POLITECNICO DI TORINO

Master of science program in Energy and Nuclear Engineering

Master thesis

Logistics and transportation study of floating wind farm foundations: analysis of challenges and consequences on project phases

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A.Y. 2024/2025

Abstract

Floating offshore wind is emerging as a key solution for expanding renewable energy generation in deep-sea areas and exploring locations far from shore and human activities corridors, where traditional fixed-bottom turbines are not technically feasible and interferences are minimized. Its scalability and high-capacity potential make it a strategic technology in the global energy transition. However, the development of such technology is complex and exposed to multiple risks, among which logistic and scheduling ones are highly critical.

The study focuses on a real-case scenario involving 35 floating wind turbines to be installed in the North Sea on an Italian EPCI contractor patented foundation. Two alternative transport approaches were evaluated: (1) shipping individual megablocks, i.e. foundations subparts, and (2) transporting fully pre-assembled floaters from East Asia to Europe. A technical assessment was conducted on vessel requirements, port infrastructure, and spatial constraints on temporary storage areas. Heavy transport vessel availability was analysed upon deck carriers and semi-submersible vessels market database. Furthermore, a study was performed through Gantt Charts to simulate the base case project schedule and various sensitivity analyses on transport vessels availability rather than different project phases delays.

The results show that transporting pre-assembled floaters reduces yard-side operations and accelerates installation readiness, but heavily relies upon a limited number of semi-submersible vessels, which are mandatory to cope with pre-assembled floaters scenario. In contrast, the megablocks option offers more flexibility in vessel sourcing but increases onshore complexity and exposure to schedule delay risks, due to an increased number of assembly operations. The sensitivity analysis, performed on the first option, shows that even minor disruptions can lead to a significant cumulative delay which may heavily affect the project overall schedule. Highlighting the importance of potential operational interferences risks and consequences.

The study pushes for the development of a structured decision-making framework for offshore wind logistics, emphasizing the importance of dynamic planning, port infrastructure readiness, and supply chain resilience as critical enablers for the scalable deployment of floating wind technologies.

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1 Introduction

1.1 Global Energy

Today, energy is a vital component of modern society, maintaining its long-standing role in driving development and progress. As shown in the graph below [2], global total primary energy demand is projected to increase by 11% by 2050, according to the Continued Momentum scenario. This increment is primarily driven by the growing demand in emerging economies, which is linked to population growth and economic development, leading to greater affluence and higher living standards. The main actor is India, indeed, it has the highest Compound Annual Growth Rate (CAGR). In contrast, North America and Organization for Economic Cooperation and Development (OECD) Europe and Asia-Pacific countries are expected to reduce their energy demand due to higher energy efficiency.

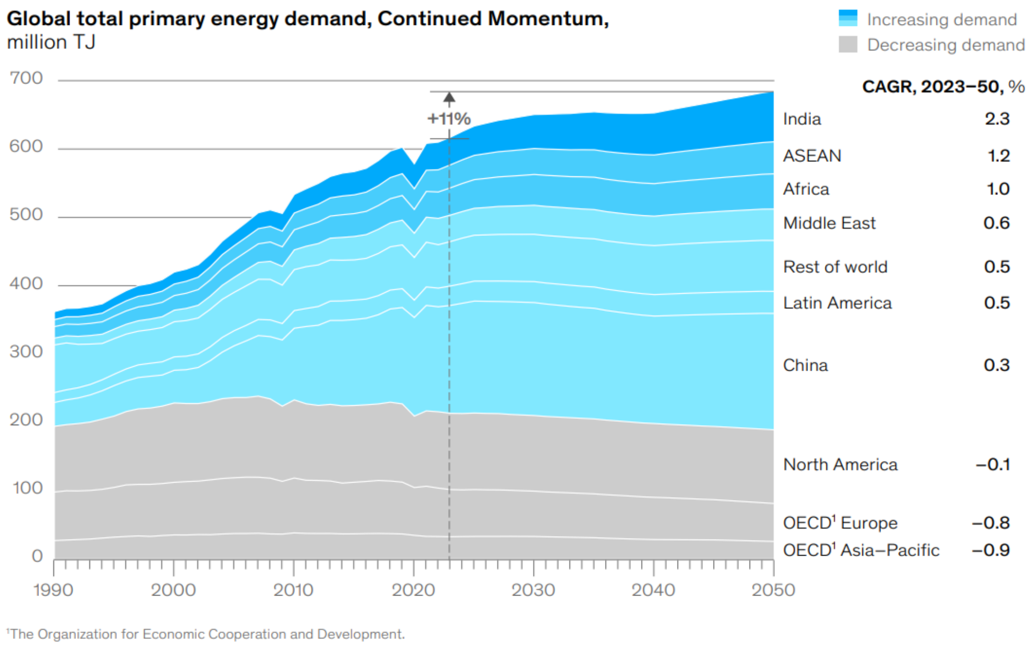


Figure 1: Global Energy demand

Energy efficiency is closely linked to energy intensity, an important parameter to consider in global analyses, measured in megajoules per capita (MJ/cap). Lower energy intensity indicates that a country can produce the same amount of goods and services with less energy, reflecting higher energy efficiency.

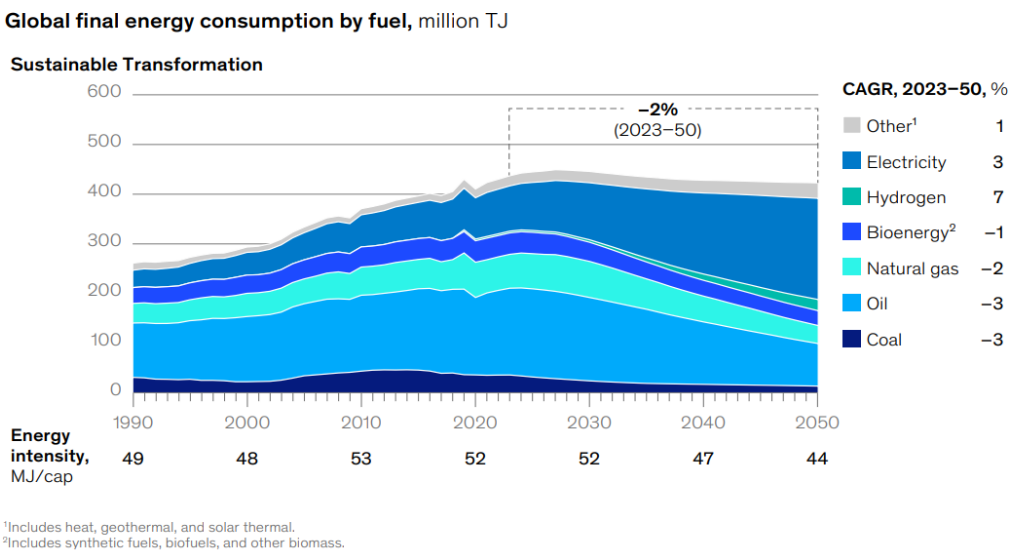


Figure 2: Global energy intensity

As can be seen in the graph above [2], a sustainable transformation can lead to a significant decrease in energy intensity. Whereas, in the Continued Momentum or in Slow Evolution scenarios energy intensity is projected to increase. In order to achieve the first scenario objectives, electricity plays a central role and it is expected to dominate the energy mix by 2050. This is because electricity can be efficiently produced with renewable resources such as wind and sunlight through technologies like wind turbines and photovoltaic panels. Considering the histogram below [2], the share of renewables is projected to double and, in particular, in the Continued Momentum scenario the source with the highest CAGR is offshore wind, followed closely by solar and onshore wind. This growth is primarily supported by government decarbonization targets and driven by new demand for virtually limitless clean energy.

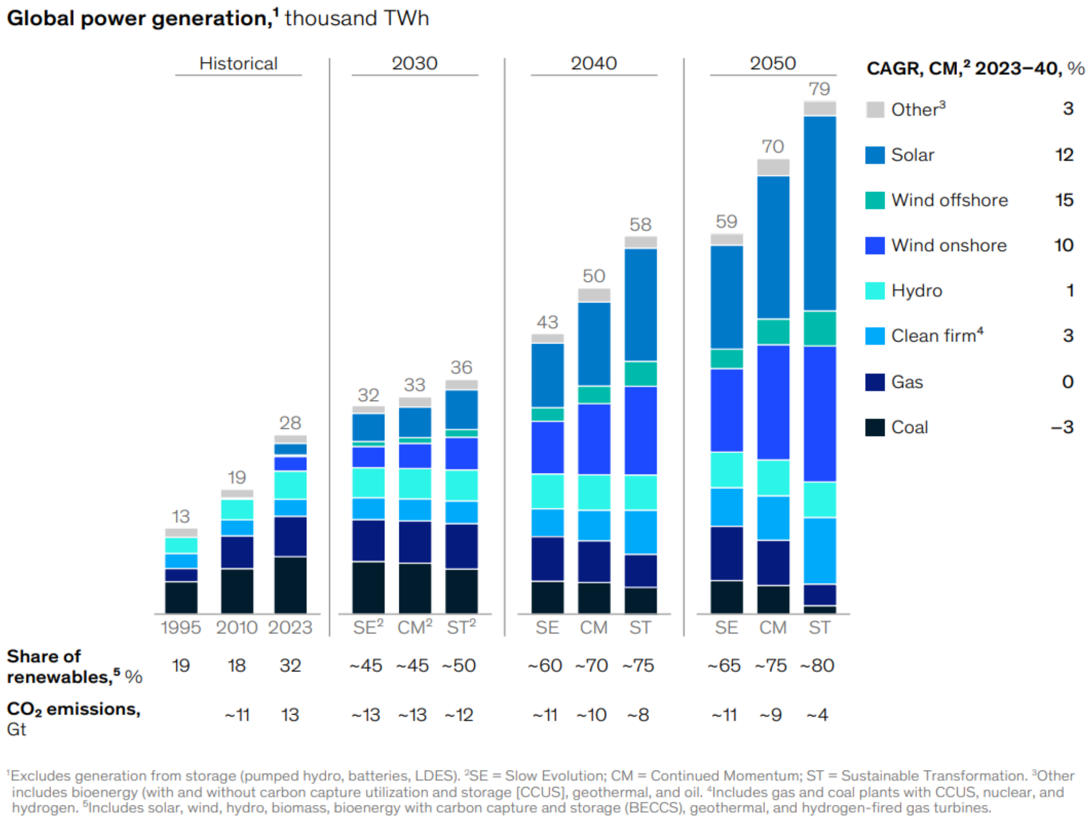


Figure 3: Global power generation

1.2 A sustainable future

On September 25, 2015, all 193 states of the United Nations subscribed to the Sustainable Development Goals (SDGs), also known as 17 Global Goals. This action plan has been a universal call to action to end poverty, protect the planet, and ensur that by 2030 all people enjoy peace and prosperity [3]. In particular, Goal 7 "Affordable and clean energy" can plays a crucial role. It is divided into 5 main targets, which have to be completed by 2030 [4]:

1) ensure universal access to affordable, reliable and modern energy services;

2) increase substantially the share of renewable energy in the global energy mix;

3) double the global rate of improvement in energy efficiency;

4) enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology;

5) expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programs of support.

On November 4, 2016, entered into force the Paris Agreement. Its goal is to hold the increase of the global average temperature to well below 2 ° C above preindustrial levels and to pursue efforts to limit the temperature increase to 1.5 ° C above preindustrial levels [5].
In 2019, the EU re-examined its energy policy framework with the scope to move from fossil fuels to cleaner energy. Specifically to meet the commitments of the Paris Agreement of the EU to reduce greenhouse gas emissions [6].
Starting from December 11, 2019, European Union adopted a new strategy, called Green Deal, to achieve climate neutrality by 2050. In 2023 a new industrial plan has been added to support the transition to the Net Zero era. Today, the aim of the Green Deal is to ensure that:

- no net emissions of greenhouse gases by 2050;
- economic growth decoupled from resource use
- no person and no place left behind

The real novelty is that the goal set out in the European Green Deal has been enshrined in the European Climate Law. This marks the first time the EU has legally bound itself to climate laws, in this way can be ensure that all EU policies contribute to this goal and that all sectors of the economy and society play their part [7]. To achieve the EU's energy and climate targets for 2030, member countries must develop a 10-year integrated National Energy and Climate Plan (NECP) for the period from 2021 to 2030. These national plans outline how each country intend to address five areas: energy efficiency, renewable, reductions in greenhouse gas emissions, interconnections, and research and innovation [8].
In conclusion, the policies of the past decade highlight the fundamental role of renewable energy in driving the energy transition and underscore its significance for both people and the planet. Today, solar and wind energy stand out as the two primary sources of green energy, as can been seen in Figure 3. In particular, the next chapter will focus on wind energy, providing a detailed analysis of its potential and impact.

1.3 Wind energy

Wind energy involves capturing the kinetic energy of wind using wind turbines and converting it into electricity. Wind energy can be classified into two main categories: onshore and offshore. The key difference between these two lies in their location. Onshore wind turbines, as the name suggests, are installed on land, while offshore ones are situated in seas or oceans.

Figure 4: Onshore and Offshore wind turbines

Due to this location difference, the onshore wind faces space constraints, has to compete with other land uses and encounters a turbine size limitation due to the dimension and the mobility of installation cranes achievable on land. In contrast, offshore wind has benefit from nearly unlimited locations with stronger and more constant wind resources, making it highly efficient for energy production. In addition, at sea, it is possible to install turbines using cranes located on ship, which do not have the same restrictive dimension limits as those on land. Furthermore, to move the crane it is necessary to reposition only the ship, eliminating a lot of logistical problems.

In the graphs below,it is possible to notice the difference between onshore and offshore wind mean speed and respective power density [9]:

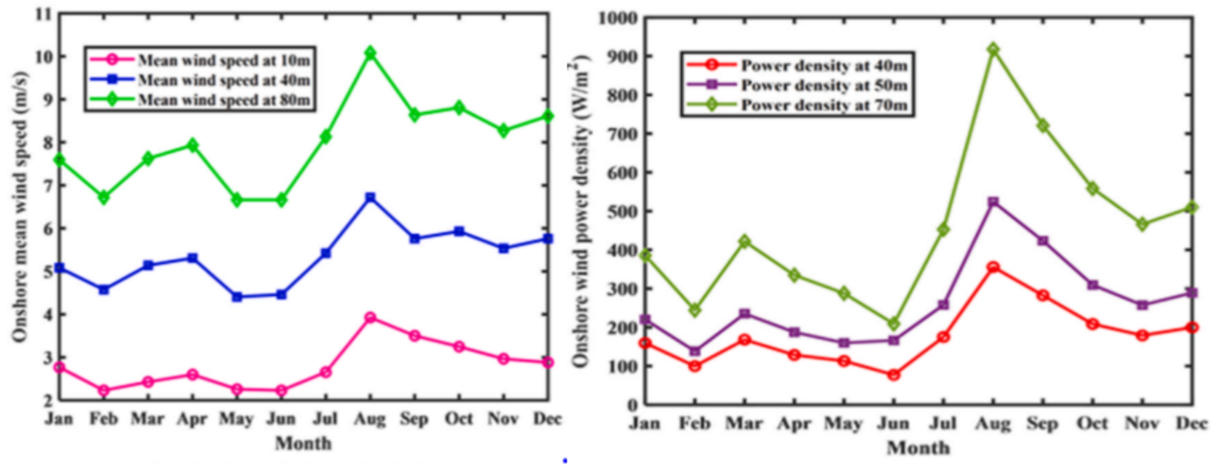


Figure 5: Onshore mean speed and power density

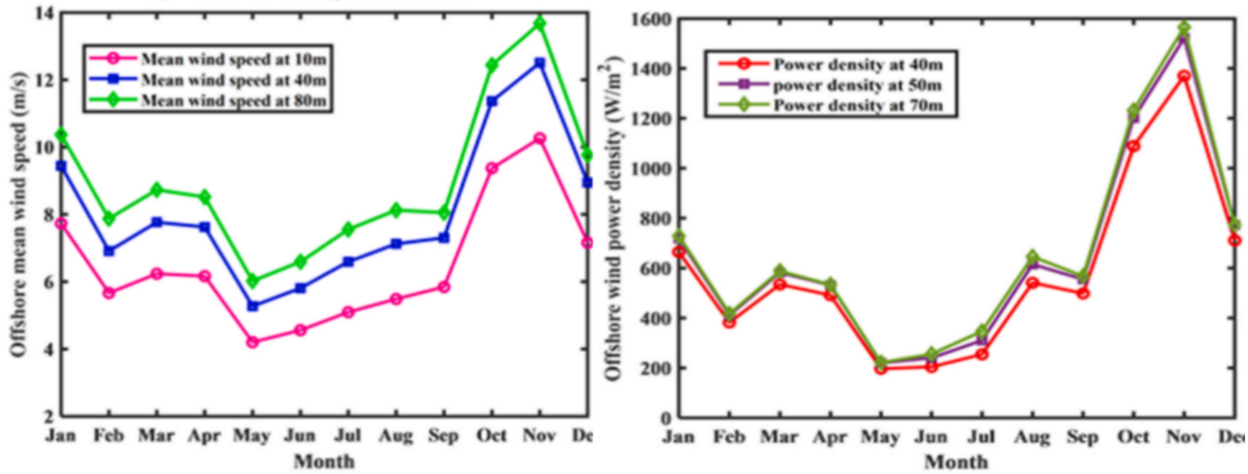


Figure 6: Offshore mean speed and power density

It is evident from the charts above that power density, i.e. the power available per square meter of swept area of a turbine, is strictly correlated with mean wind speed. In general, the two parameters exhibit the same trend: if the mean wind speed increases, the power density will rise as well, and vice versa. In addition, it is possible to notice from the charts how offshore wind speed reaches its peak value during the winter month of November and its lowest value in May, while onshore wind speed achieves its peak during summer and the lowest value between May and June. The graphs also show that offshore mean wind speeds are higher than the onshore ones due to the lack of obstacles to the wind flow, resulting in greater power density. Offshore wind can achieve mean speeds of up to 14 m/s and a power density of 1600 W/m^2, while onshore wind reaches around 10 m/s and 900 W/m^2, respectively.
From an economic perspective, the Levelized Cost Of Energy (LCOE) is the most important parameter to compare technologies that differ for life spans, project size, different capital cost, risk, return, and capacities. It is calculated as [10]:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{It+Mt+Ft}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Et}{(1+r)^t}} \tag{1}$$

In equation (1), the numerator represents the summation, at the year t, of the following terms: Investment expenditure (I_t), also called CAPital EXpenditure (CAPEX), Operations and Maintenance expenditures

(M_t), and Fuel expenditures (F_t), where the last two terms are collectively known as OPerational EXpenditure (OPEX). All actualized through the discount rate (r). The denominator represents the Electricity generation (E_t) at the year t, also discounted. Considering both onshore and offshore wind technologies, their LCOE trends are illustrated in the following graph [9].

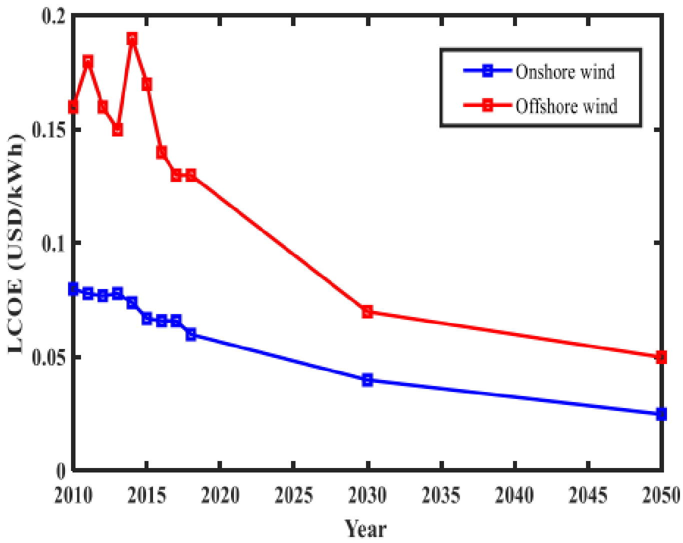


Figure 7: Onshore and offshore LCOE trend

It can be immediately observed that the LCOE for onshore wind, represented by the blu line, is lower than that for offshore wind, represented by the red line, making onshore wind technologies currently the more cost effective option. However, when analyzing the Levelized Cost of Energy trend, it becomes evident that the LCOE for offshore wind is expected to decrease rapidly in the near future, becoming a competitive technology.

1.4 Offshore wind energy

Leveraging on previous data and predictions, offshore wind leading manufacturers are now producing turbines with capacities of 15 MW or even more [11] and the largest offshore wind farm currently under construction, Dogger Bank in UK, will have a total capacity of 3.6 GW upon completion [12]. On February 2025, as can be seen in the graph below, the global operational offshore wind capacity stands at 80.9GW with a further 22.7GW undergoing offshore construction. For the first time, China makes up more than 50% of global commissioned capacity, with 41 GW, followed by the UK with 14.7 GW [13].

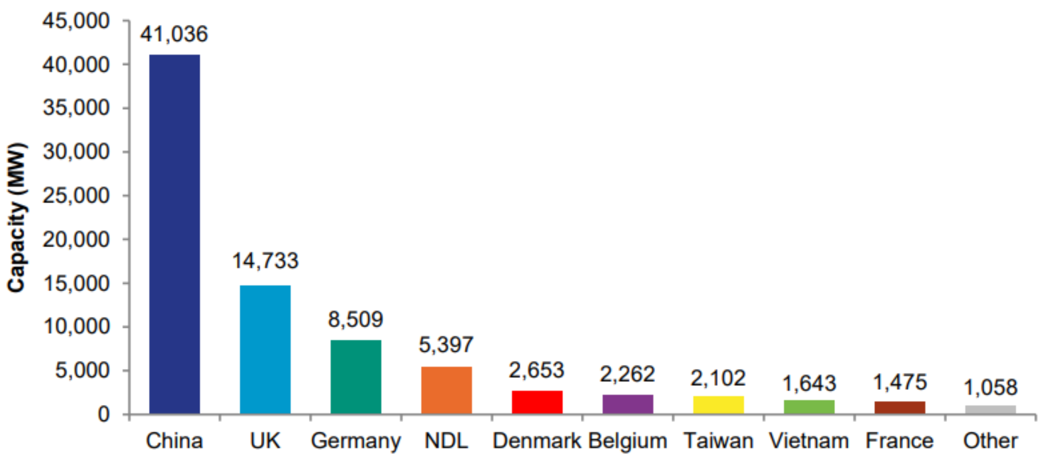


Figure 8: Global offshore wind operational portfolio by countries

The global new build portfolio, as the chart below shows [13], sees the entrance of Brazil in the international market, although China has one of the highest numbers of development projects. In addition, the graph highlights the strong presence of USA. However, it is currently unclear what will happen with offshore wind development under the last elected administration. Considering both the operational and the new build portfolio, the biggest project pipeline is in China, which has 437 projects totaling 247 GW in generation capacity. The UK remains in second position with a pipeline of 96 GW across 123 projects and is followed by the USA with 79 GW, Germany with 68 GW and Sweden with 55 GW [13].

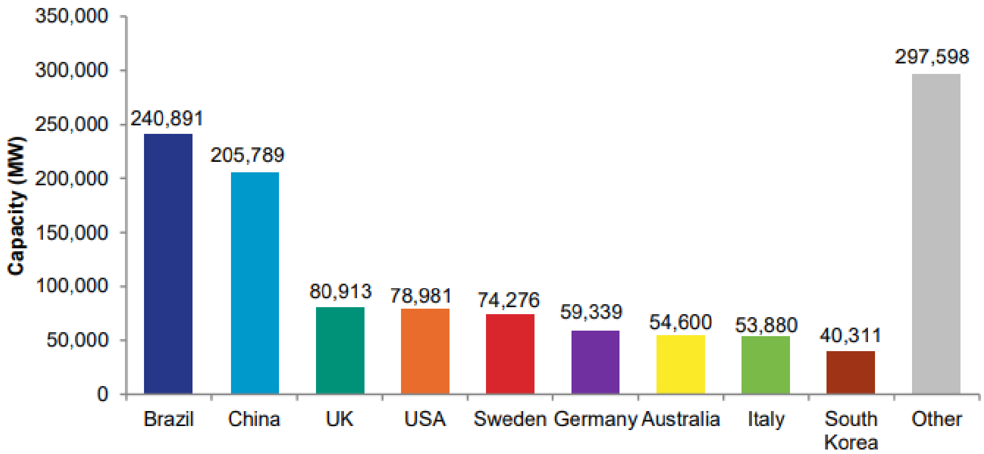


Figure 9: Global offshore wind new-build portfolio by countries

The interest in offshore wind energy is also evident in the Stated Policies Scenario (STEPS), which projects future energy trends based on current and announced government policies. It is clear that offshore wind capacity is set to increase substantially. The following chart from the International Energy Agency (IEA) [14] illustrates the installed capacity, with the light blue lines representing 2018, and the blue lines depicting the forecast for 2040, in line with the STEPS.

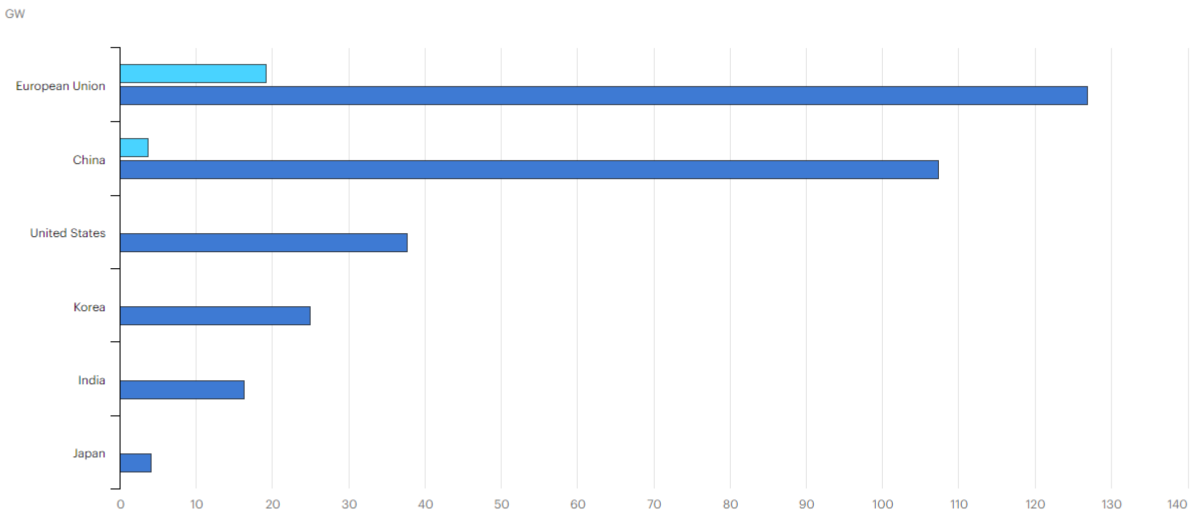


Figure 10: Installed offshore wind capacity scenario

Offshore wind energy can be divided into two main categories: fixed-bottom (for depths up to a maximum of 80 m) and floating wind turbines (for deeper waters). Both types play critical roles in the growth of renewable energy, with fixed-bottom turbines currently dominating the market, while floating turbines are the key to unlocking vast new offshore wind resources in deeper waters.

1.4.1 Fixed-bottom offshore wind

Fixed-bottom wind turbine presents different types of foundation, depending on the depth and substrate. Gravity based foundations are used at shallow depths (0-30 m) and consist of large, steel or concrete bases that rest on the seabed. Also monopile foundations are used at shallow depths (0-30 m), in some cases they are utilized for water depth of up to 55 m [15] , and consist of a pile that is driven into the seabed. Monopiles are typically cheaper than other foundation types and are the most commonly used. Tripod fixed bottom foundations are used at transitional depths (20-80 m) and consist of three legs connecting to a central shaft that supports the turbine base. Each leg is fixed to the seabed either via a driven pile or a suction pile, which creates a wide foundation that allows the piles to be placed at a deeper depth in the seabed than monopile foundations. Finally, Jacket foundations are also used at transitional depths (20-80 m) and feature a lattice framework that comprises three to four anchoring points driven into the seafloor [16].

