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Unlocking Australia's Ocean Potential via Floating Wind

Feasibility Analysis

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Abstract

The global demand for renewable energy is accelerating the development of offshore wind technologies. Floating offshore wind turbines (FOWTs) are a promising solution for harnessing wind resources in deep-water locations, yet high capital costs, technical complexity and design uncertainties continue to constrain large-scale deployment. To address these challenges, optimization strategies and a multidisciplinary design approach are essential to improve turbine performance, reduce costs and accurately capture the coupled dynamic and hydrodynamic behavior of the system.

This thesis evaluates the technical and economic feasibility of an offshore wind farm along the Queensland coast in Australia, considering both site-specific conditions and turbine performance. The study begins with a detailed site assessment, incorporating wind speed, water depth and environmental restrictions such as marine protected areas. The project design then examines the expected power output of the Siemens Gamesa SG 14-222 turbine and explores layout optimization to maximize energy production. Economic feasibility is assessed through analysis of capital expenditures, operational costs and the levelized cost of energy (LCOE), providing a clear indication of the viability of the selected site.

A coupled model is developed to simulate the hydrodynamic performance of a typical offshore wind turbine under extreme sea states offshore Queensland. It is worth noting that the focus has been on the hydrodynamic performance in extreme scenarios, when the turbines will be parked and thus the aerodynamic aspect has been ignored. The methodology integrates technical, economic and environmental considerations in a functional framework, which can be extended in future work to include installation processes and lifecycle impacts.

Overall, this work provides a comprehensive assessment of offshore wind farm feasibility offshore Queensland, combining site analysis, turbine performance modeling and techno-economic evaluation to identify optimal conditions for sustainable, efficient and resilient energy generation.

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List of Acronyms

AEP	Annual Energy Production
AIS	Automatic Identification System
AMSIS	Australian Marine Spatial Information System
CAPAD	Collaborative Australian Protected Areas Database
CAPEX	Capital Expenditure
CF	Capacity Factor
DCCEEW	Department of Climate Change, Energy, the Environment and Water
DOF	Degrees of Freedom
EEZ	Exclusive Economic Zone
EOL	End Of Life
ERA5	ECMWF Reanalysis Dataset
FOWT	Floating Offshore Wind Turbine
GWEC	Global Wind Energy Council
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IRA	Inflation Reduction Act
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Energy
NREL	National Renewable Energy Laboratory
OPEX	Operational Expenditure
RAO	Response Amplitude Operator
ROV	Remotely Operated Vehicle
TLP	Tension Leg Platform

1 Introduction

1.1 Offshore Wind Energy Worldwide

Wind energy currently represents one of the most rapidly expanding renewable energy technologies worldwide. The decisions and strategies adopted today by governments, industry and society will shape the pace and direction of its future expansion. The coming years promise strong growth, but the real challenge lies in how quickly this momentum can accelerate and how much value wind power will be able to deliver to economies and communities once existing barriers are lifted.

Over the last forty years, wind energy has transformed from a niche experiment into one of the most competitive and reliable energy sources in the world. Its large-scale deployment has driven down electricity prices, created employment, revitalized local economies and strengthened national energy security by reducing dependence on imported fossil fuels.

Globally, the energy system is entering what the International Energy Agency calls the “The Age of Electricity”. Wind power, alongside solar energy, is leading this transformation by reshaping the way the world produces and consumes energy. However, for the transition to remain balanced and sustainable, the wind industry must return to rapid, sustained growth to complement the expansion of solar power.

Across continents, investments in wind energy are already paying dividends. Nations that harness their wind potential are achieving greater energy independence and stability, protecting themselves from geopolitical disruptions and market volatility. Long-term investments in wind power are driving industrial development, from manufacturing components to supplying affordable electricity for homes and businesses. For example, in the United Kingdom, the rise of renewable generation in 2022 replaced over £6 billion worth of gas, saving households an estimated £220 each [1].

Wind power is also generating wide social and environmental benefits. The sector now supports more than 1.5 million direct jobs worldwide and is helping to cut global emissions by replacing fossil-based generation with clean alternatives. Yet, this progress could go much further if growth were scaled up. To meet global climate goals, including the commitment made at COP28 (the United Nations annual climate conference) to triple renewable energy capacity by 2030, yearly installations of new renewable power must reach approximately 320 GW [2].

Nevertheless, several challenges threaten to slow this progress. Economic pressures, higher material and financing costs and fragmented government policies have increased uncertainty across the supply chain. Trade restrictions and outdated market mechanisms further undermine competitiveness. Addressing these

obstacles requires stronger coordination among governments, industry leaders and international partners to simplify regulations, stabilize investment conditions and ensure fair access to global markets.

Despite these challenges, momentum for wind power continues to build. Many countries are reinforcing their commitments through new policies and ambitious targets. The United Kingdom, for instance, has introduced reforms to achieve up to 80 GW of total wind capacity by 2030. Germany has reached record highs in onshore wind tenders, while South Africa, Brazil, Japan, South Korea and Australia are advancing major national strategies to integrate wind into their future energy mix. Central Asia, too, is emerging as a new frontier, with large-scale projects underway in Kazakhstan, Uzbekistan and Azerbaijan.

Looking ahead, collaboration between industry, governments and civil society will be essential to unlock wind energy's full potential. By scaling up innovation, streamlining permitting processes and ensuring the integration of grid infrastructure, the sector can continue to drive sustainable growth. Wind energy is expected to play a key role in the future energy system, contributing not only to clean power generation but also to economic development, energy security and global climate stability [3].

1.2 Offshore wind developments in selected markets

1.2.1 Europe

Amid recent geopolitical tensions, European Union Member States have intensified their efforts to speed up the transition toward renewable energy. By the end of 2022, Europe had installed around 30 GW of offshore wind capacity, with the United Kingdom, Denmark, Germany and Italy leading the sector. The REPowerEU initiative aims to reduce the continent’s dependence on fossil fuels while streamlining the administrative and regulatory processes that have historically slowed down offshore wind development [4].

In 2023, the European Commission introduced the Green Deal Industrial Plan, designed to strengthen Europe’s clean energy and industrial resilience. Key elements of this strategy include the Net-Zero Industry Act, focused on boosting domestic production of green technologies and the Critical Raw Materials Act, intended to enhance Europe’s ability to source, process and secure essential materials for the energy transition. Additionally, the framework introduces more flexible state aid rules to support investment in renewable industries and strengthen the EU’s competitiveness in the global green economy.

United Kingdom

The United Kingdom remains a European leader in offshore wind energy, with strong growth and a projected annual rate of 14% through 2030, reaching a total capacity of 40 GW [5]. In 2023, Dogger Bank, the world’s largest offshore wind farm, began producing power 130 km off the Yorkshire coast (Figure 1). The project includes 277 GE Haliade-X 13 MW turbines for a total capacity of 3.6 GW, marking a major technological milestone through the use of HVDC (High Voltage Direct Current) transmission and next-generation turbine design. It is being developed by SSE Renewables in partnership with Equinor and Vårgrønn [6], [7].

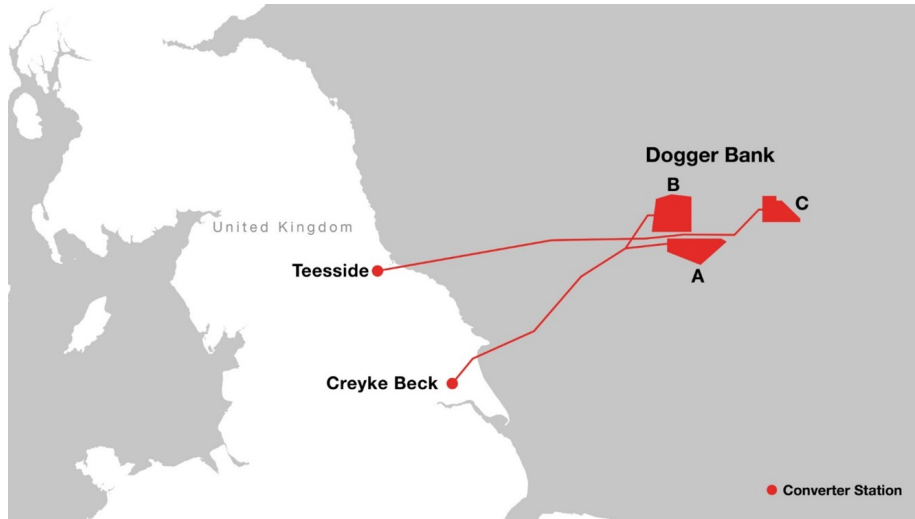


Figure 1: The Dogger Bank Wind Farm, the world’s largest offshore wind project, will be completed in 2026 through three 1.2 GW phases: Dogger Bank A, B and C.

France

As of 2025, France is transitioning from the initial deployment phase of offshore wind toward a more sustained expansion pathway. While long-term ambitions remain high, with targets of 18 GW by 2035 and 45 GW by 2050, installed and operational capacity remains relatively limited, highlighting the gap between policy targets and actual deployment. By 2023, approximately 4.6 GW of offshore wind capacity had been awarded, with around 2 GW either operational or under construction and an additional 3.4 GW progressing through the tendering process.

The year 2024 represented a key milestone, with the commissioning of France’s second fully operational offshore wind farm (500 MW). Entering 2025, the national project pipeline includes 15 offshore wind projects, four of which are either under construction or partially commissioned: Yeu/Noirmoutier (500 MW), Courseulles-sur-Mer (450 MW), Dieppe/Le Tréport (500 MW) and Saint-Brieuc (500 MW). These projects signal a gradual shift from planning and permitting toward large-scale construction and grid integration.

From a policy and market perspective, 2025 marks the beginning of a more regularized auction framework, with annual auction volumes expected to reach 2 GW per year in line with the government’s offshore wind strategy. The auction rounds planned for late 2024, with a capacity of 2.7 GW, are expected to feed directly into project development in the mid-to-late 2020s. In parallel, ongoing stakeholder consultations aimed at identifying additional offshore sites through

2050 could potentially enable between 8 and 10 GW of additional capacity in the near term and underscore the government’s intention to accelerate deployment beyond the current project pipeline. Overall, in 2025 France’s offshore wind sector remains at an early but decisive stage, characterized by increasing policy certainty, a growing construction backlog and a clear trajectory toward scale-up in the coming decade [8].

Germany

As of the end of 2022, Germany had a total offshore wind capacity of around 8 GW and it aims to reach 30 GW connected to the grid by 2030. In 2023, the Federal Maritime and Hydrographic Agency (BSH) released a new development plan outlining potential sites for offshore wind farms in the North and Baltic Seas, as well as strategies for grid connections, cable routing and coordination with major equipment manufacturers.

The plan also explores cross-border interconnections with neighbouring countries, supporting the creation of a more integrated European offshore power grid. Although Germany currently focuses mainly on fixed-bottom offshore wind technologies, its well-established role in the European supply chain positions the country to support the future development of floating offshore wind in Europe.

Germany has been a major driver of wind energy research and innovation: since 2010, the country accounts for a large share of EU public investment in offshore wind R&D (Research and Development) and private funding is also concentrated there, alongside Denmark. This highlights Germany’s central role in both technological development and the growth of the European offshore wind sector [9].

1.2.2 The Americas

United States

The Inflation Reduction Act (IRA) has strengthened US interest in offshore wind by introducing major fiscal incentives. It extends production and investment tax credits for wind and solar through 2024, which will transition to technology neutral credits available until 2032. The IRA also introduces component specific tax credits to support domestic manufacturing of clean energy equipment [10]. Although the Act includes incentives for clean hydrogen, clear strategies for integrating offshore wind with hydrogen production, particularly in relation to turbine and electrolyzer configurations, have not yet been defined [4], [11].

Canada

Canada has a technical offshore wind potential of 9321 GW, with 7282 GW accessible via floating wind technologies and 2039 GW via fixed-bottom foun-

dations. In Nova Scotia, starting in 2025, the provincial government will offer leases for up to 5 GW of offshore wind by 2030. These projects will be awarded through a competitive bidding process managed jointly with the federal government. In July 2023, EverWind Fuels announced a 1 USD billion investment to acquire three offshore wind farm development projects in Nova Scotia (530 MW total), marking a significant step toward expanding the region’s offshore wind capacity [12].

Brazil

The Brazilian government, elected in 2023, is prioritizing the development of domestic offshore wind energy. With a coastline of roughly 8000 kilometres, the country holds an estimated offshore wind potential exceeding 1200 GW. Recent legislation, including Federal Decree 10946/2022, provides clear guidelines for the management of maritime areas. Additionally, a new law (PL 576/2021) is being prepared to establish a single regulatory framework for offshore wind permits and licenses. The Brazilian Wind Energy Association (ABEEólica) plays a central role in guiding and coordinating offshore wind projects across the country [10].

1.2.3 Asia

China

China continues to dominate the global offshore wind sector, holding a leading position both in installed capacity and in manufacturing. With major projects expanding along its eastern coastline, particularly in Fujian, Guangdong, Guangxi and Jiangsu, the country is rapidly scaling up renewable energy production. Under its 14th Five-Year Plan (2021-2025), China aims to have more than half of its new energy consumption come from renewable sources. Offshore wind plays a central role in this strategy, supported by a grid parity system that allows renewable energy to compete directly with fossil fuels [10], [13].

Japan

Japan is accelerating the development of offshore wind energy with plans to reach 10 GW of installed capacity by 2030 and up to 45 GW by 2040. To achieve this, the government has relaunched public auctions with updated regulations that favour projects starting sooner and limit the capacity each consortium can secure. Several auctions have already been completed, allocating more than 3 GW of capacity, while new rounds continue to expand the sector [14]. Japan’s first large-scale offshore wind farm, located at Noshiro Port with a capacity of 84 MW, began full operations at the end of 2022, marking a key milestone in the nation’s renewable energy transition, as shown in Figure 2 [15].



Figure 2: Offshore wind turbines off Noshiro Port in Akita Prefecture.

Republic of Korea

South Korea is expanding its offshore wind energy sector as part of its strategy to cut greenhouse gas emissions by 40% by 2030 and achieve carbon neutrality by 2050. The government aims to install 14.3 GW of offshore wind capacity by 2030, a major increase from the current 140 MW. Efforts are being made to simplify the approval process through a centralized system that would coordinate site selection and stakeholder involvement. In 2023, the country held its second offshore wind auction with a target of 1.5 GW. To support this growth, South Korea is investing in better port facilities, local manufacturing and specialized workforce training to strengthen the industry’s long-term development [16].

India

In 2023, India’s Ministry of New and Renewable Energy introduced a national plan to develop 37 GW of offshore wind capacity by 2030, including fifteen pilot projects to support early deployment. The country aims to use its strong manufacturing base, especially in producing gearboxes, blades and generators, to expand its offshore wind industry [13], [17]. Between 2024 and 2025, India will launch auctions for about 7.2 GW of offshore wind projects in Tamil Nadu, with the National Institute of Wind Energy leading the process [18].

1.2.4 Australia

Australia is currently at a critical stage in the development of offshore wind energy. The gradual retirement of aging coal-fired power plants offers a unique

opportunity to integrate clean energy into the national mix, meet growing domestic demand and establish the country as a leader in the energy transition both in the Asia-Pacific region and globally.

Despite the absence of operational offshore wind farms, the country possesses enormous technical offshore wind potential, estimated by the World Bank Group's ESMAP at over 4900 GW, with approximately 1500 GW suitable for fixed-bottom foundations and more than 3000 GW for floating platforms. These figures provide a significant competitive advantage, as offshore wind energy can contribute on a large scale to clean energy production, leveraging Australia's vast marine areas with very favourable and consistent wind conditions [3].

Several factors make Australia particularly suitable for offshore wind development:

- Abundant natural resources: the coasts and deep waters offer large areas suitable for both fixed and floating installation.
- Industrial capacity and local supply chain: the country has well-established expertise in producing critical materials such as steel, copper and rare earth elements, alongside a skilled workforce and advanced maritime services.
- Political and financial support: the federal government has allocated substantial funds to support renewable energy and promote the development of the local supply chain, providing stable investments and regulatory certainty.
- Clear and innovative regulatory framework: Australian regulations facilitate project design, management and permitting, offering a transparent and predictable environment for investors.
- Strategic geographic location: Australia is situated within a rapidly developing Asia-Pacific context, with the potential to attract international investments and become a regional hub for renewable energy production and offshore technology.
- Favourable climatic conditions: consistent and strong winds along the coasts ensure efficient and predictable energy generation, reducing the risks associated with variability in power output.

These conditions place Australia in a privileged position to become a key player in the global offshore wind sector. The country combines enormous technical potential, a capable industrial base, suitable natural resources and a supportive political context, creating fertile ground for rapid, sustainable and competitive offshore wind development. The implementation of initial pilot projects will offer an opportunity to demonstrate technical and commercial feasibility, paving the way for national-scale expansion and establishing an international leadership role in renewable energy.

1.3 Market Status Overview 2024

The year 2024 marked a record for the wind energy sector, with 117 GW of new wind capacity added globally, bringing the total installed capacity to 1136 GW, an 11% increase compared to 2023. Onshore wind installations exceeded the 100 GW mark for the second consecutive year, with 109 GW connected to the grid, setting a historic high. Offshore wind, however, reached only 8 GW, a 26% drop from the previous year and the lowest level since 2021.

The Asia-Pacific region strengthened its dominance in wind power, driven by rapid growth in China and steady expansion in India, achieving a 75% share of the global market and 7% year-on-year growth.

In Europe, new wind capacity totalled 16.4 GW, including 12.9 GW in the EU-27, maintaining its position as the second-largest wind market worldwide, even though new installations and market share declined by 10% and 2% respectively.

North America remained in third place, but its global market share fell by 33%, mainly due to a slowdown in US onshore projects, reaching the lowest level since 2013.

Latin America ranked fourth, with a 1% decrease in market share, as Brazil's new capacity dropped 30% compared to 2023.

Africa and the Middle East remained the smallest markets, although their installed capacity doubled compared to the previous year.

