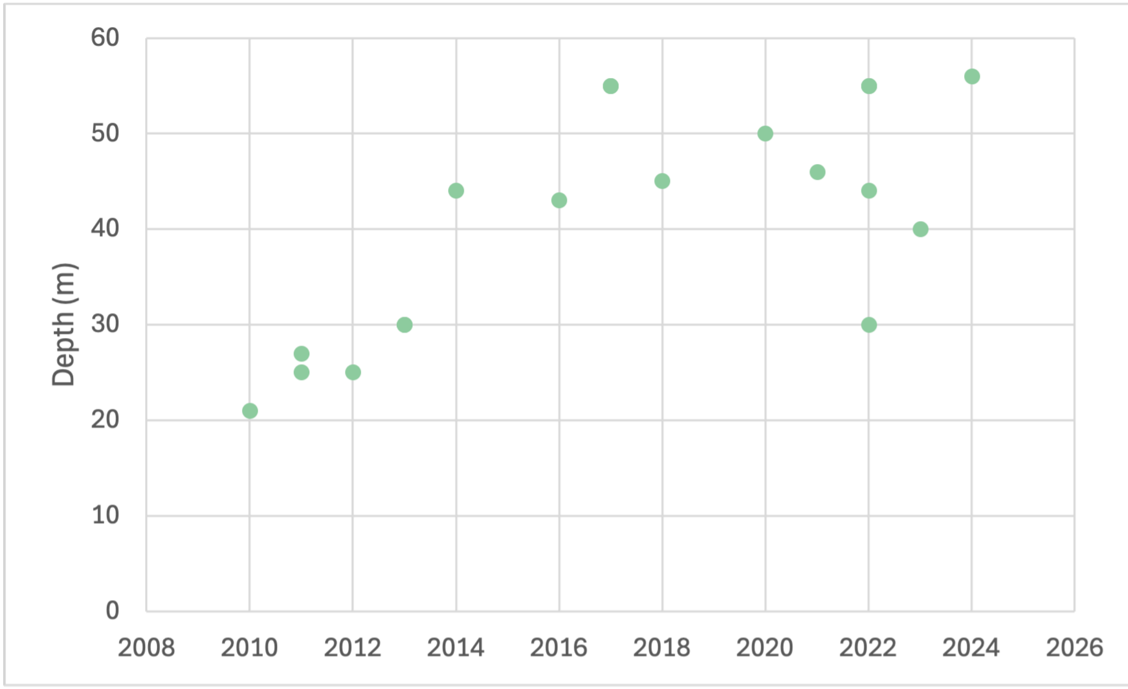

Figure D.13: Evolution of installation depths of jacket foundations

D.4. Evolution of gravity based foundations

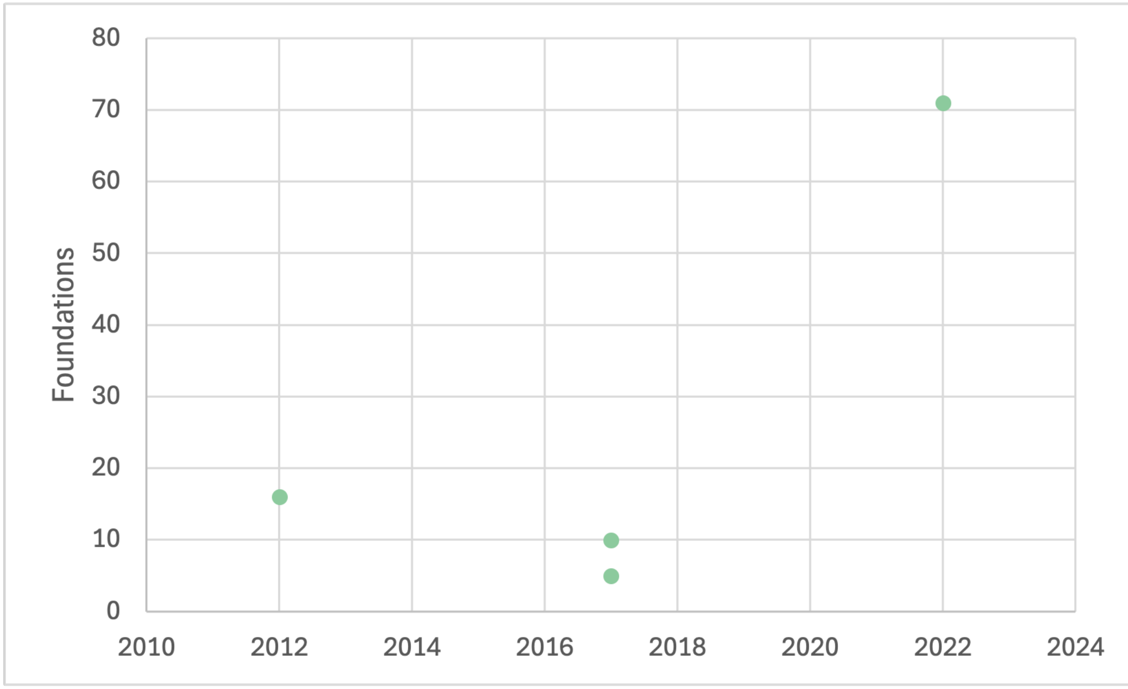

Figure D.14: Gravity based foundations installed per year