(a) Monopile foundations

(b) Gravity based foundations

(c) Tripod foundations

Figure 11: Fixed-bottom foundations

Global production capacity of fixed bottom foundation was divided in 2023 and is estimated that will be divided in 2026 as follow [17]:

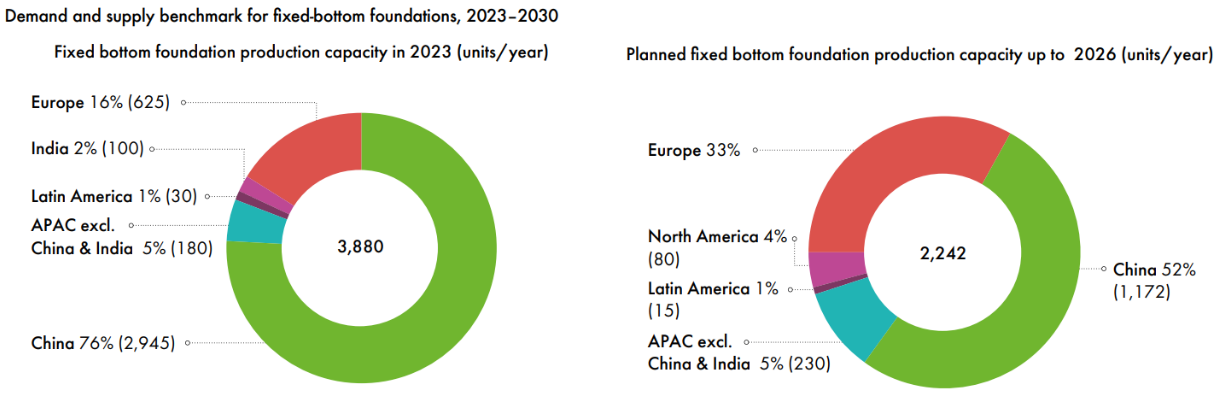


Figure 12: Fixed-bottom foundation global production capacity

The graph on the left clearly shows that China currently dominates the fixed bottom foundation supply chain with 2945 units per year out of a global production capacity of 3880 units per year. In addition, China plans to increase its capacity by 52% by 2026. Europe follows closely, with 625 units per year, and aims to increase its production capacity by 33% by 2026. All future data regarding the USA are subject to change due to the last elected administration.
In the table below, it is represented the fixed-bottom foundation demand planning, made by GWEC (Global Wind Energy Council) Market Intelligence, year by year from 2023 to 2030 [17]:

	Fixed bottom offshore foundations (units)								
	2022	2023e	2024e	2025e	2026e	2027e	2028e	2029e	2030e
Europe	347	509	252	551	734	732	1097	1306	1639
China	683	887	1263	1411	1324	1210	1154	1071	1000
India	0	0	0	0	2	0	34	34	68
APAC ex China & India	271	241	223	263	229	253	277	288	345
NORTH AMERICA	0	42	73	193	294	339	308	294	270
LATAM	0	0	0	0	0	0	0	0	108
Africa&ME	0	0	0	0	0	0	0	0	0
Total	1301	1679	1811	2418	2583	2534	2870	2994	3430

Source: GWEC Market Intelligence, CWEA, Brinckmann, September 2023
● Sufficient ● Potential bottleneck

Figure 13: Fixed bottleneck forecast

The data in the table above highlight both "sufficient" capacity (indicated in green) and "potential bottlenecks" (indicated in orange) for meeting production demands. So,it is clear that one of the problems in the coming years is a potential bottleneck due to a lack of fixed-bottom foundation units for specific countries, despite the worldwide availability. This is influenced by government decision to increase the resilience of the supply chain after events of the lasts few years, such as the pandemic and the invasion of Ukraine. For Europe the deficit will occur after 2025, as for Italy. In contrast, APAC region, excluded China and India, has a bright future ahead, after having faced challenges in recent years. China is the only country with a sufficient capacity until 2030. India enters the forecast in 2026 with minimal activity, but demand increases modestly by 2030, with no signs of capacity catching up. Regions such as LATAM (LATin AMerica), Africa and the Middle East show no production until 2030, where a modest demand appears for the second one, but it already faces bottlenecks. In conclusion, the total demand for fixed bottom offshore foundations grows significantly, from 1,301 units in 2022 to 3,430 units by 2030. This significant increase signals a growing risk of bottlenecks in multiple regions, particularly Europe, APAC ex China and India, and North America, unless substantial production capacity expansions will be implemented globally.

1.4.2 Floating offshore wind

The development of Floating Offshore Wind technologies has been driven by the limitations of fixed-bottom foundations in deep waters. In 2023, the capacity for global floating offshore wind energy projects nearly doubled, reaching a total of 231.4 MW. Today, the 88-MW Hywind Tampen plant in Norway, fully commissioned in 2023, is the largest operational floating offshore wind facility in the world. Additional projects were launched near Marseille, France (25 MW); Bilbao, Spain (2 MW); Longyuan Nanri Island, China (3.6 MW); and the Wenchang oilfield off the coast of China (7.25 MW) [18].

Compared to fixed-bottom OWT, floating wind turbine (FWT) rely on mooring and anchoring systems designed to maintain their position in deep water. Floating Wind Turbines (FWTs) achieve hydrostatic equilibrium through various restoring mechanisms, which can be categorized as ballast, buoyancy, or mooring stabilization during operation. In practice, most FWTs utilize a combination of these mechanisms [19].
Below, it is possible to see the main floating foundations:

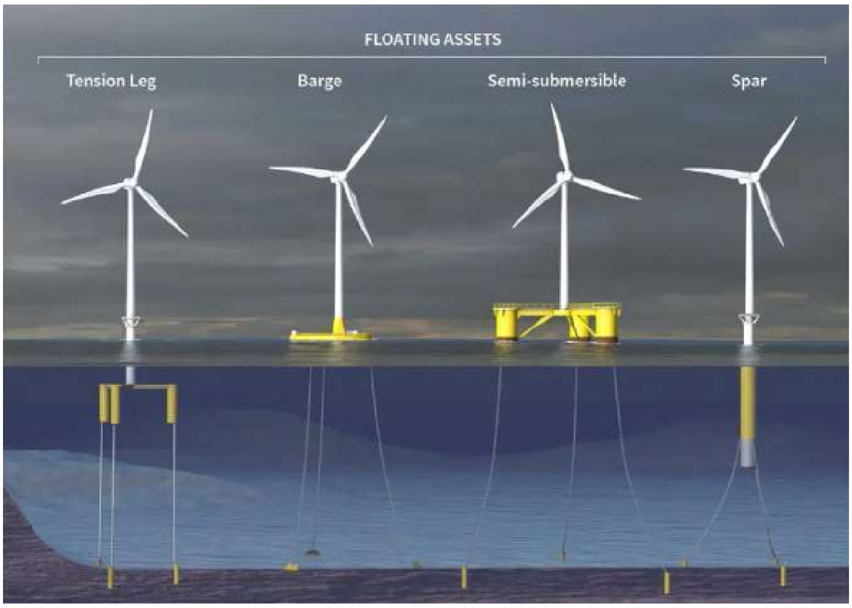
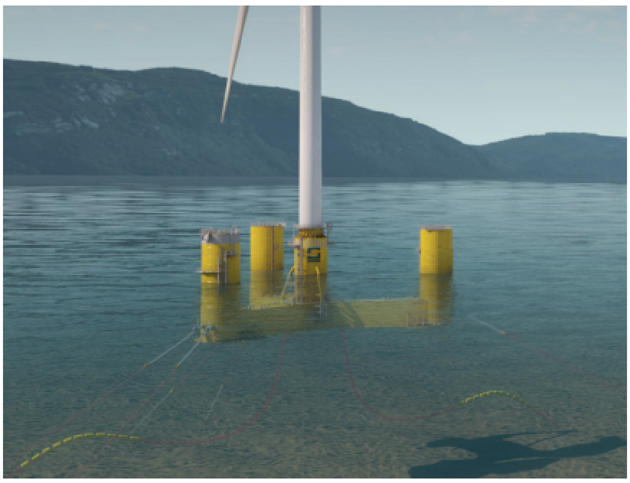


Figure 14: Floating assets

In contrast with fixed-bottom wind turbine, for FWTs are not only standard solutions for the foundations, but there are a lot of prototypes and patents from different companies. In the figures below it is possible to observe the Saipem S.p.A. floating foundation prototypes. The first one is known as " Star 1" thanks to its star shape and it uses a passive ballast system, while the second prototype is called "Hexafloat" and it is a novel pendulum structure featuring low steel mass for deep water sites [20]:



(a) Star 1

(b) Hexafloat

Nowadays, one of the most important floater is the "Damping Pool" by BW Ideol. It is characterised by a ring-shaped floating foundation which provides the stable base for the turbine that generates a power output of 15 MW or greater [20].

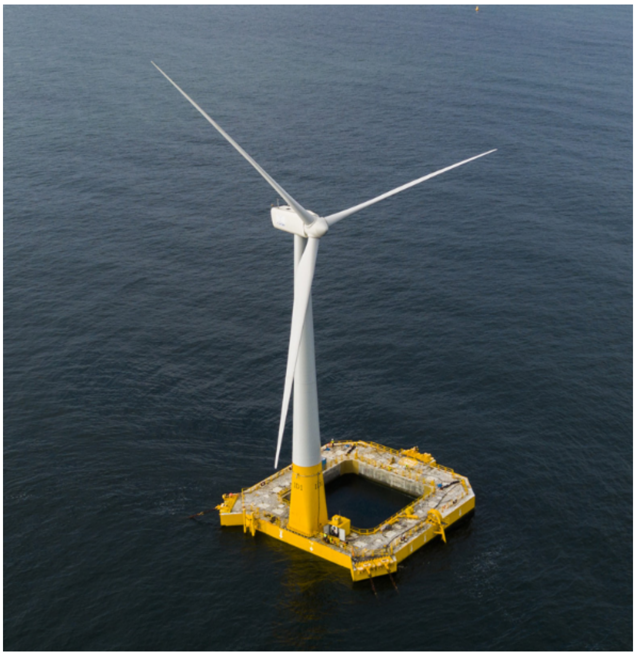


Figure 15: Damping Pool

Another interesting floating foundation is "OceanX", the double-rotors semi-submersible foundation in the shape of a horizontal "Y". In 2020, it become reality both thanks to "Nezzy^2" research project, that studied two wind turbines of 15 MW supported by two towers, which are placed at an angle in the center of the foundation and to MingYang company. In the figure below it is possible to see the prototype [21] :

Figure 16: Nezzy^2

Today, there are a lot of new projects aiming to develop innovative solutions to address the challenges related to wind turbine scale and consequently its costs. One of these is "NextFloat" project, launched in November 2022. Its objective is to demonstrate at a full-scale the innovative floating platform design, while advancing in parallel on the industrialization and scaling-up of the integrated solution up to 20 MW scale, in preparation for commercial floating wind farms under development in Europe and other continents [22].

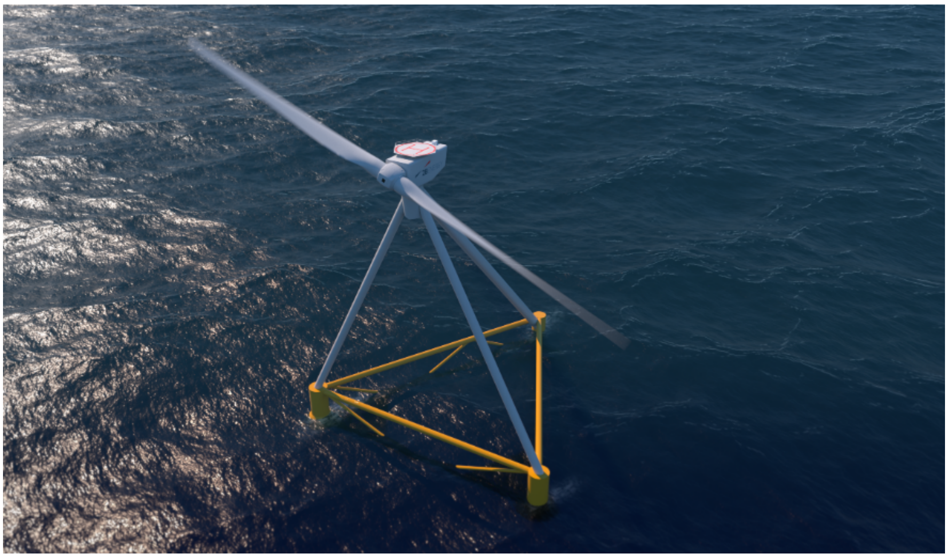


Figure 17: NextFloat project prototype

Global production capacity of floating foundations for offshore wind was divided in 2023 as explained in the graph below [17]:

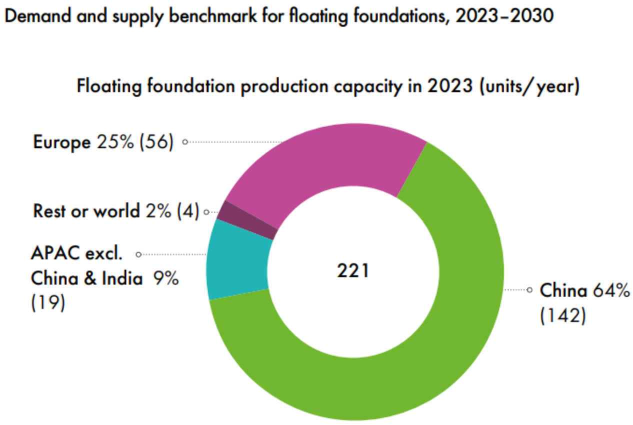


Figure 18: Floating assets

It is evident that China, with 142 units, dominates the floating foundation production capacity. In second position there is Europe, that is the world's largest market in floating offshore wind installation. Instead, a minor role is played by the APAC region.
In the future, deficits are likely to occur in all regions except China, as can be seen in the table below [17]:

	Floating offshore foundations (units)								
	2022	2023e	2024e	2025e	2026e	2027e	2028e	2029e	2030e
Europe	7	11	7	8	26	29	50	130	182
China	1	2	0	25	40	40	0	0	0
India	0	0	0	0	0	0	0	0	0
APAC ex China	0	0	8	0	11	32	57	75	77
North America	0	0	1	1	0	0	0	12	32
LATAM	0	0	0	0	0	0	0	0	0
Africa & ME	0	0	0	0	0	0	0	0	0
Total	8	13	16	34	77	101	107	217	291

Source: GWEC Market Intelligence, CWEA, Lumen Energy & Environment, September 2023 ● Sufficient ● Potential bottleneck

Figure 19: Floating assets

As in the fixed-bottom foundations table, the color-code indicate "sufficient" capacity for meeting production demands in green and "potential bottlenecks" in orange. Europe shows steady growth, with sufficient capacity until 2028. However, potential bottlenecks emerge starting from 2029, due to demand rises from 50 to 130 units. China maintains sufficient capacity until 2030 but shows a zero demand forecasts for 2028 and beyond. The APAC region (excluding China) faces bottlenecks due to demand growth, that leads to substantial shortages starting from 2027. Other regions like India, LATAM, and Africa and the Middle East do not show activity in this forecast, indicating limited or no projected involvement in floating offshore foundation production. Overall, the total demand grows from 8 units in 2022 to 291 units by 2030. This suggests a significant scaling challenge for the industry, with bottlenecks becoming a global concern in next years unless production capabilities are expanded.

Nowadays, all floating offshore wind technologies are in a pre-commercial phase and will achieve commercialization towards the end of this decade [17]. In fact, the current phase aims to scale up projects, optimize technology, and reduce costs to pave the way for large-scale deployment.

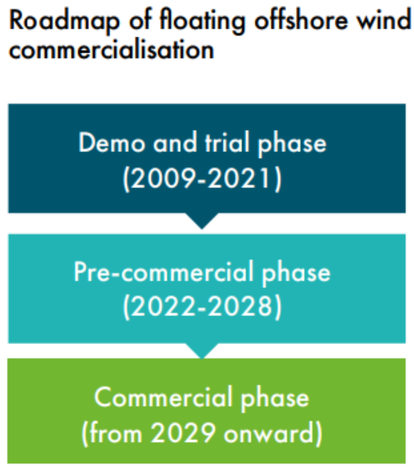


Figure 20: Floating road map

1.4.3 Comparison between fixed-bottom and floating foundations

In the following, some evaluation aspects are exposed in order to compare fixed-bottom and floating offshore wind foundations.

1) Water depth and support structure
Fixed offshore wind turbines are suitable for shallow waters with depths up to a maximum of 80 meters because they use structures anchored directly to the seabed, such as monopiles or jackets. In contrast, floating offshore wind turbines are designed for deeper waters, indeed they are mounted on platforms that float on the surface and are anchored to the seabed with mooring lines [16].

2) Technology Maturity
The Technology Readiness Level (TRL) index is a globally accepted benchmarking tool for tracking progress and supporting development of a specific technology from early stage research (TRL 1) to commercial phase (TRL 9) [23].

Offshore Power Generation Technology	Low-end cost ($/kWh)	High-end cost ($/kWh)	TRL
Fixed bottom OWT	0.06	0.11	~7-9 (high)
Floating OWT	0.07	0.17	~7-8 (medium-high)

Figure 21: Technology readiness level

In the table above [24] can be seen that fixed bottom OWT reach the highest technology readiness level, which corresponds to the commercial phase. At the same time, floating offshore wind turbine technologies have moved beyond the research and development level and achieved a higher Technology Readiness

Level (TRL), although they have yet not reached the final stage of commercialization.

3) Economic parameters
To economically compare fixed and floating offshore wind turbines with the same rating is used the Levelized Cost of Energy, which is calculated by considering both the Capital Expenditure (CAPEX) and the Operational Expenditure (OPEX).

		Offshore	
Parameter	Units	Utility Scale (Fixed-Bottom)	Utility Scale (Floating)
Wind turbine rating	MW	12	12
Capital expenditures (CapEx)	$/kW	4,640	6,169
Fixed charge rate (FCR) (real)	%	6.48	6.48
Operational expenditures (OpEx)	$/kW/yr	108	87
Net annual energy production	MWh/MW/yr	4,295	3,346
Levelized cost of energy (LCOE)	$/MWh	95	145

Figure 22: Economic parameters

Starting with the analysis of fixed costs, it is evident from the table above [25] that the CAPEX is higher for floating wind turbines compared to fixed ones. This is primarily due to the elevated Balance of System (BOS) costs associated with floating turbine technologies. These costs include substructure and foundation expenses, which are significantly higher for floating turbines because they represent a newer and more complex technology. In contrast, the operating and maintenance costs for fixed turbines are higher than those for floating turbines. This is because the analysis includes component replacements as part of these costs. For fixed turbines, replacements involve the use of a jack-up vessel, which has significantly higher costs due to its specialized equipment and operational requirements. In contrast, floating turbines use a tow-to-port strategy for replacements, which is generally more cost-effective. In addition, has been assumed that there were 30 full-time technicians in both sites, three crew transfer vessels, one cable lay vessel, and one diving support vessel per project. In the following table it is possible to notice the O&M costs in detail [25]:

Parameter	Fixed Value ($/kW-yr)	Floating Value ($/kW-yr)
Maintenance	**91**	**56**
Labor (technicians)	4	4
Materials	2	3
Equipment (vessels)	85	49
Operations	**17**	**30**
Management administration	2	2
Port fees	1	14
Insurance	15	15
Total OpEx	**108**	**87**

Figure 23: OPEX comparison

In conclusion, although the OPEX is lower for floating turbines, the Levelized Cost of Energy is higher for this type of turbine. Therefore, floating turbines are currently not cost-effective. To improve their economic viability, technological advancements are needed to reduce the capital expenditures. As shown in the graph below [26], a significant decrease in floating CAPEX is expected in the coming years:

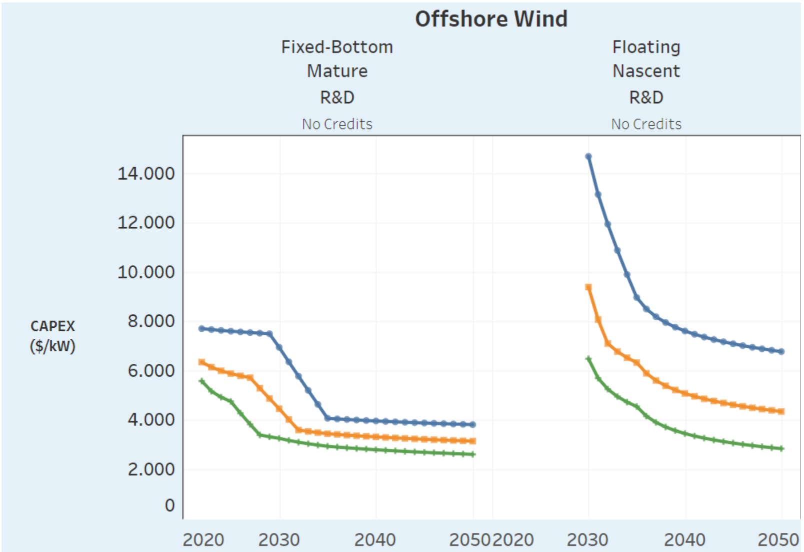


Figure 24: Offshore wind CAPEX trend

In the above chart the three lines represent different scenarios: the blue one indicates a conservative scenario, the orange one a moderate scenario and the green one an advanced scenario. Regardless of the scenario, the CAPEX trend: remains consistent across all cases, is going to decrease and it is always higher for floating foundations.

5) Environmental Impact
In order to evaluate the environmental impact of offshore wind, it is necessary to take into account many aspects. First, fixed offshore wind installations can significantly affect the seabed during both construction and operation, primarily due to activities such as drilling and the substantial physical footprint of structures in the marine environment. On the other hand, floating offshore wind turbines are less intrusive during the construction phase; however, they still require anchoring systems that, despite being relatively compact, typically consist of at least three mooring lines per turbine. From a visual impact perspective, floating installations are positioned farther offshore, making them virtually invisible from the coastline. Moreover, their placement in deep waters minimizes interference with other human marine activities, such as fishing and access routes to ports. In order to avoid any disturbance to sea animals, it is recommended to avoid important areas for breeding and foraging activities and areas with high densities of wintering or migratory species. These considerations are essential for gaining a comprehensive understanding of the environmental impacts of offshore wind technologies, enabling a holistic perspective on the entire process.

To summarize the points discussed earlier, the following lists outline the main advantages and disadvantages of fixed-bottom and floating offshore wind technologies.

Fixed-bottom offshore wind advantages [27]:

- lower costs;
- greater structural stability;
- straightforward installation and maintenance due to their permanent positioning.

Floating offshore wind advantages [27]:

- harness wind energy in deeper waters;

- stronger and more consistent wind conditions found farther offshore;
- offers larger flexibility to operate in a wider set of seabed conditions;
- reduces visual impacts;
- mitigates potential conflicts with other marine activities;
- manufacturing will take place in shipyards near future floating offshore wind farms, creating job opportunities in ports located close to these developments [28].

Fixed-bottom offshore wind disadvantages [27]:

- water depth constraints;
- high visual impacts;
- potential restrictions for foundations drilling and driving installation due to marine life protection;
- manufactured by specialist facilities around the world, so it provides few economic benefits to the local area to the offshore wind farm.

Floating offshore wind disadvantages [27]:

- higher costs;
- there are not enough yards and ports with the right combination of quayside length, water depth and storage space to support the simultaneous development of GW-scale floating offshore wind projects;
- requires further refinements to enhance stability.

In conclusion, from all the data and explanations provided in this introductory chapter, it is clear that offshore wind technology is essential to meet the increasing global demand of electrical energy. Although both fixed and floating offshore wind technologies have some inherent limitations, the trend suggests that they will continue to be developed in order to address these issues. Floating offshore wind technologies, in particular, face numerous complexities and limitations that need to be optimized. One significant challenge is logistics, as the foundations have a big and complex shape that is difficult to manage and store. Due to all the aforementioned reasons, this master thesis aims at discussing key logistical issues involved in constructing a floating offshore wind park. Various solutions will be analyzed to determine the best options for what concern the selection of the yard, the transportation of the necessary components to the selected location and the management of their local storage.

2 Floating offshore wind vessels and equipment

One of the most important elements in the construction of a floating offshore wind park is the fleet of vessels used to execute the various processes involved in the entire project. Some operations are characterized by a high level of technological complexity and as such different types of ships will be required for specific activities. The main categories of operations include: the load out, transportation and load off of structures and components from the fabrication yard to the marshalling yard, the installation of the mooring system where the wind farm will be erected, the laying and connection of electric cables once the floating turbine has been anchored, as well as operations and maintenance, and lifting operations.
In the following pages, the different types of vessel used in floating offshore wind projects will be explained.

2.1 Transportation of structures and components

When discussing transportation within the context of a floating offshore wind farm, it encompasses the logistical movement of a wind turbine components from one location to another. Specifically, this involves the conveyance of individual components or structures, either as discrete parts or pre-assembled units, from the fabrication yard to the assembly or integration yard situated in proximity of the designated site for the wind park's establishment.
Individual components and pre-assembled units of an offshore wind turbine are characterized by irregular shapes and weights in the order of thousands of tons. Consequently, vessels with specific characteristics are necessary for their transportation. These ships, known as Heavy Transport Vessels (HTVs), possess several key features: a large free deck area, considerable length, and high deadweight capacity. They can be divided into two subcategories: deck carriers and semisubmersible vessels. Specifically, deck carriers and semisubmersible vessels are capable of transporting heavy loads over long distances. For shorter distances within the yard or between nearby yards, towed barges can be utilized instead.

In the figure below [29], semi-submersible vessel by Seaway 7 can be seen:

Figure 25: Semi-submersible vessel

To better compare and understand the differences between deck carriers and semi-submersible vessels, the following table presents the main design parameters and their corresponding values. The values are derived from a market database, which gathers data on all the Heavy Transport Vessels currently available on the market.

	Deck carrier	Semi-submersible vessel
Semi-submersible capability [m]	0	7 - 21
Deck Area [m^2]	1,226 - 22,800	4,405 - 19,250
Deadweight tonnage (DWT)	2,489 - 55,000	14,715 - 116,175
Speed [kn]	8 - 17	10,5 - 16
Accomodation capacity [$people$]	16 - 60	38 - 57

Table 1: Design parameters for HTVs

The data presented in Table 1 clearly highlights that the main difference between the two categories of HTVs lies in the semi-submersible capability, which is a feature exclusive to semi-submersible vessels and absent in deck carriers. This functionality enables semi-submersible vessels to transition from a deep draft to a shallow draft by deballasting process, i.e. removing ballast water from their hulls, allowing the vessel to rise and operate as a surface ship [30]. Throughout this capability, semisubmersible vessels are able to submerge their main deck below the waterline, typically to a depth between 6 and 14 meters, making it possible to load large and heavy cargoes using the float-on/float-off method [31].

In the figure below, it is possible to notice a semisubmersible vessel with submerged deck [32]:

Figure 26: Semisubmersible vessel with submerged deck

This capability is particularly advantageous when transporting floating offshore wind turbine foundations, as it permits to transport a fully assembled floater and direct transfer it to and from the sea, without the need of heavy lifting equipment or quay-side infrastructure. On the contrary, deck carriers are limited to conventional loading methods, requiring the use of cranes or Self-Propelled Modular Transporters (SPMTs) at port. Owing to their structural configuration, they are unable to release cargo directly into the sea. This limitation becomes particularly relevant in the transportation of large offshore components, such as pre-assembled floating wind turbine foundations. In this scenario, only semi-submersible vessels are capable of carrying and deploying fully pre-assembled floaters, as their total weight typically exceeds the lifting capacity of conventional cranes. Consequently, deck carriers can only be utilized to transport individual parts of the foundation, which must then be assembled on site.

The figure below shows an SPMT transporting a transition piece of an offshore wind turbine [33]:

Figure 27: Self Propelled Modular Transporter

Since the early 2000s, with the aim of decreasing the LCOE, wind turbines have been designed with a higher and higher energy output and therefore with much wider dimensions of their components, especially the nacelle and the blades [34]. Consequently, the deck area becomes a crucial parameter to consider for the transportation of wind turbine components. As shown in the figure below presented by Orsted [35], a 14 MW turbine has a rotor diameter of 236 meters and a total height of 275 meters from sea level. This implies that, compared to previous years, all the components of a wind turbine, such as blades, foundations, and hubs, are now larger, taller and heavier. Therefore, the need for larger vessels is evident. In Table 1, it is clear that both categories of heavy transport vessels cover a similar range of deck area values. Therefore, the primary issue, in order to assess the transportation of wind turbine components, as will be discussed in the next chapter, is the availability of vessels by type.

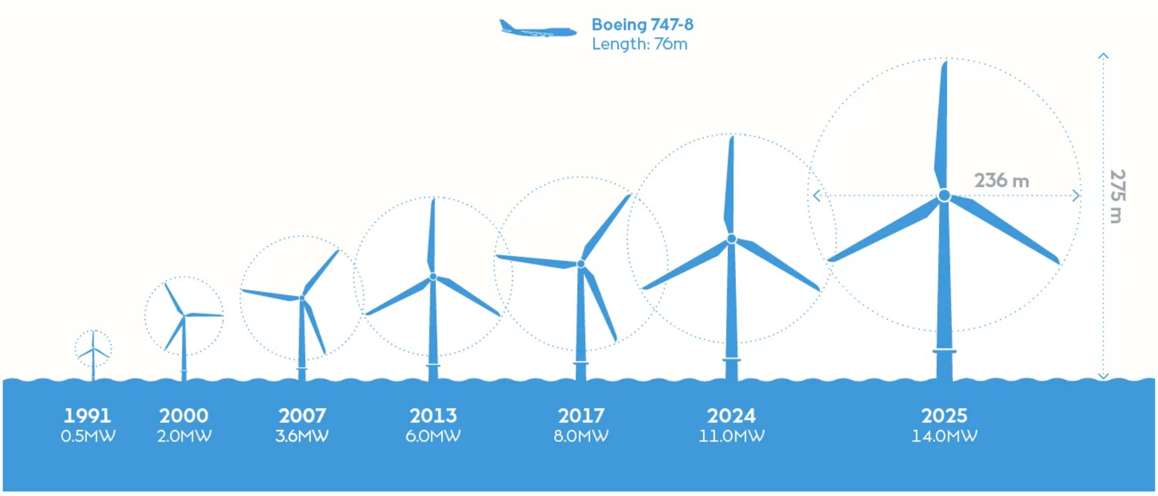


Figure 28: Wind turbine dimension through the years

Regarding the third parameter in Table 1, it can be defined as follows: "The deadweight is the difference between the displacement and the mass of empty vessel (lightweight) at any given draught. It is a measure

of ship's ability to carry various items: cargo, stores, ballast water, provisions and crew, etc." [36].
In this conext, deck carriers typically have lower deadweight values compared to semi-submersible vessels, which can reach around 115,000 metric tons. On the other hand, when considering speed, both vessel categories exhibit a similar range of performances.
Heavy transport vessels are designed to carry components over long distances. Due to the extended duration of these voyages, it is necessary to provide accommodation units for the crew. These units ensure that the team has a comfortable and safe living environment while on board. For these reasons, the last parameter considered in the Table 1 is the accomodation capacity of the HTVs. It is possible to notice that the values range is similar for deck carrier and semi-submersible vessels.