The five largest markets for new wind installations in 2024 were China, the United States, Germany, India and Brazil, accounting for 81% of global additions, slightly higher than in 2023. When considering total installed capacity, the same five countries represented 73% of global wind power, with Brazil replacing Spain in fifth place, showing modest shifts in the global ranking.

In 2024, Australia's wind sector continued to grow steadily, with total installed capacity reaching approximately 10 GW, representing around 12% of the nation's total electricity generation capacity. While Australia does not rank among the top five global markets, it is a leading wind market in the Asia-Pacific region. Most capacity comes from onshore wind farms in South Australia, Victoria and New South Wales, with new projects continuing to expand [3].

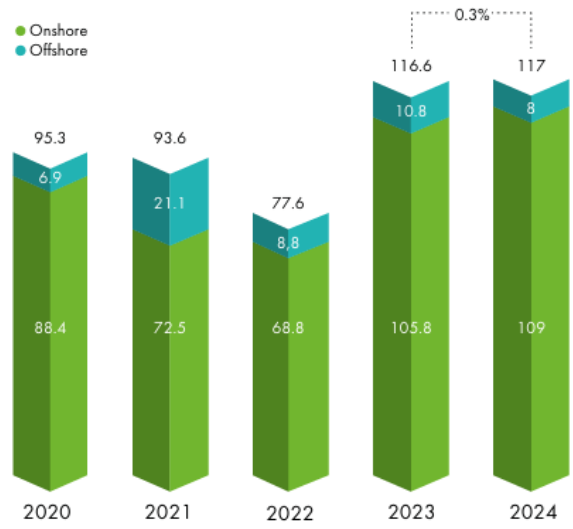


Figure 3: New installed capacity in GW, derived from GWEC 2025 (Global Wind Energy Council).

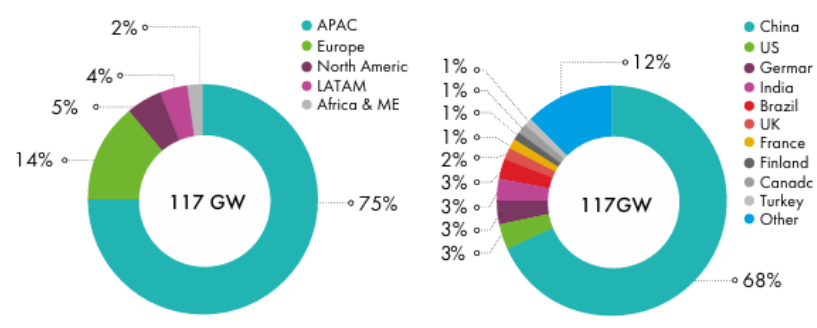


Figure 4: New capacity in 2024 installed by region (%) and New capacity 2024 and share of top 10 markets (%), derived from GWEC (Global Wind Energy Council).

1.3.1 Offshore Wind Market Status 2024

In 2024, a total of 8 GW of new offshore wind capacity was added to the grid globally, raising the world’s total offshore wind capacity to 83.2 GW by the end of the year. This represented a 26% decrease compared with 2023, making 2024 the fourth-largest year for offshore wind installations historically.

China remained the global leader in new offshore wind installations for the sev-

enth consecutive year, adding 4 GW and bringing its total offshore wind capacity to 41.8 GW by year-end. The Chinese offshore wind market has been operating under grid parity for three years, meaning electricity generated by wind receives the same compensation as coal-fired power. Despite adding 5 GW in 2022 and 6.3 GW in 2023 without central government subsidies, new additions fell by 36% in 2024 due to delays in grid connections, complex maritime approvals and a slower than expected transition from nearshore to deep-water projects.

Europe added 2.7 GW of offshore wind from nine projects across four countries, accounting for roughly one-third of new global offshore wind capacity in 2024.

The UK connected 1.2 GW of offshore wind, reclaiming the title of Europe's largest market for new installations. A total of 88 turbines were installed, including 60 SG14-222 turbines at the Moray West project and 28 SG8.0-167 turbines at Neart na Gaoithe. The 1.2 GW Dogger Bank Phase A project experienced delays, with only five GE Vernova Haliade-X turbines commissioned.

Germany brought online 730 MW of offshore wind, including 477 MW at Baltic Eagle in the Baltic Sea and 253 MW at Gode Wind 3 in the North Sea. Baltic Eagle features 23 SGRE SG11-200 turbines, while Gode Wind 3 uses 50 V174-9.5 MW turbines supplied by Vestas.

In the Netherlands, 24 GE Cypress 5.5 MW turbines replaced 28 older Nord-tank NKT 600 kW turbines at Vattenfall's Irene Vorrink nearshore wind farm in IJsselmeer Lake, becoming operational in March 2024.

France commissioned 658 MW of offshore wind, with 85 SGRE turbines connected at Fécamp and Saint-Brieuc, achieving full operation in May. The Provence Grand Large floating wind project, 25.2 MW with three SGRE 8.4 MW turbines, was Europe's only new floating offshore wind installation in 2024. Elsewhere, China launched the 16.6 MW Mingyang OceanX floating turbine platform, a twin-rotor V-shaped system with two MySE8.3-180 turbines, adding a total of 41.8 MW of floating offshore wind worldwide in 2024.

In the Asia-Pacific region outside China, Taiwan connected 933 MW from 107 turbines across multiple offshore wind farms. Japan's Ishikari Bay New Port Offshore Wind Farm, 112 MW, began commercial operations, featuring 14 SGRE SG8.0-167 turbines. South Korea commissioned 18 Doosan 5.56 MW turbines at the 100 MW Jeju Hallim Offshore Wind Farm, making it the country's largest commercial offshore wind project.

In the Americas, the US is the only country with operational offshore wind turbines. Ten Haliade-X turbines were installed at Vineyard Wind 1806 MW, but commissioning was delayed due to a blade failure in July 2024. The US did commission the 132 MW South Fork Wind Farm, consisting of 12 SGRE SG11-200 turbines, bringing its total offshore wind capacity to 174 MW.

Globally, China dominates cumulative offshore wind installations, accounting for 50% of the total market (Figure 5). It overtook the UK in 2021 and has strengthened its lead over the past three years. Germany, Netherlands and Taiwan complete the top five markets, while Denmark, previously a pioneer, fell out of the top five for the first time [3].

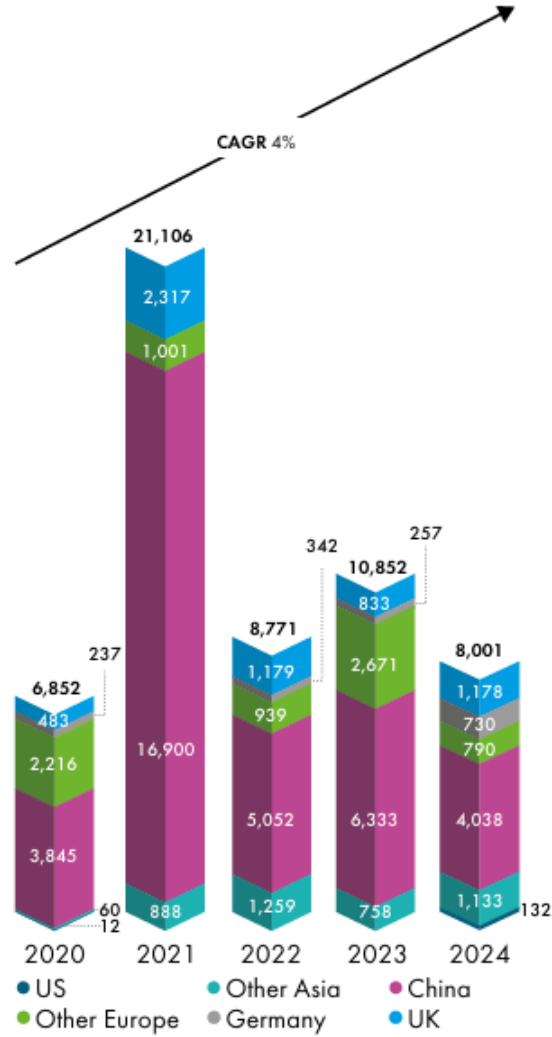


Figure 5: New Offshore Wind Installations (MW), 2020-24 (GWEC, 2024).

2 Technical Component of Floating Offshore Wind

Floating offshore wind farms represent complex multidisciplinary engineering systems composed of several interconnected technical components that ensure the structural stability, operational reliability and efficient transmission of the electrical power generated by turbines installed in deep-water environments. Unlike fixed-bottom offshore wind systems, floating wind turbines require dedicated floating substructures and station-keeping systems capable of maintaining platform stability while withstanding the combined action of aerodynamic loads, wave-induced forces and ocean currents. The successful deployment of floating offshore wind technology therefore depends not only on turbine performance, but also on the integration of several supporting technologies that guarantee safe and efficient operation under harsh offshore conditions. This chapter presents an overview of the main technical components that characterize floating offshore wind systems, with particular attention given to the floating foundations supporting the turbines, the mooring and anchoring systems responsible for maintaining platform position and the offshore electrical infrastructure required to transmit the generated power to shore. A clear understanding of the function and interaction of these components is essential for evaluating the technical feasibility, structural behaviour and overall performance of floating offshore wind installations.

2.1 Floating Foundations

A floating foundation, often called a floating substructure or floating platform, is the structure that supports an offshore wind turbine in waters too deep for fixed-bottom systems. The turbines themselves are identical to those used on fixed-bottom foundations; the difference lies in the supporting platform.

In deep offshore areas, the platform must be strong enough to withstand wind and wave forces and the motion generated by the turbine. It also needs to limit pitching movements, since excessive tilt reduces energy production. Stability can be achieved by increasing the distance between the centre of gravity and the centre of buoyancy (gravity-based stability), by exploiting the surface area in contact with the water to resist rotational movement (waterplane stability) or by using mooring lines anchored to the seabed (mooring-based stability).

Depending on how these stabilisation principles are applied, floating wind foundations are generally classified into four main types: spar structures (including multi-spar variants), barges, semi-submersible platforms (“semi-sub”) and tension leg platforms (TLPs) [19], [20]. At present, the industry does not favour a single design; instead, the most suitable option is chosen for each project based on factors such as water depth and seabed conditions (Figure 6).

Floating wind foundations are mainly built using two materials: steel and con-

crete. Semi-submersible platforms are typically made of steel, while barge and spar designs are often produced using concrete, although in practice either material can be chosen depending on project needs. Steel has historically been the standard material used in offshore wind projects. However, interest in concrete has increased due to its potential to significantly reduce both costs and associated greenhouse gas emissions. Studies suggest that concrete foundations could reduce material costs by around 50% and greenhouse gas emissions by approximately 40–50% compared with steel solutions [21].

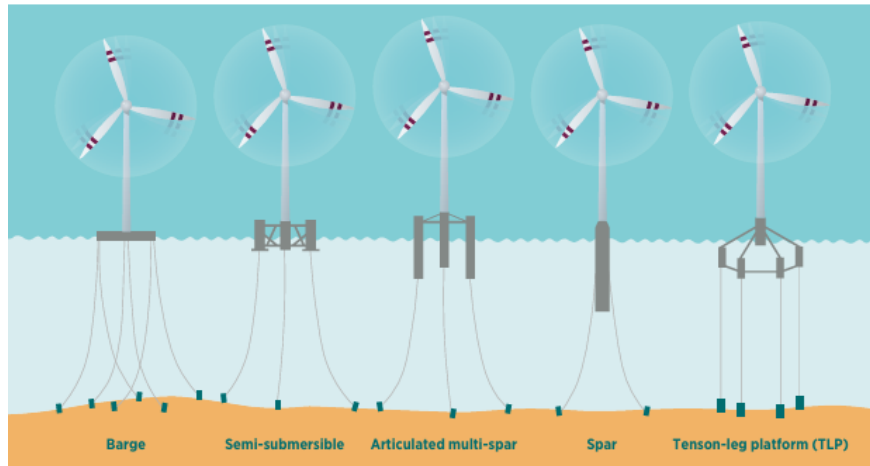


Figure 6: Main categories of floating offshore wind turbine foundations (IRENA 2024).

Figure 7 presents an overview of the different floating substructures, outlining their primary advantages and drawbacks.

SUB-STRUCTURE	DESCRIPTION	CHARACTERISTICS	EXAMPLES - PLATFORM NAME (TECHNOLOGY DEVELOPER)
 BARGE	The most common structure is a shallow and wide floating platform that sits along the water surface. Water stabilisation is used.	- No need for deep dock or special tow/ installation equipment - Proven technology (70 MW in operation) - Less material required to manufacture than spar - Not dependent on water depth - Lower pitch-and-roll motions (relative to spar) - More deck space for maintenance - Can be constructed onshore or in a dry dock - Fully equipped platforms (including turbines) can float with drafts below 10 m during transport	- Damping Pool (BW Ideol) - SATH - Floatgen (BW Ideol) - Deep Wind (Deep Wind Consortium)
 SEMI-SUB	The typical foundation comprises 3-5 vertical cylinders that are connected in a triangular shape and linked by connecting bracings / submerged pontoons. The wind turbine is attached to one of the columns and is stabilised through water and gravity stabilisation. The columns provide the hydrostatic stability, and pontoons provide additional buoyancy. The foundation is kept in position by catenary or taut spread mooring lines and drag anchors.	- Barge foundations can offer improved stability by increasing the water plane area as far from the centre of gravity - Lowering the centre of gravity of semi-subs can contribute to their stability, which is achieved by using a ballast (a weight attached to the base of the structure) Challenges: - More difficult to manufacture than spar - Large seabed footprint - Larger heave motion	- WindFloat (Principle Power) - Fuyao (CSSC Haizhuang Wind Power) - Fukushima Shinpu (Mitsubishi Heavy Companies) - Eolink (Eolink) - China Three Gorges (China Three Gorges) - W2Power (Enerocean) - Nezzy2 (EnBW) - VoltturnUS (New England Aqua Ventus) - Fukushima Mirai (Mitsuit Engineering) - FPP (Floating Power Plant) - Hakata Bay Scale Pilot Wind Lens (Kyushu University)
 SPAR	The structure comprises a single vertical cylinder with low water plane area, ballasted to keep the centre of gravity below the centre of buoyancy (stabilised through gravity) with a ballast at the bottom. The wind turbine is directly connected to the ballast. The foundation is kept in position by catenary or taut spread mooring lines with drag or suction anchors	- Manufacturing simplicity - Proven technology (118 MW in operation) - Small heave motion - Requires deep operational water (>100 m) for larger turbines Challenges: - Difficult to tow, as it requires a deep dock or sheltered area, as well as a large offshore crane to install the turbine - Heavy and large structure that has a high fatigue load on the base - Larger pitch-and-roll motion - Low deck space for maintenance	- Hywind (Equinor) - Tetraspar (Stiesdal) - SpinWind (Gwind) - SeaTwirl S1 (SeaTwirl) - Fukushima Hamakaze (Japan Marine United Corporation) - Deep Wind (Deep Wind Consortium) - Hybrid Spar (Toda Corporation)
 TENSION-LEG PLATFORM (TLP)	The submerged foundation is connected to mooring lines. A central column is the interface between the foundation and the wind turbine above the surface. The foundation is stabilised through moors and is highly buoyant, with the central column and arms connected to tensioned tendons that secure the foundation to the suction / piled anchors.	- Small heave-and-pitch motion - Low seabed footprint - Can be sited at variable water depths - Light and small structure, which implies lower material costs - Tendency for lower critical wave-induced motions - Can be assembled onshore or in a dry dock - Taut mooring lines contribute to good stability Challenges: - Requires a special purpose-built installation vessel - Expensive mooring lines and anchors with high vertical load - A single mooring line failure can result in catastrophic event. - Has a low technology readiness level compared to other categories - No space for maintenance - Not suitable for project sites with large tidal range	- Blue H (Blue H Engineering) - Float4Wind (SBM Offshore) - SWAY (Hybrid spar-TLP by Inoceen) - Pelastar (Pelastar)

Figure 7: Comparison of major categories of floating foundations, Edwards et al., 2023; Efthimiou et al., 2022a; IRENA, 2019, (IRENA 2024).

2.2 Mooring systems

A mooring system is required to control and maintain the position of the foundation. Its primary purpose is to ensure that the structure stays fixed relative to a designated point within the installation site. The main elements of the mooring system are the mooring lines (or tendons) and anchors, which transfer the forces generated by the foundation to the seabed. Maintaining stability in deep-water conditions is particularly important, as excessive or unwanted movements can cause damage to the power cables [22].

The design of the mooring system depends on multiple factors, including site-specific conditions, the type of foundation chosen and the layout of power cables. These factors all affect the six degrees of freedom experienced by the turbine (Figure 8). Mooring systems can be described as either compliant or restrained. A compliant system allows more movement, while a restrained system provides greater stability but results in higher loads on the mooring lines. Therefore, achieving an appropriate balance between motion and mooring forces is essential [23].

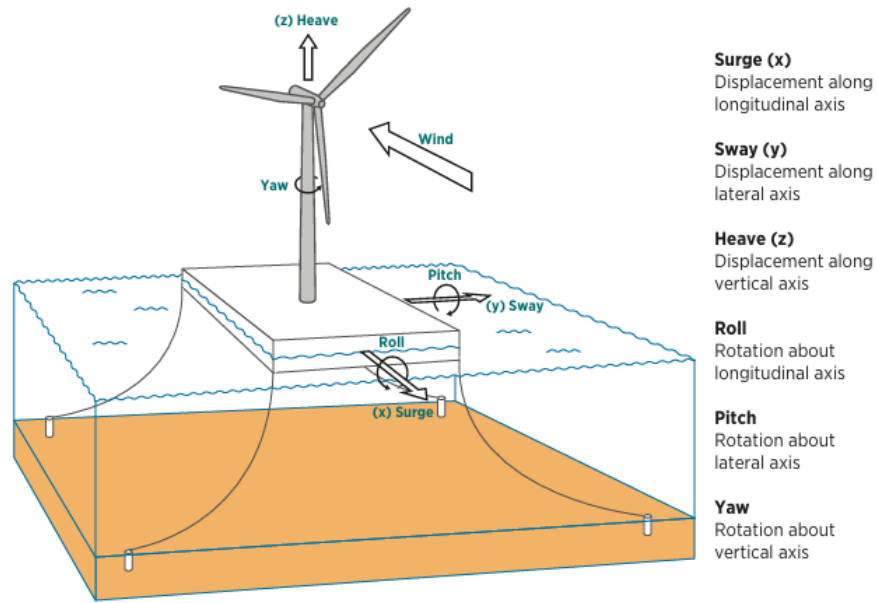


Figure 8: Six degrees of motion for a wind turbine, Efthimiou et al., 2023 (IRENA 2024).