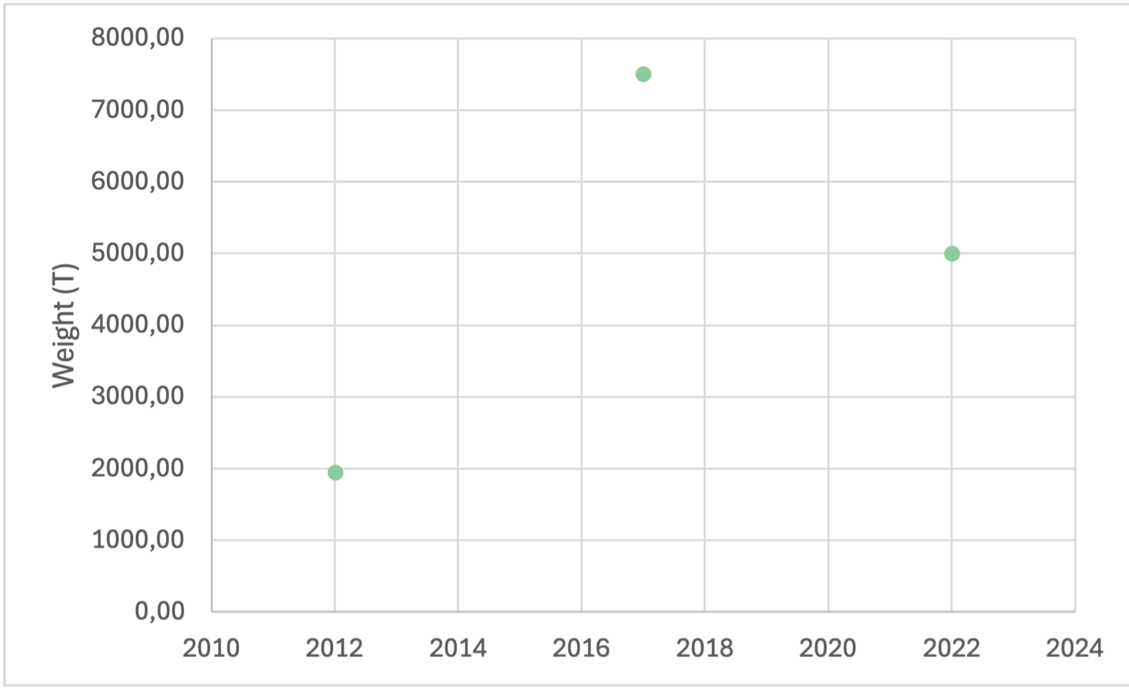

Figure D.15: Weight evolution of Gravity based foundations

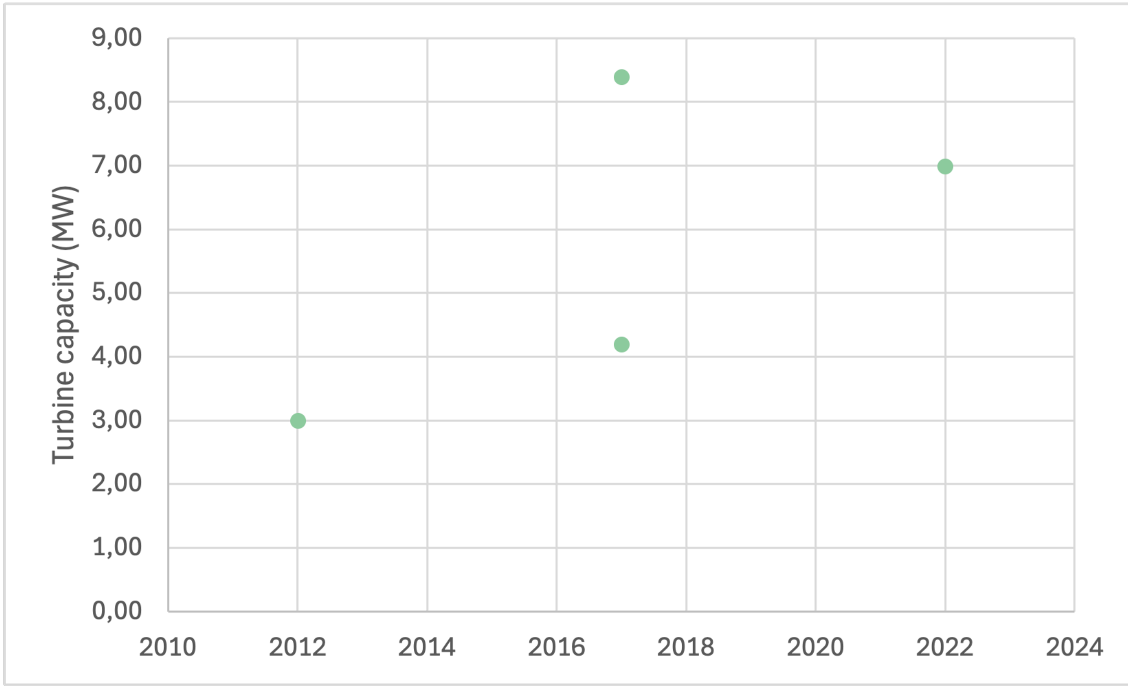

Figure D.16: Capacity evolution of offshore wind turbines that use gravity based foundations