2.2 Installation of the mooring system

The mooring system and its installation are crucial for constructing a floating offshore wind farm. This system, consisting of anchors, chains and ropes anchored to the seabed and attached to the floater, ensures the wind turbine remains stable and in its original position, even in rough sea conditions. Mooring lines attached to the substructure at an inclined angle, where the horizontal tension component maintains the position of the floater and the vertical tension component provides a restoring force that improves the stability of both the substructure and the turbine [37].

Figure 29: Anchor Handling Tug Supply vessel

All offshore operations for mooring system installation can be performed by a single vessel capable of transporting all the anchors and chains, it is called Anchor Handling Tug Supply (AHTS). In Figure 28 [38], it is possible to observe the AHTS called "Normand Sirus" by Solstad Maritime.

This type of vessel has been chosen for this specific operation because of the following characteristics:

- Mooring Line Storage Capacity (m)
  The first phase of installing a mooring system involves the load out of the mooring lines onto the vessel that will transport them to the designated installation location. To minimize trips from the quay to the designated site, the vessel must have adequate storage capacity to hold all the mooring system components required by the project schedule in a single trip. Generally, a single line is around 550 meters long and 150mm diameter wide [39], although this values can vary depending on the size of the turbine, the depth of the seabed, the mooring configuration (catenary, taut, semi-taut), and the lines materials.

- Remotely Operated Vehicles (ROV) presence
  Upon mooring system load out, the vessel proceeds with the pre-installation process. Before installation, the AHTS vessel uses a Remotely Operated Vehicle to visually survey the anchor positions and mooring line routes. This ensures the routes are clear of any objects that could interfere with the operations. The figure below shows the remotely operated vehicle "Hydrone" developed by Sonsub, a Company of Saipem [40].

Figure 30: Remotely Operated Vehicles "Hydrone"

- Dynamic Positioning (DP)
  After assessing all survey calibrations, dynamic positioning trials can begin. Dynamic positioning is the capability of a vessel to maintain or adjust its position automatically using its global positioning and propulsion systems [41].This feature is crucial for many offshore operations. Traditionally, anchors have been used to keep a vessel in place, but modern DP systems are now replacing them. Dynamic positioning systems offer quick and easy positioning and maneuverability without the need for mooring lines, tug boats, or time-consuming anchor handling. They enable operations in ultra-deep waters where mooring lines are difficult to install, allow for easy location changes to avoid bad weather, and provide quick relocation and sailing away in emergencies [42].
  Dynamic positioning systems are categorized into three main classes, as defined by the International Maritime Organization (IMO) [43]:

Class	Description	Components redundancy	Can operate in area with
DP1	It provides basic position and heading control	No. Vulnerable to single point failures	Low risk
DP2	It provides basic position and heading control, also with a fault in non-active component	Only for critical active system	Moderate risk
DP3	It offers the highest level of safety and reliability	A lot of active and static components also in different compartments	High risk

Table 2: Dynamic Positioning classes

For the installation of the mooring system, considering the different characteristics of dynamic positioning classes, at least a DP2 system is necessary [44]. This ensures that the lines and anchors are laid and connected with high precision. This precision is crucial to avoid any misalignment or tension issues that could compromise the stability and effectiveness of the mooring system.

- Anchor Handling Winch Capacity (t)
  Winches installed on AHTS vessels must be capable of withstanding extremely high loads during the installation of mooring systems, which involves the deployment of heavy chains, cables, and anchors. In particular, some catenary mooring lines can reach weights of approximately 347.7 kg per meter [39]. Therefore, winches are considered a critical component for ensuring the overall success and safety of mooring installation operations. Furthermore, a consistent bollard pull is indispensable for the necessary load test which will ensure the correct installation of the drag anchors.

- Shark Jaws
  Shark jaws are mechanical clamping devices mounted on the deck of offshore vessels, typically located near the stern [45]. These components are specifically designed to safely clamp, guide and maintain tension on wire and chain, without the presence of crew [46]. In addition, shark jaws act as securing mechanism [46]. Generally, Anchor Handling Tug Supply vessels are equipped with two shark jaws, positioned on either side of the stern. This configuration can be observed on AHTS vessels such as UGBANA [47] and MMA Morgan [48]. In particular, during the mooring system installation process, shark jaws on the AHTS are used to maintain proper tension during the deployment and positioning of anchors on the seabed, to ensure safe control of the mooring chains as they are released into the sea without requiring direct crew intervention, and to guide and secure the chains when two segments need to be connected offshore, preventing misalignment. In the figure below it is possible to observe a shark jaw [49]

Figure 31: Shark jaw

- Deck area (m^2)
  Anchor Handling Tug Supply vessel with a deck area large enough to safely facilitate the connection and disconnection of chains is required for the installation of mooring system. In particular,it is necessary a deck area of at least 700 m^2 for this process. For instace, the AHTS vessel "Normad Sirius" by Solstad Marine features a deck area equal to 754 m^2 [50].

- Bollard Pull (MT)
  Once the mooring system is installed, the plan involves the towing of pre-assembled floating wind turbine from the integration yard to the designed location where the mooring system has already been set up and wet stored i.e. laid on the seabed in readiness for its subsequent recovery. This transportation is carried out by a main Anchor Handling Tug Supply vessel and by two or three support tugs, with the exact number depending on the specific circumstance. For this reason, the AHTS vessel requires a high bollard pull, defined as "the force (kN) exerted by a vessel under full power, on a shore-mounted bollard through a tow-line" [51]. For this process, it is reasonable to consider bollard pull values in the range of 200 - 300 MT for the main AHTS vessel. Support tugs, which can be smaller, typically have bollard pull lower values, around 150 MT. For instace, the AHTS vessel "Normand Sirius" by Solstad Marine, it presents a bollard pull value equal to 259 MT [50]. In the figure below it is possible to observe an AHTS vessel that tow a floating wind turbine [52].

Figure 32: Floating turbine towed by an AHTS vessel

2.3 Electric cables laying

Before positioning the floating wind turbines at their final location and securely connecting them to the mooring system, the electric cables, known as inter-array cables (IACs), must be laid. This is necessary to ensure the optimal placement of the electric cables without the turbines obstructing the process. Additionally, the vessel laying the cables must maintain a certain distance from the turbines, which would be more challenging if the turbines were already installed. Once the turbines are in place, the IACs can be connected to ensure electrical connectivity within the wind farm. These cables are responsible for transmitting the generated alternating current between turbines and ultimately to an offshore substation. The substation converts the current to a higher voltage to minimize transmission losses, then delivers the energy to the onshore grid [53]. In order to cope with the constant motion and hydrodynamic forces acting on floating platforms, the cables used in these systems are dynamic cables by design. They are engineered for high flexibility and fatigue resistance to withstand environmental loads and continuous movement over long operational periods [54]. On average, these dynamic inter-array cables weigh approximately 70 kg/m and have an outer diameter of about 140 mm [55], ensuring both mechanical integrity and operational durability. Sometimes to improve the dynamic inter-array cable reliability, specially installation aids such as buoyancy modules and/or band restriction are employed. For a typical configuration involving 15 MW turbines with a rotor diameter of 224 m, turbines are usually spaced about seven times the rotor diameter, resulting in an average distance of about 1,5 km between units [56]. The figure below shows a dynamic inter-array cable [55]:

Figure 33: Inter-array cable

Considering the weight and the dimensions of the inter-array cables, and the distances between floating wind turbines, the IACs installation requires the use of a vessel with high cable storage capacity. For this purpose, Cable-Laying Vessels (CLVs) are typically employed, as they are specifically designed for handling and deploying submarine cables. These vessels are equipped with one or more turntables, which serve as storage units for the cables during transport and installation. For example, the CLV "Ndurance" by Boskalis, in the figure below [57], is equipped with a single turntable capable of storing up to 4,300 tons of cable. An important aspect to consider is the ongoing trend in the offshore wind sector: wind farms are being developed farther from shore, and both turbines and farms are growing in size, as can be seen in the previous Figure 28. Consequently, inter-array cables are also increasing in length and diameter, requiring vessels with even greater storage capacity and more powerful laying performances. In response to this, Jan De Nul has announced the planned production by 2026 of two cable laying vessels equipped with three turntables and a total cable storage capacity of 29,500 tons [58].

Figure 34: Cable laying vessel

Once the inter-array cable has been loaded onto the cable laying vessel, the laying operation can begin. This phase requires a high level of precision and speed. Anchored vessels rely on anchors and mooring

lines to maintain or adjust their position, making them more susceptible to environmental conditions like wind and currents. In contrast, vessels equipped with dynamic positioning systems use thrusters and sensors to automatically maintain position and course, enabling faster and more precise movements. Therefore, it is essential that the vessel is equipped with dynamic position capabilities. In particular, for inter-array cable installation in floating offshore wind farms, DP Class 2 is often considered the minimum standard to ensure safe and uninterrupted operations. Furthermore, the vessel must be equipped with specialized tools and systems, such as Remotely Operated Vehicles (ROVs), which assist in monitoring, guiding, and, if necessary, intervening during the cable laying process. Deck cranes, tensioners, chutes and other cable handling equipments are also required to perform cable laying activities.
In many cases, the CLV is supported by a Cable Burial Vessel (CBV) or by a CLV equipped with integrated burial systems. These vessels are fitted with specialized tools for cable trenching, burial, and protection, including ploughs, jetting sleds, or tracked ROVs equipped with jetting or cutting capabilities. These systems are essential to ensure that the cables are buried to a sufficient depth to protect them from external mechanical threats such as fishing gear or anchor drag [59].

There are three primary methodologies for the installation and burial of inter-array cables, each suited to specific seabed conditions and project requirements [60]:

- Simultaneous lay and burial: In this method, the cable is laid and buried in a single continuous operation. It ensures immediate protection of the cable after installation but may be slower, depending on the equipment used. Common tools employed for this technique include jet trenchers, jet plows, and mechanical plows, which excavate a trench as the cable is laid, particularly effective in soft to medium soils.

- Post-lay burial: This approach involves first laying the cable directly onto the natural seabed, followed by a separate burial operation. It allows for more flexible planning and is often used when precise cable positioning is required before trenching. Jetting tools, mechanical trenchers, and tracked ROVs equipped with jet swords or cutting chains are typically deployed in this phase, especially in variable or challenging seabed conditions.

- Pre-lay trenching: In this technique, a trench is excavated along the cable route prior to the cable being installed. This method is suitable when the seabed requires significant preparation or when cable protection must be assured before installation. Tools such as mechanical trenchers or ploughs may be used to prepare the trench, which is later backfilled once the cable is laid. In this case, a good operations synchronization is required, since cable laying should follow soon after the trench preparation in order to avoid an unacceptable trench natural backfilling which would jeopardize the cable protection.

2.4 Operations and Maintenance

Once the construction phase, typically lasting between one and two years, is completed, the floating offshore wind farm project progresses into the operational phase, which generally spans 20 to 30 years [61]. This long-term phase includes the Operation and Maintenance (O&M) stage, during which a broad range of activities is carried out to ensure the continued functionality, safety, and efficiency of the overall system. These operations require the use of various specialized vessels, depending on the nature and complexity of the tasks involved. The following pages provide a description of the main types of vessels employed in these activities.

- Crew Transfer Vessels (CTVs)
  Crew Transfer Vessels are typically around 20 meters in length and are primarily used for the daily transportation of wind farm technicians and other personnel from onshore yard to offshore wind farms. Their lack of onboard accommodation confines their operational range to wind farms located within 30 nautical miles from shore, where daily commuting is still feasible. Additionally, crew transfer vessels are capable of carrying light equipment weighing between 1 and 10 tonnes on the deck, which can be transferred to wind turbine platforms using onboard deck cranes. Crew transfer vessel operations are highly dependent on favorable sea conditions, with a maximum allowable significant wave height limit of approximately 1.5 meters. Due to these limitations, particularly regarding sea state operability and range, there is a growing preference for alternative vessels [61]. In the figure below, it is possible to observe the crew transfer vessel "Manor Venture" by OEG renewables [62].

Figure 35: Crew Transfer Vessel

- Service Operation Vessels (SOVs)
  Service Operation Vessels are versatile ships, typically around 70 meters in length, capable of transporting and accommodating up to 60 technician. These vessels provide an offshore O&M base, with staff working from the vessel for periods of two to four weeks at sea. Designed for extended offshore operations, SOVs are equipped with onboard accommodation facilities, spare parts warehouses, and deck cranes for handling equipment and components, making them the preferred choice for maintaining wind farms located far from shore. In favorable sea conditions, typically with significant wave heights below 1 meter, technicians can be transferred to wind turbines using daughter crafts launched from the SOV. Under rougher conditions, motion-compensated gangways are employed to ensure safe personnel transfers directly from the vessel to the turbine platforms [61] [63].
  The figure below represent the advanced Service Operation Vessel "SOV T60-18" by Royal IHC [64].

Figure 36: Service Operation Vessel

Compared to crew transfer vessels, that transport small teams of up to 20 technicians to offshore wind power plants on a daily basis, service operation vessels can accommodate up to 60 technicians. They stay at sea for several weeks and only need to return to port for fueling and the replenishment of supplies and equipment. This means that maintenance work with SOVs entails far less transport and unproductive time, which in turn improves productivity and turbine availability. That's why SOVs are especially suitable for wind power plants that are far from shore. Additionally, service operation vessels provide a larger weather window, because their motion-compensated gangway system enables technicians to access the turbines at wave heights of up to 2.5 meters [65]. The table below summarizes the key differences between crew transfer vessels and service operation vessels [61].

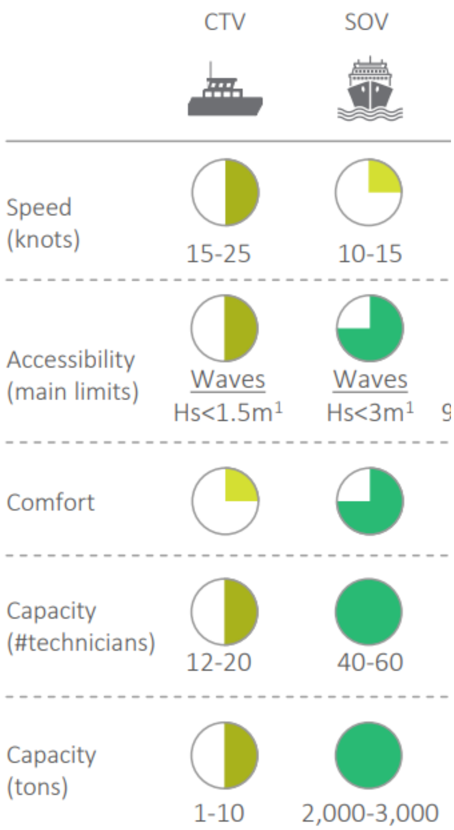


Figure 37: CTV vs SOV

- Construction Service Operation Vessels (CSOVs)
  Construction Service Operation Vessels serve as offshore bases for technical personnel during the commissioning and maintenance phases of offshore wind projects. Designed for long-term deployment, these vessels offer extensive open deck space and substantial accommodation capacity, enabling them to remain on site for extended periods, particularly during large-scale or complex operations. CSOVs are typically equipped with heavy-lift cranes and are capable of supporting both surface and subsea operations, including the installation and maintenance of offshore structures. They also play a key role in IRM (Inspection, Repair, and Maintenance) activities, which may include transition pieces installation, grouting, scouring protection and various maintenance tasks. Many CSOVs are outfitted for ROV (Remotely Operated Vehicle) operations and can also perform general supply duties, making them versatile assets in the offshore wind sector [66].
  In the figure below it is represented the "Windcat Offshore Elevation Class H2 Csov" by Windcat [67].

Figure 38: Construction Service Operation Vessel

- Offshore Supply Vessels (OSVs)
  Offshore Supply Vessels are essential assets for logistical support in offshore operations. Their primary role is to transport goods, materials, equipment, and personnel from onshore port to offshore facilities or vessels already stationed at sea. These vessels are designed to carry a wide range of cargo, including dry bulk, liquid mud, freshwater, and excess fuel, stored in below-deck tanks, as well as packaged goods and equipment on deck. Many OSVs are equipped with dynamic positioning systems, which enable them to maintain a stable position near offshore structures during cargo transfer operations, ensuring safety and precision. In compliance with maritime regulations, they are also capable of transporting hazardous materials and transferring fuel to offshore platforms or vessels as needed. Thanks to their versatility and cargo capacity, OSVs play a critical role in supporting both the construction and ongoing operation of offshore energy projects [68].
  The figure below shows the offshore supply vessel "Viking Lady" [69].

Figure 39: Offshore supply vessel

In operation and maintenance phase, several types of vessels are employed, each tailored to specific operational needs and environmental conditions. Their effectiveness is determined by a range of technical features that enable safe access, reliable station-keeping, and efficient support of offshore activities:

- Dynamic Positioning
  An essential characteristic required by O&M vessels is the ability to maintain position with high accuracy near floating turbines. This capability is crucial for safely conducting maintenance or personnel transfer operations without the need for mooring or anchoring. [70]. Consequently, many modern O&M vessels are equipped with DP systems, typically DP2 or DP3. Compared to traditional anchoring systems, DP systems allow for quick and easy positioning and maneuverability of the vessel, even in deep waters or congested seabeds [42].

- Motion-Compensated Gangways (MCGs)
  Motion-Compensated Gangways are advanced systems engineered to ensure safe, stable, and efficient transfer of personnel and equipment between offshore vessels and fixed or floating structures. By dynamically adjusting to the movement of both the vessel and the offshore installation, MCGs provide a secure connection that enhances operational safety and comfort during transfers. These systems integrate hydraulic, mechanical, and electronic components to actively counteract the relative motion between the vessel and the structure it is servicing. The gangway is mounted on a motion-control platform that continuously adjusts its position and orientation in real-time. By reacting to wave-induced movements, the system maintains the gangway in a stable position, effectively neutralizing pitch, roll, and heave. This allows technicians and cargo to be transferred safely even in moderate sea states, significantly improving accessibility and reducing operational downtime [71]. For instance, the Ampelmann E1000 system offers a 30-meter gangway with a cargo capacity of 1000 kg, fully motion-compensated in all six degrees of freedom, ensuring stable transfers in rough sea conditions [72]. In the figure below can observe a technician transitioning from the vessel to the wind turbine. In this scenario, a motion-compensated gangway proves to be highly beneficial [73].

Figure 40: Offshore supply vessel

- Accommodation Capacity
  SOVs and CSOVs offer onboard accommodation for 40 to 60 personnel, as represented in Figure 37, depending on vessel size. This allows technicians to remain offshore for extended periods, significantly increasing operational windows and reducing transit times. Some vessels of this typology can accommodate a higher number of personnel. For instance, the Windea Leibniz CSOV can now house up to 85 technical staff following its recent upgrade [74].

2.5 Lifting operations

In the construction of floating offshore wind farms, lifting operations are primarily concentrated in the pre-installation phase and are typically carried out onshore, on the quayside within the assembly yard or in a sheltered area in close proximity of the yard. These operations typically consist of two main processes: 1) Lifting the floater and launching it into the water. 2) Assembling the wind turbine by lifting and installing its components, such as the tower sections, nacelle, and blade, onto the floater. The completed unit is then transported directly from the assembly yard to the designated offshore location, so heavy lifting operations are confined to the onshore or nearshore environment. For this reason, lifting operations are typically carried out using cranes available at the quayside in the assembly yard, as this represents a more cost-effective solution compared to deploying a specialized vessel. However, due to limitations such as crane unavailability, insufficient lifting capacity, or inadequate hook height, onshore cranes may not always be suitable. In such cases, Heavy Lift Vessels (HLVs) can be employed as an alternative. These vessels are specifically designed to handle large and heavy components and are often used to lift and transfer floaters and offshore wind turbines components.
The figure below represents the Heavy Lift Vessel "Saipem 7000" by Saipem [75].

Figure 41: Heavy Lift Vessel

The most important parameters to consider for a heavy lift vessel are indicated below:

- Crane Lifting Capacity (t)
  A heavy lift vessel is equipped with a specialized crane capable of lifting extremely heavy loads, often up to several thousand tonnes. These vessels are essential for handling large and heavy subsea structures, such as floaters. Most Heavy Lift Vessels (HLVs) are equipped with cranes that have lifting capacities ranging from 500 to 1,000 tons (approximately 454 to 907 metric tons), significantly exceeding the capabilities of standard construction vessels, which typically do not surpass 250 tons (226 metric tons) [76]. A notable example is the HLV Saipem 7000, which features two main cranes, each capable of lifting 7,000 tons, allowing for a combined lifting capacity of up to 14,000 tons [75]. Currently, the heavy lift vessel with the highest crane capacity in operation is the SSCV Sleipnir. It is equipped with two revolving cranes, each capable of lifting 10,000 tons. These cranes can also be operated in tandem, enabling a combined lifting capacity of up to 20,000 tons [77].

- Crane Hook Height (m)
  The crane hook height on a heavy lift vessel is an essential factor, determining the crane's maximum vertical extension from the deck. This height is essential for safely lifting and accurately positioning large and heavy components, particularly tall structures such as the components of an offshore wind turbine. One key advantage of cranes on heavy lift vessels compared to those onshore is the vessel's

ballast system. By adjusting the ballast, the vessel can be lowered or raised in the water, effectively increasing the relative hook height when needed. This flexibility allows heavy lift vessels to achieve greater lifting heights than fixed quayside cranes, which are limited by their static position and elevation and are therefore indispensable to follow the continuous turbine power generation and their blades length [78].

- Dynamic Positioning
  Dynamic positioning systems (typically DP2 or DP3) are essential for maintaining a vessel's exact location during critical offshore operations without the use of anchors. For HLVs, this capability is particularly important during lifting and installation tasks, where even minor drift can compromise the accuracy and safety of the operation. A high DP class ensures redundancy and position-holding accuracy, which is vital in harsh sea conditions and congested offshore sites [79].

In the figure below the two cranes of the heavy lift vessel "Saipem 7000" has been represented [75].

Figure 42: Cranes on Saipem 7000 HLV

3 Transportation of floating offshore wind turbine foundations

In the following pages, an analysis of the logistic features involved in the construction of a floating offshore wind farm will be undertaken. The installation of a floating wind park is characterized by great complexity and numerous variables. Therefore several assumptions have been made, and these will be explained at each stage of the analysis. Through various logistical studies that will be conducted, the analysis of the transportation of floating offshore wind turbine foundations will also be assessed. These foundations, whether in their entirety or as individual sub-components, will be transported from the fabrication yard, where they are initially constructed, to the integration yard. At the integration yard, the foundations will be assembled with the other components of the wind turbine, such as the towers, nacelles, and blades. This process is critical to ensuring the efficient and effective construction of the wind farm. To provide a concrete basis for these studies, an example floating wind farm has been selected as case study. In the following pages all the details will be explained. This selection allows for a detailed examination of the logistical processes in a real-world context, ensuring that the findings are both relevant and applicable, as well as it helps in identifying possible contingency cases that can be used for sensitivity analyses.

3.1 Description of the case study

To perform all the logistic studies on a floating offshore wind farm, a floating wind farm located in the North Sea has been considered as case study. When selecting the location, it is essential to consider the proximity of an integration yard facility, in this case an example can be Cromarty Firth in Scotland. This yard will serve as the site where the foundations are integrated with the turbine towers, nacelles, and blades using one or more cranes as well as other yard facilities. Additionally, if the floaters are transported from the fabrication yard in different parts, the integration yard will also be used to assemble these components to complete the floaters. Therefore, it is essential to find a port near the designated location that has sufficient space to accommodate these processes. The wind farm considered as base case comprises 35 turbines, each with a capacity of 15 MW. The offshore development area is anticipated to occupy an array area of about 116 km^2, with a maximum export capacity of approximately 525 MW. Indicative water depths in this area range from 100 to 115 meters below lowest astronomical tide. The floating foundation selected for the turbine is the "Star1" foundation, developed and patented by Saipem. This foundation has been chosen due to its exceptional stability and adaptability. Unlike similar foundation prototypes where the tower is installed at one of the three angles, the "Star1" foundation features a central installation of the tower. This design choice enhances the overall stability and performance of the turbine even in extremely harsh environment. In the following section, a more detailed explanation of the "Star1" floating foundation will be provided.

3.1.1 Floating foundation

Currently, there are numerous types of floating foundations available on the market. As a matter of fact, this as well as the lack of standardization, is pointed out as one of the main drawbacks of the floating wind farm development with respect to the fixed ones leveraging on monopiles rather than tripods. For the case study under consideration, the "Star1" floating foundation, developed by Saipem, has been selected. This foundation was chosen due to its symmetrical design, which positions the turbine tower at the center. This configuration not only provides stability but also enhances adaptability to larger turbines. It is represented in the figure below [80].

Figure 43: Star1

The "Star1" is composed of three primary sections, referred to as megablocks (MB), which feature two distinct shapes. Specifically, two of these megablocks are designed in an "L" shape, while the third is configured in a "U" shape. Assembled together two L-shaped blocks with one U-shaped block, as illustrated in the figure below, they will make up the entire floater, on which the tower, the nacelle, and the blades of the turbine will be integrated.

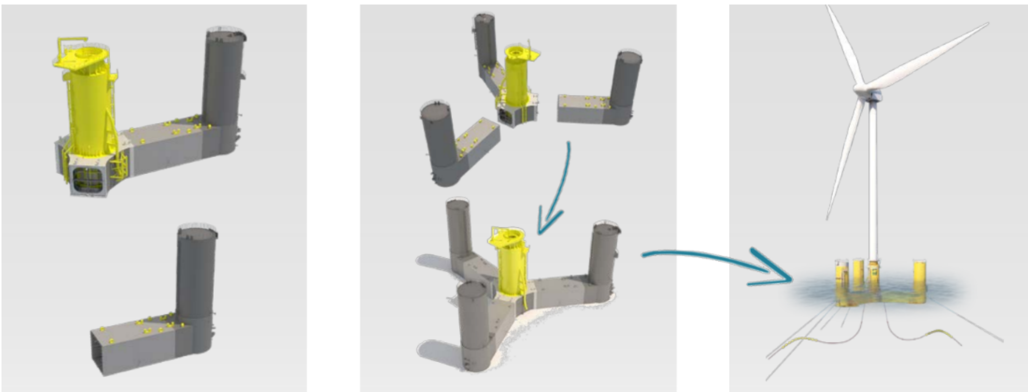


Figure 44: Sequence of construction of a STAR1 floater

Once the megablocks are assembled, the final floater achieves dimensions comparable to those of an Airbus A380 in both length and width. This is due to the fact that the megablocks have the following dimensions:

- U-block (l x w x h): 60 x 25,5 x 31,05 m;
- L-block (l x w x h): 37,5 x 9,3 x 30,55 m

Regarding the weight, the U-block reaches 2000 tons each, while the L-block is approximately 783 tons each. Consequently, the entire floaters achieve a maximum overall length of approximately 100 meters, a maximum overall width of around 90 meters, and an overall height ranging between 30 and 36 meters. In terms of weight, the total figure can reach up to 4000 tons.
Given the shape and dimensions of megablocks, it is clear that their fabrication, movement, transportation, storage, and installation necessitate the use of specialized yards, equipment, vessels, and personnel. This complexity is even more pronounced for fully preassembled floaters, which also require a great logistical coordination and specialized resources. In the next section, the logistics related to the transportation of foundations will be analyzed, along with an evaluation of the best available options.

3.2 Megablocks and Pre-assembled floaters

In this thesis, particular attention is devoted to the floating foundation, as it represents a critical component that has not yet been extensively studied and for which there are several different typologies, but very few actual project realizations at the time of writing. While the transportation and standardization of other turbine parts, such as the tower, nacelle, and blades, have been well-documented, also in connection with fixed offshore wind farms, the logistics surrounding the "Star1" remain relatively unexplored. Consequently, the following sections will explore various scenarios to identify the most efficient methods for the fabrication and transportation of these foundations.
Beginning with logistics aspects related to fabrication of the floating foundations, the initial assumption is that the megablocks, which will compose the final foundation, are entirely made and assembled in a fabrication yard in Far East, where steel material and fabrication costs will be significantly lower than in West countries. Starting from this, it is possible to undertake two different strategies. The first one see the transportation of MBs from the fabrication yard in Far East to the assembly yard in Europe, where they will be assembled together in order to obtain the final floater. The second way see both the fabrication and assembly of megablocks in Far East and then transport the pre-assembled floaters directly to Europe. The decision to transport only megablocks or fully pre-assembled floaters depends on various factors and analyses. In particular, this thesis will analyze the following aspects:

- Availability of free area in the yard near the wind farm;
- Risk assessment analysis;
- Availability of Heavy Transport Vessels.