2.2.1 Mooring Lines

Mooring lines can generally be divided into two main types: taut lines and catenary lines. Taut lines, typically made of rope, run from the platform to a high-capacity vertical anchor and are commonly employed in tension leg platform (TLP) foundations. In contrast, catenary lines, usually composed of freely hanging chains, extend along the seabed in a horizontal manner and are anchored at the ends using drag anchors; these are typically used in spar, barge and semi-submersible foundations [22]. Figure 9 shows simplified schematics of these mooring line configurations. Placing the connection points on the platform above the water surface can simplify both the installation and ongoing maintenance processes [19].

Mooring lines can be further divided into:

- Plain catenary: a simple chain running between the anchor and the floating foundation, generally employed in shallow-water applications;
- Multi-catenary: a combination of chains and synthetic ropes that leverages both weight and stiffness to reduce platform motion;
- Buoyant semi-taut: a hybrid line with a higher proportion of synthetic rope, incorporating buoyancy modules to avoid damage from seabed contact;
- Taut: high-tension ropes anchored directly to the seabed; this configuration forms the basis of tension leg platforms (TLPs).

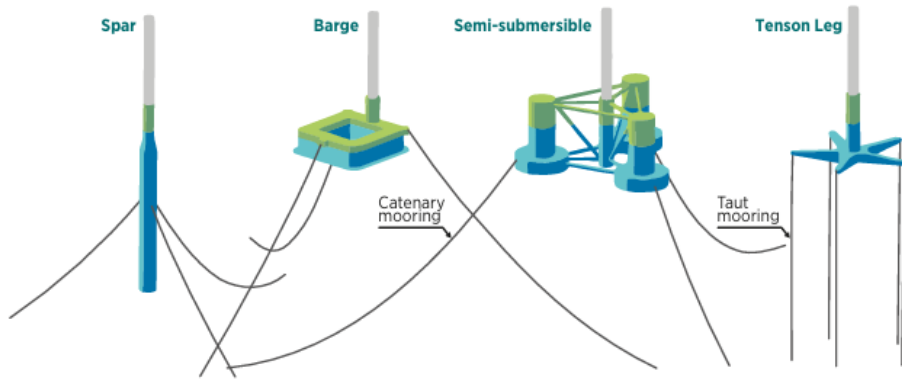


Figure 9: Floating foundation mooring lines, Edwards et al., 2023 (IRENA 2024).

A recent development in floating wind mooring technology is the use of synthetic ropes, made from materials such as polyester or carbon fiber, as an alternative to traditional steel chains. The key advantages of these ropes include corrosion

resistance, high fatigue strength and low failure rates. They are also suitable for large-scale production and can be transported to the installation site more easily. However, some challenges remain, including biofouling on the exposed portions of the rope, ingress of seabed particles causing increased wear and potential mechanical damage from cuts or abrasions.

To enhance stability and reduce stress on the mooring lines, load reduction devices are often installed on the upper sections. These devices can lower peak loads by up to 50% and reduce fatigue stresses by around 30%, potentially shortening the required rope length and offering 5-8% savings in CAPEX. Additionally, tensioners positioned on the lower sections allow for quick adjustments to line tension.

Some tension leg platform (TLP) foundations utilize a single-point mooring system, where a taut or catenary line is attached to a single foundation point. This setup allows the platform to rotate around the connection point, enabling the turbine to align with wind direction, a process known as weathervaning. This mooring configuration can also be applied to semi-submersible platforms and barges, particularly for multi-turbine installations [22], [24].

2.3 Anchors

Several types of anchors can be employed, including deadweight, driven pile, drag, suction pile, gravity drop and vertical load anchors (Figure 10). The selection of an anchor is largely determined by seabed conditions, which in turn affects the choice of mooring lines. Anchors are a well-established component of floating wind systems, but recent innovations are exploring shared anchor systems for deep-water applications, where a single anchor can serve multiple foundations. For instance, Equinor’s Hywind Tampen project off Norway utilizes 19 anchors for 11 turbines, whereas the Hywind Scotland project employs 15 anchors for 5 turbines, demonstrating a more efficient use of anchoring infrastructure [22], [24], [25].

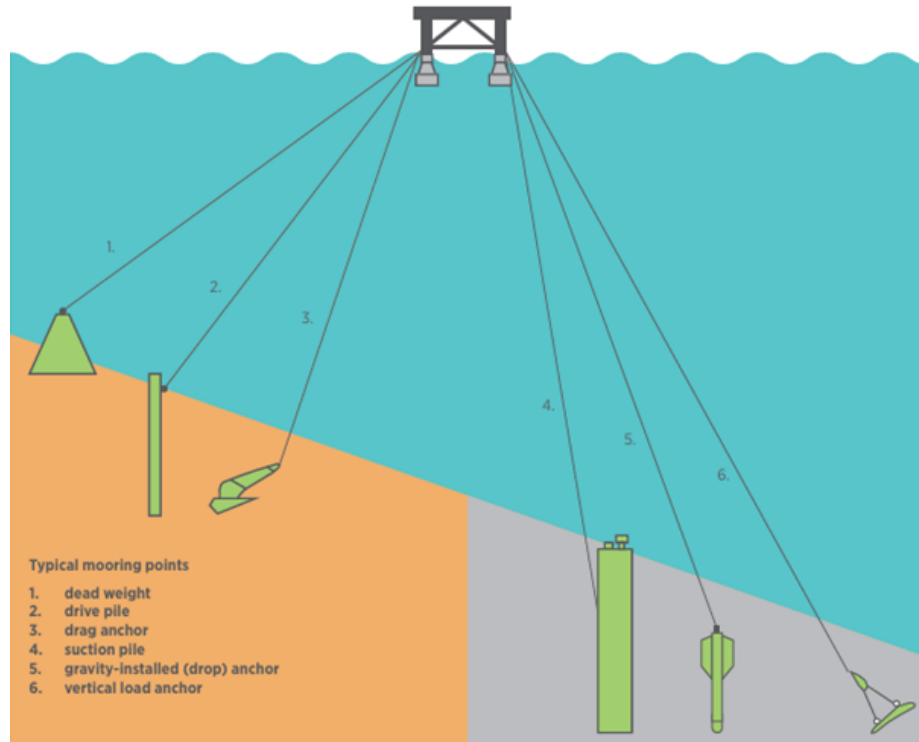


Figure 10: Types of anchors for floating foundations, Efthimiou et al. 2023 (IRENA 2024).

2.4 Power transmission

In order to deliver electrical power from offshore installations to onshore facilities, a reliable offshore power transmission system is required to manage the high levels of energy generated. Figure 11 presents a simplified illustration of the main components of such a transmission system.

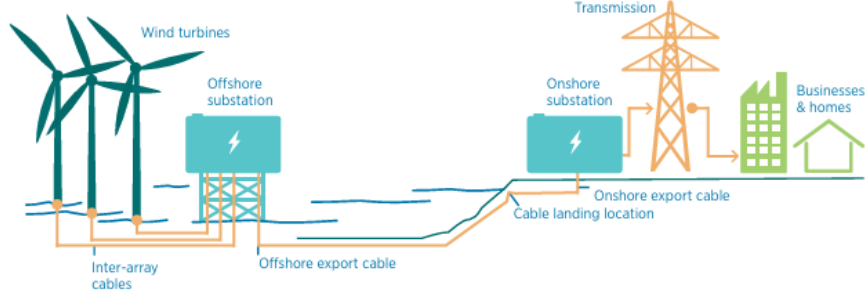


Figure 11: Offshore wind transmission components – AC export cable, DOE et al. 2023 (IRENA 2024).

Prior to the installation of cabling for a floating offshore wind farm, the project developer conducts a comprehensive seabed survey to identify and avoid any obstacles. This is typically followed by the removal of debris using a grapnel sweep. The cable installation process then proceeds with cable laying, which is subsequently accompanied by testing and inspection, often carried out using remote video monitoring [24].

2.4.1 Cables

The typical sequence for offshore to onshore power transmission begins with array cables, which transfer electricity from individual wind turbines to an offshore substation. From there, export cables carry the power to an onshore substation.

Standard offshore wind subsea cables are composed of multiple layers, including sealing, insulation and protective coverings. Proper insulation of the power core is essential and three primary types of insulated power cores exist: dry (with a lead sheath), semi-wet (with a polyethylene sheath) and wet (without a sheath but with a metallic screen). Among these, the wet design is often preferred due to its lighter weight and increased flexibility.

For floating offshore wind applications, a crucial characteristic of the cables is that they are dynamic, meaning they are engineered to accommodate the movements of the floating structure caused by wind, waves and currents. These cables are specifically designed for saltwater exposure, high fatigue loads and the motions of both foundations and ocean conditions. Compared to static cables,

dynamic cables generally feature a non-lead insulated sheath and an additional armouring layer to enhance durability [25]. Figure 12 provides an overview of a typical dynamic cabling system.

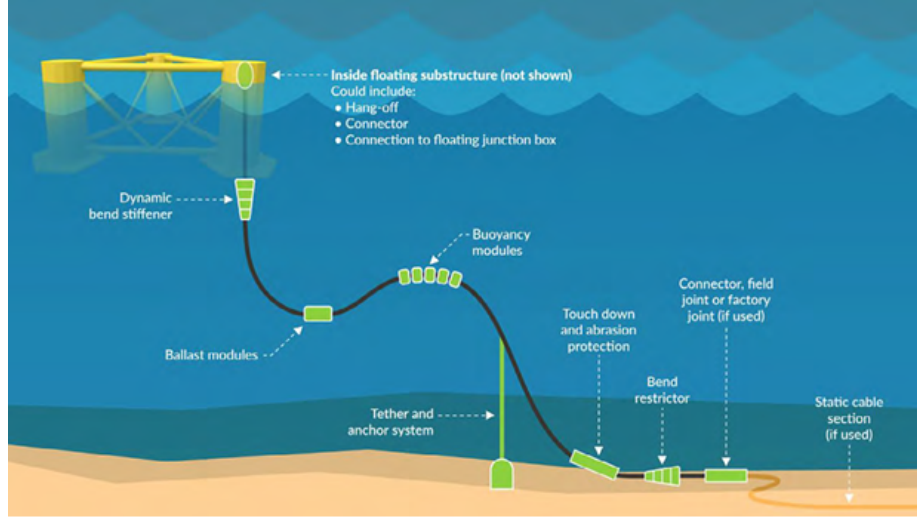


Figure 12: Floating offshore wind dynamic cabling system, BVG Associates, 2023, (IRENA 2024).

2.4.2 Array cables

Array cables are typically engineered to link multiple turbines to the offshore substation. In floating wind installations, these cables are designed to operate dynamically between the floating structure and the seabed. The configuration can consist of either a single dynamic cable running from turbine to turbine or separate dynamic cables connected to each turbine, with a static section completing the connection.

Array cables may be attached to the floating foundation either before or after the foundation is installed. However, the preferred approach is to connect the cables prior to installation, following procedures similar to those used for export cables. If the cables are installed after the foundation is in place, the process involves pulling the cable into the offshore substation (when it is the first point of the array or loop), followed by installing bend stiffeners and buoyancy modules. After this, the cable-laying vessel positions the cable toward the next turbine in the array. A remotely operated vehicle (ROV) is then used to connect the cable to the turbines and to the offshore substation [25], [26].

2.4.3 Export cables

The export cable is the essential connection that enables the transmission of electricity generated offshore to the onshore grid by linking the offshore and onshore substations. Offshore export cables are generally static, as most of the route lies along the seabed; only the segment connected to the offshore substation is dynamic.

Cable installation begins at the offshore wind farm, where export cables are deployed from a cable-laying vessel toward the offshore substation. In many cases, the cables are buried 1-4 meters beneath the seabed using a plough mounted on the vessel. Alternatively, the cable may first be laid on the seabed and then guided and buried by a remotely operated vehicle (ROV).

The subsea portion of the cable ends at a transition joint pit, where it is connected to the onshore section. Once the onshore part is installed, several tests are performed to verify that the cable can operate near its designed voltage level before final integration with the onshore substation.

A recent development in export cable technology is the growing adoption of High-Voltage Direct Current (HVDC) systems. HVDC export cables are used for large-scale projects (1 GW or more) and for wind farms located more than 60 km offshore. The primary advantage of HVDC lies in the reduction of electrical losses over long transmission distances and in the avoidance of additional equipment, such as costly shunt reactors, which would otherwise be required to manage reactive power in High-Voltage Alternating Current (HVAC) cable systems.

However, HVDC converter stations have a significant drawback: they are expensive. Their use becomes economically viable primarily for offshore projects located far from shore, although they also offer additional functionalities such as voltage regulation, grid forming capability and black start capability [25], [26]. Figure 13 illustrates the power transmission chain when HVDC infrastructure is implemented.

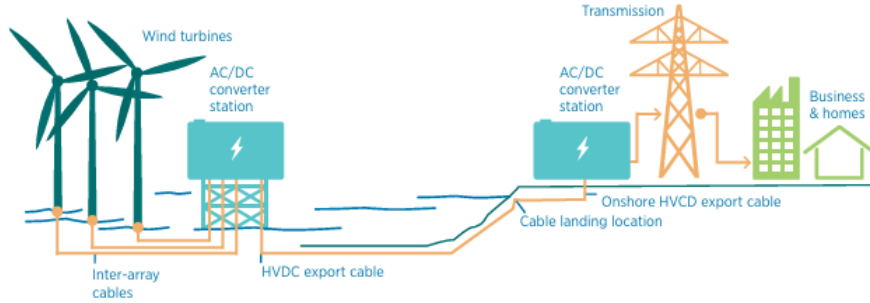


Figure 13: Offshore wind transmission components – HVDC (High Voltage Direct Current) export cable, DOE et al., 2023, (IRENA 2024).

2.4.4 Offshore substation

The offshore substation serves as the central hub between the array cables, which transport electricity generated by the wind turbines and the export cables responsible for transmitting power to shore. Its setup includes the electrical system (with the transformer as the main component), auxiliary equipment, a supporting structure to house all systems and a fixed foundation, which is typically a jacket foundation. Substations may operate using HVAC or HVDC technology. In HVAC configurations, a single offshore substation generally serves one wind farm and manages power outputs in the range of several hundred megawatts. In contrast, an HVDC system allows multiple wind farms to be connected via AC (66-132 kV), sometimes through intermediate transformer stations that increase voltage levels before reaching an offshore HVDC converter station.

The offshore substation is usually assembled on land and then transported offshore for installation on a pre-installed jacket or monopile foundation. Since substations are extremely heavy structures, their installation requires specialized lifting vessels capable of handling at least 2000 tonnes. If such vessels are unavailable, the substation can be transported using a barge and lifted into place with cranes [25].

Current industry developments are focused on creating floating offshore substations, a necessary step toward deploying wind farms in waters deeper than 100 metres. A joint industry project led by DNV is actively working on this advancement [27].

2.4.5 Offshore-onshore network topology options

There are two main approaches for transmitting electricity from offshore wind farms to the onshore grid: radial systems and networked systems. In a radial transmission layout, electrical power flows along a single route from the offshore

generation site to the onshore grid connection point. As illustrated in Figure 14, two primary configurations can be identified:

- Dedicated export lines: each offshore wind farm is connected to a single onshore grid entry point through its own export cable, representing the most commonly adopted solution due to lower risks and faster implementation.
- Shared export lines: multiple offshore wind farms transmit electricity through a common export cable, reducing the total number of cables required and potentially providing environmental and social benefits, although this configuration requires greater coordination among projects and stakeholders.

A networked transmission layout expands upon the radial approach by creating electrical links between offshore nodes or by connecting multiple offshore nodes to more than one onshore grid point. With this structure, power can flow in several directions, allowing for rerouting when needed and helping to ease congestion on transmission lines [28]. Although such configurations are being considered for fixed-bottom offshore wind farms, their application to floating projects is significantly more challenging due to greater water depths and the need to install multiple subsea cables, which increases technical complexity and tends to extend project timelines.

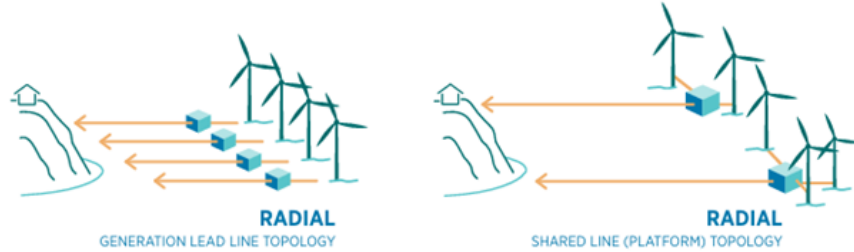


Figure 14: Radial offshore network configuration, DOE et al. 2023, (IRENA 2024).

3 Focus on the Australian Situation

Australia and the world are undergoing a major transformation aimed at achieving a safe climate future and net zero emissions by 2050, which requires clear pathways to address climate change. The Australian Government is implementing a wide range of climate policies and programs designed to grow the economy, reduce greenhouse gas emissions across different sectors and help communities adapt to climate impacts. These measures aim to ensure that the economy remains prosperous, communities are protected and land and water resources remain sustainable. Reducing emissions across the economy is the most effective way to prevent the worst impacts of climate change and maintain economic security as other countries transition to cleaner energy systems. Australia is committed to a fair, orderly and efficient transition to net zero by 2050, with an interim target for 2035 of reducing emissions by 62-70% compared to 2005 levels, based on expert advice from the Climate Change Authority [29]. The Net Zero Plan, together with six sector plans, outlines how these targets will be achieved and the benefits they will deliver for Australians.