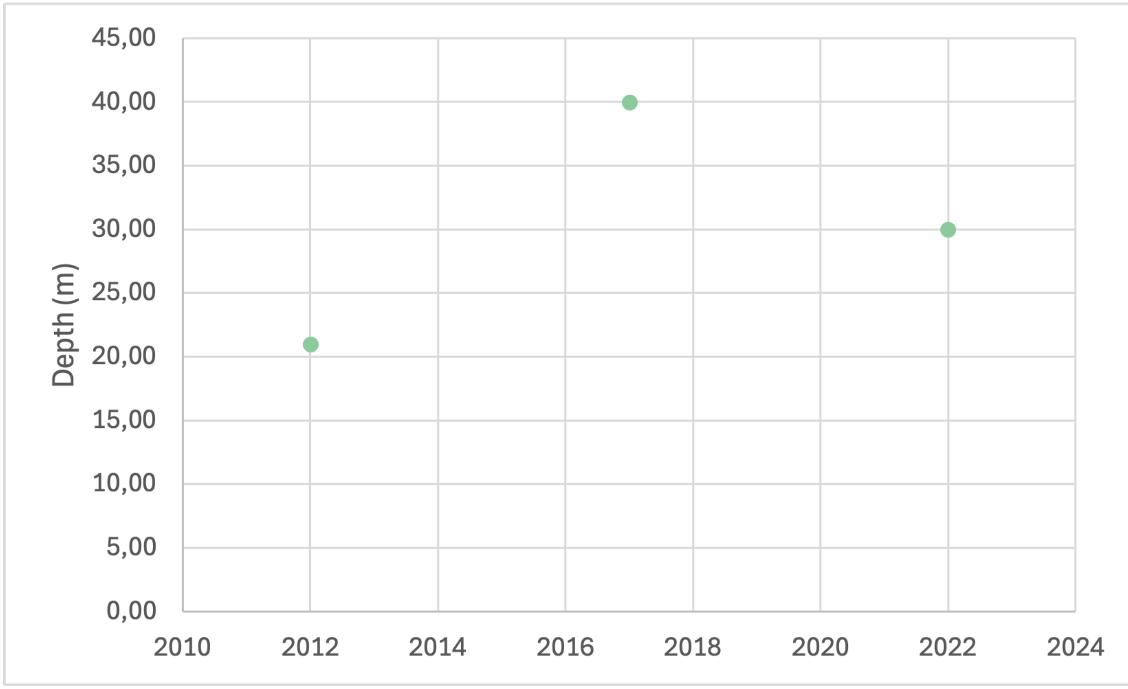

Figure D.17: Installation depths of offshore wind farms that use gravity based foundations

D.5. Equipment

	Power (kJ)	First use	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
S-280	280									Nissum Bredning							
MHU 300S	300																
S-500	500	2010	Ormonde														Kita Kyushu
MHU 550S	550									Blyth							
MHU 600B	600																
S-600	600																
MHU800S	800																
S-800	800	2011		Thornton Bank phase 2				Westermeer wind							Fecamp		
MHU 1200S	1200	2010	BARD		Global tech 1				Wikinger								
S-1200	1200	2010	Baltic 1				Baltic 2 jackets	Kentish flats 2 extension									
S-1400	1400	2010	Walney phase 1 + Sheringham Shoal		Global tech 1	Northwind + West of Duddon Sands	Luchterduinen		Nobelwind	Nissum Bredning			Fryslan	Changfang & Xidao	Taranto		
S-1800	1800	2010	Sheringham Shoal		Gwynty Mor				Nordergrunde								
MHU 1900S	1900	2010	BARD	Lincs		Humber Gateway					East Anglia one		Moray East				
S-2000	2000	2011		Walney phase 2		West of Duddon Sands	Borkum Riffgrund 1 MPs + Butendiek + DanTysk + Westermost Rough + Amrumbank west	Gemini + Gode Wind 1&2							Fecamp	Nyuzen + Vineyard	
S-2500	2500								Rampion								
IQ2	3000	2022													Kaskasi	Vesterhav Nord+Syd & Jeonnam	Hai Long 2&3
S-3000	3000	2016							Dudgeon East + Nordsee One + Race Bank	Horns Rev 3	Borkum Riffgrund 2 MPs + Albatros + Hohe See + Borkum 2	Northwester 2					
MHU 3500S	3500	2015						Sandbank	Burbo Bank extension + Rampion	Walney extension	Norther		Borssele 3&4 + Borssele 5 + Kriegers flak				
IQ4	4000	2022													Arcadis Ost 1 & HKN	Baltic Eagle + Vineyard	Moray West & Coastal Virginia & Sofia
S-4000	4000	2016							Galloper + Veja Mate	Arkona + Merkur + Rentel	Deutsche Bucht MPs + Hornsea One	Seamade	Borssele 1&2 + Hornsea two + Triton Knoll	Saint Nazaire			
IQ6	5500	2023														Borkum Riffgrund 3 & Gode Wind 3	