3.2.1 Free area in the yard

Nowadays it is possible to assist to a continuously increasing of goods and items exchange all over the world led by an always growing globalization. As a results ports, and especially those ones of the economical and industrial leading countries, are exceedingly busy due to a more and more robust maritime traffic [81]. This high level of activity can create significant logistical challenges, especially for large-scale projects such as the transportation and installation of floating offshore wind farms. The construction of a floating wind farm consisting of 35 turbines requires a significant amount of space, whether transporting megablocks or fully pre-assembled floaters.
The availability of free area in the yard near the wind farm is a fundamental parameter to consider when deciding whether to transport megablocks or pre-assembled floaters. If megablocks are transported, a sufficient area in the yard is required to store all the blocks, as well as an additional area with all the relevant equipment and appurtenances where they can be integrated to form the final foundation. As previously indicated, megablocks have significant dimensions, making it a considerable challenge to find a yard with adequate space for the blocks that comprise 35 floaters, totaling 105 megablocks. Furthermore, two other critical parameters to consider are the availability of a crane or Self Propelled Modular Transporters at the quay for unloading the megablocks and the yard's ground capacity, given that the blocks have substantial weight. On the other hand, if pre-assembled floaters are transported, the necessity of an integration space becomes less important, as does the need for storage area on land. This is because pre-assembled floaters can also and it becomes more convenient to temporarily store them in the sea, this procedure being known as wet storage. Consequently, this leads to the necessity of finding a yard with significant surrounding free area at the sea, not impaired by ship transit and with suitable depth characteristics. Additionally, wet storage can offer logistical advantages by reducing the need for extensive land-based infrastructure and minimizing the handling of heavy components, which would require suitable cranes difficult to find and with an expensive rate. The figure below [82] depicts an example of storage area in the port on land where numerous turbine components have been stored although with no floating foundations.

Figure 45: Storage area in the port

3.2.2 Risk assessment analysis

Risk assessment forms one of the major components of risk analysis, and for this reason, it is performed for each project. This type of analysis involves the systematic study and identification of potential hazards and risks in a given situation, followed by an evaluation of the potential consequences should these hazards occur using the risk matrix represented in the figure below. This matrix calculates risk by multiplying the probability of an event occurring by the severity of its impact. In this way it becomes easier to visualize and prioritize risks based on their likelihood and impact. As a decision-making tool, risk assessment seeks to determine which measures should be implemented to eliminate and reduce as low as reasonably practicable the consequences of control these risks. Risk analysis encompasses a multi-step process designed to identify and evaluate all potential risks and issues that could be detrimental to the business or enterprise. This comprehensive approach ensures that all possible threats are considered, and appropriate strategies are developed to mitigate their impact [83].

			Rare *so unlikely that is not expected to happen again*	Unlikely *not expected to re-occur in foreseeable future*	Possible *event may occur*	Likely *will re-occur but not as an everyday occurence*	Certain *It will happen again*	
			LIKELIHOOD / PROBABILITY					
			1 Very Unlikely	2 Improbable / Unlikely	3 Remote / Possible	4 Likely	5 Very Probable	Risk Level
Minor No damage, no downtime, no effect on stakeholders, no financial impact, no polluting effect	SEVERITY	1 Minor	1	2	3	4	5	1-2 (Negligible)
Low Potential for small/minor finanical impact, low impact from stakeholder perspective, negligble downtime/lost time		2 Low	2	4	6	8	10	3-6 (Low Risk)
Medium Personnel injury that requires time away from workplace, polluting effect to the size of site/significant area, cost implications that could exceed 7 days project downtime, important effect to project stakeholders		3 Medium	3	6	9	12	15	8-12 (Medium Risk)
High Potential for fatality/life-threatening impact, long term absence of personnel, pollution impact requiring local authority mobilisation, major damage to project with losses above > £1,000,000 Over 14 days of project downtime. Stakeholder senior management/directorate involvement		4 High	4	8	12	16	20	15-20 (High Risk)
Major More than 1 fatality, irreversible impact to human life, mass pollution affecting entire local area, financial impact greater than > £15,000,000, All activties under severe scrutiny from stakeholders, potential project cancellation		5 Major	5	10	15	20	25	25 (Very High Risk)

Figure 46: Risk assessment matrix

In the context of constructing a floating offshore wind farm, a comprehensive risk assessment has been conducted for the entire project, considering two different scenarios: the transportation of megablocks and the transportation of fully pre-assembled floaters. This assessment systematically identifies potential hazards and evaluates their consequences for each transportation method. By determining the necessary measures to control these risks and prioritizing them based on their likelihood and impact, the risk assessment ensures that the chosen approach is both efficient and reliable. This thorough analysis contributes to the overall safety and success of the project by ensuring that all potential risks are effectively managed. In the graphs below, all the risks identified in the risk assessment analysis have been assessed and ranked, so it is possible to notice the general results for both megablocks and fully pre-assembled floaters transportation scenarios.

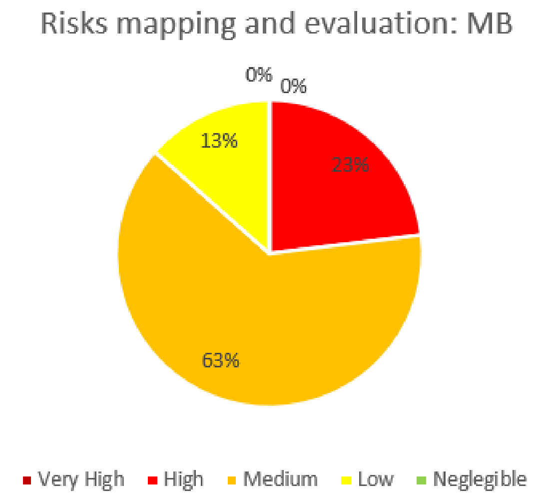


Figure 47: Risks mapping and evaluation: megablocks

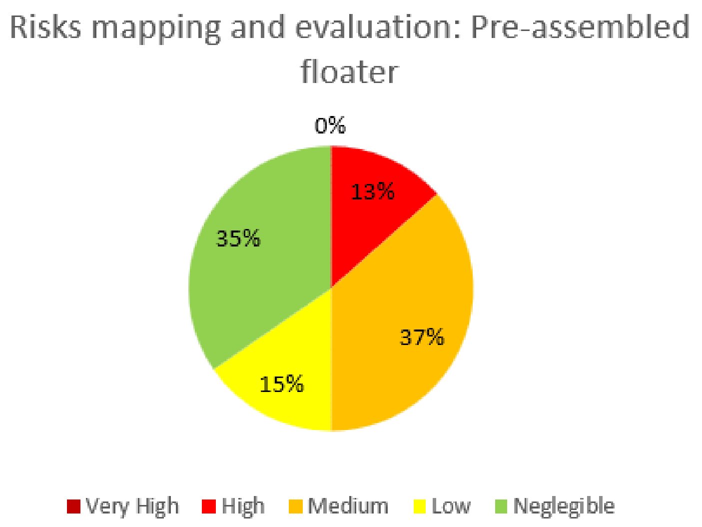


Figure 48: Risks mapping and evaluation: pre-assembled floaters

The two graphs above illustrate the risk assessment for both megablocks (MB) and fully pre-assembled floaters. It is evident that there are zero very high risks for both cases. However, the analysis reveals that the use of fully pre-assembled floaters results in a 10% reduction in high risks and a more than 20% reduction in medium risks. Despite these improvements, there is a slight increase of 2% in low risks associated with fully pre-assembled floaters.

Furthermore, a detailed examination of the risks typologies associated with the various phases of constructing a floating offshore wind farm has been undertaken and is depicted in the graphs below. These graphs provide a comprehensive overview of the potential hazards and their respective risk levels throughout the project. By analyzing these risks in detail, it is possible to identify critical areas that require focused mitigation strategies to ensure the project's overall safety and efficiency.

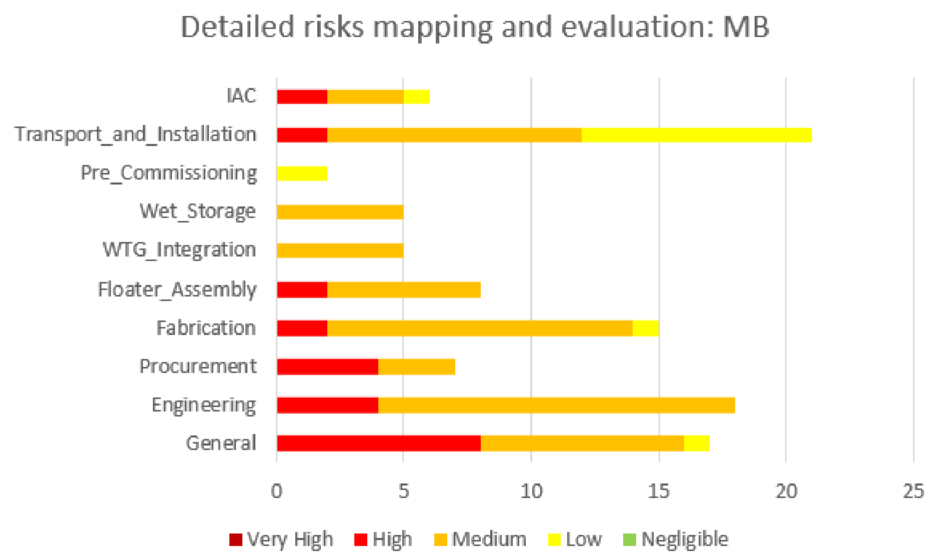


Figure 49: Detailed risks mapping and evaluation: megablocks

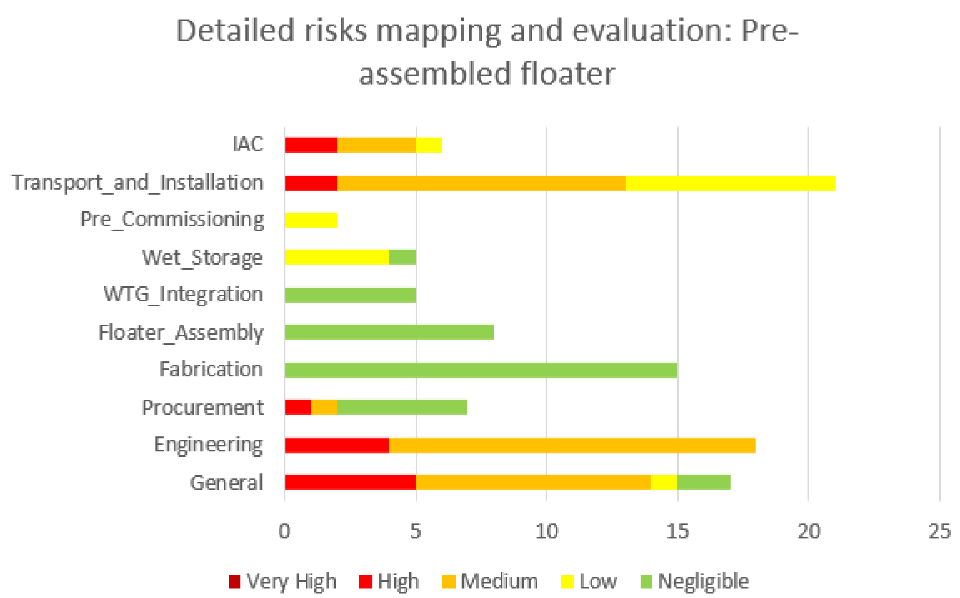


Figure 50: Detailed risks mapping and evaluation: pre-assembled floaters

From the two graphs above it is possible to notice that the reduction in risks associated with fully pre-assembled floaters can be categorized into five primary areas: procurement, fabrication, floater assembly, wind turbine generator integration, and WET storage. This is due to the fact that firstly, pre-assembled floaters eliminate the necessity for additional fabrication facilities in the country where the wind farm is located. This leads to significant cost savings and a reduction in associated risks. By centralizing the fabrication process, the complexities and uncertainties related to establishing new facilities are avoided, thereby streamlining the overall project execution. Secondly, by separating the floater fabrication from the Transportation and Installation (T&I) scope and especially starting fabrication process with due

advance, the two phases can be kept well separated and the risk of delays in one part affecting the other is minimized. This segregation ensures that any potential issues in the fabrication phase do not cascade into the T&I phase, thereby maintaining the project timeline and reducing the likelihood of compounded delays. Lastly, the risk of Megablocks arriving in the destination country with fitting issues is entirely mitigated with fully pre-assembled floaters. The pre-assembly process ensures that all components are accurately fitted and tested before transportation, eliminating the uncertainties and potential complications that could arise from on-site assembly. This preemptive measure enhances the reliability and efficiency of the installation process, contributing to the overall success of the wind farm project. In conclusion, the adoption of fully pre-assembled floaters presents a strategic advantage by addressing key risk factors in procurement, fabrication, floater assembly, WTG integration, and WET storage. The elimination of additional fabrication facilities, the separation of fabrication from T&I scope, and the mitigation of fitting issues collectively contribute to a more streamlined, cost-effective, and reliable project execution.
In the transportation phase, the overall risk levels remain relatively consistent across both scenarios. However, a closer examination reveals that the transportation of fully pre-assembled floaters, which are larger structures, presents higher risk factors in certain activities. Specifically, there is an increased risk of fatigue damage occurring during transportation. Additionally, there is an increased possibility that the vessel may encounter significant wave heights (Hs) that exceed the limits specified in the analysis. Furthermore, there is a risk of cracks or faults developing in the foundation structure during transit, which could be attributed to engineering or quality assurance errors. For these reasons, the analysis of stability, motion, and slamming was conducted on a semisubmersible vessel transporting three fully pre-assembled floaters, the specific layout and configuration of this transportation setup will be detailed in the following pages. The results of this analysis indicate that the transportation configuration satisfies the stability criteria. Although there is a slightly higher local heave at the forward and aft centers of gravity of the "Star1" units, the local heave accelerations at all extremities are acceptable. Additionally, the slamming frequency, impact speed, and immersion at the extremities of the "Star1" units are satisfactory.

3.2.3 Heavy Transport Vessels analysis

The primary objective of the analysis on Heavy Transport Vessels is to determine the number and types of vessels (deck carriers or semisubmersible) that are suitable for transporting megablocks or pre-assembled floaters. This analysis aims to ascertain whether it is more advantageous to assemble the megablocks directly in the Far East or in Europe. In the following pages the results of the analysis will be illustrated. The analysis was conducted using a market database, which lists all the heavy transport vessels currently available on the market and outlines their principal characteristics. Given the constantly evolving nature of the HTV market, it is impractical to maintain a daily updated list of available vessels. Therefore, after a thorough data verification process, it was decided to take a snapshot at the beginning of 2025 of the vessels listed in the document and use that information for the analysis. Below are the characteristics detailed in the document for each vessel.

- General parameters: name of the ship, IMO (International Maritime Organization) code, ownership, vessel typology, and building data;
- Technical characteristics: Level of dynamic positioning system, maximum speed;
- Dimensional Parameters: LOA (Length Overall), Draft, Deck Length, Deck Width, Deck Surface;
- Capacity Parameters: Deadweight tonnage and deck strength.

The original file enumerated 189 heavy transport vessels; however, the analysis has been conducted on 143 vessels because the following categories of vessels were excluded from the analysis due to their lack of relevance to the study's objectives, incomplete data, or outdated specifications.

- Scrapped vessels;
- Vessels where the main parameters were unknown;
- Vessels with the same IMO number;
- Private yatch;
- Crane vessel;

- Vessels with no category.

In the document, the vessels that have been announced by shipowners for future production are also listed. A total of six deck carriers are scheduled to be produced in 2025 or later. At present, no semisubmersible vessels are announced for production in the upcoming years. The remaining fleet of 137 heavy transport vessels comprises 53 semisubmersible vessels and 83 deck carriers, as illustrated in the figure below.

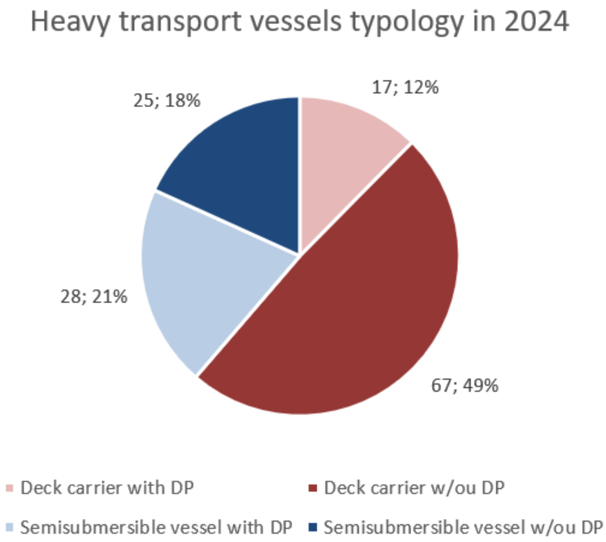


Figure 51: Heavy Transport Vessels typology

In the figure above, the semisubmersible vessels equipped with a dynamic positioning system, also known as DP system, are represented in light blue. These vessels account for 28 out of the 53 semisubmersible ships, which corresponds to 21% of the heavy transport vessels, therefore including also the deck carriers, on the market. The vessels without DP system are depicted in dark blue. Similarly, the deck carriers are shown in red. It is evident that the HTV fleet is predominantly composed of deck carriers without a DP system, which constitute approximately half of the total number of HTVs.
Considering both the currently available vessels and those scheduled for future production, totaling 143 vessels, an analysis has been conducted on the production trends for both deck carriers and semisubmersible vessels. This analysis aims to understand the direction that the market is likely to take. In the following graphs the two trends are represented:

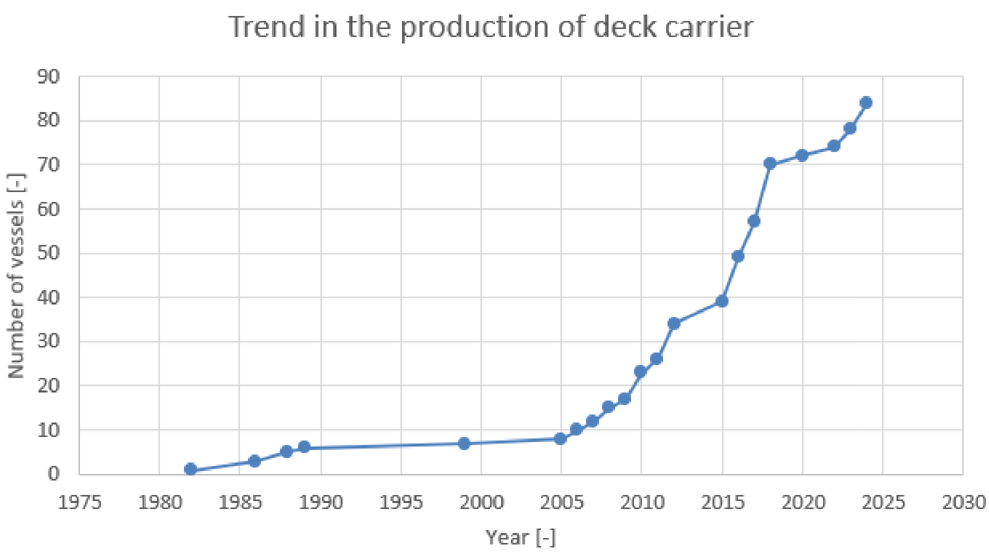


Figure 52: Deck carriers production trend

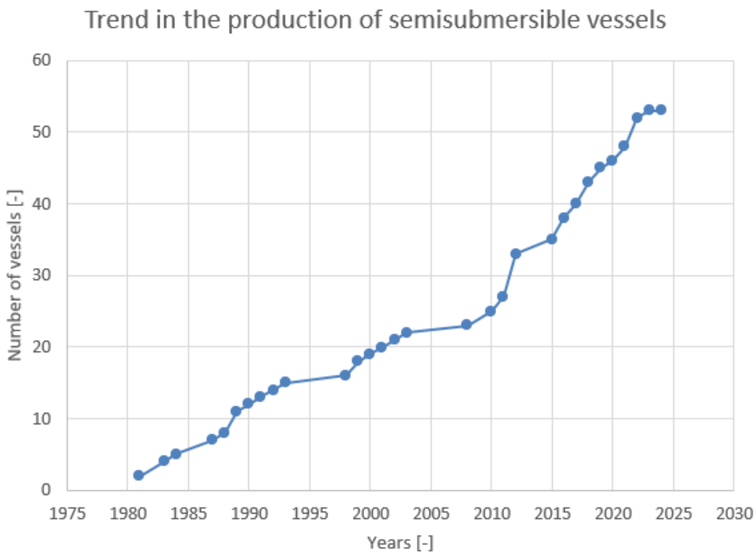


Figure 53: Semisubmersible vessels production trend

The primary noteworthy aspect of the two graphs above is the consistently increasing trends observed in both cases. For deck carriers, a significant increase in production begins around 2005, following an extended period from approximately 1990 to 2005 during which no deck carriers were produced, with the exception of a single vessel. This marked increase in production rate post 2005 highlights a notable shift in the industry. In contrast, the production of semisubmersible vessels exhibits a steady and continuous rise over time. Although there are some short periods of halted production that coincide with the stoppage periods of deck carriers, the overall trend for semisubmersible vessels remains more constant. This suggests a more stable production pattern for semisubmersible vessels compared to the more variable production of deck carriers. Another significant element is the final part of the trend, where it is evident that deck carriers are projected to experience upward momentum in the coming years. In contrast, semisubmersible vessels appear to be reaching a plateau at this time. This trend for semisubmersible vessels may be attributed to the fact that shipowners have not yet announced the production of new semisubmersible vessels. Therefore, this trend should not necessarily be interpreted as an indication that no new semisubmersible vessels will be produced.
In recent years, wind turbines and their associated components have been increasing in size, as illustrated in Figure 28. Consequently, a study has been conducted to examine how the length overall and deck area of heavy transport vessels have evolved over the years. In the two graphs below it is possible to see the results.

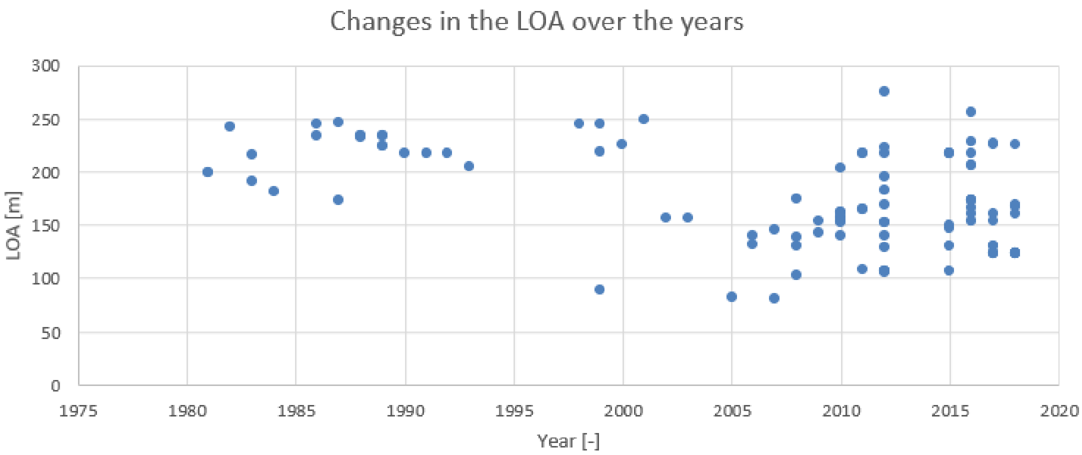


Figure 54: Length overall over the years

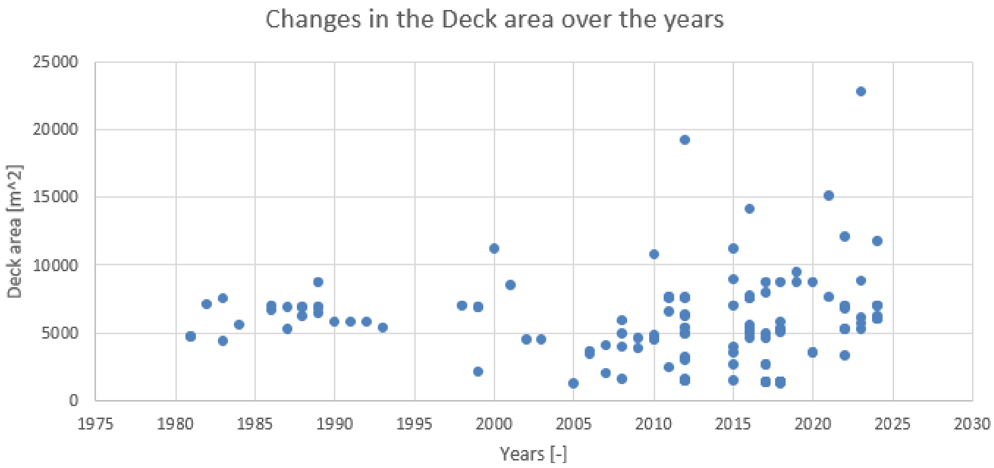


Figure 55: Deck area over the years

Regarding the length overall of ships, there have not been significant changes over the years. However, it is noticeable that in recent years, there are many heavy transport vessels with a shorter length compared to those from approximately 40 years ago. This observation suggests a trend towards larger and shorter ships, which may indicate an improvement in space efficiency on the deck. This supposition finds partial confirmation in the graph related to the deck area over the years. Indeed, in recent years, the deck area has increased although slightly, even though there are still many vessels with a smaller deck area with respect to the ones produced between 1980 and 1995. On the other hand, an analysis of the correlation between deck length and the deck width has been conducted to understand if the hypothesis of shorter and larger ships is trustworthy. Furthermore an analysis on the correlation between deck length and length overall has been assessed. The results are shown below.

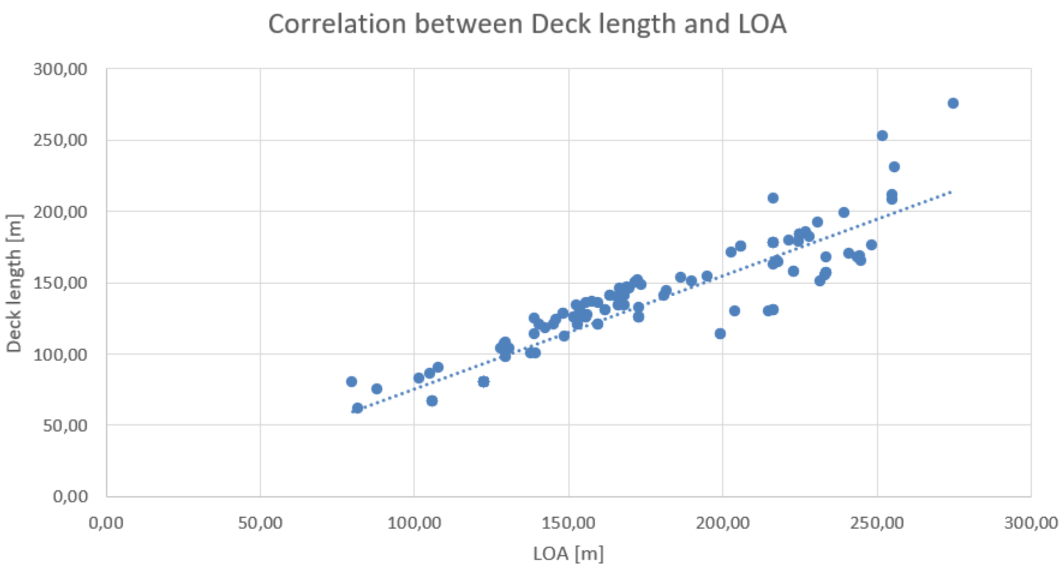


Figure 56: Correlation between deck length and length overall

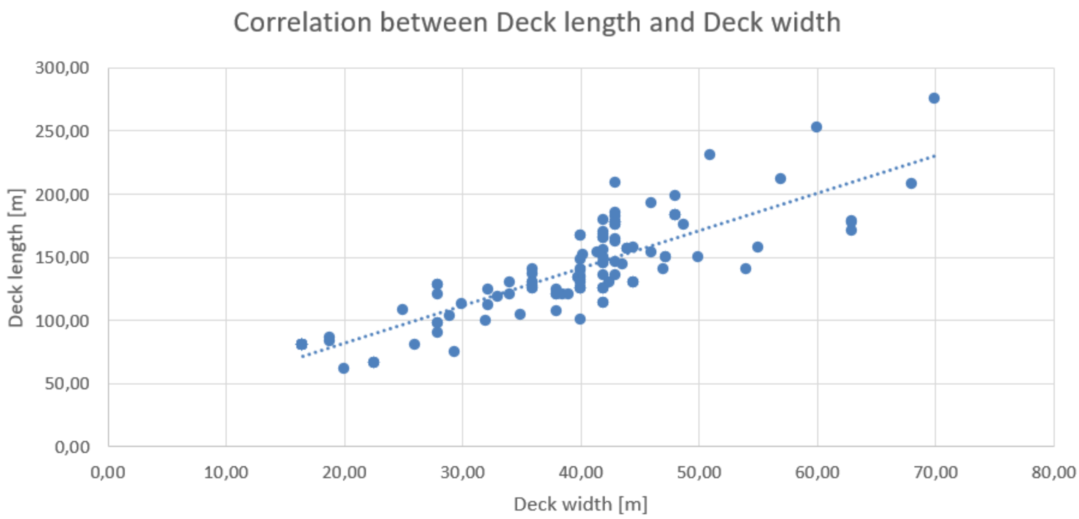


Figure 57: Correlation between deck length and deck width

Beginning with the first graph, it is evident that there is a strong correlation between the deck length and the overall length of the vessel. This relationship is particularly pronounced for lower values, which closely align with the trend. In this case, it can be observed that a greater overall length corresponds to a greater deck length, and vice versa. The second graph illustrates the relationship between deck length and deck width. Here, the correlation between the two parameters is not as strong as in the previous case. Despite the general trend that a larger width corresponds to a greater length, there are instances where the same deck width is associated with a wide range of deck lengths. For example, within the deck width range of 40 to 50 meters, the deck length can vary from 100 to more than 200 meters. In conclusion, these data suggest that ships have not significantly increased their overall dimensions in recent years. Instead, the ability to transport larger components can be attributed to either an increase in deck width, more efficient use of deck space, or a combination of both factors.