In the energy sector, the transition to renewable sources underpins the net zero transformation. Key initiative include:

- building a larger, modern and cleaner electricity grid;
- ensuring sufficient renewable and reliable energy for current demand and future electrification;
- implementing renewable energy agreements with states and territories;
- securing affordable energy for consumers through the National Consumer Energy Resources Roadmap;
- using solar and wind electricity to create and export green resources needed for the global net zero economy.

The shift to a net zero economy represents significant economic opportunities for Australia, its regions, industries and workforce. New clean industries, such as renewable hydrogen and green steel, will reduce emissions and strengthen the future economy. Australia's abundant solar and wind resources and skilled workforce provide a strong foundation to develop these industries. Priority sectors with economic advantages, including hydrogen, are being accelerated and initiatives such as Solar Sunshot support the creation of secure clean energy supply chains, generating jobs and economic growth across regional areas.

Australia also plays a key role in global climate action. As a party to the Paris Agreement since 2016, the country contributes to efforts to keep global warming well below 2°C and strives to limit it to 1.5°C. Australia is addressing this by assessing climate risks through the National Climate Risk Assessment, guiding national adaptation via the National Adaptation Plan and ensuring

First Nations communities are included in the clean energy transition. This involves advisory committees and strategies to ensure benefits reach everyone, as well as support for regional industries to reduce emissions and remain competitive. Training programs are preparing workers for emerging roles in new energy sectors and the Net Zero Economy Authority coordinates the transition from coal-fired power stations to renewable energy sources.

Progress is closely monitored through multiple channels:

- National Inventory Reports;
- Quarterly updates from the National Greenhouse Gas Inventory;
- State and territory inventories;
- National Inventory by economic sector;
- Annual emissions projections comparing future emissions with national targets.

Finally, the Annual Climate Change Statement to Parliament summarizes progress on greenhouse gas reduction targets, international developments, policy effectiveness, impacts on rural and regional areas, national security risks from climate change and adaptation measures, ensuring transparency and accountability in Australia’s journey towards net zero emissions [30].

As part of Australia’s transition to renewable energy, the government has established a formal framework for the development of offshore wind energy. In August 2022, the Minister for Climate Change and Energy announced the identification of six priority offshore areas. These areas were selected because they:

- have strong and consistent winds;
- are close to regions of high electricity demand;
- have existing electricity transmission infrastructure;
- have existing transport and port infrastructure;
- have industry interest in developing projects there.

The declaration of these areas follows extensive consultation with existing industries, including fishing, offshore oil and gas and other marine users, as well as state and local governments, First Nations communities and local stakeholders. This process is governed under the Offshore Electricity Infrastructure (OEI) regulatory framework, which designates specific offshore areas for renewable energy projects, such as floating offshore wind farms. The designation allows developers to apply for feasibility licenses and ensures that planning and development occur in areas carefully assessed for technical suitability, infrastructure proximity and environmental considerations. This legislative process provides certainty for

developers and investors while aligning offshore wind projects with community, environmental and industry priorities, supporting a safe and orderly transition to net zero energy.

3.1 Declared offshore renewable areas

Suitable areas are declared by the Minister for Climate Change and Energy of the Australian Government. These declarations follow thorough consultations with existing industries, including fishing, offshore oil and gas and other marine users, as well as with state and local government representatives, First Nations people and local communities. In this context, OEI (Offshore Electricity Infrastructure) refers to the formal regulatory framework used to designate specific offshore areas for renewable energy development, such as floating offshore wind farms. This designation allows developers to apply for feasibility licenses and ensures that planning and development occur within areas that have been carefully evaluated for technical suitability, proximity to existing infrastructure and environmental considerations. Considering the previously described criteria, the areas identified as suitable, as illustrated in Figure 15, are:

- Gippsland, Victoria;
- Hunter, New South Wales;
- Southern Ocean, Victoria;
- Illawarra, New South Wales;
- Bass Strait, Tasmania;
- Indian Ocean off Bunbury, Western Australia.



Figure 15: Declared Offshore Renewable Energy Infrastructure Regions, derived from Australian Marine Spatial Information System 2025(AMSIS).

3.1.1 Gippsland Region, Victoria

In December 2022, the Australian Minister for Climate Change and Energy officially declared the Gippsland area (Victoria) as the country’s first offshore wind development zone (Figure 16). The declared area covers up to 15000 km² in

Bass Strait and has an estimated potential to generate up to 25 GW of offshore wind power, supporting approximately 15000 jobs during construction and 7500 permanent jobs.

The site offers favourable technical and environmental conditions, with significant variations in bathymetry. The central areas are relatively shallow, with depths of less than 60 m, which makes them suitable for cost-efficient fixed foundations such as monopiles or jackets. In contrast, the outer sections reach depths of around 90-100 m or more, making them more appropriate for floating platforms, particularly semi-submersible designs.

The seabed is predominantly sandy-silty with localised rocky sections, compatible with commonly used anchoring systems such as suction or drag anchors. Wind conditions are strong and consistent, while wave energy is less intense than in the Southern Ocean, allowing greater flexibility in design and installation.

Currently, 10 feasibility licences have been granted (out of 37 applications), allowing developers to carry out surveys, environmental assessments, marine studies (e.g., LiDAR buoys) and ongoing consultation with local communities, First Nations groups, fisheries and maritime industries. The feasibility stage may last up to 7 years, after which commercial licences will be required to build and operate wind farms.

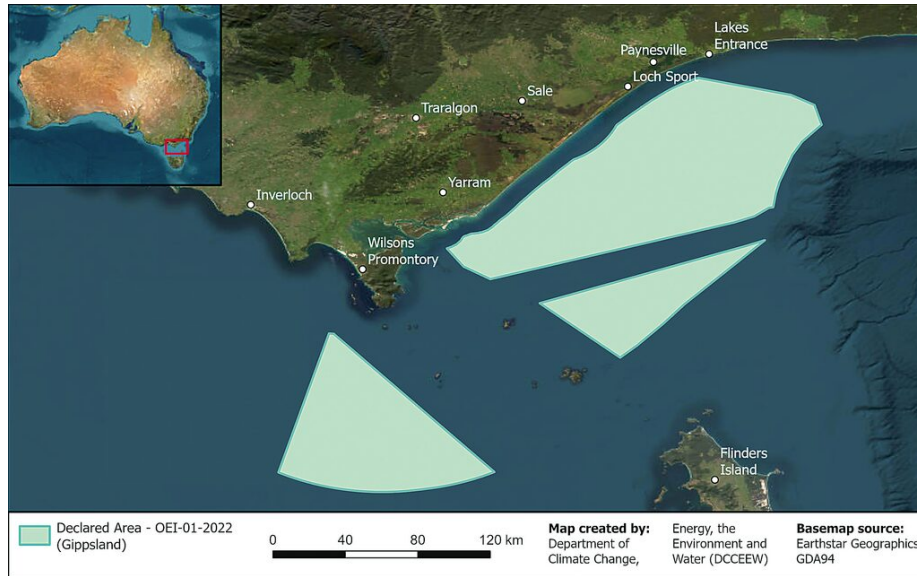


Figure 16: Map of Declared Area for Gippsland region (Victoria), taken from Department of Climate Change, Energy, the Environment and Water (DCCEEW).

Within this context, Star of the South stands as the flagship project for the Gippsland declared area and illustrates how these site characteristics can be translated into a real development. Positioned within the shallower portion of Bass Strait, where water depths largely remain below 60 m, the Star of the South project is designed to use fixed-bottom foundations, taking advantage of the favourable seabed composition, mainly sand and silt and the area's consistently strong wind resource. With an estimated capacity of 2.2-2.5 GW, the project could supply electricity to around 1.2 million homes, becoming a critical enabler of Victoria's energy transition as coal-fired power plants in the Latrobe Valley retire. The project already holds a feasibility licence and is conducting marine surveys, environmental studies, seabed investigations and consultation with First Nations groups, local communities, fisheries and other marine users. If developed, Star of the South would not only be Australia's first offshore wind farm, but also the anchor project that catalyses the wider offshore wind industry in Gippsland unlocking local supply chains, long-term regional jobs and positioning the region as a strategic renewable energy hub.

Figure 17 highlights the ten active feasibility licence areas for offshore wind projects located off the Gippsland coast in Victoria, showing the spatial distribution of the zones and identifying the companies that hold each licence [31].

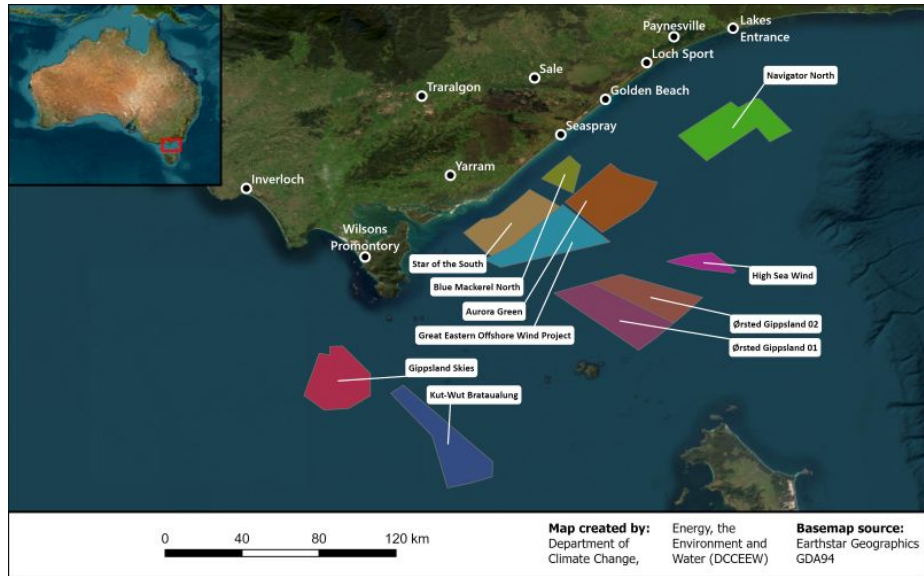


Figure 17: Map of the Gippsland Region (Victoria) showing the 10 currently active feasibility licences, taken from the Department of Climate Change, Energy, the Environment and Water (DCCEEW).

3.1.2 Hunter Region, New South Wales

In July 2023, the Australian Minister for Climate Change and Energy formally designated an offshore area in the Pacific Ocean, near the Hunter region of New South Wales, as suitable for future offshore wind development (Figure 18). Covering around 1854 km² between Norah Head and Port Stephens, the area is one of six priority offshore energy zones identified by the federal government. It was selected for its combination of favourable conditions, including strong and consistent winds, proximity to existing high-capacity grid infrastructure linked to coal-fired power stations, closeness to major industrial energy users such as the Tomago aluminium smelter and access to port facilities in Newcastle to support construction and maintenance. The site also aligns with the NSW Hunter-Central Coast Renewable Energy Zone, enhancing opportunities for energy transition.

Located approximately 20-35 km offshore, the area features seabed depths ranging from 60 to 150 m with a mixed composition of sand, silt and occasional rocky patches. These characteristics, combined with favourable wind conditions and variable sea states, make the site particularly suitable for floating wind technology, with semi-submersible platforms considered the preferred foundation type due to their adaptability and compatibility with local port logistics, while spar-buoy options may be viable in deeper, uniform seabed sections.

Prior to the declaration, a 65 days public consultation was held from February to April 2023, inviting local residents, councils, First Nations groups, commercial and recreational fishers, tourism operators and other stakeholders to information sessions and submission opportunities. A total of 1916 submissions were received, raising concerns regarding environmental impacts, fishing and shipping activities and visual effects, while also emphasising support for local economic benefits and renewable energy development. In response, the government reduced the size of the originally proposed area, excluding marine parks, key ecological habitats and recreational fishing zones and positioned the zone further offshore to minimise visual impact. Additional conditions were introduced, requiring developers to consult with authorities responsible for defence, meteorology, maritime safety, civil aviation and fisheries management.

When feasibility licence applications opened, only one project, Novocastrian Wind Pty Ltd, reached the offer stage in February 2025 but ultimately declined the licence. Consequently, no feasibility licences have yet been granted, though the area remains available for future offshore wind development. Overall, the Hunter area exemplifies a carefully planned offshore wind zone, designed to balance renewable energy development with environmental protection, community input and existing marine uses [32].

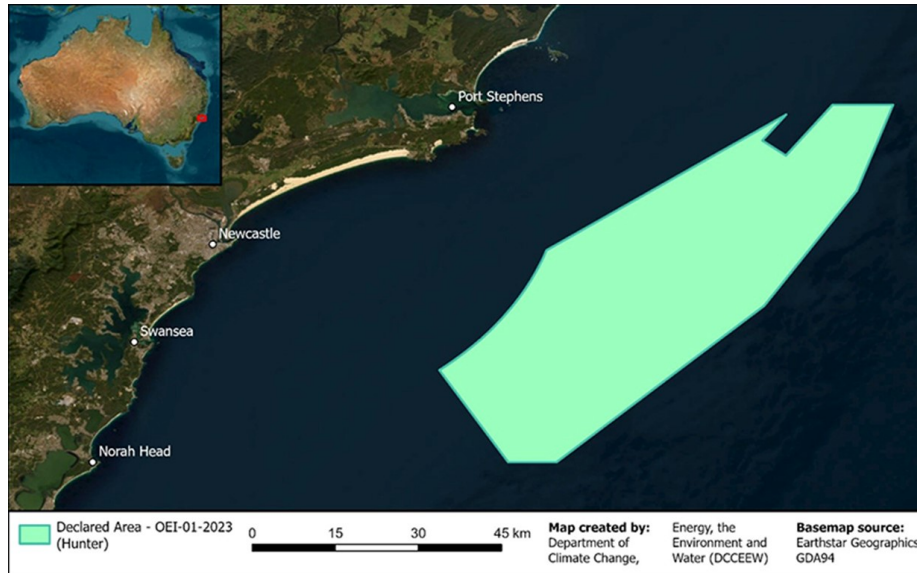


Figure 18: Map of Declared Area for Hunter Region (NSW), taken from Department of Climate Change, Energy, the Environment and Water (DCCEEW).

3.1.3 Southern Ocean Region, Victoria

The Southern Ocean region off western Victoria, shown in Figure 19, covering approximately 1030 km² and located about 15-20 km offshore from Warrnambool and Port Fairy, has been officially designated for offshore renewable energy as of 6 March 2024. This site is exposed to the full force of the Western winds from the Southern Ocean, providing strong, consistent wind resources, but also bringing long waves and rough sea conditions.

The seabed bathymetry in the region deepens rapidly beyond the continental shelf, with depths ranging from about 60 m up to over 150 m and in some segments exceeding 200 m. These conditions make fixed-bottom foundations impractical, while floating platforms are the most suitable solution. In particular, semi-submersible platforms are preferred due to their stability, dynamic performance in rough seas and flexible mooring options using drag anchors or suction piles. The seabed is generally sandy or compact silty, suitable for these anchoring methods. In deeper, more homogeneous sections, spar-buoy platforms could be considered, although they involve more complex installation and port logistics.

A feasibility license has been granted to the Spinifex Offshore Wind Farm, allowing developers to undertake detailed environmental and marine surveys, assess project viability and engage with local communities, First Nations groups and industry stakeholders. During a 64 days public consultation, over 3200 submissions were received, leading to adjustments to the declared area to protect ecologically sensitive zones, major fishing grounds and culturally important sites like Deen Maar.

Overall, the Southern Ocean area represents a prime site for floating offshore wind, particularly via semi-submersible platforms, offering significant potential for renewable energy production, local economic benefits and supporting Australia's transition to low-carbon electricity.

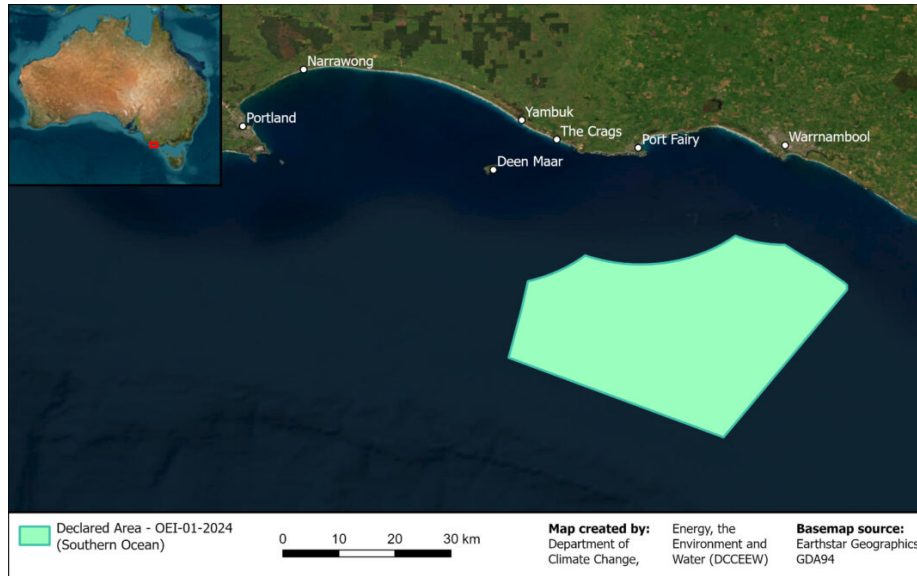


Figure 19: Map of Declared Area for Southern Ocean Region (Victoria), taken from Department of Climate Change, Energy, the Environment and Water (DC-CEEV).

The Spinifex Offshore Wind Farm, located in the Southern Ocean off southwestern Victoria, is a leading proposed project in Australia’s emerging offshore wind sector (Figure 20). Covering part of the 1030 km² declared zone, the project aims to generate around 1 GW of clean energy, potentially supplying 10% of Victoria’s electricity demand. It benefits from strong, consistent winds, proximity to existing grid infrastructure and connections to industrial users such as the Portland Aluminium Smelter. The project is expected to create significant regional economic benefits, including thousands of construction jobs and ongoing operational roles. Engagement with local communities and Traditional Owners is central, ensuring environmental and cultural considerations are respected [33].