Figure D.18: Track record of hammers

E
Vessels used during the installation

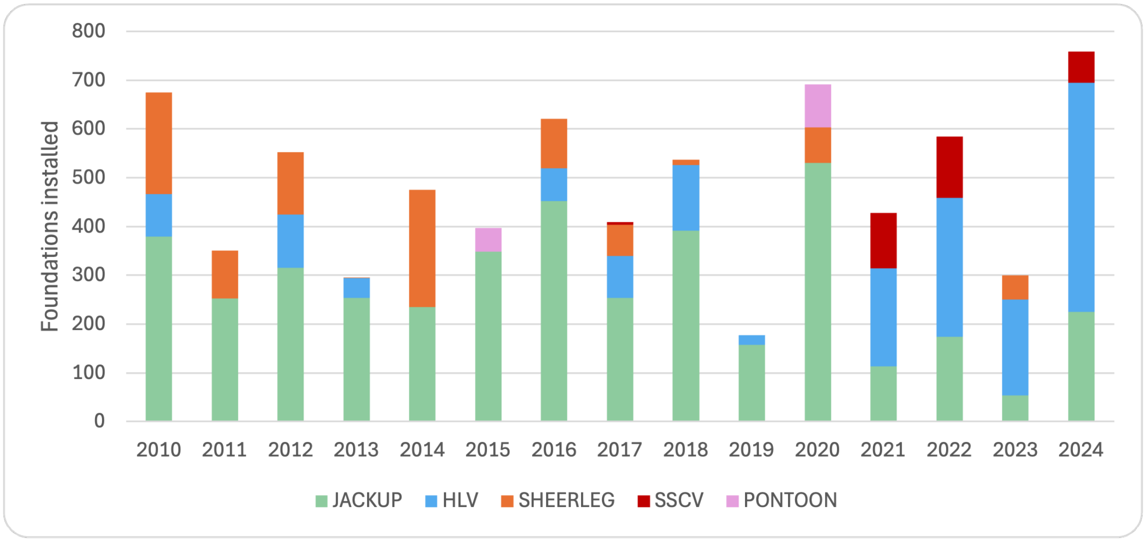

Figure E.1: Number of foundations installed by each different vessel type

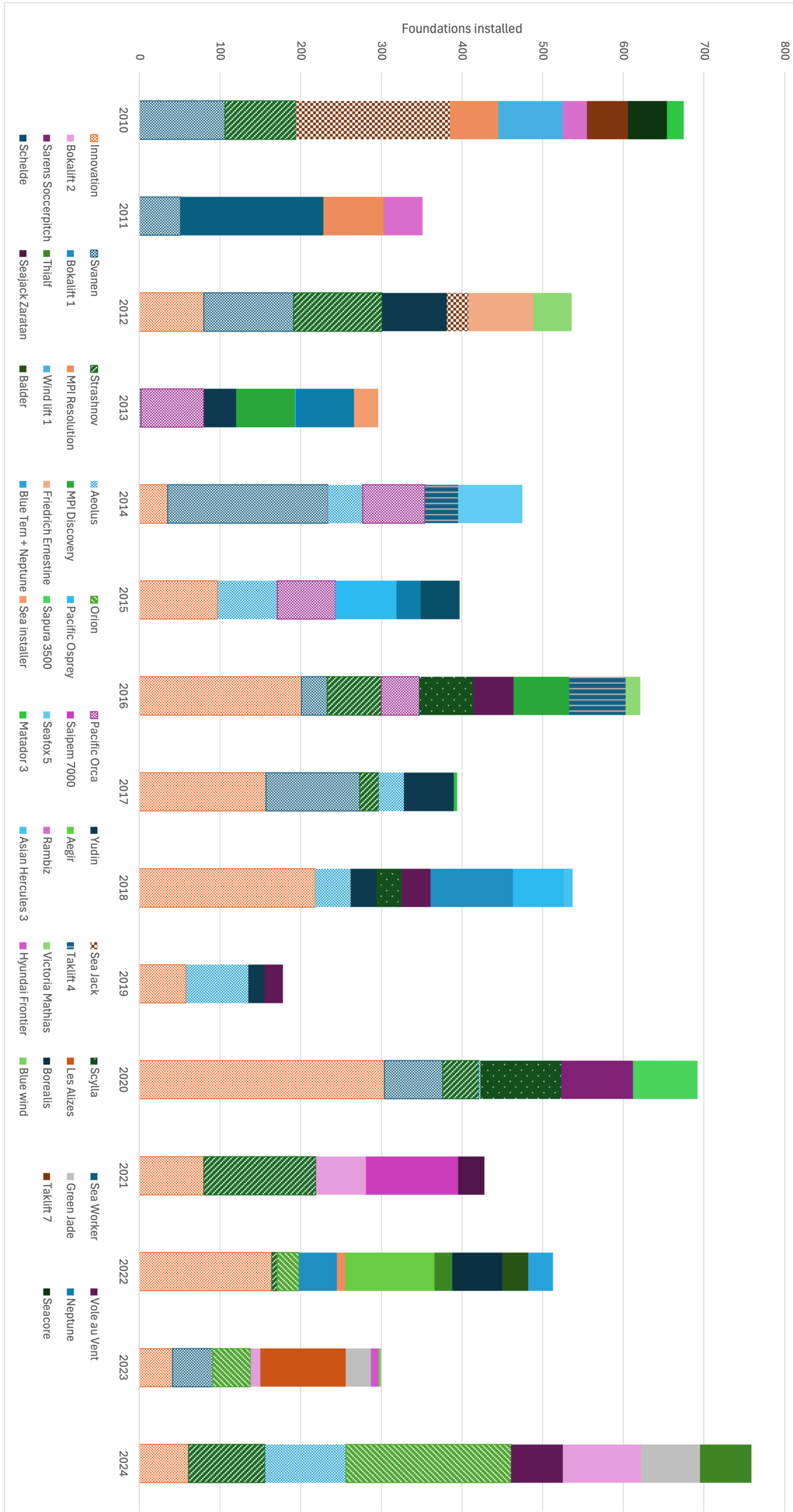