After conducting a comprehensive analysis of the changes and correlations in the dimensional parameters of heavy transport vessels, a more focused study was undertaken to evaluate the most distinctive parameters of these vessels. This detailed analysis aimed at understanding how the current fleet can accommodate the complex structures of megablocks and fully pre-assembled floaters, which are essential components in floating offshore wind farm construction projects. The study examined various parameters, including deck strength, draft, speed, and deadweight tonnage to determine the suitability of different vessels for transporting substantial loads such as floating foundations. By analyzing these factors, the study provides insights into the current capabilities and potential limitations of the heavy transport vessel fleet in handling megablocks and pre-assembled floaters.
In the charts below it is possible to observe the deck length and the deadweight tonnage distributions.

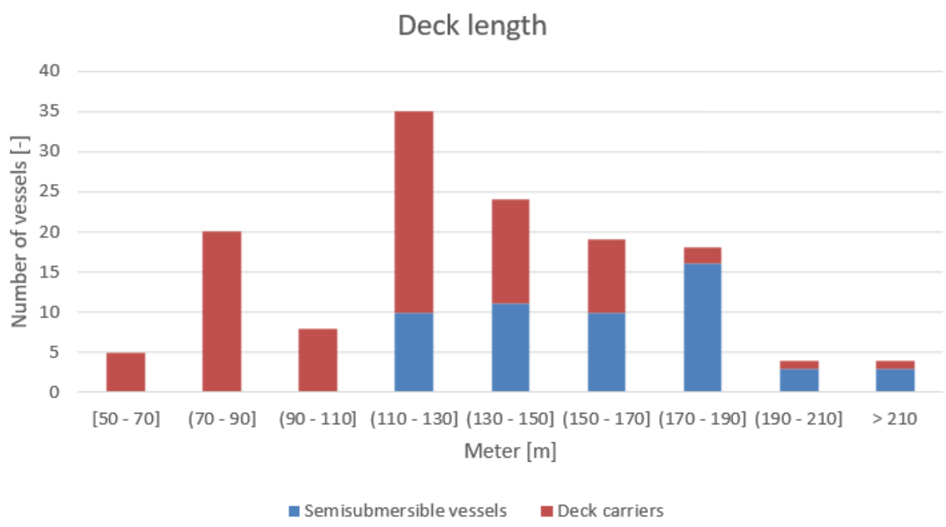


Figure 58: Deck length distribution

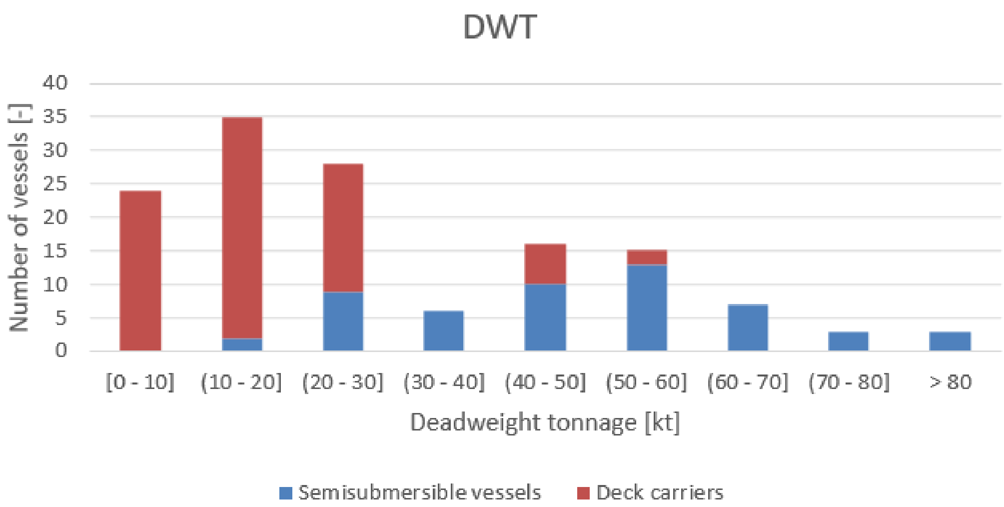


Figure 59: Deadweight tonnage distribution

In the histograms above, the red lines represent the cluster of the deck carriers, while the blue lines indicate that one of semisubmersible vessels. Upon examining the graphs, it is evident that semisubmersible vessels generally exhibit the highest values for both deck length and deadweight tonnage, whereas deck carriers tend to display the lowest values. Regarding deck length, the vast majority of vessels fall within the range of 110 to 190 meters. This is a favorable result considering the dimensions of megablocks and fully pre-assembled floaters as indicated in paragraph "3.1.1 Floating Foundation". On the other hand, concerning the deadweight tonnage parameter, it is evident that deck carriers predominantly cover values up to 30 kt, while semisubmersible vessels accommodate higher values. This distinction underscores the varying capacities and roles of the two types of heavy transport vessels. It is crucial to remember that megablocks can be transported by both deck carriers and semisubmersible vessels. In contrast, fully pre-assembled floaters can only be transported by semisubmersible vessels due to their unique offloading method by adjusting their draft and sinking till their main deck goes under water. This method involves floating off the fully pre-assembled floaters directly into the sea, eliminating the need for a crane, which would be impractical given the substantial weight of the fully pre-assembled floaters.

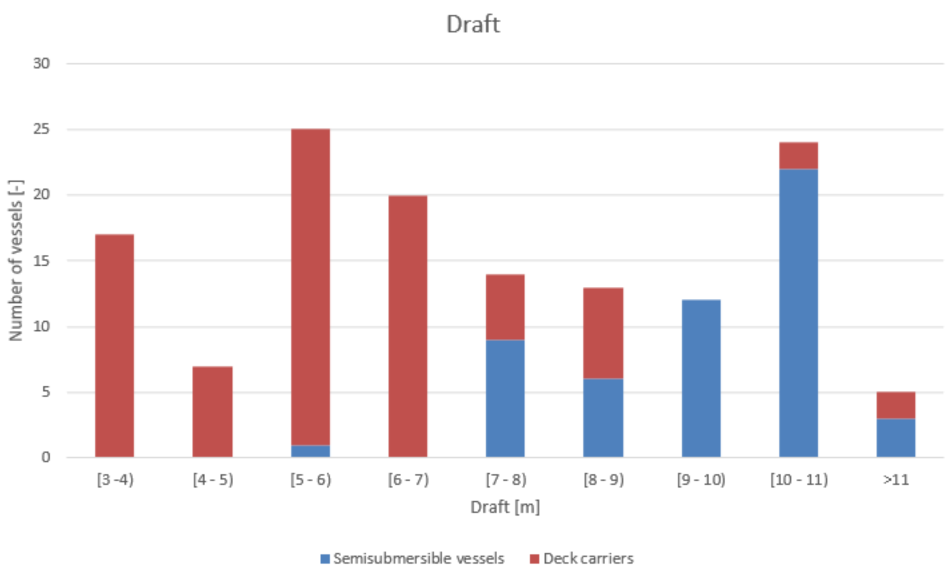


Figure 60: Draft distribution

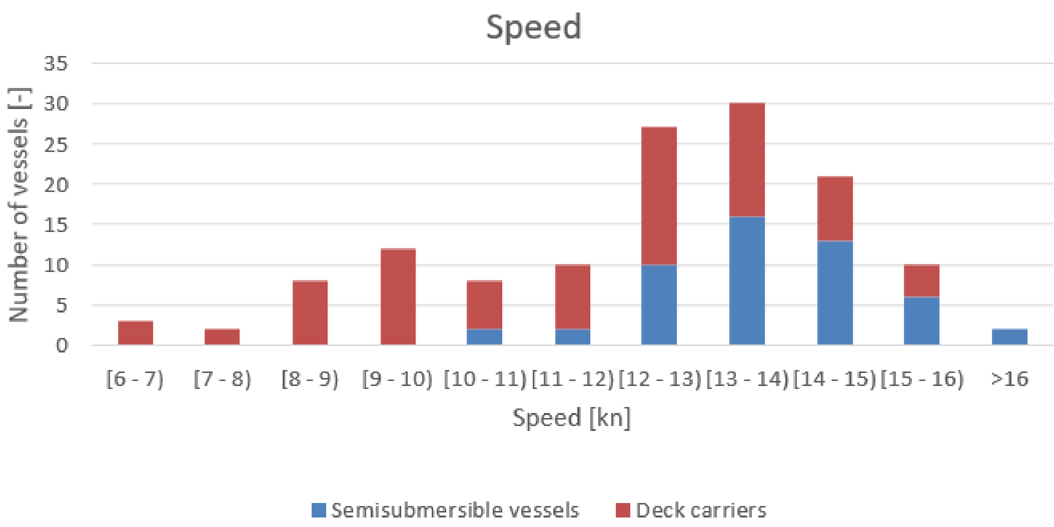


Figure 61: Speed distribution

Draft is an important parameter and it refers to the depth of a ship's hull submerged in water, measured from the waterline to the lowest point of the keel or other reference points. A high draft indicates a greater submerged depth, often signifying that the ship is heavily loaded or designed to carry substantial cargo. Such ships require deeper waters for safe navigation and loading/offloading operations. Conversely, a low draft denotes a shallower submerged depth, suggesting that the ship is lightly loaded or intended for operations in shallow waters, such as rivers or ports with low depths [84]. Considering the histogram depicting draft values, it is evident that semisubmersible vessels, represented in blue, exhibit higher draft values compared to deck carriers, which occupy the lower end of the draft spectrum. This disparity in draft values can lead to significant challenges regarding port access, as vessels with higher drafts may be unable to enter ports with shallow depths. Consequently, the operational flexibility of semisubmersible vessels is constrained by their draft requirements, necessitating careful planning and consideration when selecting loading and offloading ports. On the other hand, it is important to consider that while deck carriers transporting megablocks need to offload the pieces directly onto the quay using cranes or Self-Propelled Modular Transporters, semisubmersible vessels have the advantage of being able to float off the pre-assembled floaters away from the quay, where the bathymetry is suitable. This capability allows semisubmersible vessels to operate in deeper waters, mitigating the issues associated with high draft

values and getting rid of any cranes. However, challenges may still arise when semisubmersible vessels transport megablocks and have the necessity to reach the quay.
Regarding the speed of heavy transport vessels, it is evident from the collected data that the vast majority operate at speeds ranging between 12 and 15 knots.

3.2.4 Availability of Heavy Transport Vessels

Building upon the general analysis presented in the preceding pages concerning megablock measurements and the heavy transport vessels available on the market, a more detailed examination of the number of vessels capable of transporting megablocks or fully pre-assembled floaters is now warranted. This analysis seeks to provide valuable insights into the capabilities and limitations of the current fleet, thereby facilitating informed decisions regarding the most effective transportation strategies for floating foundations from the Far East to Europe. Before proceeding, it is important to consider the classification of heavy transport vessels based on their dimensions. Although not officially standardized, these vessels are commonly categorized into three main classes:

- K class: Vessels with a length of approximately 125 meters;
- X class: Vessels with a length of approximately 178 meters;
- Super X class: Vessels with a length of approximately 200 meters;

These classifications provide a useful framework for understanding the capabilities and limitations of different types of heavy transport vessels in relation to their size and the selected "Star1" foundation size for 15MW turbine generator.
In particular, when considering the transportation of megablocks, it is important to note the dimensions of the individual blocks. A single "U block" measures 60 meters by 25.5 meters, while "L block" measures 37.5 meters by 9.3 meters. To transport six megablocks, comprising four "L blocks" and two "U blocks," which together form two complete floating foundations, a ship with a deck length of at least 125 meters is required, i.e. a K-Class vessel. This calculation is based on the optimized layout illustrated in the figure below.

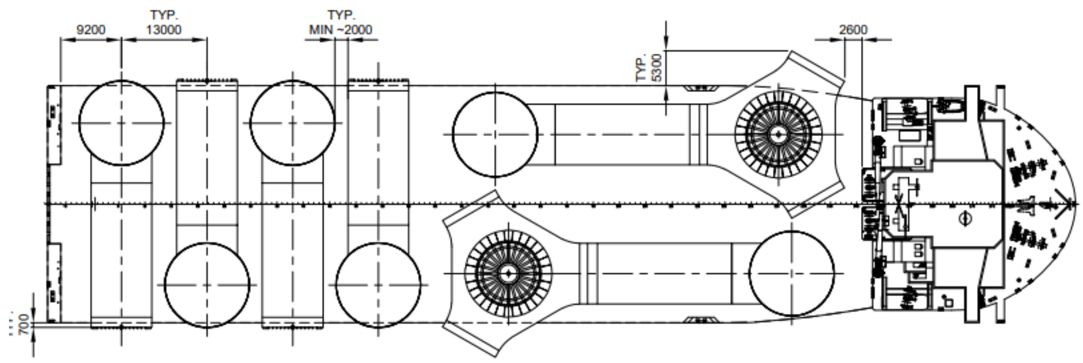


Figure 62: Megablocks layout on a K class HTV

Based on the analysis conducted using the HTVs file, it has been determined that the vessels possessing adequate deck dimensions to transport all the megablocks necessary for the assembly of two complete floaters are comprised of 40 deck carriers and 51 semisubmersible vessels.

The option of transporting only 3 megablocks (1 U block and 2 L blocks) necessary for one floater was not considered, due to the high number of shipments required to transport all the megablocks necessary for the construction of 35 foundations in an acceptable time and the budget related to such a scenario leading to unacceptable costs and “diseconomies of scale”.

Considering the scenario of transporting nine megablocks, which are essential for the construction of three complete floating foundations, it has been calculated by the ownership that a vessel with a minimum length of 177.6 meters is required, i.e. an X-Class ship. The figure below illustrates the layout of the deck.

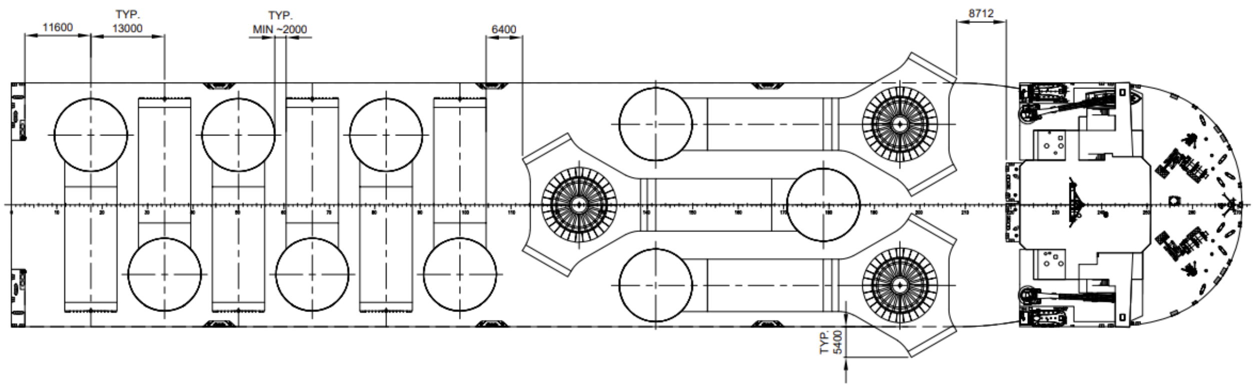


Figure 63: Megablocks layout on a X class HTV

Based on the analysis conducted using the HTVs file, it has been determined that the vessels with adequate deck dimensions to transport all the megablocks necessary for the assembly of three complete floaters include 4 deck carriers and 24 semisubmersible vessels. From these results, it is evident that there is a strong prevalence of semisubmersible vessels compared to deck carriers in terms of availability.

The transportation of fully pre-assembled floaters can only be achieved using semisubmersible vessels due to their unique capabilities. Specifically, for the transportation of three fully pre-assembled floaters, it is essential to employ at least an X class vessel. The figure below provides an illustration of the deck layout used for this purpose. This layout has been already meticulously analyzed to ensure the stability, motion, and slamming characteristics of the vessel and its cargo. The stability analysis confirms that the vessel configuration meets all necessary criteria, while the motion analysis evaluates the heave, pitch, and roll movements to ensure safe transportation. Additionally, the slamming analysis assesses the impact forces and immersion levels at the extremities of the floaters, ensuring that the structural integrity is maintained throughout the journey.

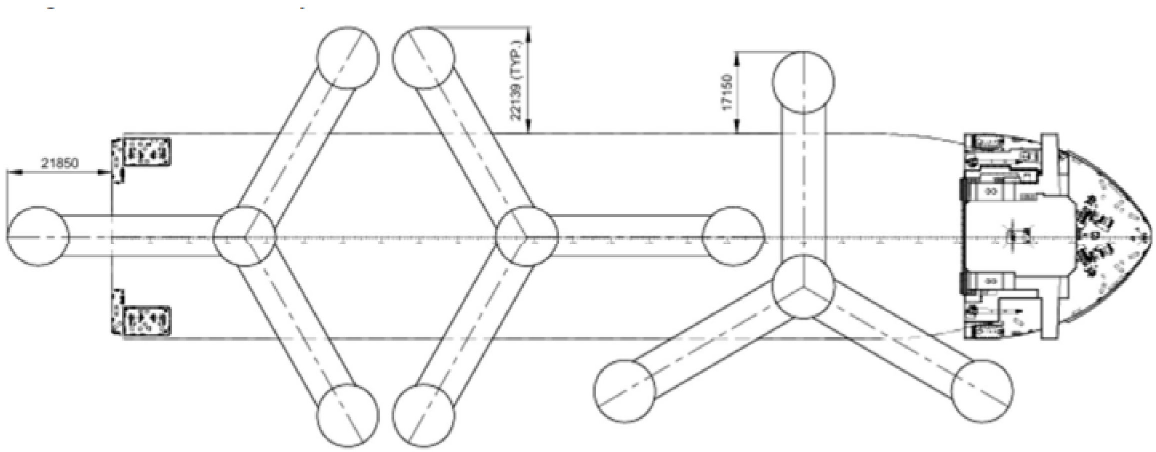


Figure 64: Pre-assembled floaters layout on a X class HTV

Based on the HTVs analysis, the number of semisubmersible vessels available for this type of transportation is 24.

Regarding super X class vessels, which are defined as vessels with a deck length exceeding 200 meters, the HTV market database identifies a total of six vessels in this category. Given that these vessels are not exclusively used for floating wind projects but also serve other markets, the availability of only six vessels is deemed insufficient for a dedicated floating wind project with the size of the base case considered. Consequently, it is reasonable to anticipate that the limited number of super X class vessels will result in significantly higher costs for their use in floating wind projects. For these reasons, this thesis will consider X class vessels as the reference ships.
The deck carriers and semisubmersible availabilities obtained for the two different scenarios, i.e. MBs

to be then fully assembled in Europe and floating foundations already fully constructed and shipped from the far east, show that there is not a strong prevalence of deck carriers availability, but the figures are comparable, therefore the final decision if to ship MBs and complete the fabrication in Europe and transport foundations already fully assembled will be driven by other considerations which shall especially duly account also for fabrication yard availability and cost in Europe, possibility for fully assembled foundation wet storage, project schedule flexibility, total number of foundations to be transported and, last but not least, fabrication and transport contingencies.

3.2.5 Conclusions

All analyses conducted in this study are based on a set of assumptions, acknowledging the complexity of the construction of a floating wind farm and the multitude of variables that influence each phase of this project typology. Consequently, each case must be evaluated individually to determine the most suitable option. Considering the main aspects analyzed in the previous pages, which explore different scenarios involving the integration of megablocks either in the Far East or in Europe, and the transportation of floating foundations either in separate parts or as fully pre-assembled floaters, it becomes evident that the most efficient scenario is the transportation of fully pre-assembled floaters.
The assembly of megablocks outside the fabrication yard introduces several logistical challenges that must be carefully considered. One of the primary issues is the requirement for a substantial storage area at the integration yard in Europe. Currently, there are no ports in Europe that can dedicate such extensive space exclusively for the floating wind project. This limitation poses significant constraints on the feasibility of assembling megablocks at these locations. In addition, the integration yard must accommodate not only the storage of large megablocks but also the necessary infrastructure to support their assembly. This includes heavy-lift cranes, specialized handling equipment, and sufficient space for maneuvering and staging the various components. The lack of available space at European ports suggests that transporting fully pre-assembled floaters directly from the Far East could be a favorable alternative. Unlike megablocks, fully pre-assembled floaters do not require extensive storage space on land; instead, they can be stored in the sea. While this approach mitigates the issue of land storage, it does introduce some other challenges. Sea space, although more flexible, is not unlimited and requires a well-designed mooring system to secure the floaters. Furthermore it has to be a sheltered one. This solution, however, can still be more efficient and practical compared to the logistical complexities of land storage. Regarding the risks associated with the integration of the floating foundation in Europe or the Far East, the risk assessment analysis presents a clear scenario. It indicates that fabricating and integrating the foundation in the Far East entails fewer overall risks. Although the transportation phase does not exhibit significant differences in terms of risks between transporting megablocks and fully pre-assembled floaters, the overall risk profile favors the Far East option. The transportation of both megablocks and fully pre-assembled floaters involves similar levels of risk, such as potential damage during transit. However, the integration phase in the Far East benefits from more established infrastructure and expertise, which mitigates many of the risks associated with the project. In summary, while the transportation risks for megablocks and fully pre-assembled floaters are comparable, the overall risk assessment favors the fabrication and integration of the floating foundation in the Far East due to the reduced logistical and infrastructural challenges. Finally, regarding the vessels capable of transporting these types of foundations, whether they are megablocks or fully pre-assembled floaters, it has been determined that the number of suitable vessels is approximately the same for both scenarios. Specifically, for the transportation of nine megablocks, which would constitute three complete floaters, there are 4 deck carriers and 24 semisubmersible vessels available. In comparison, for the transportation of three fully pre-assembled floaters, there are 24 semisubmersible vessels available. This indicates that semisubmersible vessels play a crucial role in the transportation of floating foundations. However, their draft can pose challenges for the transportation of megablocks, which require offloading at the quay. The deep draft of semisubmersible vessels may limit their accessibility to certain ports, complicating the logistics of offloading megablocks. In conclusion, considering all the previous analyses and evaluations, it has been decided to fabricate the pre-assembled floaters in Far East and transport them to Europe, where they will be integrated with the tower and other turbine components. The transportation will be carried out as depicted in Figure 64, utilizing an X class semisubmersible vessel to transport three pre-assembled floaters. This method ensures that the floaters are securely and efficiently transported, ready for final assembly upon arrival in Europe. The subsequent pages of this thesis will concentrate on the scheduling and timing of the various stages of the project. These analyses will be grounded in the findings and decisions outlined in this chapter.

3.3 Transit paths from the Far East to Europe

To transit from the Far East to Europe, there are two primary routes available. The first route involves passing through the Suez Canal, which offers a more direct and shorter path. The second route takes vessels around the Cape of Good Hope, which, although longer, may be chosen for various safety strategic or logistical reasons that will be explained here below. It is important to note that the fully pre-assembled floaters overhang does not pose any issues for passage through the Suez Canal. This has been thoroughly checked and approved by the Suez agent. The figure below illustrates these two transit paths, highlighting the options available for maritime transportation between these regions.

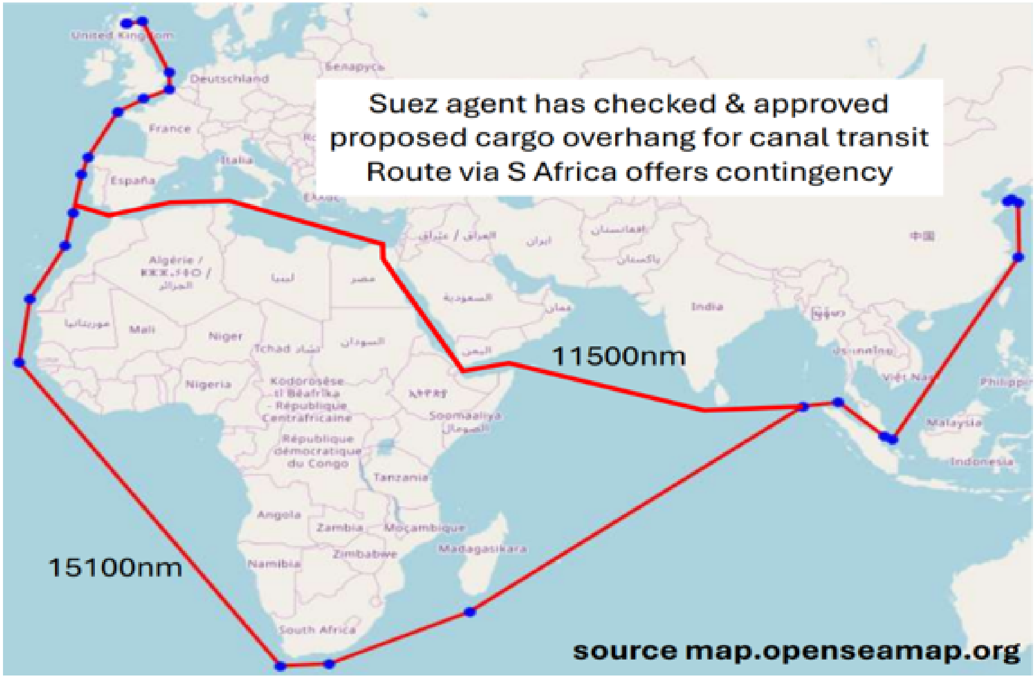


Figure 65: Transit paths

As illustrated in the figure above, the route through the Suez Canal spans approximately 11,500 nautical miles, whereas the transit path around the Cape of Good Hope is roughly 4,000 nautical miles longer. At first glance, it may seem that the transit through the Suez Canal is more convenient due to its shorter distance, which results in reduced transit time and ship deployment. However, there are numerous variables that must be considered. Firstly, the passage through the Suez Canal incurs a significant cost, which tends to increase annually. If the project plans to transport 35 floating foundations, three at a time, from the Far East to Europe, it would necessitate 12 voyages. Consequently, the cumulative cost of the Suez Canal passage could become substantial and cannot be overlooked. In addition, it is important to consider the international geopolitical situation. In recent years, ships flying Western flags, as opposed to Chinese flags, have increasingly become targets for piracy. Consequently, it has become necessary to pay for additional security escorts when transiting through the Suez Canal. This added security measure further increases the overall cost and complexity of using this route. The Suez Canal is highly congested, which could result in delays. Additionally, the speed of transit would be reduced as it is necessary to follow the convoy speed of the ships passing through the canal. On the other hand, the passage through the Cape of Good Hope offers a contingency plan. This route does not involve any passage tax, allowing for free transit. Additionally, it is free from the threat of piracy, although it is a longer journey. Furthermore, this route provides greater flexibility in scheduling and can be advantageous in avoiding the congestion and potential delays associated with the Suez Canal. In conclusion, each case must be evaluated separately based on the specific needs of the project and its schedule. In this thesis, the passage through the Suez Canal will be considered the base case, as ownership quotations for semisubmersible vessels indicate that the lump sum costs for both routes are equivalent. This cost equivalence arises because all expenses associated with the Suez Canal are comparable to the increased deployment time and fuel consumption required for the passage around the Cape of Good Hope.

4 Sensitivity Analyses

In Chapter 4, the optimal scenario, referred to as the "base case", for the production and assembly of floating foundations for the development of a floating wind farm has been identified. This base case entails the fabrication of 35 fully pre-assembled floaters at a dedicated yard located in the Far East. The completed floaters will then be transported to Europe via the Suez Canal, using X-class semisubmersible vessels. The transportation strategy involves a fleet of three of such vessels, each carrying three fully pre-assembled floaters per voyage. Each vessel will undertake four round trips, resulting in a total of 12 voyages required to deliver all units to their destination.