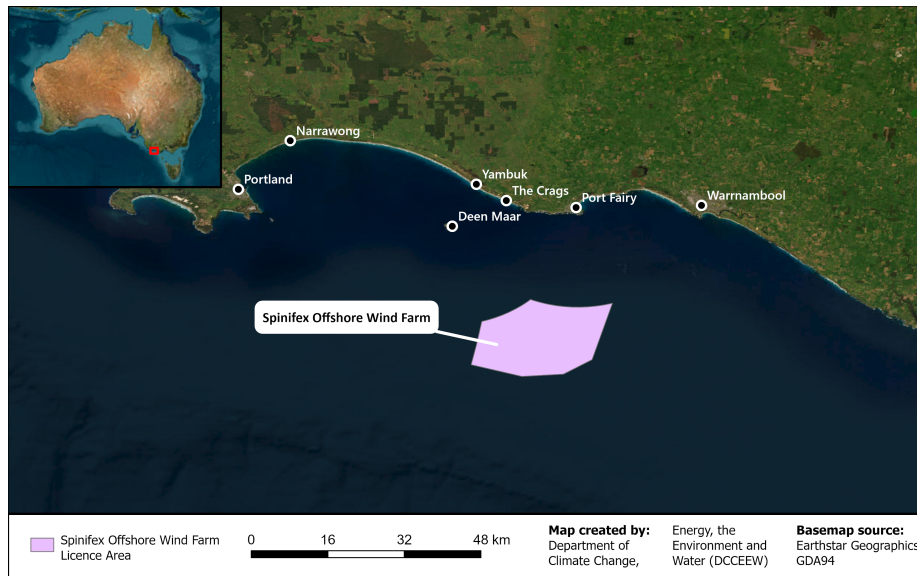


Figure 20: Map of the Southern Ocean Region (Victoria) showing the only one active feasibility license, taken from the Department of Climate Change, Energy, the Environment and Water (DCCEEW).

3.1.4 Illawarra Region, New South Wales

The Illawarra offshore wind area, officially declared in June 2024, encompasses approximately 1022 km² and is located around 20 km off the coast of the Wollongong region in New South Wales (Figure 21). The final boundaries of the zone were carefully adjusted following extensive public consultation, with the aim of minimizing visual impacts and avoiding environmentally sensitive areas such as marine parks, key whale migration routes and habitats for species like the Little Penguin. Despite the reduction in size, the area remains highly favourable for offshore wind development due to strong and consistent wind resources, proximity to major industrial users such as the Port Kembla steelworks and existing grid and port infrastructure that can support construction and maintenance activities.

Bathymetric conditions in the Illawarra area present additional considerations for development. Water depths range roughly from 60 to 200 meters, which generally makes fixed-bottom foundations economically and technically unviable. The seabed is predominantly sandy and silty, with occasional harder or rocky patches. These conditions favour floating wind solutions, which can be adapted to deeper waters and varying seabed types, while reducing installation challenges.

Among floating foundation options, the semi-submersible platform emerges as

the preferred solution. It provides robustness in medium to deep waters, demonstrates favourable dynamic response to wind and wave loads and is operationally manageable within the existing port logistics of the region. In select areas where water depths are greater and the seabed is relatively uniform, spar platforms could be considered. However, due to higher costs and more complex installation requirements, semi-submersibles remain the baseline choice for the majority of the site [34].

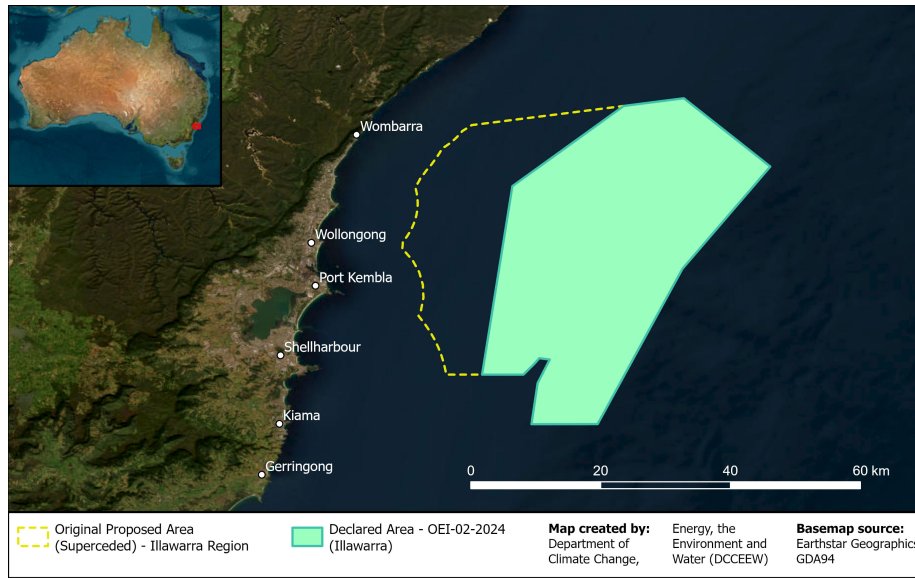


Figure 21: Map of the Illawarra Region (New South Wales) showing the Original Proposed area and the Declared Area, taken from the Department of Climate Change, Energy, the Environment and Water (DCCEEW).

3.1.5 Bass Strait Region, Tasmania

The Bass Strait offshore wind area, declared in December 2024, covers approximately 7100 km² off the northern coast of Tasmania, extending from Burnie to Bridport and located about 30 km from the shore (Figure 22). This zone was selected due to its world-class wind resources, proximity to high-demand electricity areas and access to port infrastructure at Bell Bay, making it highly suitable for large-scale offshore wind development.

Bathymetry across the site ranges from 50 to 150 m, with shallower areas (50-60 m) theoretically suitable for fixed foundations, but most of the area favours floating platforms, primarily semi-submersibles. Spar platforms may also be considered in deeper, more uniform sections. The seabed varies between sandy and rocky segments, requiring detailed MBES and geotechnical surveys to guide

anchor design.

Public consultation, conducted from October 2023 to January 2024, received 270 submissions highlighting environmental concerns, impacts on fishing and visual effects, while supporting renewable energy development and local employment. Following this feedback, the declared area was adjusted to be smaller, further offshore and to reduce overlap with commercial fisheries and bird migration pathways.

In short, the Bass Strait site is predominantly suited for floating wind, with semi-submersible platforms as the primary solution and spar platforms as a secondary option where conditions allow [35].

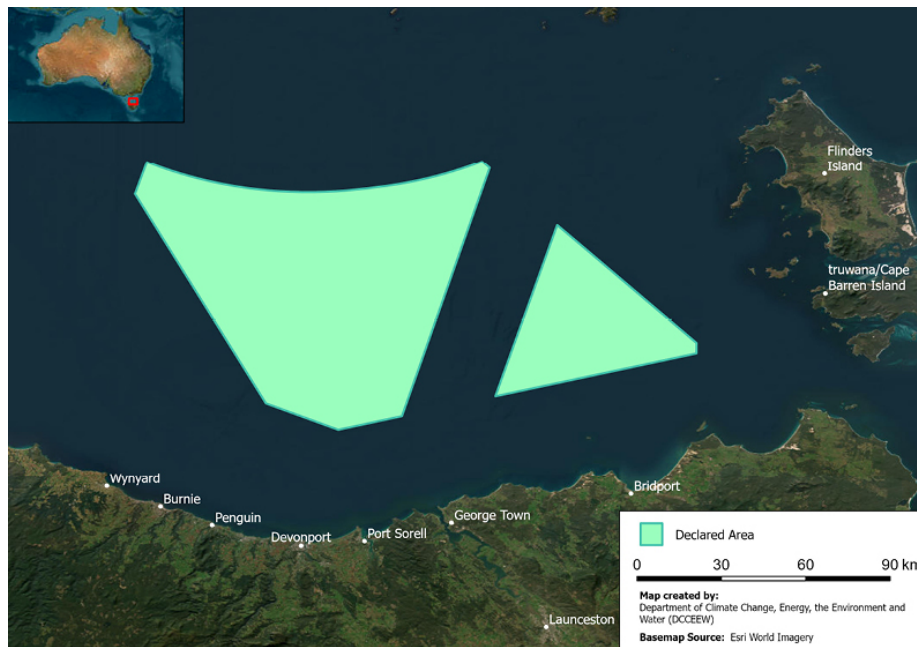


Figure 22: Map of Declared Area for Bass Strait Region (Tasmania), taken from Department of Climate Change, Energy, the Environment and Water (DCCEEW).

3.1.6 Indian Ocean off Bunbury Region, Western Australia

The Bunbury Offshore Wind Area, declared on 30 August 2024, covers approximately 3995 km² off the southwest coast of Western Australia, between Dawesville and Cape Naturaliste, at over 30 km from the shore (Figure 23). The area was selected for its strong and consistent wind resources, proximity to high-demand electricity centers and access to port infrastructure in Bunbury,

which facilitates construction and maintenance of offshore wind projects.

Public consultation, held from February to May 2024, engaged around 2670 participants, including local communities, environmental groups, fishers and First Nations representatives. Concerns raised included environmental impacts, visual amenity and effects on commercial and recreational fishing. In response, the declared area was reduced, positioned further offshore to minimize visual impact and adjusted to avoid sensitive marine habitats, migratory whale routes and key fishing zones.

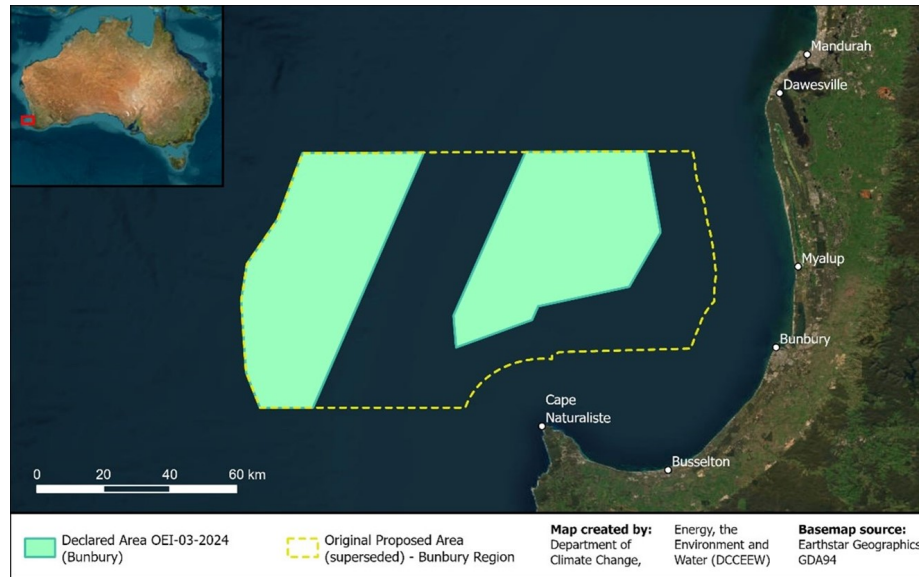


Figure 23: Map of the Bunbury Region (Western Australia) showing the Original Proposed area and the Declared Area, taken from the Department of Climate Change, Energy, the Environment and Water (DCCEEW).

Preliminary decisions have been made to offer feasibility licences for three projects: Bunbury OWP North (280 km²), Bunbury OWP South (246 km²) and the Westward Wind Project (206 km²), as illustrated in Figure 24, with a potential combined generation capacity of 4 GW. Final licence approval will require consultation with First Nations groups under the Native Title Act 1993 to assess any traditional rights or interests in the area. The site is suitable for offshore wind foundations, with semi-submersible platforms recommended for most of the area due to water depth and sea conditions, while turbines will follow a 15 MW reference model with a total height of 268 m and hub height of 150 m.

In summary, the Bunbury Offshore Wind Area exemplifies a carefully planned approach to offshore wind development, balancing renewable energy generation with environmental protection, maritime safety and consideration of local com-

munities and indigenous rights [36].

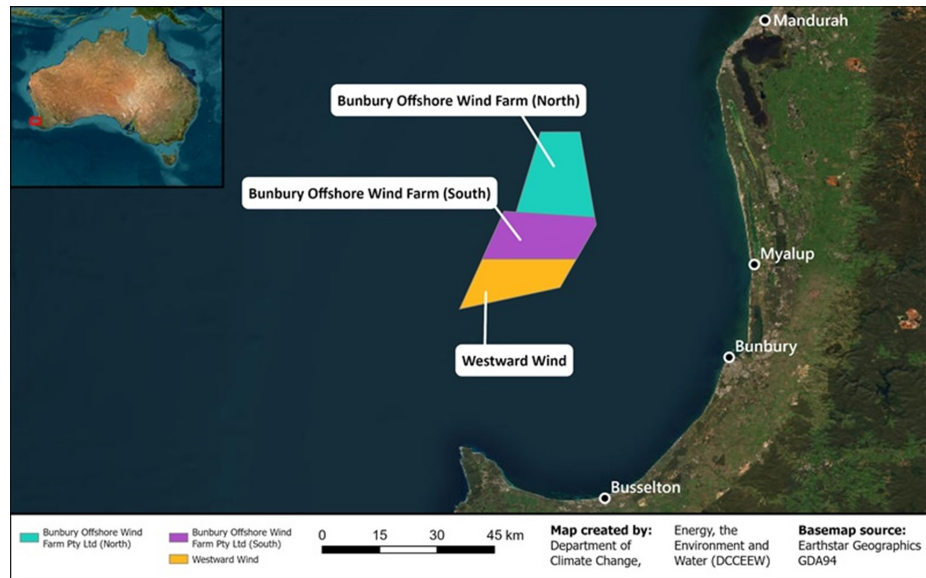


Figure 24: Map of the Bunbury Region (Western Australia) showing the 3 currently active feasibility licences, taken from the Department of Climate Change, Energy, the Environment and Water (DCCEEW).

4 Site Selection

After establishing the global context of the offshore wind market, presenting the main technologies associated with floating offshore systems and introducing the concept of Declared Offshore Marine Areas, the next objective of this work is to identify a suitable offshore site along the Queensland coast. The selected location should be appropriate for submission to the Australian Government and, subject to the relevant evaluation and approval procedures, may potentially be designated as an Offshore Renewable Energy Infrastructure Area in accordance with the requirements outlined in the Notice of Proposal.

In this phase, we will assess environmental constraints, maritime traffic, existing infrastructure and compatibility with other marine activities, in order to ensure that the selected location complies with legislative, technical and environmental criteria.

4.1 Australian situation

Global mean annual 100 m level wind speeds are shown in Figure 25 a). Panel b) displays a zoomed in perspective in the Australian region, in which the high offshore wind speeds relative to those experienced onshore can be clearly resolved.

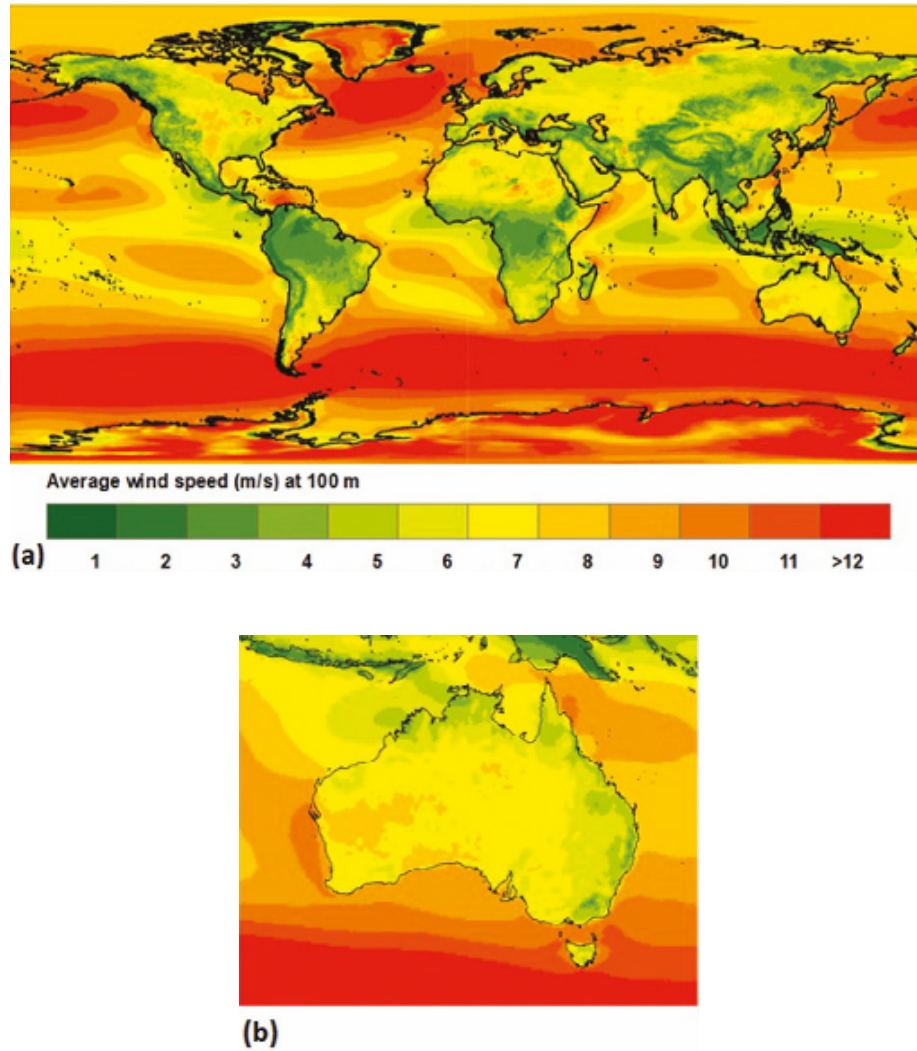


Figure 25: Mean wind speed (m/s) at 100 m level, derived from ERA-5 reanalysis, showing (a) global and (b) Australian wind distribution (BECRC Offshore Wind Energy in Australia 2021).