Figure E.2: Foundations installed per vessel

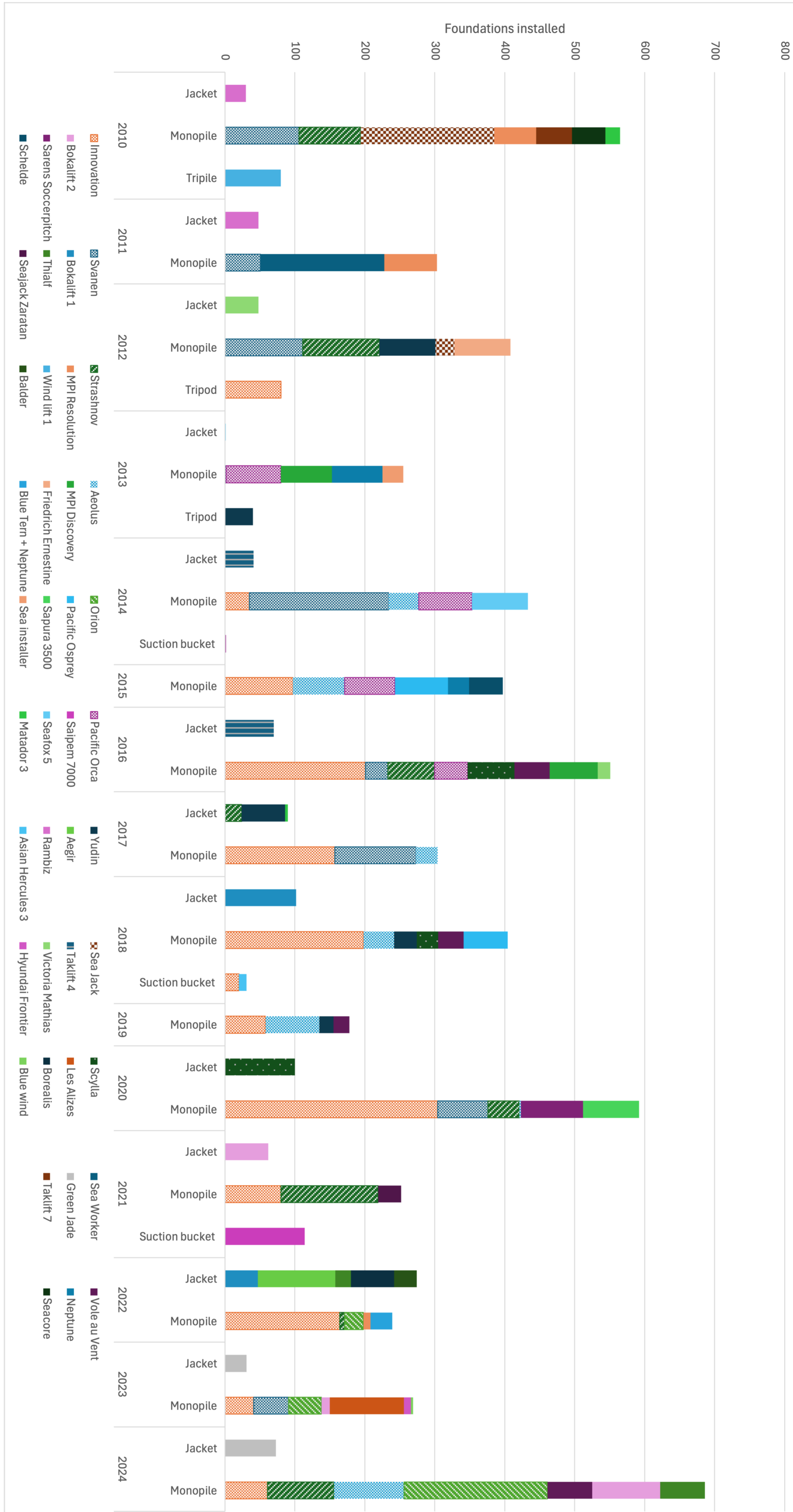

Figure E.3: Foundation types installed per vessel

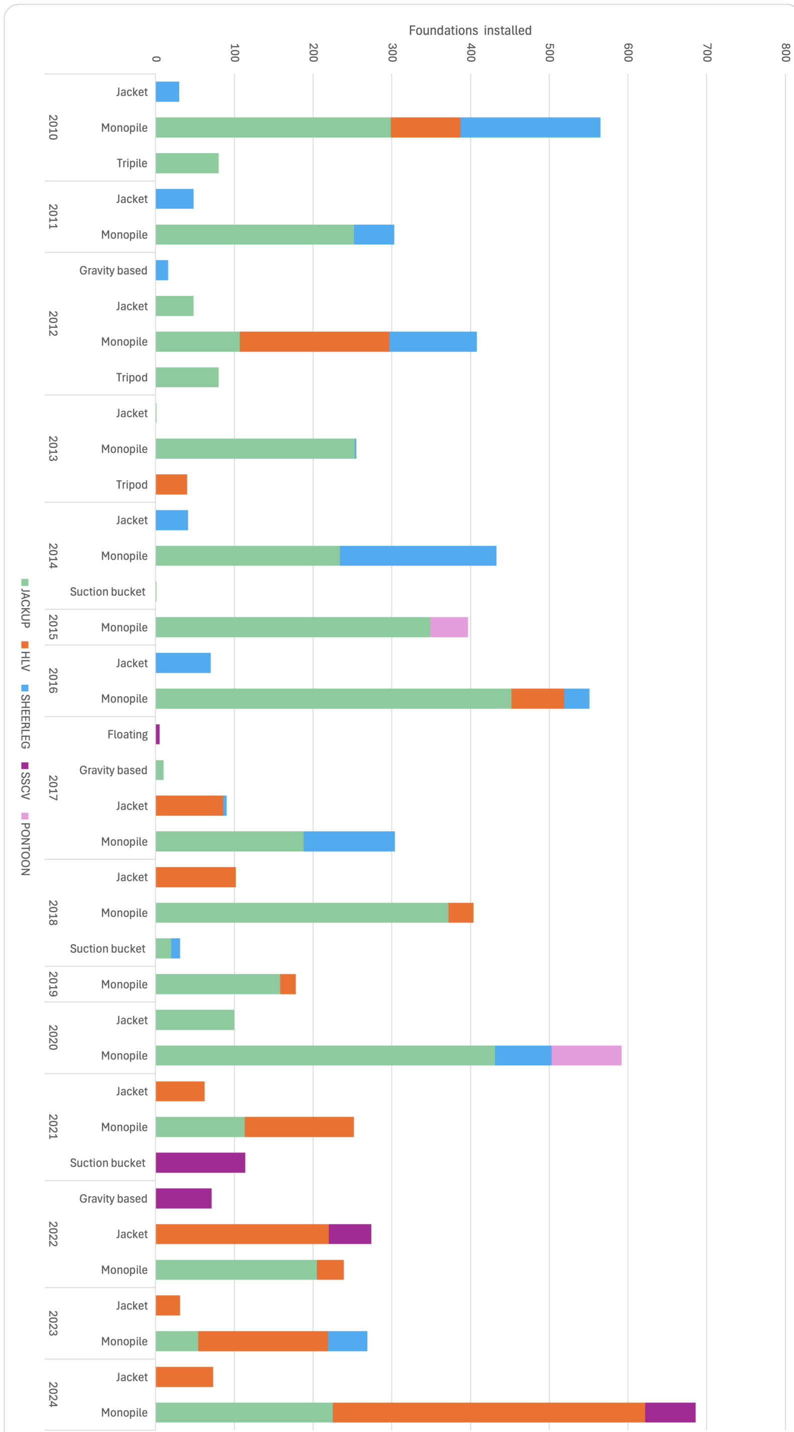

Figure E.4: Vessel types used for the installation of different foundation types