In this chapter, the base case project schedule will be simulated with the objective of assessing the feasibility and timing of the proposed logistics strategy. Furthermore, a series of sensitivity analyses are carried out to evaluate the impact of varying levels of transport vessel availability on the overall project timeline, rather than examining delays arising from other project phases, such as fabrication, integration and installation. Gantt charts have been employed to assess the impact of these analyses on the overall project delivery timeline. Given the complexity of the project, several assumptions have been made to enable the simulation and analysis. It should also be noted that, for the purposes of this study, particularly in the base case, potential issues or unforeseen incidents have not been taken into account. These considerations will be specified for each case throughout the chapter.

The main operational phases accounted for in the scheduling framework include:

- Fabrication of fully pre-assembled floaters
  Fabrication of the first foundation requires a period of nine months. However, once the initial foundation is completed, a set of three fully pre-assembled floaters can be delivered every 30 days. This obviously implies that more floating foundations are fabricated in parallel.
- Transportation of fully pre-assembled floaters from Far East to Europe
  Transportation process encompasses a total transit cycle of 95 days. This cycle is divided into several distinct phases: 45 days are allocated for the outbound voyage from the Far East to Europe, 40 days are designated for the return transit of the vessel from Europe back to the Far East, 6 days are required for the loading of the fully pre-assembled foundations onto the ship at the fabrication facility, and an additional 4 days are necessary for their float-off at their final destination in Europe. The return transit is quicker compared to the outbound voyage because the vessel is unloaded, allowing it to travel at a faster speed despite covering the same distance.
- Tests on fully pre-assembled floaters
  Upon the float-off of the foundations at the integration yard in Europe, a series of tests will be conducted to ensure the proper functioning of all instrumentation following the voyage. This verification process is crucial to ascertain that the equipment has not been compromised during transit and is operating within the expected parameters. Each foundation will undergo a testing period of 30 days and is fundamental to ensure the fully pre-assembled foundation is ready to undergo the next project phase.
- Integration of the Wind Turbine Generator
  Following the successful testing of the foundations, the integration phase can commence. This stage involves the assembly of the floating foundation with the main components of the wind turbine, including the tower, the generator and the blades. The integration process is estimated to require approximately 10 days per turbine.
- Installation of the Fully Assembled Units
  The final phase of the schedule covers the installation of fully assembled wind turbines at their designated offshore locations, where the wind farm will be developed. As this process entails offshore operations, it is subject to seastate limitations and therefore cannot be carried out year-round. For the purposes of this analysis, the installation window has been restricted to the period between the beginning of April and the end of September, when weather and sea conditions are generally more favorable in the North Sea. The installation process is estimated to require 8 days per turbine.

4.1 Base Case

The primary objective of the project is to install all 35 wind turbines in a continuous process within the shortest possible timeframe, thereby minimizing costs associated with equipment, personnel, and other related resources. Consequently, the project schedules have been developed, considering the installation phase as the leading process, as this is the only process constrained by a specific time window, starting on April the 1st and ending on September the 30th, due to the open sea operations being limited by sea state conditions. By anchoring the schedule to the installation period, the integration phase is planned immediately before installation, preceded by the testing phase, the transportation phase, and finally the fabrication phase. This backward scheduling approach has made it possible to identify the exact start date for the fabrication of the fully pre-assembled floaters, thereby ensuring proper alignment with the overall project timeline.
The base case overall schedule is represented in the figure below. In particular, the first important aspects to notice are the two installation windows highlighted in light green. Each window spans a total duration of 183 days. Given that the installation of each turbine requires an average of 8 days, it is feasible to install 22 turbines during the first installation season, which in this study has been considered to occur in spring/summer 2027. The remaining 13 turbines are scheduled to be installed in the second season, which will occur in spring / summer 2028. In the graph below, it is also possible to notice the delivery date of the first batch of fully pre-assembled floaters, November 2026, indicated by a green circle. By adding a fabrication lead time of nine months from this date, necessary to produce the first fully pre-assembled floater, the corresponding fabrication start date can be determined as February 2026.

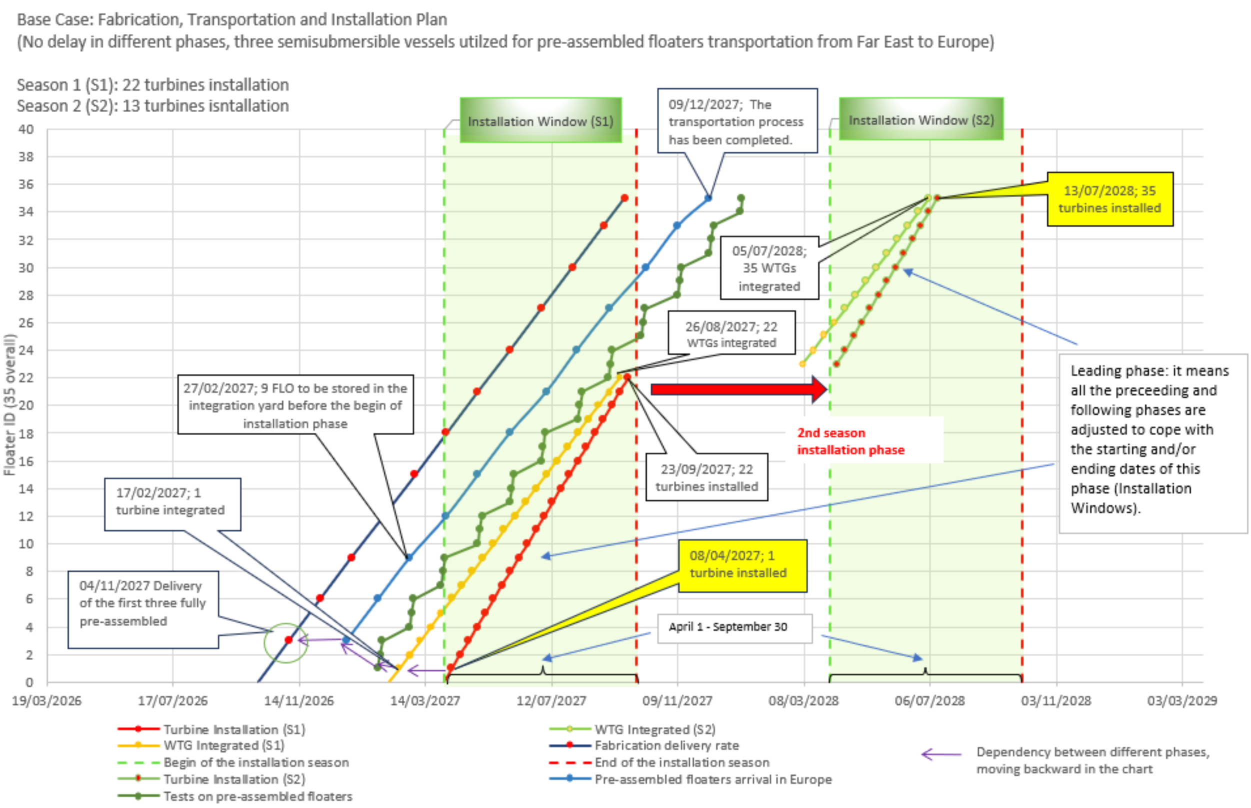


Figure 66: Base case overall schedule

In the graph above, it can be observed that continuous, non-stop fabrication, transportation and testing phases have been assumed, meaning that once started, these processes continue uninterrupted until all 35 turbines are completed. This once again aims at minimizing project disruption and involved costs for equipment rental and mobilization/preparation and demobilization/dismantling activities costs.
The Gantt chart below provides a detailed illustration of the relationship between the fabrication, transportation, and testing phases in the base case scenario. Each number within a block corresponds to a specific foundation or turbine associated with that block. For example, the numbers 1-2-3 in the first green block indicate that the fully pre-assembled foundations for turbines 1, 2, and 3 will be produced

during this time period. This pattern continues throughout the chart, clearly delineating the sequential production and subsequent phases for each foundation and turbine.

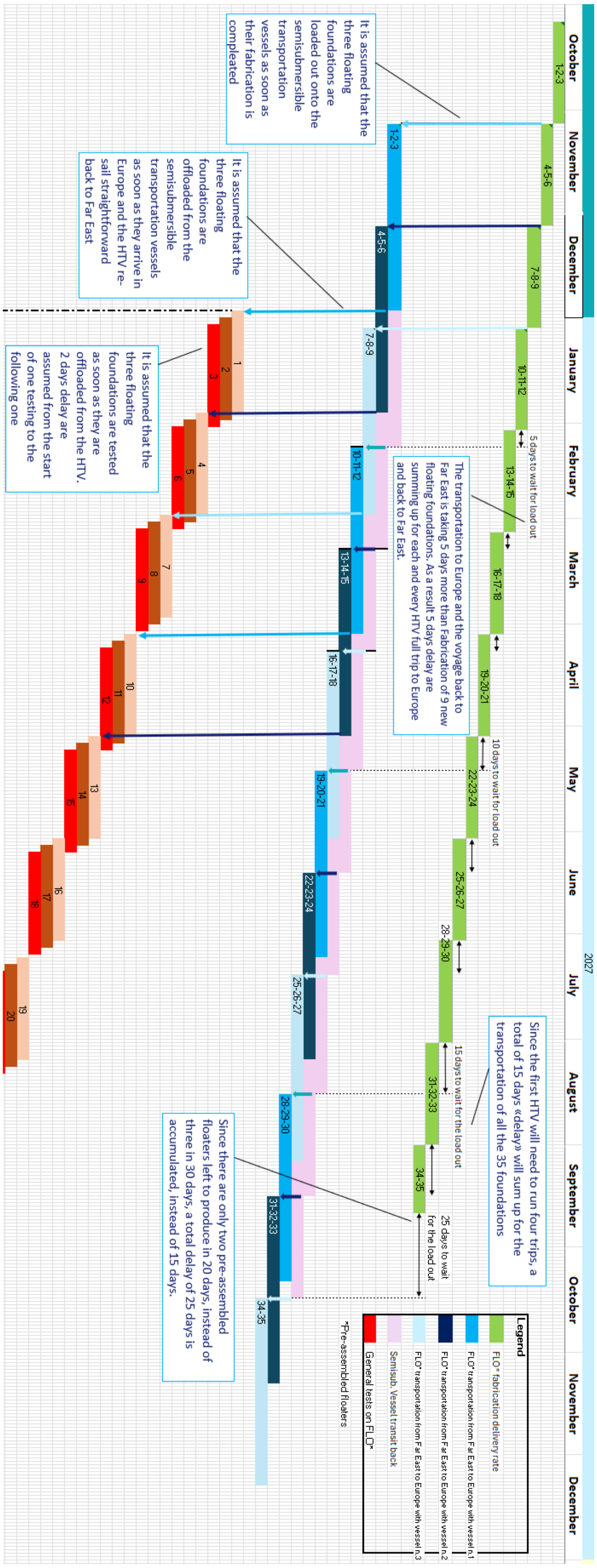


Figure 67: Base Case: Relationship between fabrication and transportation processes

In the schedule above it is possible to notice in green the fully pre-assembled floating foundations fabrication phase, in three different shades of blue, one for each vessel, the transportation phase, and finally, in pink, brown and red the testing phase. Starting from the relationship between the first two processes, as highlighted by the blue arrow, the first three batches of fully pre-assembled floaters fabricated are loaded onto the vessels, readily available in the port, immediately upon completion of their fabrication. On the contrary, the following nine batches have to wait in the fabrication yard until the vessels return to the Far East from Europe. In particular:

- Fully pre-assembled floaters from No. 1 to No. 9 do not have to wait for the load-out phase.
- Fully pre-assembled floaters from No. 10 to No. 18 have to wait in the fabrication yard for 5 days.
- Fully pre-assembled floaters from No. 19 to No. 27 have to wait in the fabrication yard for 10 days.
- Fully pre-assembled floaters from No. 28 to No. 33 have to wait in the fabrication yard for 15 days.
- Fully pre-assembled floaters No. 34 and No. 35 have to wait in the fabrication yard for 25 days.

The fully pre-assembled floaters waiting period in the integration yard introduces a degree of scheduling flexibility, as it creates a buffer that helps absorb minor fabrication delays without affecting the overall project timeline. Nevertheless, this does not imply any idle time for the vessels, as they resume loading operations immediately upon arrival at the fabrication yard, ensuring a continuous transport cycle. Once the fully pre-assembled floaters are loaded off in Europe, they are immediately subjected to testing operations. For the purposes of this study, it has been assumed that three floaters can be tested in parallel, with a two days offset between the test of the first and the second and the second and the third fully pre-assembled floater of each and every batch. After examining in detail the correlations between the first three processes involved in the construction of a floating wind farm, the subsequent steps upon their arrival in Europe will now be explained. The explanation can start from the graph below, which depicts the testing, integration, and installation phases.

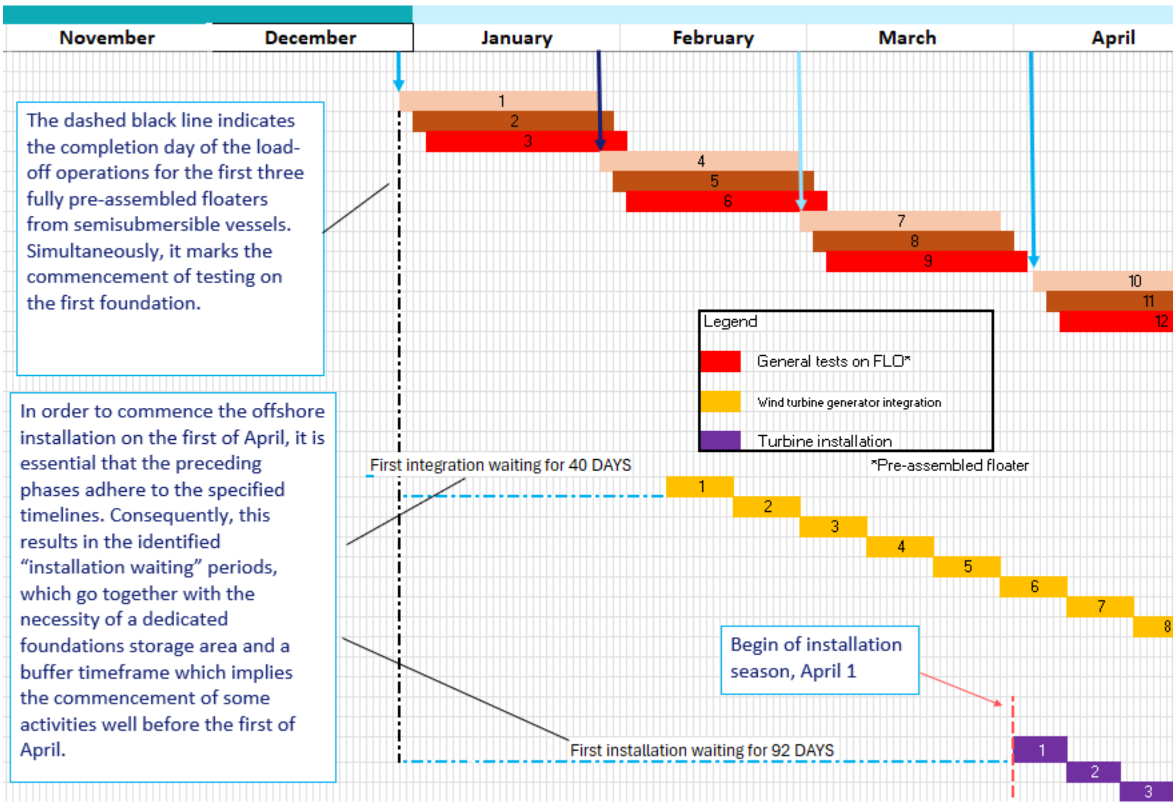


Figure 68: Base case: Fully pre-assembled floaters waiting periods

Upon arrival in Europe, the fully pre-assembled floaters undergo a testing phase that lasts for 30 days. To adhere to the transportation and integration schedule, there is a one-day pause between the testing of each set of three batches of fully pre-assembled floaters. However, once the foundations reach Europe, they must remain in the integration yard for 40 days before the integration process can begin, as indicated by the yellow section in the chart above. In addition, there is a waiting period of 92 days before the installation phase begins, which is represented by the purple section in the chart above. This installation phase is scheduled to start on April the 1st. This waiting period is necessary to ensure a continuous installation sequence aligned with the predefined start date. As a result, a wet storage area located near the integration yard is required to temporarily store the floating foundations during this period, as well as the already integrated turbines that are awaiting installation. In particular, a long-term wet storage is required for the floating foundations that will not be installed during the first installation window but during the second. Assuming continuous fabrication and transportation processes, all 35 foundations are expected to be delivered to Europe by December 2027, as shown in Figure 66. However, turbines numbered 23 to 35 are scheduled for installation starting from April the 1st, 2028. Consequently, these 13 floaters will need to be stored for approximately four months prior to their final installation. In conclusion, in the schedule below it is possible to notice the relationships between testing, integration and installation phase.

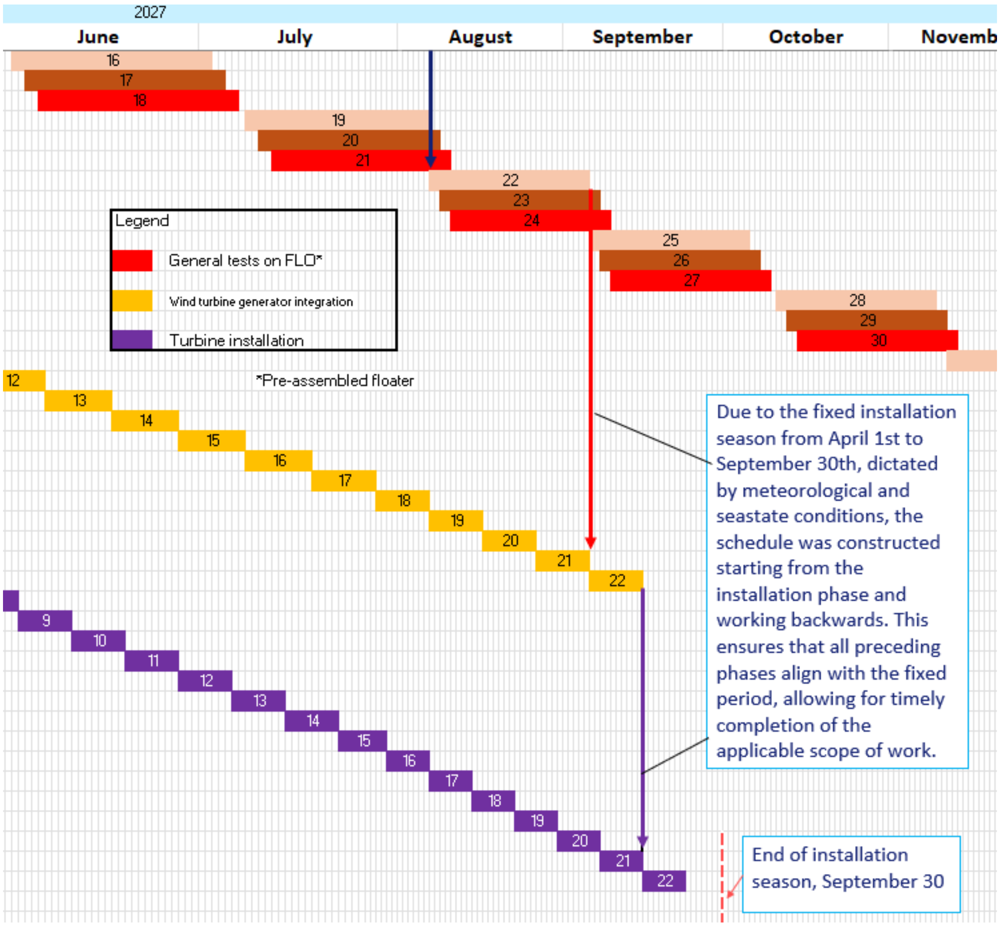


Figure 69: Base case: Relationship between tests, integration and installation processes

The most significant aspect illustrated by the graph above is the representation of the construction of the schedule, which is made backwards. Specifically, turbine No. 22, which is the final turbine to be installed during the first installation season, completes its integration phase on the day immediately preceding its installation. This same sequential relationship is observed between the testing and integration phases. This backward scheduling approach ensures a seamless transition between phases, thereby supporting a continuous and uninterrupted installation process in order to minimize the stops and hidden periods of the installation spread such as anchor handling tugs, towing tugs, survey and supporting vessels which are the most expensive asset in terms of daily rate the project will need to pay for.

4.2 Case 1: Deployment of four semisubmersible vessels

In this scenario, the deployment of four Heavy Transport Vessels, always of semisubmersible type, for the transportation of 35 fully pre-assembled floaters from the Far East to Europe is considered. All other assumptions from the base case stay the same. As illustrated in the following graphs, the fabrication process remains unchanged with respect to the base case. However, this configuration results in an earlier completion of the transportation phase. The use of four vessels ensures that not only the first three batches of fully pre-assembled floaters, but also all the subsequent batches, are promptly loaded and shipped as soon as their fabrication is completed. This approach effectively eliminates any waiting time for fully pre-assembled floaters at the fabrication yard, thus removing also any need of storage area. Consequently, the final batch of floating foundations arrives in Europe on November the 14th, 2027, compared to December the 9th, 2027, in the base case. For this reason, the testing phase, which begins as soon as the foundations arrive in Europe, can commence earlier compared to the base case and consequently also conclude earlier. Conversely, the schedule for all the other project phases remains unchanged.

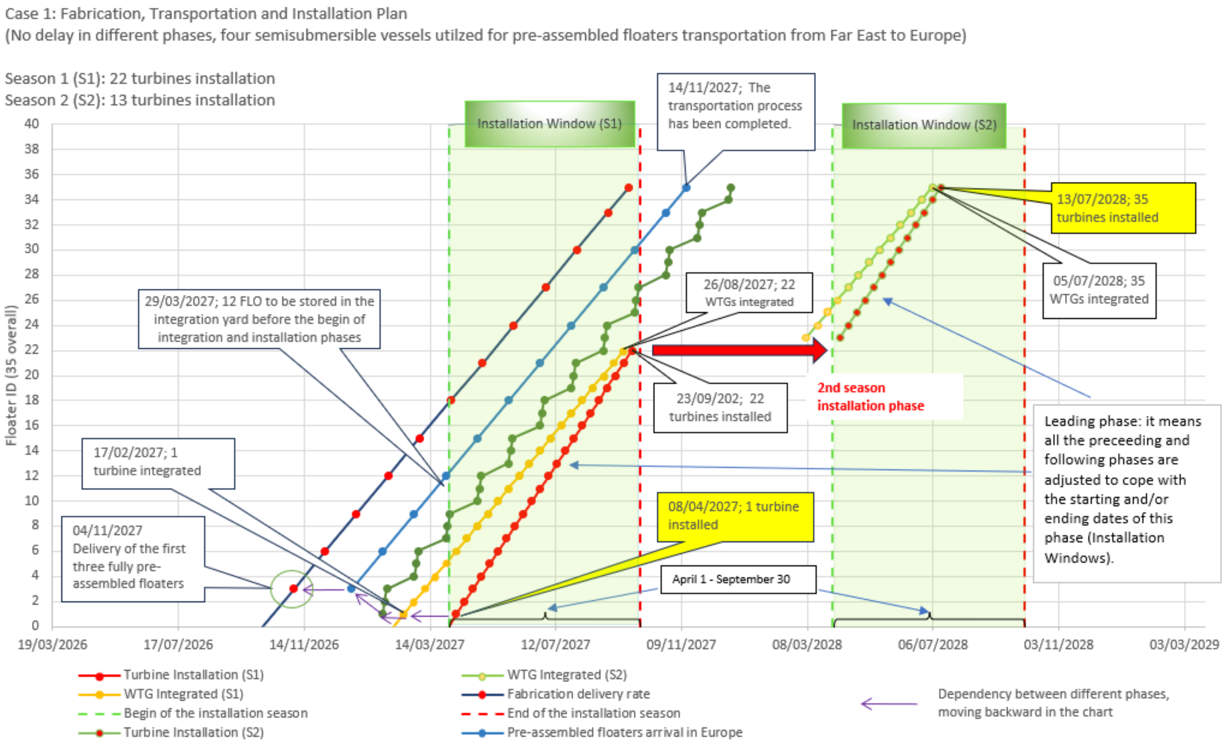


Figure 70: Case 1 overall schedule

The Gantt chart below illustrates the relationship between the fabrication and transportation processes. It becomes evident that the earlier delivery, compared to the base case, is attributed to the increased availability of vessels. However, this increased availability results in the vessels remaining idle in the port for 25 days for each cycle, with the only exception of the first cycle which is not subjected to the transit cycle. This leads to a total of 50 days of idleness for each vessel. The last batch of fully pre-assembled floaters consists only of foundations No.34 and No.35, as a consequence of having a fabrication delivery rate of 20 days instead of 30. Consequently, the vessel designated to transport this final batch needs to wait only 15 days instead of 25. This situation poses a significant cost issue, as each day that a vessel remains idle in the port incurs in additional costs.

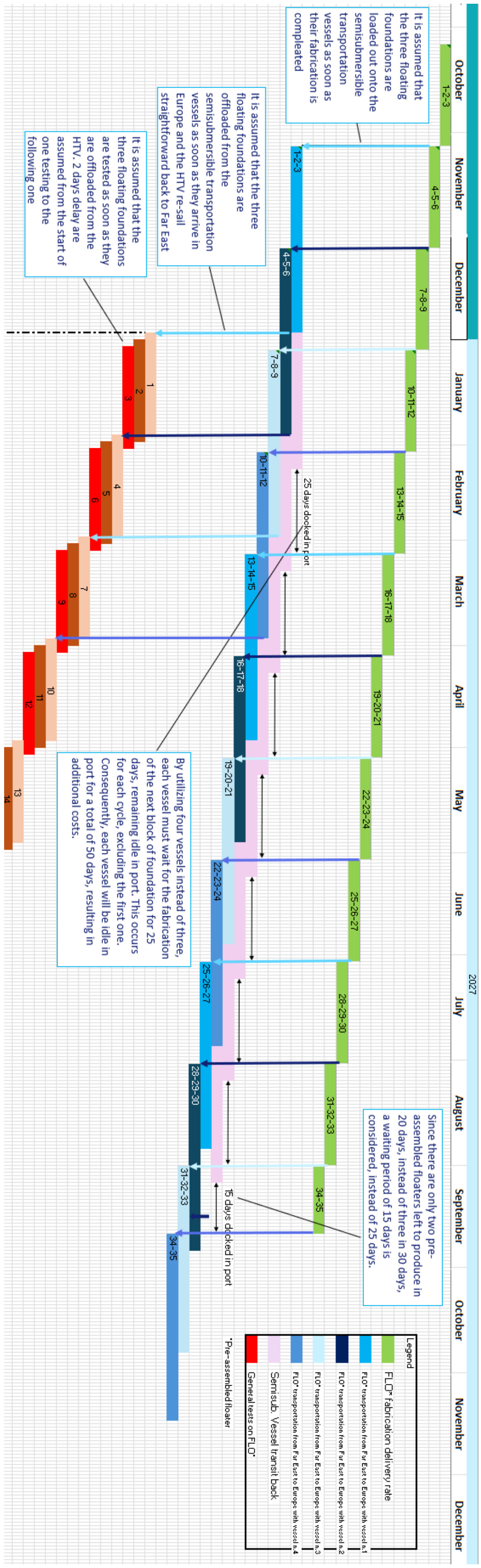


Figure 71: Case 1: Relationship between fabrication and transportation processes

In Figure 72, the waiting periods associated with the integration and installation phases are illustrated. It is evident that these periods are identical to those in the base case. This consistency arises from the fact that the fabrication, transportation, and subsequent testing processes remain unchanged for the first three batches of fully pre-assembled floaters. In fact, as soon as these foundations are fabricated, they are immediately loaded onto the Heavy Transport Vessel ready to be transported and then tested. This buffer period can be useful in case of delays in fabrication, transportation, or testing phases.