4.1.1 Mean Wind Speed

Australia's wind resource is primarily concentrated in the southern latitudes, where most of the southern coastline experiences average wind speeds above 7.5 m/s, with peak averages exceeding 12 m/s south of Tasmania. Moving northward, wind speeds generally decrease, with regions such as the Kimberley in north-western Australia showing average speeds below 6 m/s, which are typi-

cally excluded from resource assessments. In contrast, the northeastern coast of Queensland, between Cooktown and Cape York, exhibits higher wind speeds, with averages exceeding 9 m/s. Across all regions, wind speeds tend to increase with distance offshore, as is generally expected. The Australian offshore wind resource can also be classified according to international standards, highlighting areas suitable for potential development. The next figure, displays categorisation of Australia's offshore wind resource using the IEC criteria.

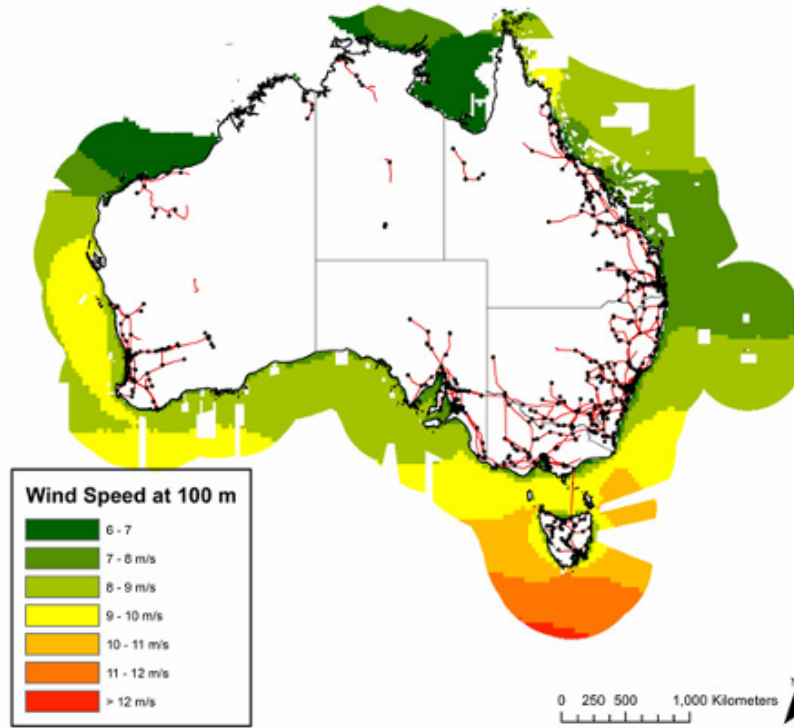


Figure 26: National average wind speed (m/s) from 2010-2019 within the EEZ study area at 100 m height. White regions represent areas where average wind speeds below 6 m/s or environmental restrictions exist (BECRC Offshore Wind Energy in Australia 2021).

4.1.2 Capacity Factor

Australian offshore wind resources have strong capacity factor, as highlighted in the figure below, which reflect the consistency of wind and indicate the proportion of the time that the generator can produce electricity.

Using the IEA reference 15 MW turbine model [37], capacity factor estimates

for the study area indicate significant variation across Australian waters. Predicted gross capacity factors range from around 20% in northern regions to over 80% south of Tasmania, with the highest values found offshore in the ‘Roaring Forties’ of the Southern Ocean. This area is characterized by consistently strong winds, resulting in theoretical capacity factors approaching 85%. More accessible regions, including Bass Strait, the western coast of Australia and northern Queensland, also exhibit substantial potential, with predicted capacity factors exceeding 55%.

For comparison, Australia’s onshore wind farms equipped with modern turbines typically achieve capacity factors around 45%, while most range between 28% and 38% [38]. The high predicted offshore capacity factors indicate that Australian waters could support performance levels comparable to some of the leading offshore wind projects internationally, such as the Scottish floating Hywind farm, which reported a 57% capacity factor over twelve months with average wind speeds near 10 m/s [39].

Overall, the assessment highlights multiple promising regions for offshore wind development in Australia. These include the western and south-western coasts of Western Australia, where high-quality wind resources are accessible in relatively shallow waters near the coast; a limited area in northern Queensland with elevated capacity factors; and offshore locations along the New South Wales and Queensland coastlines. Many of these sites are advantageously located close to major industrial demand centers, such as Port Kembla, Newcastle, Gladstone and south of Perth, enhancing their potential for integration into the electricity grid.

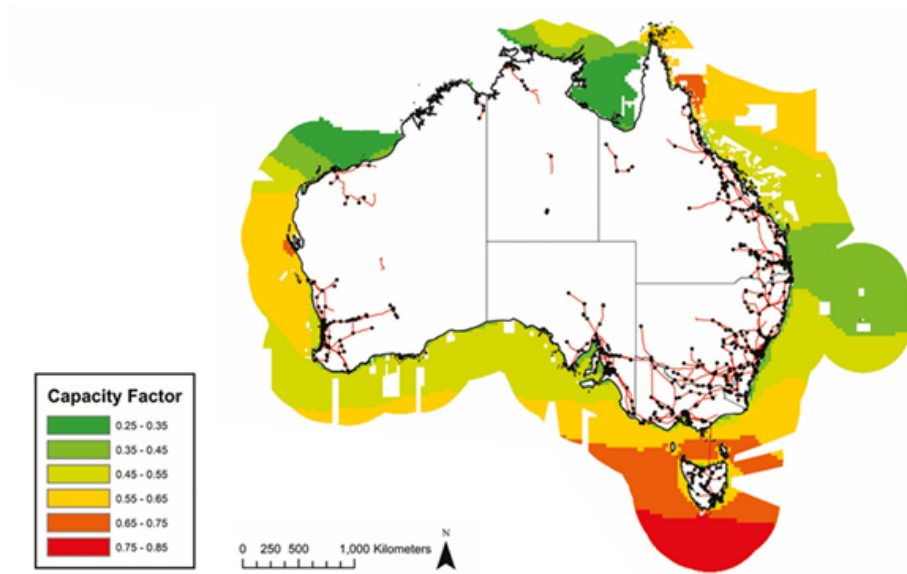


Figure 27: Gross Capacity Factor determined using ERA5 hourly wind speeds for the NREL 15 MW turbine (BECRC Offshore Wind Energy in Australia 2021).

4.2 Queensland Region

As previously mentioned, none of the six Declared Offshore Marine Areas identified by the Australian Government is located along the Queensland coastline. However, our objective is to explore a potential area in Queensland that is feasible for future offshore wind development.

Based on the analysis of mean wind speeds at 100 m hub height, two potential regions emerge as promising candidates. The first is located in northern Queensland, between Cooktown and Cape York, where average wind speeds reach approximately 9 m/s. The second area is situated along the Gold Coast, where wind speeds range between 7-8 m/s.

The capacity factor is a key performance indicator for wind farms, representing the ratio between the actual energy produced over a specific period and the maximum theoretical energy that could be generated if the turbine operated at full capacity 100% of the time. Higher capacity factors reflect greater efficiency and more predictable wind conditions, which are essential for reducing project risk and improving economic viability. These findings are consistent with capacity factor estimations. In northern Queensland, predicted capacity factors range between 0.55 and 0.75, indicating highly favourable and consistent wind conditions that could support efficient energy production. In contrast, the

southern region near the Gold Coast shows capacity factors in the range of 0.35 to 0.45, still technically viable but comparatively less productive.

4.2.1 Choosing the area

When selecting a potential area for offshore wind development, it is necessary to follow specific conditions and requirements established by the Australian Government. The “Offshore Electricity Infrastructure Act 2021” (OEI Act) regulates the development of offshore renewable energy projects in Australian waters beyond three nautical miles from the coast. The Act, administered by the Department of Climate Change, Energy, the Environment and Water under the Minister for Climate Change and Energy, provides the legal framework for planning, licensing and operating offshore energy infrastructure. Its purpose is to ensure that offshore renewable projects are technically viable, environmentally sustainable and compatible with other marine activities.

To designate an area as suitable for offshore wind development, the Australian Government publishes a Notice of Proposal, accompanied by detailed Environmental and Technical Assessments (e.g., Gippsland, 2022). These assessments evaluate multiple parameters, such as wind resource quality, seabed depth, maritime routes, existing marine uses, ecological constraints and the presence of suitable grid connections.

Typical reference criteria include:

- water depth less than 60 m for fixed-bottom foundations or greater for floating platforms;
- average wind speeds of at least 7–8 m/s at 100 m hub height;
- a sufficient distance from the coastline to minimize visual impact and avoid interference with coastal activities.

Before assessing the conditions set out in the Notice of Potential, it would be advisable to narrow the area of interest by carefully considering the presence of marine protected areas, the maritime traffic, the proximity to port infrastructure and the connection to the electrical grid.

4.2.2 Marine Protected Areas

Marine protected areas play a crucial role in preserving biodiversity and maintaining the health and resilience of ocean ecosystems. Their importance becomes particularly relevant in the context of offshore wind development, which represents a significant opportunity for Australia in its transition toward renewable energy sources. Although offshore wind farms provide substantial benefits in terms of clean electricity generation and decarbonization, their deployment must be carefully planned to ensure compatibility with environmental protection and marine ecosystem conservation.

The need for careful environmental planning is further reinforced by the strong connection between Australian society and its coastal and marine environments. Marine biodiversity and wildlife protection are widely regarded as important elements of the country's environmental heritage and tourism sector. Species such as whales, dolphins, sea turtles and seabirds are iconic components of marine ecosystems and hold significant ecological and cultural value. As a result, public opinion and community engagement play an important role in shaping offshore development decisions and projects perceived as posing risks to marine ecosystems may encounter significant opposition from local communities and stakeholders.

Successfully integrating offshore renewable energy development with marine conservation therefore represents not only a regulatory requirement but also a broader social and environmental responsibility. Through comprehensive environmental impact assessments, the implementation of mitigation measures and transparent engagement with local communities, Australia has the opportunity to pursue a development pathway in which renewable energy expansion and environmental protection are addressed simultaneously.

In this context, offshore wind development can be interpreted not only as a response to the need for reducing greenhouse gas emissions and strengthening energy security, but also as an opportunity to demonstrate that economic development and ecosystem protection can coexist within a sustainable and balanced energy transition.

An analysis of the spatial distribution of marine protected zones, derived from Figure 28 and based on the Marine Protected Areas (CAPAD) dataset from the Australian Marine Spatial Information System (AMSIS), shows that a large portion of the Queensland coastline is subject to strict environmental protections. This is mainly due to the presence of highly sensitive ecosystems, endangered marine species and internationally protected areas such as those associated with the Great Barrier Reef. As a result, the northern Queensland area originally considered during the resource assessment must be excluded from further evaluation, as it falls within these protected zones.



Figure 28: Marine Protected Areas (CAPAD), derived from Australian Marine Spatial Information System (AMSIS).

Conversely, the offshore region located in front of the Gold Coast does not overlap with marine protected zones, as highlighted in the detailed mapping on Figure 29, and can therefore be further evaluated as a potential candidate for an offshore wind development site.



Figure 29: Marine Protected Areas(CAPAD), derived from Australian Marine Spatial Information System (AMSIS) focusing on the Gold Coast region.

4.2.3 Maritime traffic

Based on the previous assessments, the only remaining area along the Queensland coast suitable for further analysis is the offshore zone south of Brisbane, in front of the Gold Coast.

Analysis of the “Shipping” (AIS 2020 Vessel Tracks) dataset from the Australian Marine Spatial Information System (AMSIS) shows that this area experiences

minimal maritime traffic, making it highly suitable for the installation of floating offshore wind turbines (Figure 30). The low vessel density reduces the risk of collisions and simplifies permitting and safety procedures. This allows for the identification of a sufficiently large development zone where turbines can be optimally spaced to maximize energy production while minimizing wake effects.

Additionally, the low traffic environment facilitates the planning of submarine cable routes, reducing the need for complex deviations and supporting efficient connections to the onshore electrical network. From a technical standpoint, floating foundation technologies such as spar-buoys or tension leg platforms (TLPs) require defined safety distances between turbines, which can be easily maintained in this zone due to the ample available space and the minimal interference with other maritime activities.

Overall, the offshore area south of Brisbane presents highly favorable conditions, offering the opportunity to develop a safe, efficient and environmentally responsible floating offshore wind farm.

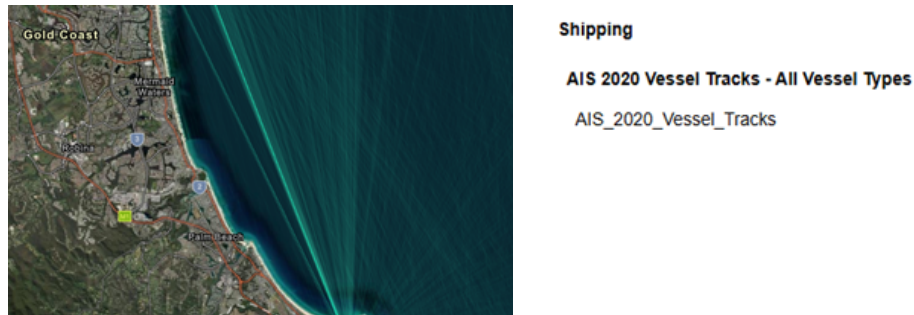


Figure 30: Shipping (AIS 2020 Vessel Tracks), derived from Australian Marine Spatial Information System (AMSIS) focusing on the Gold Coast region.

4.2.4 Proximity to port infrastructure and connection to the electrical grid

The selection of a suitable site for an offshore wind farm is strongly influenced by the presence of nearby port facilities, which play a key role during both construction and operation. In this context, the Port of Brisbane represents a strategic asset for the development of an offshore project along the Gold Coast. As one of Australia's major commercial ports, it already offers established industrial infrastructure, heavy-load handling capacity and experience in managing complex maritime logistics.

Although the port is well equipped, the installation and assembly of large offshore wind components, such as turbine blades, nacelles and floating foundations, may require dedicated areas for pre assembly, storage and specialized

loading operations. Nevertheless, having such infrastructure close to the deployment area significantly reduces transportation distances, construction times and overall project costs, which are factors that strongly influence the feasibility and competitiveness of offshore wind projects.

Additionally, the proximity of the site to the metropolitan area of Brisbane provides another major advantage: the existing grid infrastructure around the city is already capable of managing and distributing large amounts of power. This allows the electricity generated offshore to be integrated into the network efficiently, maximizing energy utilization and reducing the need for costly new transmission upgrades. The presence of industrial consumers and a strong demand for electricity further supports the economic viability of the project.

In summary, the combination of well developed port infrastructure, short logistical distances and an already established electrical grid makes the Gold Coast area, supported by the Port of Brisbane, a highly favorable location for the development of an offshore wind farm (Figure 31). While detailed planning is still required regarding logistics, assembly space and regulatory approvals, the context offers excellent conditions for an efficient and sustainable offshore wind development.

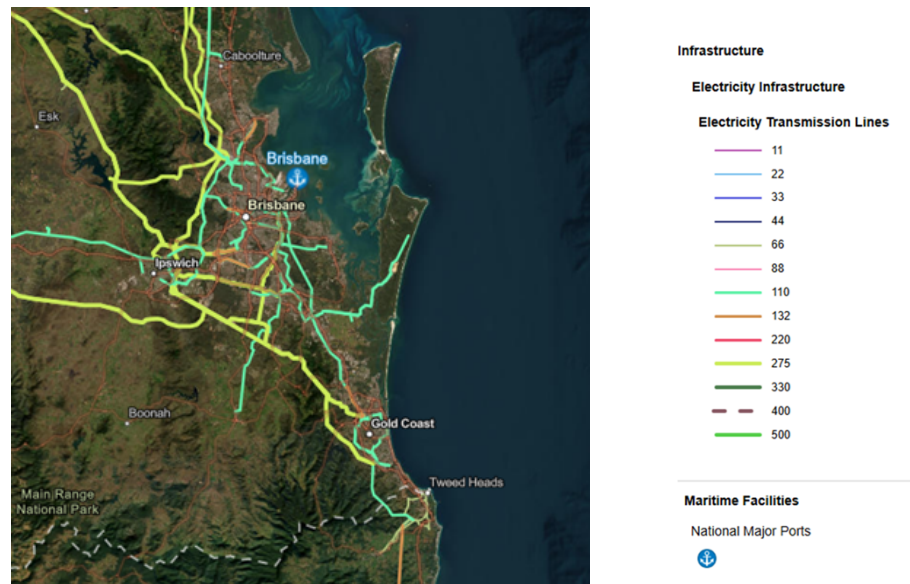


Figure 31: Electricity Infrastructure and Marine Facilities, derived from Australian Marine Spatial Information System (AMSIS) focusing on the Gold Coast region.

4.3 Proposed Area

Following our preliminary study, which considered several key constraints such as marine protected areas, commercial and fishing routes, existing port infrastructure and the electrical grid capacity of nearby urban centers, we identified the offshore area in front of the Gold Coast as the only potentially suitable location along the Queensland coastline.

Based on this result, the analysis can now focus specifically on the offshore zone near Palm Beach. This location provides an opportunity to assess the feasibility of the project in terms of installable capacity and to estimate the number and arrangement of wind turbines that could be placed within the designated area, while complying with environmental, technical and logistical constraints.

Figure 32 illustrates a potential section of the offshore area that could be considered suitable for the installation of an offshore wind farm. The area covers approximately 215 km² and is situated about 45 km offshore, which minimizes visual impact from the coastline and provides ample space for the installation of multiple wind turbines.



Figure 32: Proposed area, in function of the previous considerations, derived from Department of Climate Change, Energy, the Environment and Water (DC-CEEW).

After defining the potential offshore area of interest, the next step is to confirm that the location satisfies all the criteria established in the Notice of Proposal. This verification phase is crucial, as only sites that comply with these requirements can be considered suitable for further development.