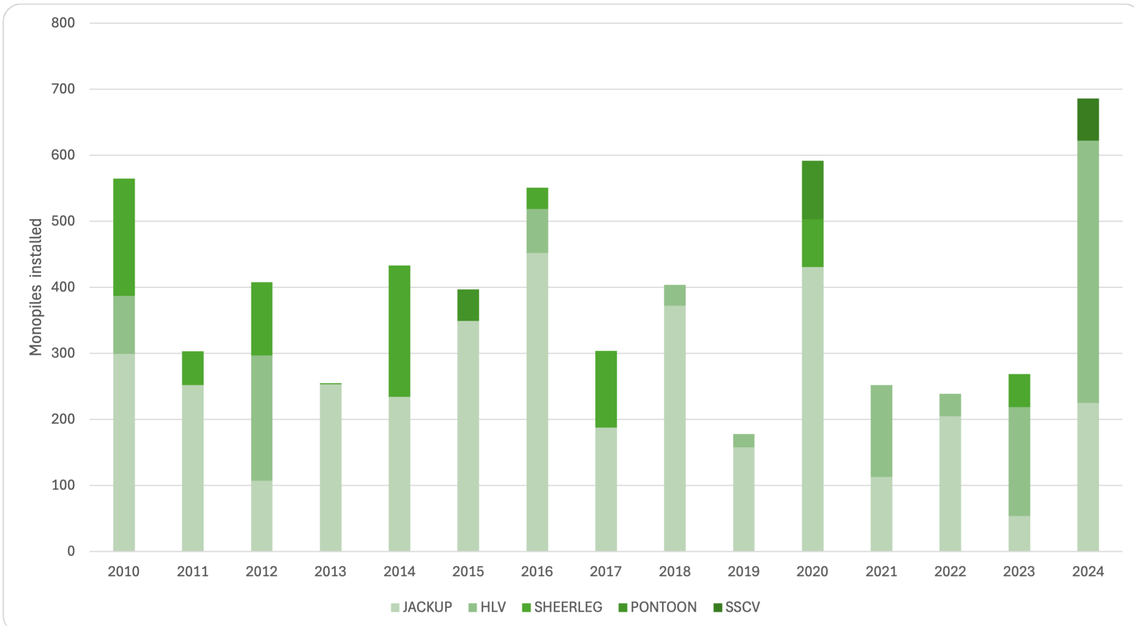

Figure E.5: Vessel type used for the installation of monopile foundations

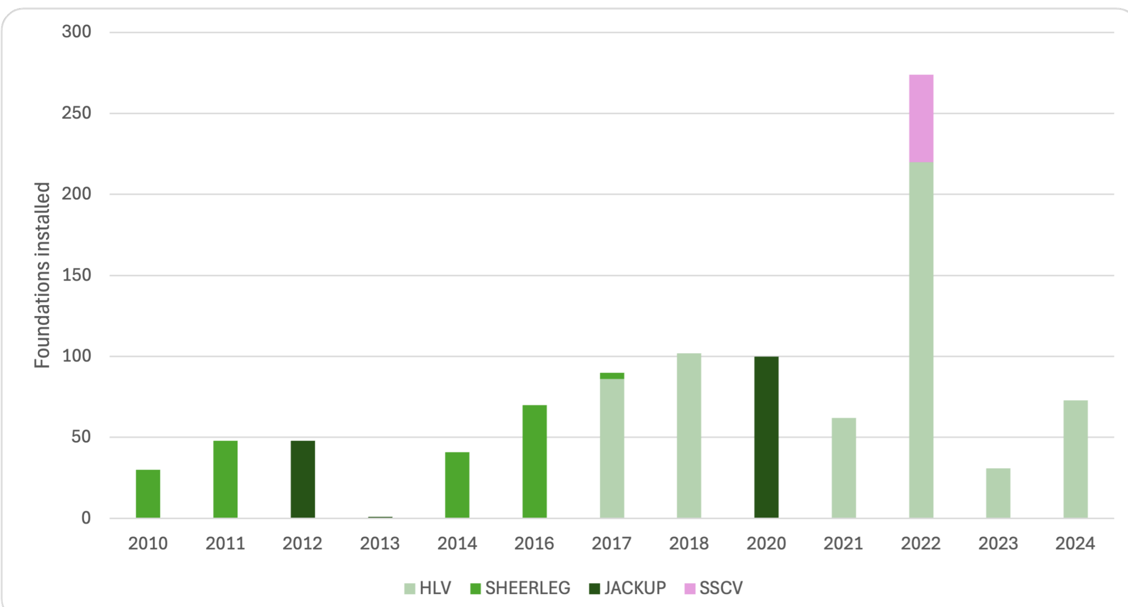

Figure E.6: Vessel types used for the installation of jacket foundations