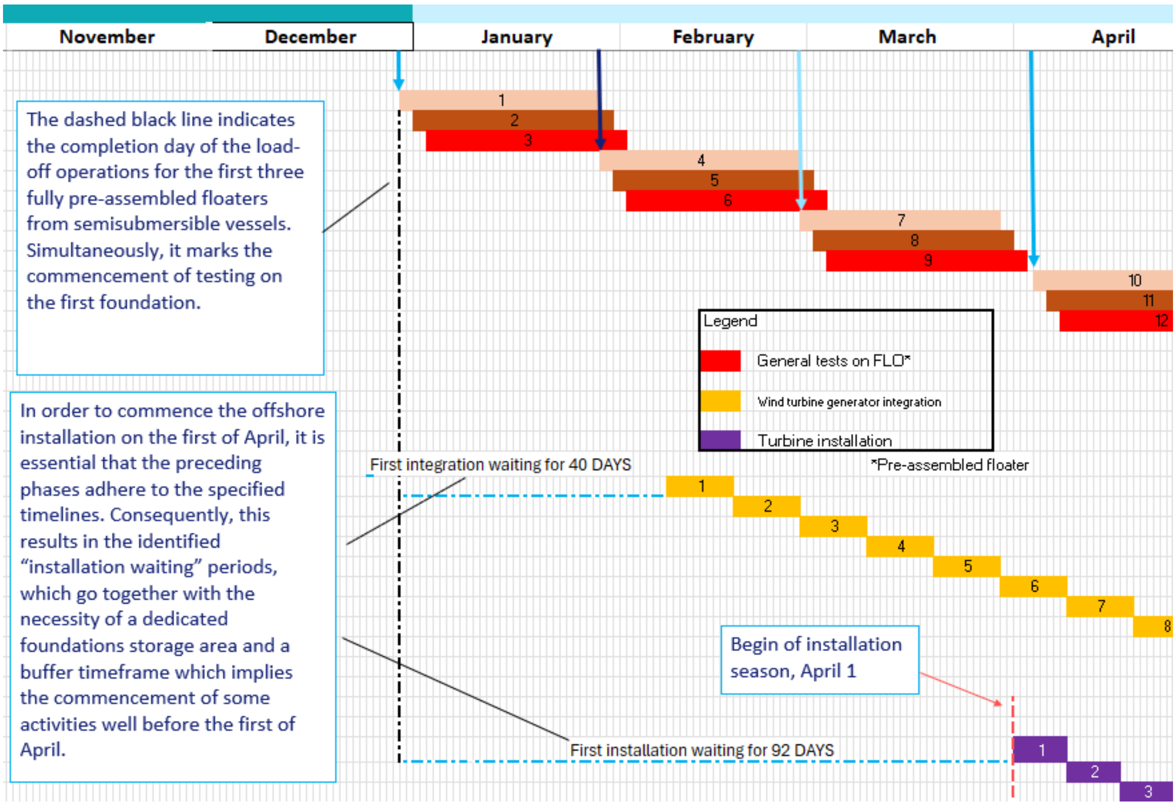


Figure 72: Case 1: Fully pre-assembled floaters waiting periods

Although the fabrication, transportation and testing schedule for the first three batches of fully pre-assembled floaters remains unchanged, the subsequent batches are affected by the earlier commencement of the transportation phase. This earlier start is facilitated by the presence of an additional vessel compared to the base case, allowing transportation to begin immediately upon the completion of the fabrication of a batch of three fully pre-assembled floaters. As a result, the initiation of tests on the foundations in the integration yard differs from the base case. In this scenario, the 35 turbines are tested in a continuous process, without any days of interruption. This is clearly illustrated in the Gantt chart below, where it can be observed that, for the aforementioned reason, the testing of turbine No. 22 concludes ten days earlier than the base case scenario. This earlier completion can serve as a buffer period, accommodating potential delays in the preceding processes. Alternatively, with the deployment of four semisubmersible vessels, it is possible to shift the schedule forward by ten days, thereby achieving a seamless connection between the different phases which implies starting the fabrication process ten days after and always matching the desired installation schedule and project completion day.

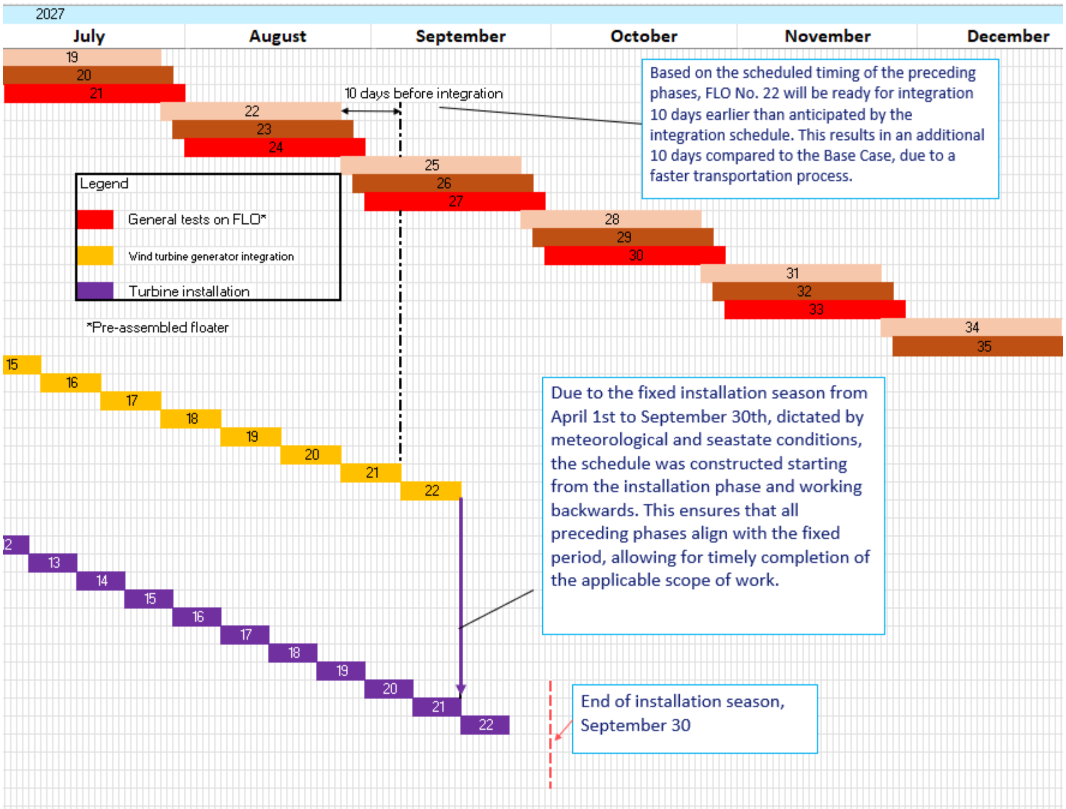


Figure 73: Case 1: Relationship between tests, integration and installation processes

Analyzing the market of semisubmersible vessels reveals that the availability of these ships is limited and they incur significant costs. Therefore, it is worthwhile to analyze and compare the base case and Case 1, which involve the deployment of three and four Heavy Transport Vessels respectively, to evaluate all the pros and cons. Below all the considerations have been exposed:

Costs

One of the most significant owners of semisubmersible vessels has been contacted to obtain a quotation for both the base case and case 1. His replies indicate that the cost for deploying three semisubmersible vessels is slightly lower than that for deploying four, even though the total number of voyages required to transport 35 fully pre-assembled floaters from the Far East to Europe remains the same. In addition, in Case 1, each vessel must wait a total of 50 days idle in the port, leading to an additional cost of approximately $50,000 to $60,000 per day for each vessel during the idleness period. On the contrary, in the base case, vessels do not remain idle in the port for any day. This idle time significantly impacts the overall cost-effectiveness of case 1 compared to the base case.

Project schedule

Regarding the project schedule, the fabrication phase is identical in both cases. However, when examining the transportation process, it is evident from the previously analyzed Gantt charts that the deployment of four vessels results in the transportation of the 35 fully pre-assembled floaters being completed earlier than in the scenario involving the deployment of three semisubmersible vessels only. Consequently, Case 1 requires a shorter deployment period for the Heavy Transport Vessels (HTVs) compared to the base case. Despite this, as previously explained, this does not lead to lower costs compared to the base case and on the contrary it is expected to cost significantly more due to the rate of the idleness period.

Foundations storage

With the deployment of three semisubmersible vessels, fully pre-assembled floaters must wait for the vessels to transit back to the fabrication yard before they can be loaded out. This necessitates a storage area in the fabrication yard, but it also provides a buffer period that helps to avoid impacting the overall schedule in the event of minor delays in the fabrication phase. Additionally, this scenario requires storage in the integration yard. Conversely, the deployment of four semisubmersible vessels eliminates the need for storage in the fabrication yard, as the vessels are readily available to load out the fully pre-assembled floaters as soon as they are fabricated. However, this configuration means that there is no buffer period related to the fabrication process, so if there are any delays in this phase, the entire schedule will be impacted and the semisubmersible vessels will incur in additional idleness costs. To conclude, the case 1 configuration requires a longer storage period in the integration yard compared to the base case.

The comparison between the two cases has demonstrated that the base case is the most cost-effective scenario. This is because it tolerates some delays, utilizes the minimum number of Heavy Transport Vessels (HTVs), and avoids standby times for the HTVs. Consequently, it has been decided to proceed with the sensitivity analysis using the base case scenario as the term of comparison.

4.3 Case 2: Delays in project processes

In the following pages, the cases related to the delays in different project phases and their impact on the project schedule will be explained. In particular, the analysis will focus on:

- Case 2a: Delays in fabrication process
- Case 2b: Delays in integration phase
- Case 2c: Delays in installation phase

A general assumption assessed for all the previous cases is that one day of delay for every five working days has been considered. Additionally, it has been assumed that the days of delay are applied equally to each batch of turbines or single turbine, depending on the analyzed case. In reality, it is unrealistic to assume that the delay is perfectly distributed among all the batches or turbines. Often, more delays are experienced at the beginning of each process due to inexperience. However, once the process is underway, fewer problems and delays typically occur. This study has considered the above assumptions to analyze the impact on the project schedule in the event of incorrect estimation of each phase's duration. It is important to note that delays due to accidents or rare events have not been considered since intrinsically affected by a random occurrence.

4.3.1 Case 2a: Delays in fabrication process

The fabrication of one fully pre-assembled floater requires an initial period of nine months. Following this, with additional 10 days, will be delivered the second one, and in the next ten days also the third one. Consideration of above, every 30 days, the fabrication of a batch of 3 turbines will be completed. In the project schedule, only the delivery time has been taken into account, as the initial nine months is a fixed period required for the fabrication of each fully pre-assembled floater. Consequently, a delay of six days has been considered for the production of each batch of three floaters.
The impact of fabrication delays on both the fabrication process and the transportation phase is illustrated in the relative Gantt chart. Beginning with the fabrication phase, it is evident that this phase will conclude 70 days later than the base case scenario. This delay is attributed to an additional six days required for each batch from turbine No.1 to turbine No.33, and an additional four days for the final batch, which includes turbines No.34 and No.35. For the last batch, only four days of delay have been considered, as it comprises only two pre-assembled floaters instead of three, resulting in a duration of the fabrication phase equal to 20 days, with 10 days allocated for each fully pre-assembled floater. Looking at the transportation phase, the most important aspect to note is that, with six days of delay for each batch of fully pre-assembled floaters, the floaters do not have to wait in the fabrication yard. Instead, the three semisubmersible vessels are readily available to load them out. However, due to these additional days in the fabrication process, even though three vessels have been deployed, they each have to wait idle in the port for 13 days per cycle, instead of the previous zero days of the base case scenario. This idle time results in extra costs, which significantly impacts the overall cost-effectiveness of the project as already explained during the discussion of case 1.

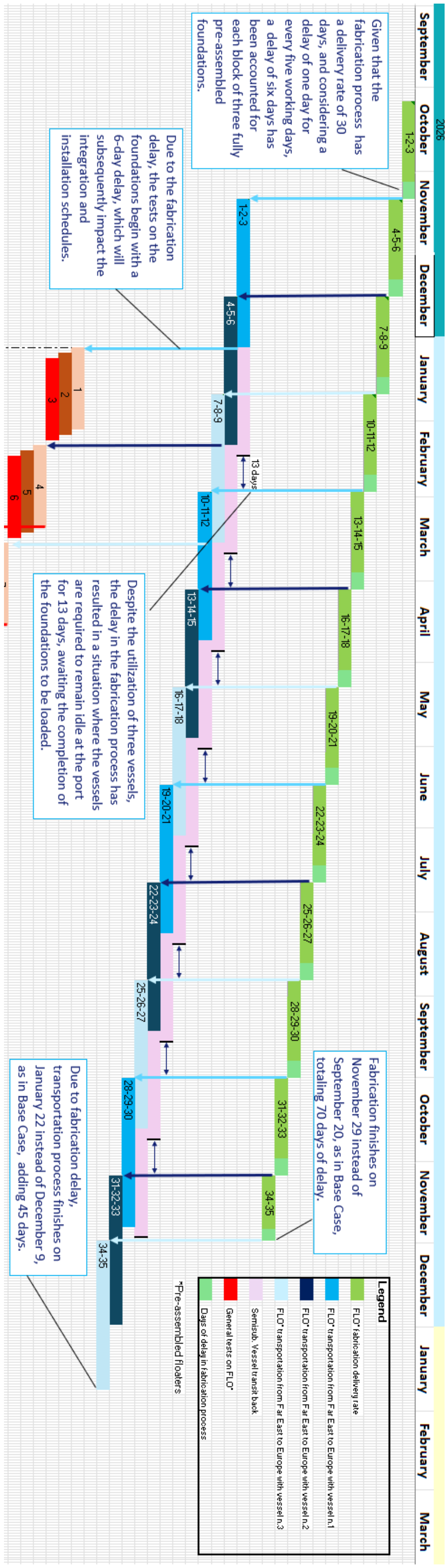


Figure 74: Case 2a: Relationship between fabrication and transportation processes

Regarding the relationship between the arrival of fully pre-assembled floaters in Europe and the commencement of the integration and installation phases, delays in the fabrication process have a notable impact. As illustrated in the graph below, the waiting periods amount to 34 days for the integration phase and 86 days for the installation phase. Compared to the base case, in scenario 2a, the waiting periods are shorter. This is because the transportation phase will commence six days later than in the base case, resulting in the foundations arriving in Europe six days later, thereby reducing the waiting periods prior to the integration and installation phases.

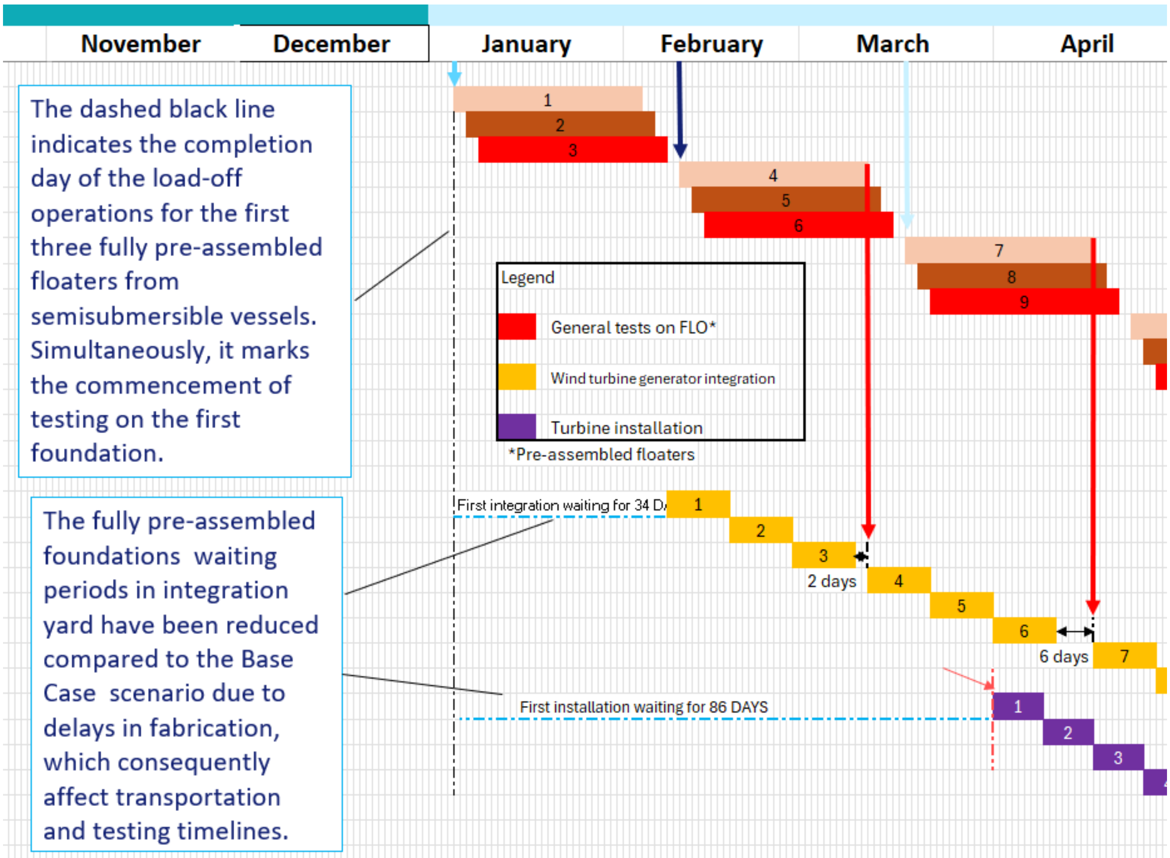


Figure 75: Case 2a: Fully pre-assembled floaters waiting periods

As previously mentioned, the fully pre-assembled floaters arrive at the integration yard six days later than the base case due to delays in the fabrication process. Consequently, the testing phase, which is strictly dependent on the transportation phase, will also shift in accordance with the changes in the transportation schedule. This shift results in only 21 fully pre-assembled floaters being tested, instead of 22, before the end of the installation window. For this reason, and others that will be explained in the following sections, delays in the fabrication process significantly impact both the integration and installation phases. As illustrated in the Gantt chart below, after the first batch of foundations, two days of stop is necessary for the integration process to align with the new testing schedule. Additionally, after the second batch, six days of stop are required between each subsequent batch of foundations until the last foundation. Between the first and second batches, there are only two days of stop, instead of six, because the integration starting date has been considered unchanged with respect to the base case. Considering these stop periods in the integration process, only 20 turbines can be integrated, instead of the original 22, before the end of the first installation window. This highlights that a six-day delay in the fabrication phase for each fully pre-assembled floater batch makes it impossible to install 22 turbines during the first installation season. This is clearly underscores in Figure 77, where the impact of fabrication delay on integration and consequently installation phases is represented.

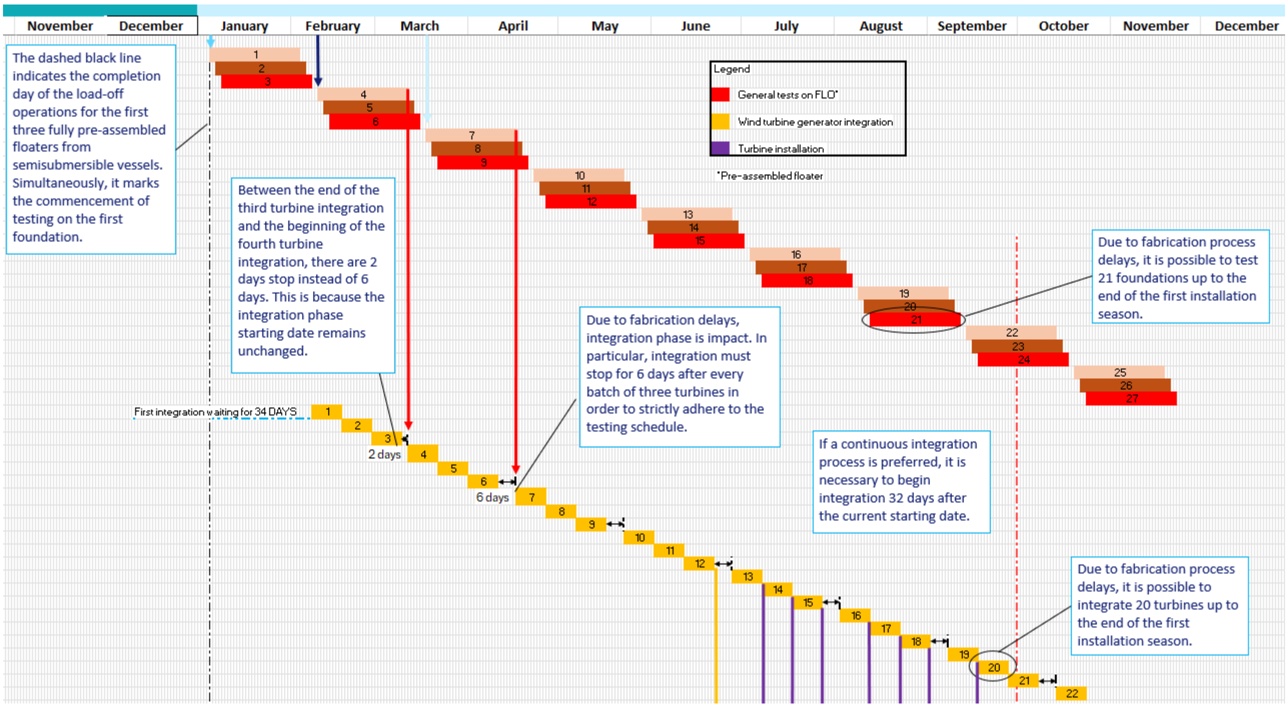


Figure 76: Case 2a: Relationship between testing and integration phases

In the Gantt chart below, it is evident that the installation schedule remains unchanged up to turbine No.12. However, starting from turbine No.13, the installation process must stop for two days between each turbines of the same initial batch and for eight days between turbines of different batches to adhere to the integration schedule. These stop periods result in the inability to install 22 turbines during the first installation window. Nevertheless, it is possible to install 19 turbines.

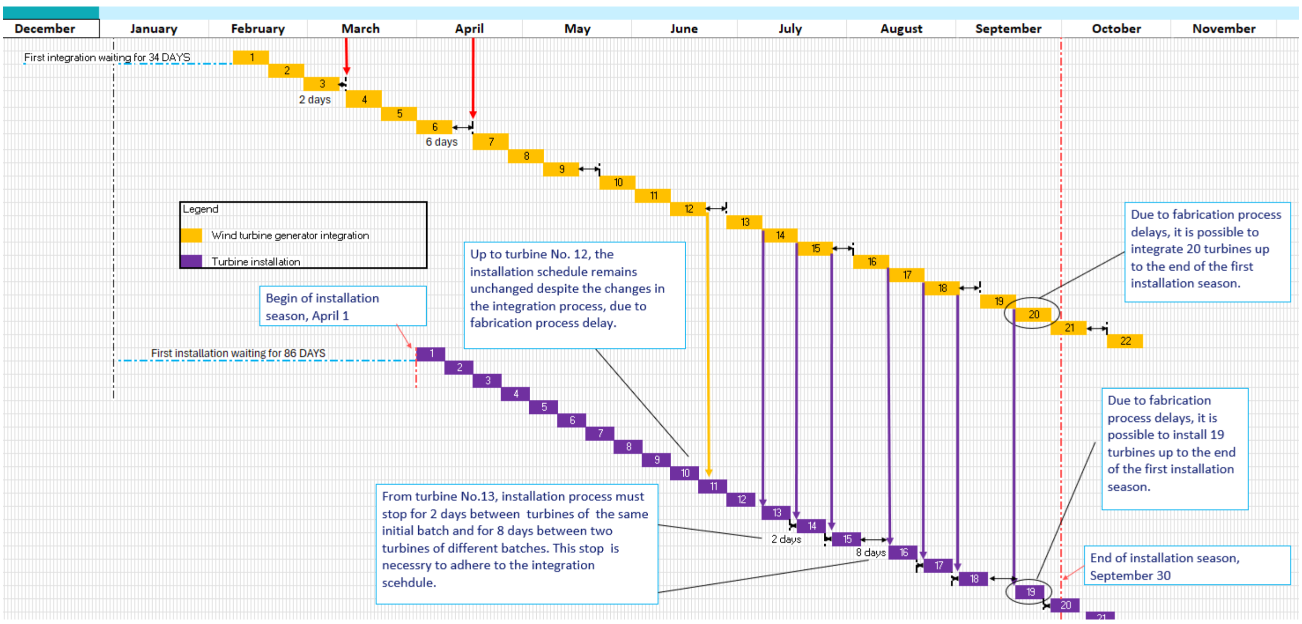


Figure 77: Case 2a: Relationship between integration and installation phase

Given that the consequences of fabrication delays on other project schedule processes can be anticipated in advance, it is possible to make the necessary adjustments. If continuous integration and installation phases are required, all the stop periods can be summed, and the beginning of these processes can be shifted accordingly to accommodate the delays. This can be observed in the graph below. In particular, concerning the integration process, it is necessary to sum six days for five batches and two days for the first batch. This results in a total of 32 days. Therefore, to achieve a continuous integration phase without interruptions, it is necessary to shift the starting date of the integration phase by 32 days. Regarding the installation phase, it is necessary to add eight days for each pair of different batches and two days for each pair of turbines within the same batch. Consequently, to achieve a continuous installation phase without interruptions, the starting date of the installation phase must be shifted by 26 days. This considerations help understanding the strict relationships of each and every construction phase and the power of the instrument set up and used for this thesis work which makes it relatively simple to assess the schedule impacts on the final project delivery milestone.

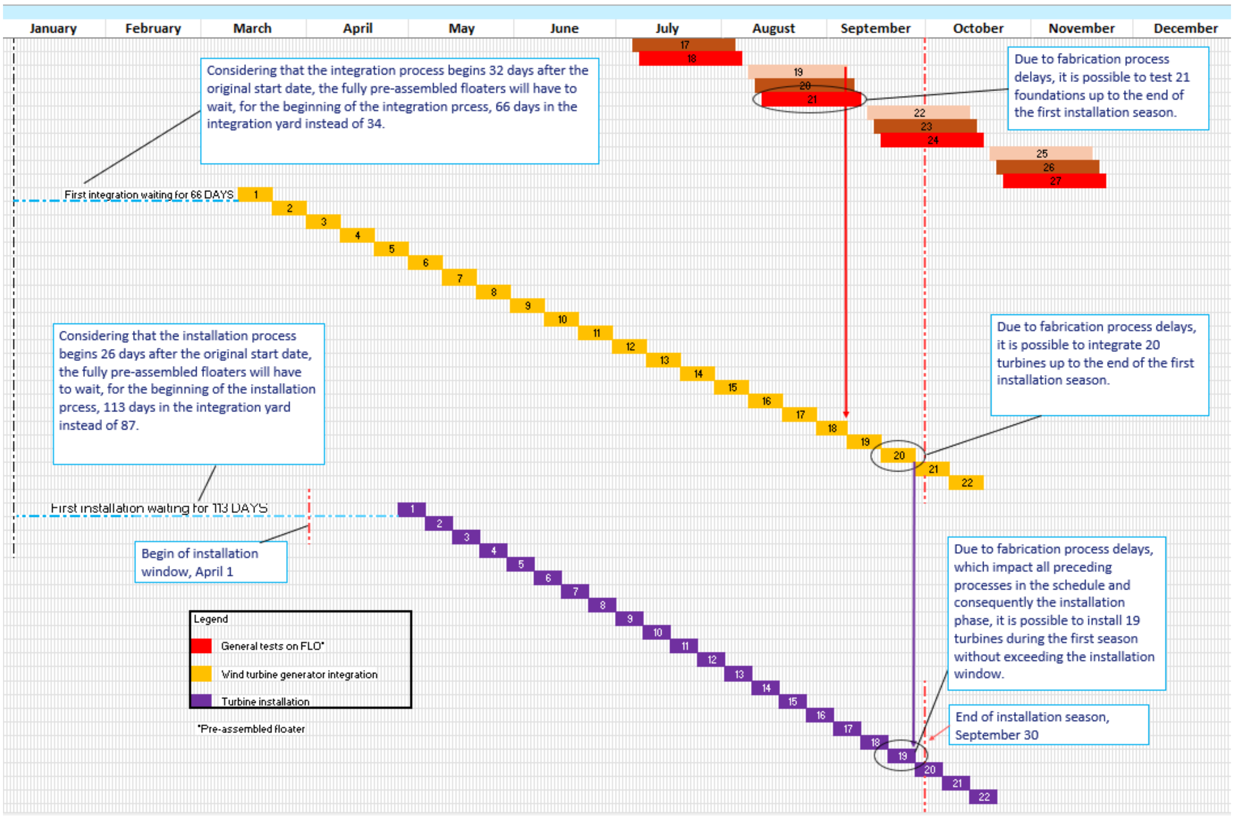


Figure 78: Case 2a: Never stop integration and installation phases

In conclusion, it is crucial to underscore that even a few days of delay in the fabrication process for each fully pre-assembled floater batch can significantly affect the entire project schedule. Firstly, this results in vessels experiencing idle waiting periods at the port, which incurs additional costs. Secondly, it leads to the inability to install 22 turbines during the first installation season, thereby limiting the installation to only 19 turbines. Indeed, only 21 foundations can be tested and 20 integrated by the end of the first installation season. On the other hand, since fabrication is the first process in the schedule, it allows for adjustments in the schedules of other phases to mitigate time and cost damages. Nevertheless the completion of the full project with the installation of 35 turbines in two seasons can still be achieved. However, this study highlights the need to pay close attention to the fabrication phase, as its progress can determine the success or failure of the project since longer delays will end up in needing a further and third installation season.

4.3.2 Case 2b: Delays in integration phase

The integration phase involves the assembly of fully pre-assembled floating foundations and other wind turbine components, such as the tower, the generator and the blades. This process requires a duration of ten days for each turbine. Considering the initial general assumption that there is one day of delay for every five working days, a delay of two days has been accounted for each turbine. The other assumptions remain consistent with the base case.
Changes in the integration schedule do not impact the previous processes such as fabrication, transportation, and testing phases. However, they will affect the installation process. Specifically, considering an

integration time of 12 days, instead of 10 days, for each turbine leads to the impossibility of integrating 22 turbines by the end of the first installation season, while allowing for the integration of a maximum of 19 turbines, as can be seen in the graph below. Additionally, some mandatory stop periods in the installation phase are necessary to allow for completing the integration of the turbine before it can be installed. In the Gantt chart below, it is evident that up to turbine No.11, the installation schedule remains unchanged. However, starting from turbine No.12, four days of stop are necessary until turbine No.22.