First, the Notice of Proposal sets limits regarding permissible water depth for the technologies to be used. As shown in Figure 33, the water depth at the site is approximately 320 m, clearly meeting the deep-water condition defined in the document. This depth automatically rules out fixed-bottom foundations and directs the analysis towards floating offshore wind turbine solutions, consistent

with the technological options allowed by the Notice of Proposal.

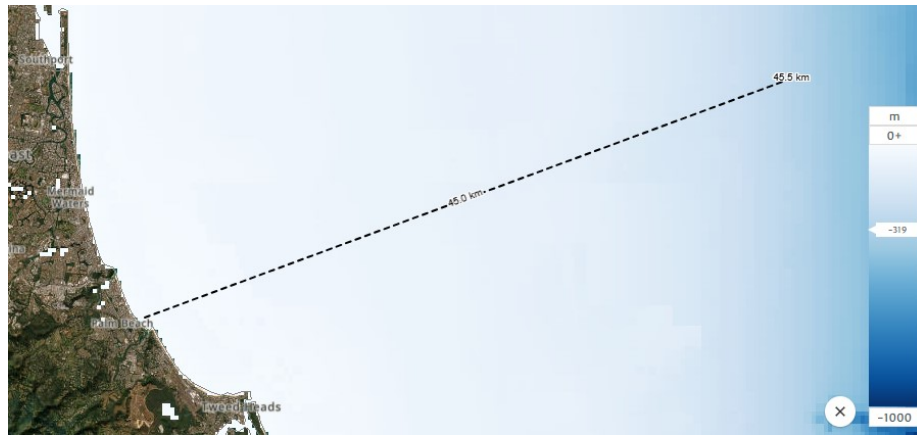


Figure 33: Bathymetry evaluated at 45 km from the coast of Palm Beach, derived from Global Wind Atlas.

Second, the document requires suitable wind resource availability for viable energy production. As shown in Figure 34, the average wind speed at 100 m hub height at the selected location is 7.64 m/s, a value that complies with the wind resource threshold reported in the Notice of Proposal and falls within the operational range of commercial offshore wind turbines.

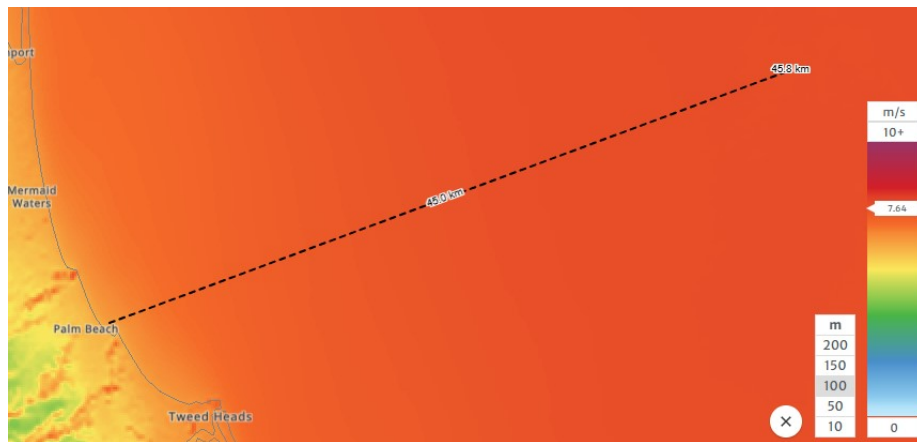


Figure 34: Mean wind speed evaluated at 45 km offshore from Palm Beach at a hub height of 100 m, derived from the Global Wind Atlas.

Finally, the Notice of Proposal specifies that the offshore wind project must be located beyond a certain distance from the coastline to avoid interference with

coastal activities and visual impact concerns. The identified site lies approximately 45 km offshore, therefore fulfilling the minimum distance requirement and ensuring sufficient separation from recreational areas, tourism zones and near-shore marine habitats.

Having verified that all the conditions imposed by the Notice of Proposal are met, including adequate water depth, sufficient wind resources and an appropriate distance from the shore, the analysis can now focus on evaluating the most suitable floating wind turbine technology for the selected site. This involves comparing different platform concepts (such as spar-buoy, semi-submersible and tension-leg platforms), each offering distinct advantages in terms of stability, installation feasibility and cost-effectiveness. This evaluation will allow us to identify the optimal solution for deploying a floating offshore wind farm in the Palm Beach area.

5 Development of Offshore Wind Farm

5.1 Optimal Turbine Design for Floating Offshore Deployment

Given the characteristics of the selected offshore site, which is located approximately 45 km from the coast and characterized by a water depth of 320 m and an average wind speed of 7.64 m/s at a hub height of 100 m, the selection of the wind turbine represents a critical design decision. The turbine must ensure high energy production while remaining compatible with floating platform technology, as confirmed earlier by the depth and wind resource assessment.

The analysis must consider that extremely large turbines (above 20 MW) are specifically designed for high wind sites. In the context of the Palm Beach offshore area, the available wind resource is not strong enough to fully exploit such machines. Installing oversized turbines in moderate wind conditions would lead to reduced capacity factors, resulting in sub-optimal annual energy production and making the investment economically inefficient.

Conversely, selecting smaller turbines (below 10 MW) would require a significantly larger number of units to reach the desired installed capacity. This would increase the number of floating foundations, mooring systems, dynamic cables and installation activities. As a consequence, the overall project costs, including both capital and operational expenditures, would increase substantially without proportional gains in energy yield. For this site, the optimal compromise is represented by a mid-size turbine in the range of 12-15 MW (Figure 35). Turbines of this class offer:

- high energy production, with approximately 40 GWh/year per turbine under the given wind conditions;
- compatibility with floating platforms, avoiding excessive structural loads;
- reduced number of units, simplifying installation, maintenance and cabling layouts.

A suitable configuration would include a rotor diameter between 200 and 220 meters, allowing efficient wind capture even at moderate speeds. The hub height should be positioned between 120 and 140 meters, enabling the turbine to operate in steadier and less turbulent airflow, thus improving performance and reducing fatigue loads. Long and lightweight blades, combined with advanced pitch and yaw control systems, allow the turbine to adapt dynamically to changing wind conditions and maximize annual energy production while maintaining platform stability.

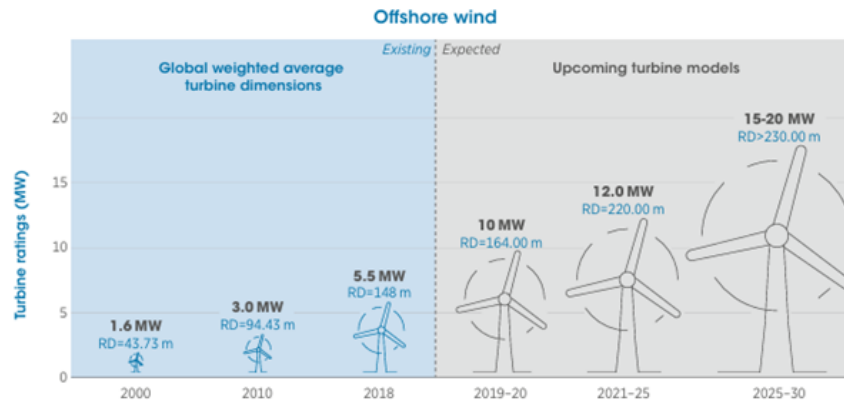


Figure 35: Average size of existing and expected offshore wind turbines, GE Renewable Energy, 2018; IRENA, 2019c, 2016b; MHI Vestas, 2018.

5.2 Floating turbine foundation

The selection of an appropriate foundation is intrinsically linked to the characteristics of the chosen turbine, as the foundation must provide sufficient stability to ensure safe and efficient operation while remaining economically and technically feasible. Among the available floating platform concepts, the Spar-buoy represents a highly suitable solution for medium-sized offshore turbines in the 12–15 MW range. The Spar-buoy consists of a long, cylindrical structure that is partially submerged, relying on ballast at its lower section to achieve the necessary stability. Its primary advantage lies in its structural simplicity and inherent reliability: the submerged mass lowers the center of gravity, providing effective resistance against pitch and roll motions induced by waves and wind. Additionally, the Spar-buoy requires a relatively straightforward mooring system, typically involving catenary anchors, which reduces both the technical complexity and the installation effort compared to other floating solutions.

This type of platform is particularly compatible with turbines featuring rotor diameters between 200 and 220 meters and hub heights of 120–140 meters, as these dimensions allow for substantial energy capture while remaining within the operational limits of a Spar-buoy structure. The combination of moderate size and floating stability ensures that energy production is maximized without introducing excessive engineering or operational complexity. Moreover, the simplicity of the design translates into manageable installation and maintenance costs, an essential consideration for offshore projects, where logistical challenges and vessel mobilization significantly impact overall project economics.

In contrast, the Tension Leg Platform (TLP) represents a more technologically advanced alternative. TLPs consist of one or more buoyant columns connected to the seabed using vertical, tensioned tendons. This configuration creates a nearly rigid platform, which dramatically reduces vertical motion (heave) and improves overall stability. Such characteristics are particularly advantageous for ultra-large turbines above 15 MW, where even minor oscillations can lead to increased structural stress, accelerated fatigue of components and potential reductions in energy yield over the turbine’s lifespan. However, the advantages of a TLP come at a significant cost. The mooring system is highly complex, requiring precise tensioning of the tendons and custom engineering to account for site-specific hydrodynamic and geotechnical conditions. Furthermore, installation operations are more sophisticated, involving specialized vessels and longer project timelines, which increase both capital expenditure and project risk.

Given the environmental and operational conditions of the Palm Beach offshore site, namely a water depth of approximately 320 meters, moderate wind speeds of 7.64 m/s and a distance of 45 km from shore, the Spar-buoy foundation represents the most suitable solution (Figure 36). When combined with a 12–15 MW turbine, this platform provides the best balance between stability, energy production and cost-effectiveness, while minimizing technical complexity and

operational risk. This choice allows for efficient deployment of a floating offshore wind farm, ensuring high energy yield while maintaining economic and engineering feasibility within the constraints imposed by the site.

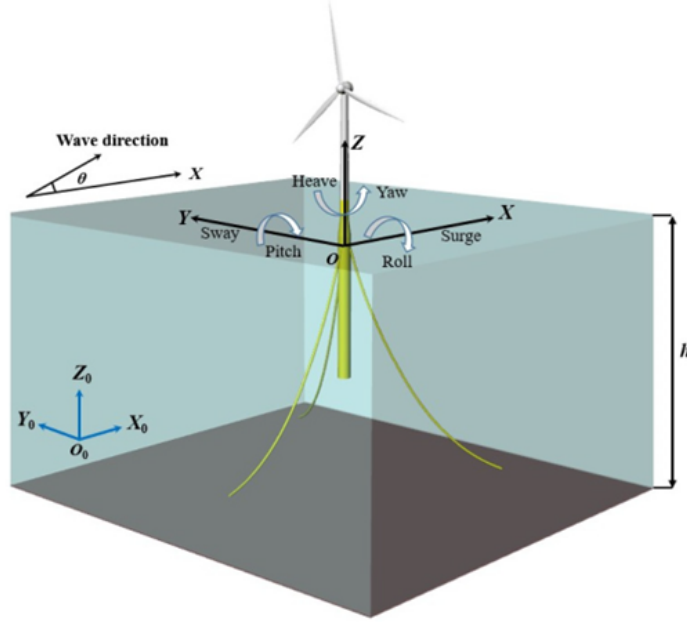


Figure 36: Dynamic representation of a Spar-Buoy floating offshore wind farm, (Source: Investigation of Hydrodynamic Forces for Floating Offshore Wind Turbines on Spar Buoys and Tension Leg Platforms with the Mooring Systems in Wave).

5.3 Turbine Model

5.3.1 Suitable Turbine Selection

For the Palm Beach offshore project, the optimal technical solution is represented by a 12-15 MW offshore wind turbine mounted on a Spar-buoy foundation.

This configuration provides an effective balance between high energy yield, structural reliability and cost-effectiveness. The large rotor diameter and elevated hub height maximize energy capture, while the simplicity and robustness of the Spar-buoy platform reduce installation complexity and operational risks. In contrast, Tension Leg Platforms (TLPs) remain a more suitable option primarily for ultra large turbines above 15 MW, where the additional stability justifies the higher construction costs, complex mooring systems and challenging installation requirements.

Following a detailed analysis of the selected offshore site, located approximately 45 km from the coast of Palm Beach in Queensland and characterized by a water depth of around 320 m, an average annual wind speed of 7.64 m/s and typical wave heights between 2 and 3 meters, the Siemens Gamesa SG 14-222 DD turbine was identified as the most suitable option for this project (Figure 37). This turbine represents a significant advancement in offshore wind technology. With a rated capacity of 14 MW, upgradable to 15 MW through a power boost and a rotor diameter of 222 meters, the SG 14-222 DD is specifically designed to maximize energy capture under moderate to strong wind conditions, while minimizing the Levelized Cost of Energy (LCOE).

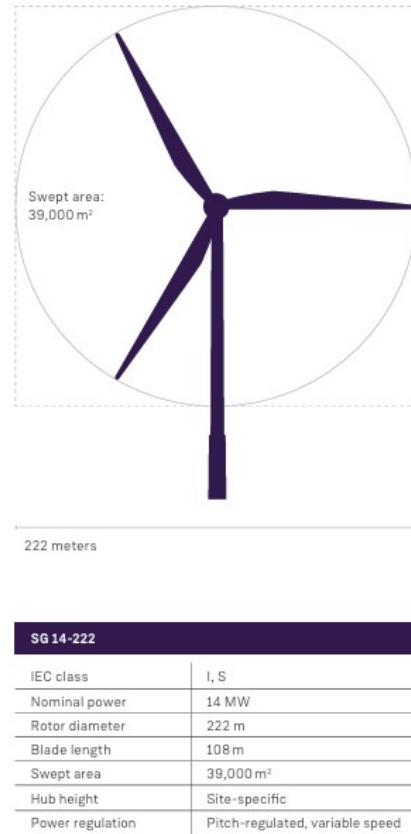


Figure 37: Technical Specification of Siemens Gamesa SG 14-222DD.

The turbine has been successfully prototyped and tested at Østerild, Denmark, where it set a world record in 2022 by producing 359 MWh in a single 24-hour period. Following these successful tests, the SG 14-222 DD entered commercial production in 2024, marking Siemens Gamesa’s flagship entry into the new generation of ultra-large offshore turbines. Early large-scale deployments demonstrate its global relevance, including the Moray West project in Scotland (60 turbines, operations starting in 2025), Hai Long 2 in Taiwan (the first Asian project utilizing the SG 14-222DD, grid-connected in 2025) and the Coastal Virginia Offshore Wind project in the USA (one of the world’s largest offshore wind farms, with a planned capacity of 2.6 GW, scheduled for installation by 2026).

The SG 14-222 DD combines direct-drive technology, advanced lightweight materials and a modular design, which together improve efficiency, reduce mechanical losses and simplify maintenance. Its integration with a Spar-buoy foundation

ensures stable operation in deep-water conditions while maintaining high performance across a range of wind and wave scenarios. Overall, the adoption of the SG 14-222 DD for the Palm Beach offshore site represents a technically sound and economically viable choice, setting a benchmark for next-generation floating offshore wind projects and reinforcing the potential of this region as a hub for large-scale renewable energy development [40].

5.3.2 Power Production Analysis – Siemens Gamesa SG 14-222 DD

To evaluate the power output of our selected turbine the Siemens Gamesa SG 14-222 DD, it is essential to take into account both the turbine specifications and the site conditions. The theoretical power available from the wind can be estimated using this equation:

$$P_{\text{Theoretical}} = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot c_p$$

where, ρ represents the air density, A is the rotor swept area, v is the wind speed and c_p is the power coefficient, which describes the efficiency of the turbine in converting the kinetic energy of the wind into mechanical power. So, the theoretical power for a single turbine will be:

$$P_{\text{Theoretical}} = 0.5 \cdot 1.225 \cdot 39000 \cdot (7.64)^3 \cdot 0.45 = 4.8 \text{ MW}$$

At the average wind speed, the turbine would produce roughly 4.8 MW on average.

To estimate the expected energy production of the selected turbine, it is necessary to consider both the rated power of the turbine and the local wind resource conditions. For the Palm Beach offshore site, a capacity factor (CF) of approximately 39% has been derived from data provided by the Global Wind Atlas, which reflects the moderate offshore wind regime at the location (Figure 38). Using this value, the Annual Energy Production (AEP) can be calculated using the standard relation:

$$AEP = P_{\text{rated}} \cdot T \cdot CF$$

where $T = 8760$ hours per year. Substituting the relevant values for our turbine yields:

$$AEP \approx 4.8 \text{ MW} \cdot 8760 \text{ h} \cdot 0.39 \approx 16700 \text{ MWh/year}$$

Rounding this figure, the theoretical energy production of a single turbine is therefore in the range of 16-17 GWh per year. However, this represents an idealized estimate. In practice, operational and electrical losses - including downtime for maintenance, transformer and cable losses and other system inefficiencies - reduce the actual energy delivered to the grid. Accounting for typical losses of approximately 10%, the realistic Annual Energy Production for a single turbine at this site can be expected to be around 15 GWh per year.