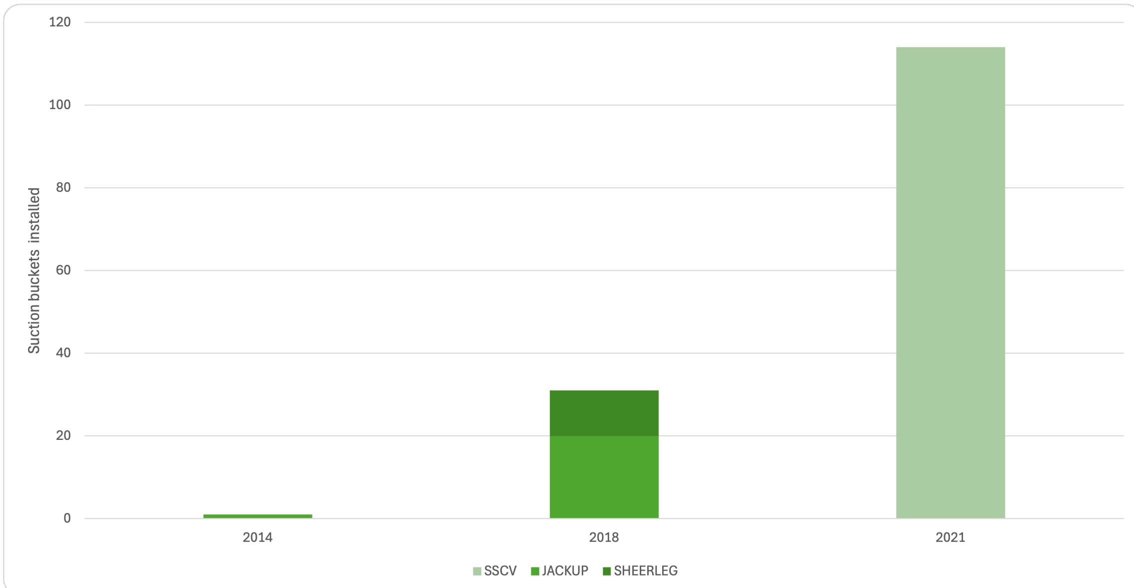

Figure E.7: Vessel type used for the installation of suction bucket foundations

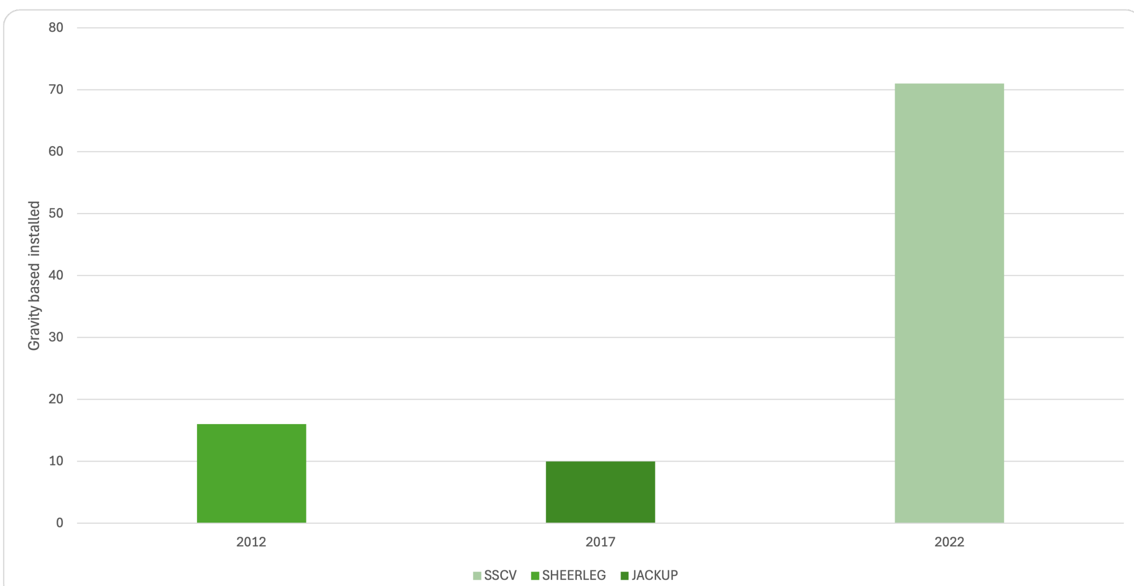

Figure E.8: Vessel type used for the installation of gravity based foundations