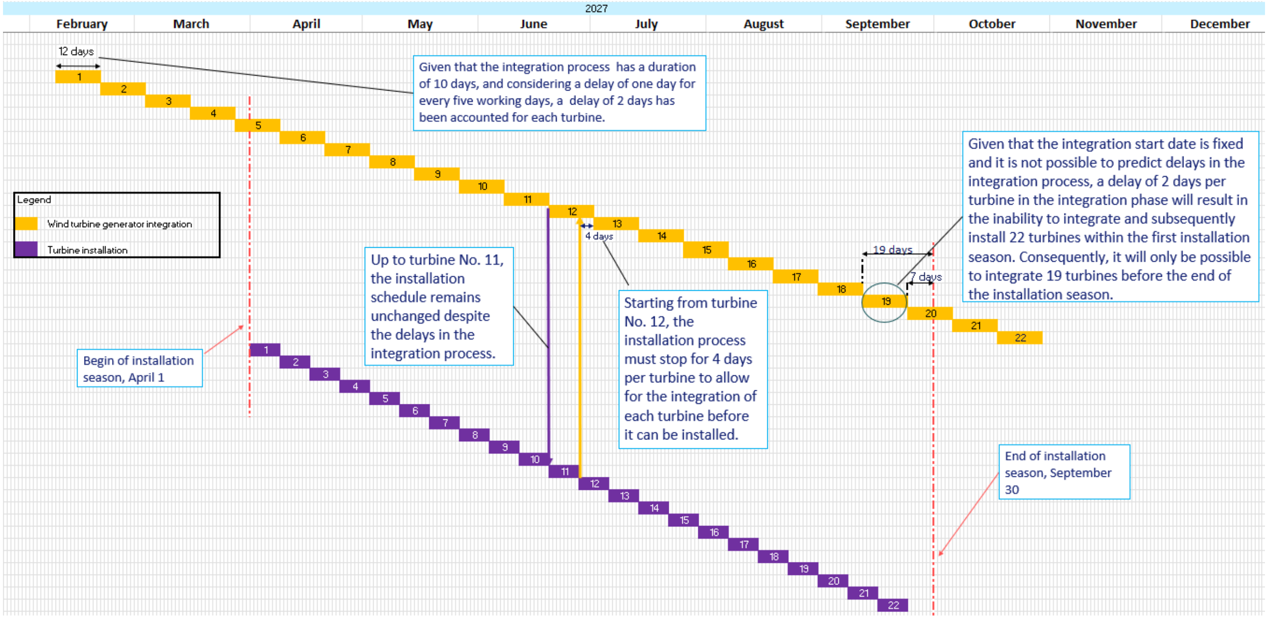


Figure 79: Case 2b: Relationship between integration and installation phases

Considering four days of stop for each turbine in the installation phase starting from turbine No.12, the installation schedule results as represented in the graph below.

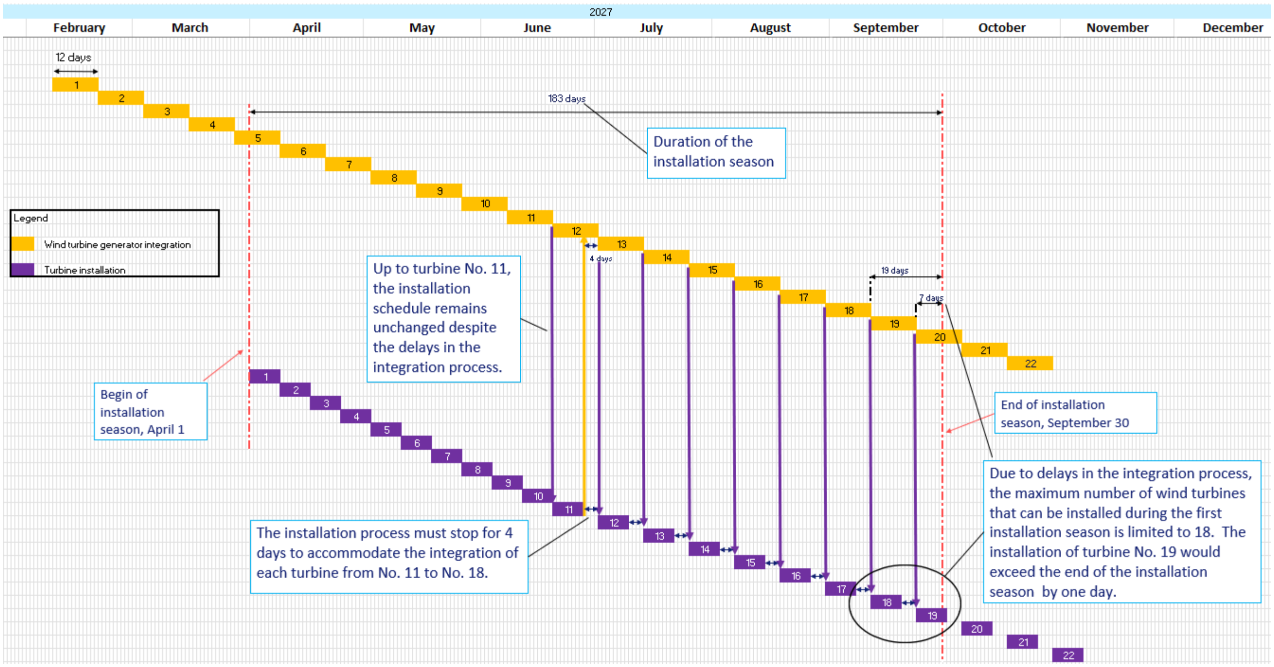


Figure 80: Case 2b: Periods of stop during installation process

In the chart above, with the installation start date fixed on April the 1st, it is possible to ensure a continuous installation process for up to 11 turbines. However, beyond this point, the installation must be halted as the integration process cannot keep pace. If, after the installation of 11 turbines, the installation is made dependent on the integration process, an additional 8 turbines can be installed with a delay of 4 days to align with the integration phase. This approach may be beneficial if the installation itself is delayed. Nevertheless, it is not feasible to install 22 turbines within the first installation season, only 18 turbines can be installed to avoid exceeding the September the 30th. An alternative approach to achieve an uninterrupted installation process would be to initiate the installation 32 days subsequent to the initial start date. This strategy would facilitate the continuous installation of 18 turbines during the first installation season. Nevertheless, due to integration delays, it would still be unfeasible to install 22 turbines within the same period. In the chart above, this option is represented.

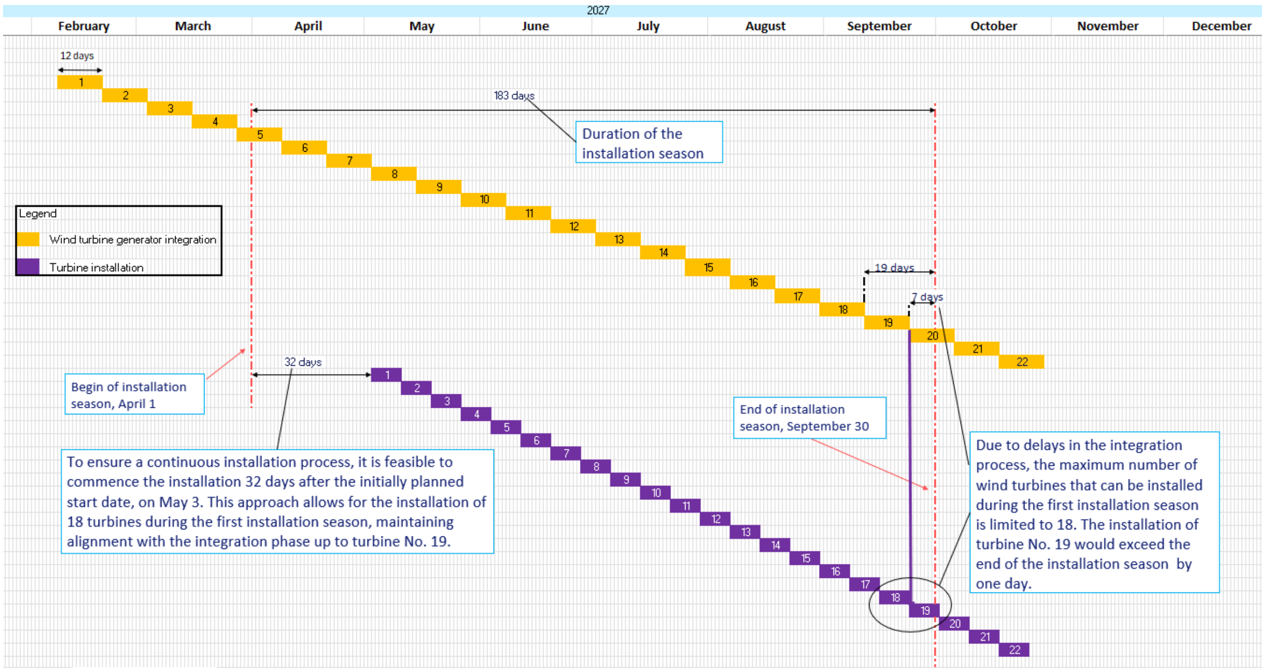


Figure 81: Case 2b: Never stop installation process

In conclusion, it is crucial to note that if the integration process is delayed, it becomes impossible to install 22 turbines during the first installation season, limiting the installation to only 18 turbines, which also affects the second installation period. However, it has to be said that it will be barely feasible to foresee delays in the integration process, making it impossible to intervene in advance. For this reason, this process requires the utmost attention.

4.3.3 Case 2c: Delays in installation phase

The installation phase includes the transportation of turbines from the integration yard to the designated and final location of the floating wind park, anchoring the turbines to the mooring system, and the return of the tugs to the integration yard. The entire cycle has a duration of eight days. Due to the complexity of the operation, an additional delay of two days for each turbine has been considered, for the sake of this study. All other assumptions remain consistent with the base case.
In the Gantt chart below, it is possible to notice what happens when adding two days of delay for each turbine during the installation phase. Firstly, it becomes clear that it is not possible to install 22 turbines during the first installation season. Considering the installation period from April the 1st to September the 30th, it is possible to install a maximum of 18 turbines if each turbine requires 10 days for installation. This represents the equilibrium point, as it leaves 17 turbines to be installed in the second installation season, which is manageable since it basically replicate the installation sequence of the first season and spread the whole project into two almost identical installation periods. However, if the delay exceeds two days per turbine, resulting in a total of 26 days per season, it becomes evident that a third season will be required to conclude the installation. Delays in the installation phase do not impact other project phases since it is the last activity on the chain of the construction phases. However, it is not possible to anticipate these delays and intervene in advance. For this reason, it is crucial to pay close attention to this phase and do the best to stick with the original plans even because, due to the daily rates of the

asset involved in the execution of this phase, delays in this activity will impact the most on the project economics.

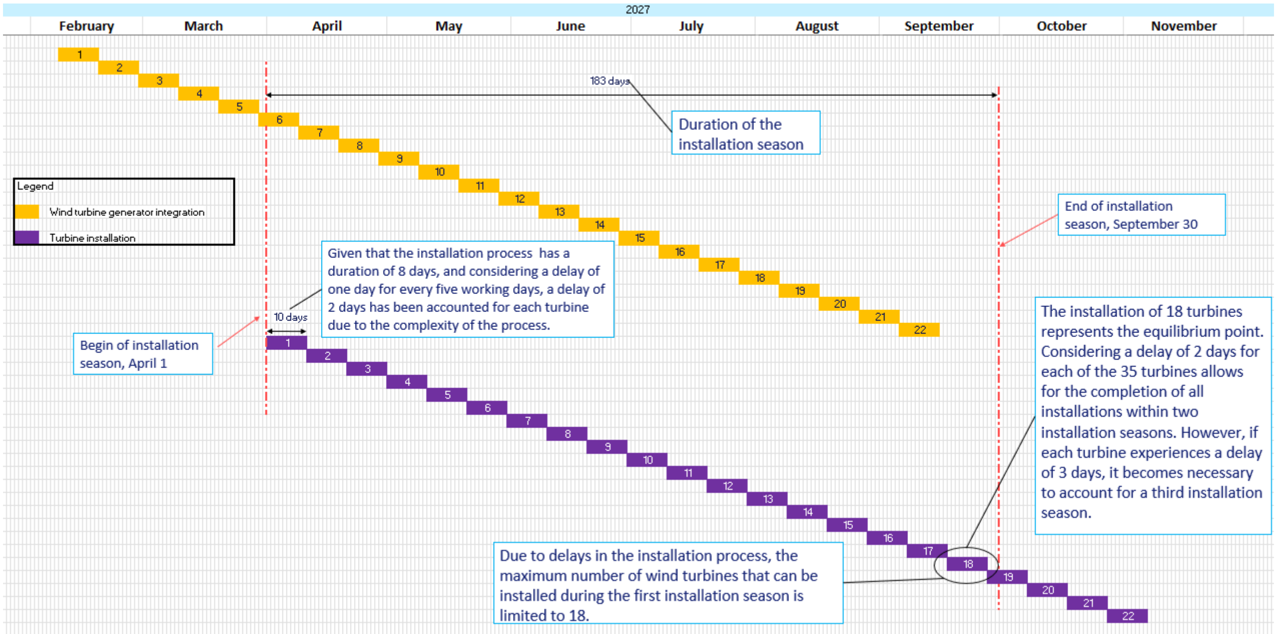


Figure 82: Case 2c: Delays in installation process

4.4 Case 3: Division of the fabrication process

In this case, fabrication of the pre-assembled floaters and their transportation to Europe will be divided into two seasons. In the first season, 22 turbines, which are intended for installation in the first season, will be produced. The remaining 13 turbines will be produced and transported in the second season. This assumption allows for the occupation of a storage area in the integration yard in Europe only for the time necessary to proceed with the different phases of the project, avoiding long-term storage. Conversely, if all the turbines were fabricated and transported to Europe consecutively and continuously, it would be necessary to secure a storage area for a longer period. Additionally, this scenario helps to determine the optimal solution between continuous fabrication and transportation of all components versus splitting the process, taking into account the HTV and yard contracts. The other assumptions remain equal to base case.

In Figure 83, the construction of the second season schedule is illustrated. It is evident that the construction logic mirrors that of the base case. Specifically, the schedule has been constructed by initiating from the installation phase and working backward to the fabrication phase. The most important consideration is related to the transportation phase. With the division of the fabrication and transportation processes, it is essential to align the number of turbines to be installed in each season to avoid long-term storage. Consequently, the transportation of a single fully pre-assembled floater from the Far East to Europe is required, and for each season.

In Figure 84, both the fabrication and transportation schedules of Case 3 are illustrated. Notably, the first season of fabrication involves the production of 22 turbines, which will be installed during the first installation season. This is followed by the transportation phase, which requires only 8 voyages, as opposed to the 12 voyages in the base case. It is evident that in the first transportation season, a single fully pre-assembled floater needs to be transported. Consequently, 8 voyages are necessary in the first season and an additional 5 voyages in the second season. Thus, in this case a total of 13 voyages are required for the transportation of 35 fully pre-assembled floaters from the Far East to Europe, which is one more voyage compared to the base case that foresees only 12 voyages. The testing, integration, and installation phases remain unchanged compared to the base case, although they will also undergo a pause between the first and the second installation season. Additionally, it is possible to observe that between the end of the first fabrication season and the beginning of the second one, there is a gap of 169 days, approximately 5.5 months. Furthermore, between the end of the first transportation season and the beginning of the second one, there is a gap of 114 days, approximately 4 months. This data can help in making decisions in case of delays or adjustments needed in the schedule.

In conclusion, it can be stated that Case 3 offers a significant advantage over the base case in terms of long-term wet storage for fully pre-assembled floaters. By considering two distinct fabrication seasons, the 13 turbines designated for installation in the second season arrive in Europe just in time to be tested, integrated, and installed according to the schedule, thereby avoiding winter storage in the integration yard in Europe, as seen in the base case. However, to avoid long-term wet storage, it is necessary to fabricate, transport, and test 22 foundations in the first fabrication period and 13 in the second period, aligning with the number of turbines planned for the installation in each season. Given that three fully pre-assembled floaters can be transported at a time by one vessel, it becomes necessary to add one more voyage compared to the base case. This is because 8 voyages are required in the first transportation period and 5 during the second. In summary, dividing the fabrication process effectively avoids long-term wet storage in the integration yard but necessitates one additional fully pre-assembled transportation voyage compared to the base case. This approach also entails the associated consequences of stopping and restarting the fabrication, transportation, and testing processes, which for the sake of clearance, will surely imply significant extra costs, thus the economic viability of this case shall be carefully evaluated.

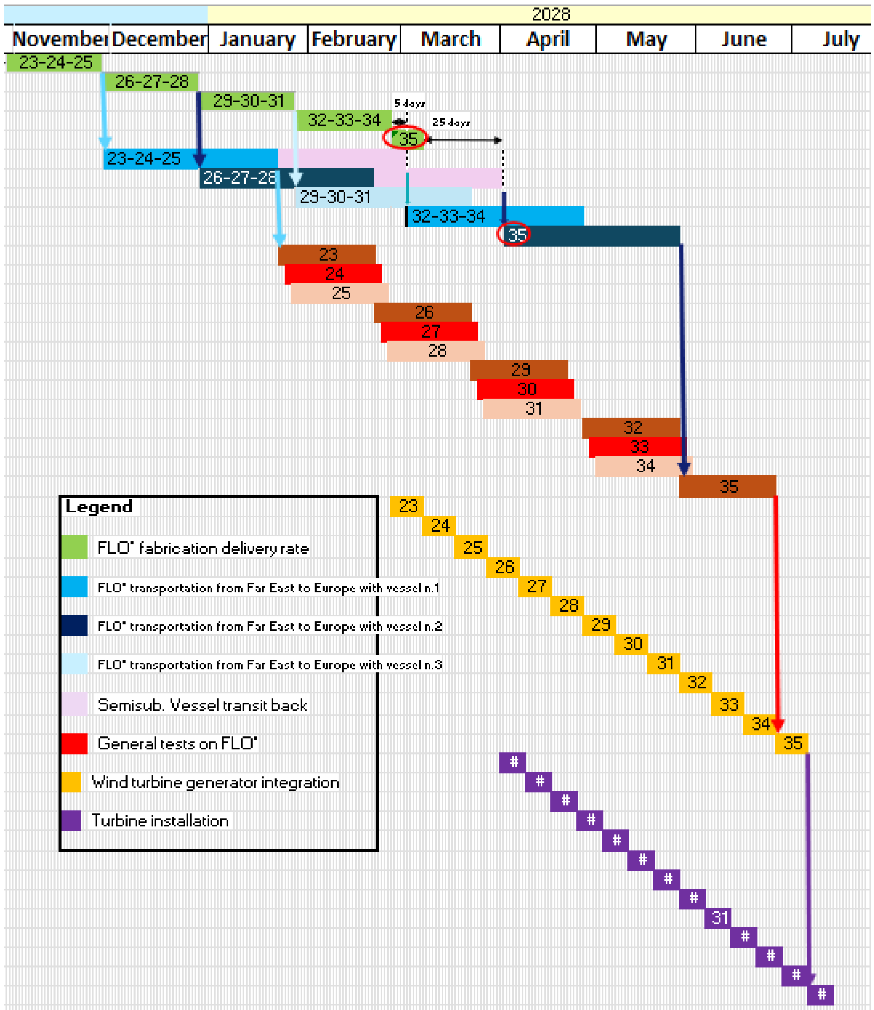


Figure 83: Case 3: Schedule of the second season

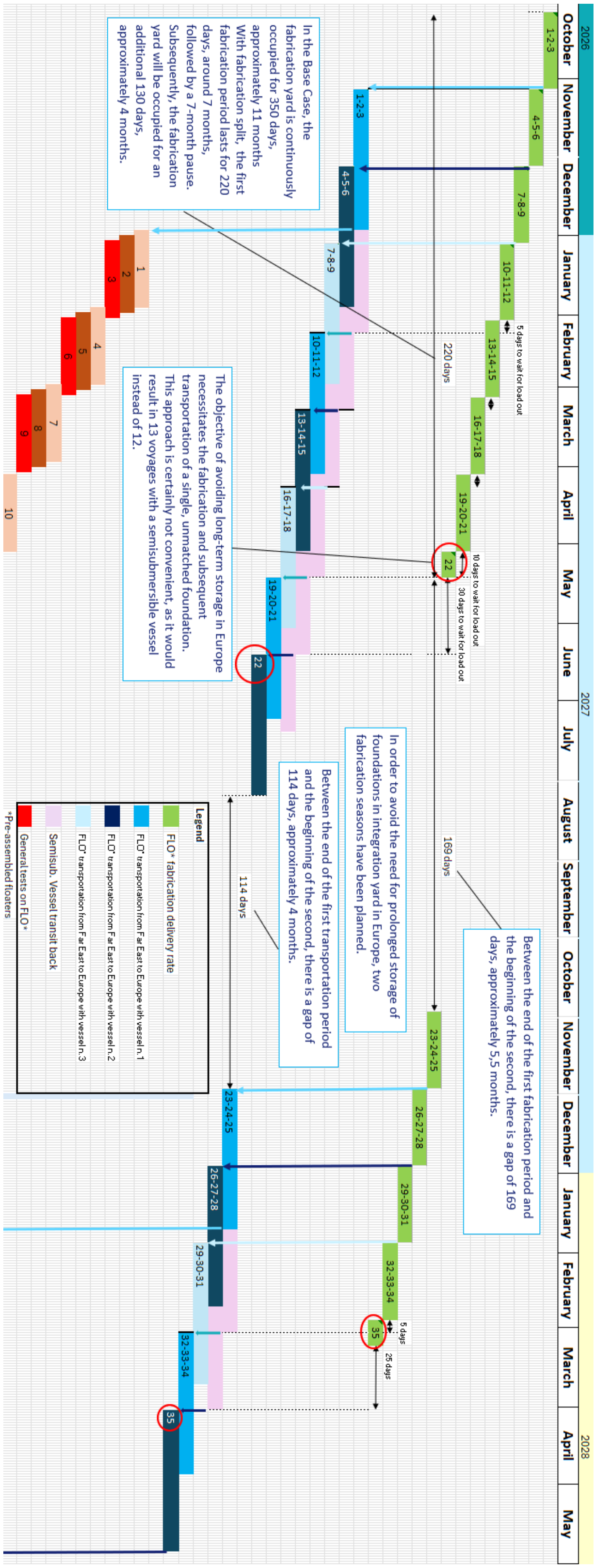


Figure 84: Case 3: Fabrication and transportation schedules

5 Conclusions

This thesis has addressed the logistical and operational challenges involved in the construction of a floating offshore wind farm, through the analysis of a case study comprising 35 turbines to be installed in the North Sea. The study has highlighted how the realization of such projects requires careful planning and coordination, due to the large scale, the repetition of activities, the interdependence between different project phases, and the significant dependence on various expensive asset and equipment that sometimes are scarce and difficult to retrieve and hire on the market. The floating wind sector, still in an early commercial stage, presents additional complexities compared to fixed-bottom solutions, particularly in terms of fabrication, transport, assembly, and installation of large and heavy components. It is therefore clear how logistic discipline may assume the utmost importance in the planning and execution of such projects. In this context, and among the many logistical issues, the transportation of floating foundations represents a key element. The comparison between transporting megablocks and fully pre-assembled floaters has shown that the latter option can reduce risks and activities at the integration yard in Europe, eliminating the necessity to duplicate some assembly, welding and non destructive testing activities and the relevant equipment. However, such a strategy relies heavily on the availability of semi-submersible vessels, which are globally limited in number and therefore difficult to find and expensive to hire. This aspect should be carefully considered in the early planning phase, as it can affect the overall project feasibility and milestones achievement.

A central aspect emerging from the analysis is the importance of monitoring the actual progress in constant comparison with the planned schedule from the installation of the very first turbine. The project has been broken down into multiple phases: fabrication of the fully pre-assembled floaters, transportation to the integration yard, floating foundation testing, on-site integration, and final turbine installation to the offshore wind farm location. These phases are both sequential and interdependent, meaning that a delay in one can directly impact the timing and execution of the next. Through the use of Gantt chart simulations and sensitivity analyses, the thesis has shown that even small deviations occurring in the early stages, such as a delay in foundation fabrication, can propagate through the schedule, affecting the originally planned deployment of all 35 turbines. This cumulative effect is particularly relevant due to the repetitive structure of the project: each unit follows the same sequence, and any inefficiency tends to repeat itself unless corrective measures are implemented straightforward. Therefore, continuous monitoring of the actual versus planned progress becomes essential. Tracking performance from the outset enables the early identification of delay trends or critical deviations. This proactive approach is necessary to preserve the overall project timing and to limit the risk of bottlenecks during execution.

To support this need, the thesis proposed the use of multi-phases analysis method and dedicated planning tools such as Gantt charts and sensitivity analyses, which allow the evaluation of different scenarios and the identification of critical activities, the ones to be carefully monitored for an efficient project execution. These tools, together with vessel availability studies and spatial assessments, such as the availability of storage and temporary parking areas, contribute to improving the robustness of the planning process and provide useful support for decision-making prior to and during the execution phase.

In conclusion, the development of a floating offshore wind farm requires an integrated and flexible planning approach, capable of accounting for operational constraints and potential delays. The results presented in this thesis describe an organized and structured method for the various construction phases analysis which can contribute to a better understanding of some of the most relevant logistical dynamics involved in the realization of a floating wind farm and offer useful insights for future projects in the sector. Some possible future improvements embrace the development of macros for a fully automatic update of the main project milestones and the Gantt charts as well as the study of less frequent or more random contingency scenarios to be assessed as additional sensitivity cases.

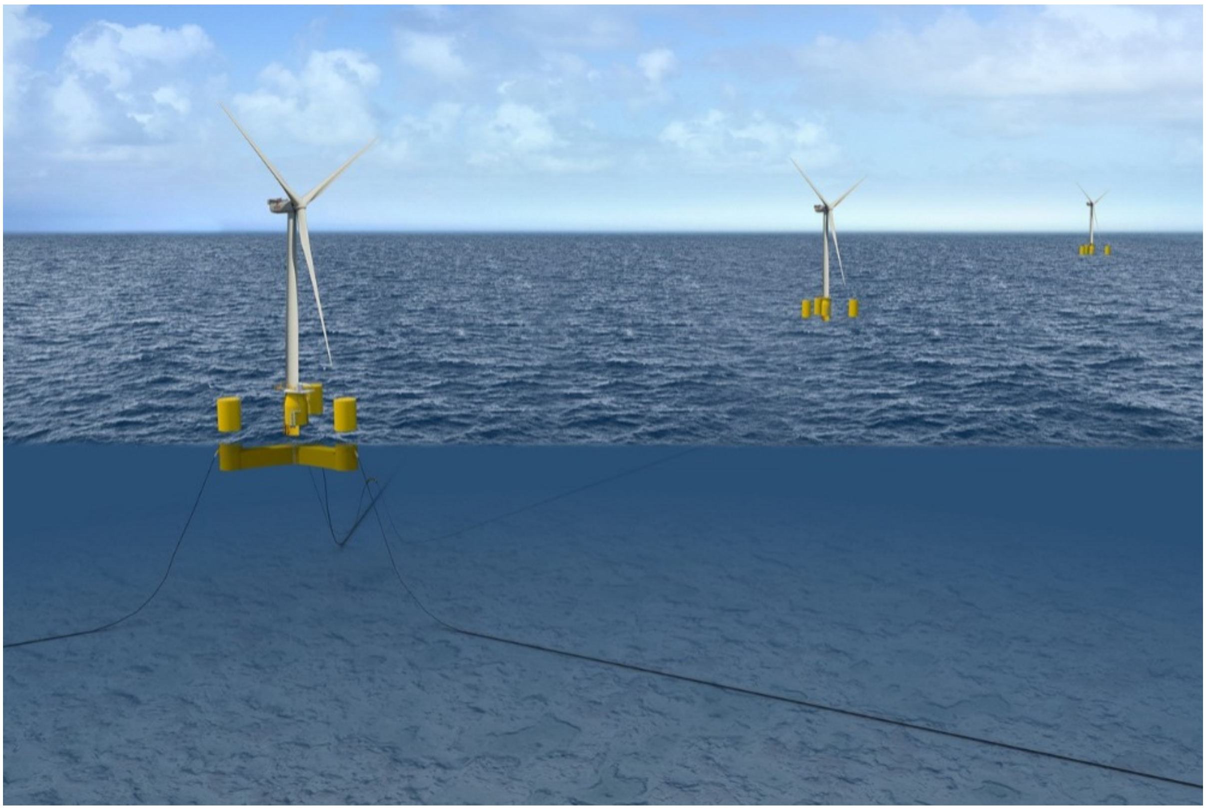


Figure 85: Floating wind farm [1]

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