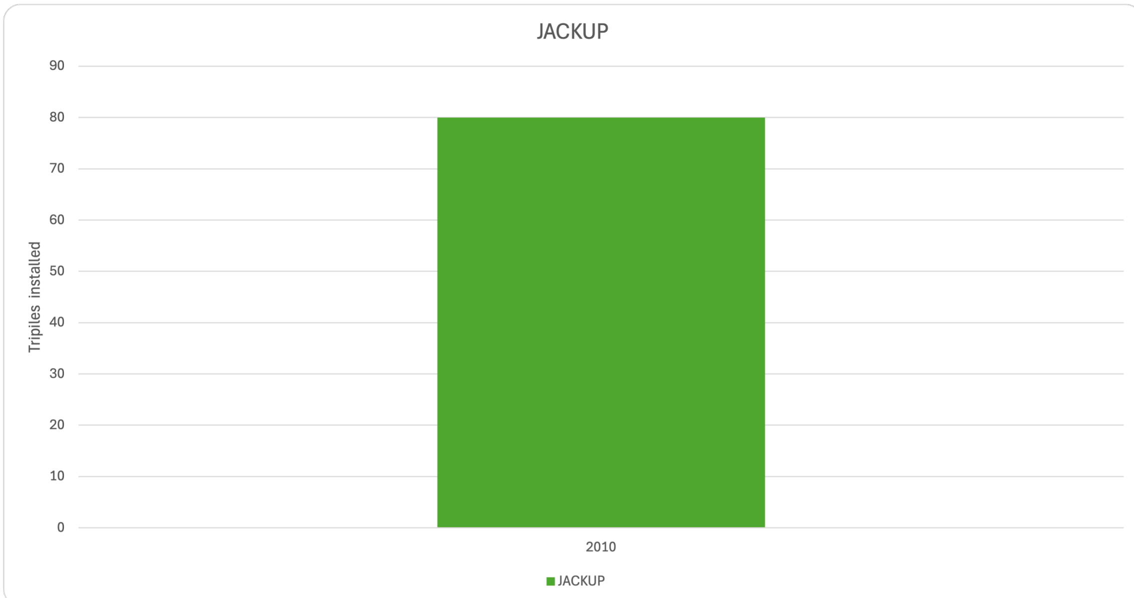

Figure E.9: Vessel types used for the installation of tripile foundations

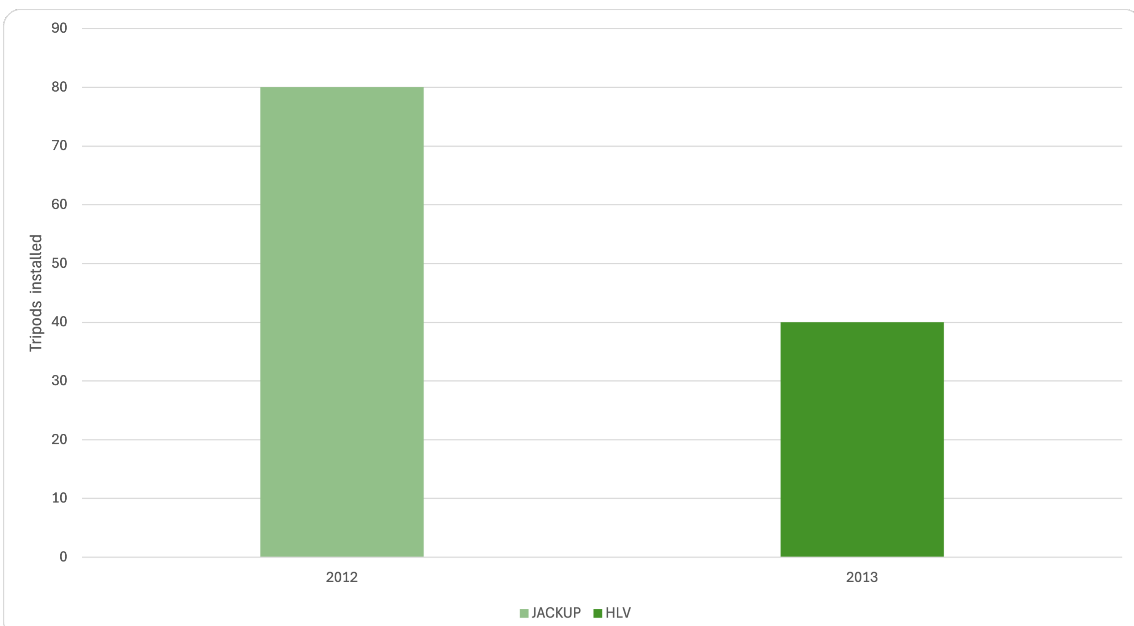

Figure E.10: Vessel type used for the installation of tripod foundations