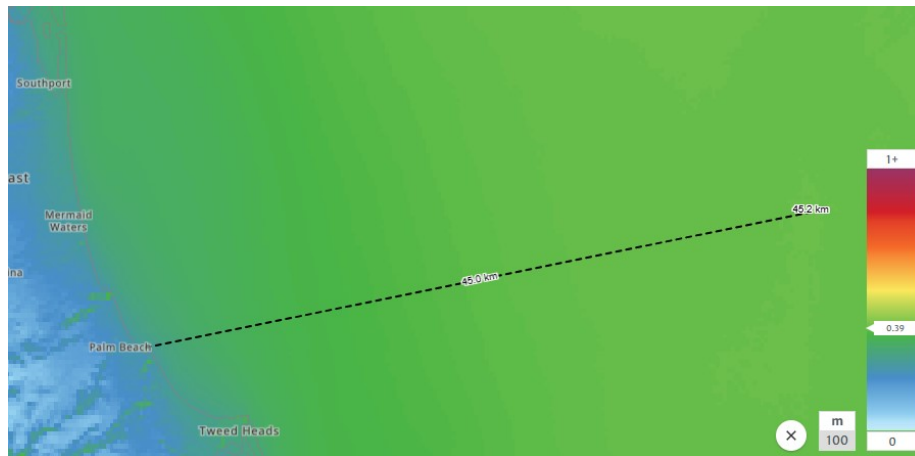


Figure 38: Capacity factor evaluated at 100 m hub height, based on data from the Global Wind Atlas, specifically for the Gold Coast region.

This value provides a practical benchmark for evaluating the overall energy yield of the offshore wind farm and forms the basis for subsequent economic and performance analyses, including the estimation of revenue, Levelized Cost of Energy (LCOE) and the assessment of the number of turbines required to meet the project's energy targets.

5.4 Offshore Wind Farm Layout and Energy Potential

Considering the offshore area identified for analysis, the next step is to determine how to utilize this space most effectively for the installation of an offshore wind farm. Before proceeding with turbine layout design, it is important to provide some background on the requirements for the safe and efficient placement of turbines.

When discussing the space required for an offshore wind turbine, it is not the physical footprint that is of primary concern, which is relatively small, typically only a few meters in diameter at the base, but rather the aerodynamic and operational space needed around the turbine for optimal performance. In offshore wind planning, this concept is captured by the parameter known as spacing, which defines the minimum distance that must be maintained between turbines to minimize production losses and ensure operational safety.

The need for adequate spacing arises from the wake effect, a phenomenon caused by the turbine rotor as it extracts energy from the wind (Figure 39). The wake generates a region of reduced wind speed and turbulent vortices downstream of the turbine. If another turbine is positioned too close within this wake, its energy production can be significantly reduced and mechanical loads on its structure can increase, potentially shortening its operational lifespan.

To mitigate these effects, turbines must be strategically positioned in both the aligned direction along the prevailing wind and the transverse direction perpendicular to the prevailing wind. Proper spacing ensures that each turbine operates in relatively undisturbed wind, maximizing overall farm efficiency while reducing structural stress and maintenance requirements.

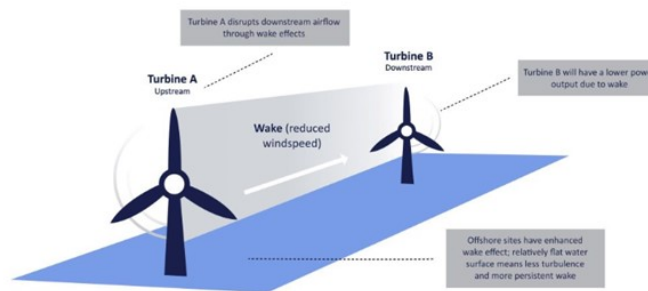


Figure 39: Schematic representation of the wake effect in an offshore wind farm. The upstream turbine reduces wind speed and increases turbulence in its wake, leading to lower power production for the downstream turbine.

In the case of the Siemens Gamesa SG 14-222 DD turbine, the rotor diameter is 222 meters, which is exceptionally large and directly influences the required spacing between turbines. To minimize energy losses due to wake effects and to ensure safe operation, international offshore wind planning guidelines recommend maintaining a distance of approximately 6 to 7 rotor diameters in the direction of the prevailing wind and 5 to 6 rotor diameters in the transverse direction. However, for large offshore turbines and high-capacity wind farms, more conservative layouts are often adopted to further mitigate wake interactions and optimize long-term energy yield.

For the present study, a more spacious configuration equivalent to approximately 7 rotor diameters in the prevailing wind direction and 6 rotor diameters in the transverse direction is considered. Converting these distances into metric units results in a spacing of about 1.55 km by 1.33 km, corresponding to an average area of roughly 2.06 km² per turbine. This layout provides improved aerodynamic performance while allowing adequate space for operational and safety requirements.

Beyond purely aerodynamic considerations, this area also provides critical space for operational and safety requirements, including:

- safe corridors for maintenance and technical operations;
- transit routes for service vessels;
- space for laying submarine connection cables;
- safety margins required by maritime regulations;
- protection of sensitive seabed areas.

It is important to emphasize that no single turbine physically occupies 2.06 km². Rather, this area represents the optimal zone of influence required for the wind farm to operate efficiently, avoiding wake interference and ensuring a uniform distribution of wind loads across the turbines.

Given that the offshore area under analysis covers approximately 215 km², it is possible to estimate the number of turbines that could theoretically be installed and the corresponding potential energy production. Considering the reference spacing of 2.06 km² per turbine, which accounts only for aerodynamic wake effects, the area could geometrically accommodate roughly 104 turbines.

Using the selected Siemens Gamesa SG 14-222 DD turbine with a rated capacity of 14 MW, the theoretical installed capacity of the wind farm would be approximately 1.46 GW, representing a substantial contribution to the local energy supply and highlighting the strong potential of the site for large-scale offshore wind deployment.

In terms of energy production, each turbine is expected to generate approximately 43 GWh/year, accounting for operational and electrical losses of around

10%. Multiplying this value by the total number of turbines results in an estimated annual energy production of roughly 4.5 TWh for the entire wind farm.

The estimated number of 104 turbines represents a purely geometric approximation derived from the assumption of a regular and uniform spacing between turbines across the available site area. This calculation therefore provides a preliminary indication of the maximum number of turbines that could theoretically be accommodated within the selected offshore area under idealized conditions. However, in practical offshore wind farm development, the final layout rarely follows such a simplified geometric distribution. During the detailed design phase, several additional constraints must be considered, including internal corridors required for array cable routing, safety buffer zones along the external perimeter of the wind farm, navigation safety areas for maritime traffic and irregularities in the actual geometry of the site. Furthermore, environmental and regulatory constraints, such as shipping lanes, seabed conditions and protected marine areas, may further limit the available space for turbine installation. As a consequence, these practical limitations typically lead to a reduction in the number of turbines that can effectively be installed compared with the maximum value obtained from the geometric estimation. Since the installed capacity of the wind farm is directly related to the number of turbines deployed, a reduction in turbine count would also result in a proportional decrease in the final installed capacity of the project. Therefore, the value obtained in this preliminary assessment should be interpreted as an upper-bound estimate of the potential capacity of the site rather than as the final design configuration of the wind farm.

Overall, this preliminary evaluation highlights the significant potential of the Palm Beach offshore site for the development of a large-scale floating wind farm, capable of generating substantial amounts of renewable energy while maintaining operational efficiency and safety. The results presented here should therefore be interpreted as a preliminary order of magnitude assessment of the site’s potential rather than a final wind farm layout.

5.4.1 Contribution of the Offshore Wind Farm to Brisbane’s Grid

The proposed Palm Beach offshore wind farm, with an installed capacity of approximately 1.46 GW and an estimated annual production of 4.5 TWh, represents a major source of renewable energy for southeastern Queensland, particularly for the city of Brisbane. To put this into perspective, the average household in Brisbane consumes around 5750 kWh per year. Based on this consumption, the wind farm could supply electricity to over 780000 households, effectively covering a substantial portion of the city’s residential energy demand. Assuming the total annual residential electricity consumption in Brisbane is approximately 9 TWh, the wind farm could theoretically meet about 50% of that demand [41].

It is important to note that this 50% figure represents an idealized estimate. In practice, the actual contribution to the city's electricity supply may be lower due to several factors: variability in wind speeds and generation, temporal mismatches between production and peak demand, transmission losses along the power grid and operational constraints such as maintenance downtime or curtailment to balance the grid. Additionally, part of the generated electricity may be directed to industrial, commercial or regional loads beyond the residential sector, further reducing the share directly available to households. Therefore, while the 50% figure provides a useful reference for the scale of the project's potential impact, real-world performance would likely be somewhat lower and would require integration with storage, demand management and other grid flexibility measures to maximize effective utilization.

Beyond household supply, the integration of this volume of renewable energy into the electricity grid carries several strategic and operational benefits. From a grid perspective, the consistent generation profile of offshore wind can help smooth peak demand, particularly during the hot summer months when electricity use for cooling is at its highest. When combined with energy storage systems or demand-response strategies, this generation can enhance grid stability, improve frequency regulation and reduce reliance on fossil-fuel-based peaking plants.

From an environmental standpoint, producing 4.5 TWh of clean electricity annually would offset millions of tons of CO emissions that would otherwise result from coal or gas-fired power plants. This makes a significant contribution toward regional and national climate goals, supporting Queensland's transition toward a decarbonized electricity sector.

The economic and social impacts of a project of this scale are equally notable. Construction and installation phases generate substantial employment opportunities, including specialized roles for offshore engineers, turbine technicians and logistics personnel. The operational phase similarly requires skilled staff for turbine maintenance and offshore management. Additionally, the development of such renewable capacity can stimulate local industries, encourage electrification of transport and promote low-carbon economic activity across the region.

Furthermore, by supplying a significant share of Brisbane's electricity needs, the wind farm reduces dependence on fossil fuels that are subject to price volatility and supply risks, thereby enhancing energy security. Integration with advanced storage and smart grid technologies can further optimize the use of generated power, enabling peak shaving, load balancing and greater flexibility in responding to demand fluctuations.

In conclusion, the Palm Beach offshore wind farm has the potential to supply electricity to a large portion of Brisbane's households and could theoretically cover approximately 50% of the city's residential electricity demand; while also strengthening the regional electricity network, supporting environmental objec-

tives, stimulating economic growth and advancing the city and region toward a more sustainable, low-carbon energy future. This estimate, however, should be interpreted as an idealized upper limit, with real-world performance dependent on system integration and operational factors.

It is also very interesting to consider what the potential impact of such a project could be on the electricity demand during the 2032 Brisbane Olympic Games. Evaluating this scenario provides insight into how a large-scale offshore wind farm could support exceptionally high, short-term energy requirements, highlighting the strategic value of renewable energy infrastructure for major international events. Had the wind farm been developed earlier, even a partial deployment of the Siemens Gamesa SG 14-222 DD turbines, each producing roughly 43 GWh/year, could have supplied a meaningful share of the electricity needed for Olympic facilities, including the Olympic villages, transport systems, media centers and temporary event lighting. This example demonstrates not only the practical benefits of large-scale offshore wind but also its potential to enhance energy security and leave a lasting low-carbon legacy for the city and the region.

5.5 Port Infrastructure

The installation of a floating offshore wind farm located approximately 45 km off the Gold Coast, comprising Siemens Gamesa SG 14-222 DD turbines, represents a project of national and strategic significance. Each turbine, featuring a 222 meters rotor diameter and 108 meters blades, requires highly specialized logistics and infrastructure for construction, assembly and offshore transport. Consequently, a careful assessment of Queensland's major ports: Port of Brisbane, Gold Coast City Marina (GCCM) and Port of Gladstone; it is essential to determine their suitability for the various phases of the project (Figure 40).

The Port of Brisbane emerges as the most suitable candidate for serving as the primary assembly and load-out hub. Its relative proximity to the offshore site, extensive wharves, direct road and rail connections and experience in handling heavy cargo and complex industrial operations make it a logical choice. However, the exceptional weight and dimensions of the SG 14-222 DD components, with nacelles exceeding 500 tonnes, present significant logistical challenges. Current port cranes, capable of lifting approximately 150 tonnes, are insufficient; therefore, the use of heavy-lift vessels or installation of higher-capacity cranes will be necessary. Additionally, the storage and handling of 108 meters blades will require reinforced laydown areas, wide transport corridors and durable surfaces capable of supporting Self-Propelled Modular Transporters (SPMTs). The ongoing Channel Enhancement Project, which involves deepening and widening the port's access channel, represents a strategic advantage that could reduce adaptation costs if synchronized with the wind farm's development schedule [42].

The Port of Gladstone, Queensland's largest and most industrialized port, offers substantial industrial infrastructure and expertise in heavy fabrication and prefabrication. Its extensive storage and handling areas, combined with the Northern Land Expansion Project (NLEP) at Fisherman's Landing, make it well-suited for the fabrication and preliminary assembly of floating foundations and heavy steel structures, including OSOM (Oversize-Over-Mass) cargo such as turbine blades and towers up to 100 meters in length. The primary limitation of Gladstone is its distance from the Gold Coast site, which would increase offshore transport complexity and costs. Nevertheless, its role in the supply chain as a fabrication hub is essential for developing regional industrial capabilities and creating highly skilled employment opportunities in the renewable energy sector.

The Gold Coast City Marina (GCCM), historically focused on yacht refitting and maritime services, is undergoing significant expansion with the Titan Yard development, initially raising lifting capacity to 820 tonnes and targeting 1800 tonnes, thereby becoming technically capable of supporting the assembly of SG 14-222 DD components. Its proximity to the offshore site offers a strategic advantage for operations and maintenance (O&M) activities, including service

vessel operations, turbine inspections and daily offshore management. Full-scale accommodation of large offshore wind operations would require reinforced quays, expanded laydown areas and improved access routes; however, GCCM is positioned to become a long-term O&M hub, delivering sustained economic benefits to the region.

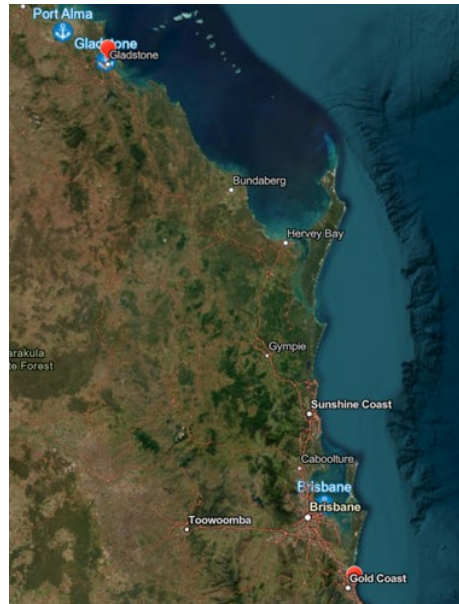


Figure 40: National major ports in Queensland, based on data from the Department of Climate Change, Energy, the Environment and Water (DCCEEW).

Considering the technical and logistical requirements of the SG 14-222 DD turbines, a distributed port strategy emerges as the most effective approach:

- Gladstone for fabrication and prefabrication of floating substructures;
- Brisbane for final turbine assembly and load-out operations;
- Gold Coast as the permanent O&M and support base.

This approach maximizes the use of existing infrastructure, minimizes adaptation costs and distributes economic benefits across Queensland. The project will serve as a catalyst for industrial growth and job creation, accelerating Australia's transition from fossil fuels to renewable energy.

5.5.1 Employment and Socio-Economic Impact

A key aspect of assessing the feasibility and overall impact of the Palm Beach offshore wind farm is understanding its employment and socio-economic implications. Large-scale renewable energy projects not only provide clean energy but

also serve as significant drivers of regional economic development, skill creation and industrial growth. To evaluate these effects, the project can be divided into three main phases: planning and engineering, construction and assembly and operations and maintenance, each generating different types and levels of employment. Examining these phases provides a clear picture of the workforce requirements, the distribution of economic benefits across Queensland and the development of specialized expertise in the offshore wind sector.

Considering the revised configuration of the wind farm, consisting of 104 turbines, the employment estimates have been updated accordingly. Based on national and international benchmarks for offshore wind projects of comparable scale (Clean Energy Council, 2022; PwC Australia, 2023; Blue Economy CRC, 2022), it is estimated that the Palm Beach project could generate approximately 4000–5000 direct and indirect jobs across all phases of development. Specifically:

1. Planning and Engineering Phase (2 years):
 - Creation of approximately 200–320 skilled jobs in civil, marine and structural engineering, environmental and GIS analysis, as well as legal and administrative roles;
 - Engagement of local universities and research centers, strengthening national offshore wind expertise.
2. Construction and Assembly Phase (3 years):
 - Peak employment of approximately 1500–1900 direct jobs for floating platform fabrication in Gladstone, turbine assembly and load-out in Brisbane and offshore installation;
 - Around 1800–2200 indirect jobs generated across the supply chain, logistics, manufacturing and support services.
3. Operations and Maintenance Phase (after the installation):
 - 150–200 permanent direct jobs for technicians, electricians and marine operators;
 - An additional 350–500 indirect jobs related to ports, logistics and O&M activities, primarily managed from the Gold Coast Marina.

Overall, despite the reduction in the number of turbines compared with larger offshore wind developments, the Palm Beach project is still expected to generate around 4000–5000 direct and indirect jobs. The project would therefore contribute significantly to Queensland’s industrial diversification, support the development of local heavy engineering and maritime capabilities, foster the creation of specialised skills and promote the growth of a skilled green workforce within the emerging offshore wind sector.

6 Offshore Wind LCOE Calculation Model

6.1 Levelized Cost of Energy (LCOE): Concept and Calculation Methods

6.1.1 Introduction to the concept of LCOE

Offshore wind development faces significant technical and economic challenges, largely driven by water depth, foundation type and distance from shore, all of which influence installation and operational costs. Accurate assessment of these variables is critical for determining site viability. Additional factors, including contract structures, government incentives and long-term electricity prices, also affect project economics [43].

Investment in offshore wind has lagged behind onshore capacity growth, despite overall renewable energy investment rising over the past decade. Installation costs exhibit a non-linear trend: technological advances, such as monopile foundations and larger turbines, reduce costs, but the adoption of floating foundations can temporarily offset these gains. Advantages like higher wind speeds and proximity to demand centres may compensate for higher initial expenditures [44].

End-of-life strategies such as repowering, complete replacement or full removal of the installations involve different cost levels, which depend on site specific conditions and the residual value of the recovered materials. To attract investors, developers rely on the Levelized Cost of Energy (LCOE), which averages total lifecycle costs against energy output. LCOE encompasses non-recurring development and construction costs, decommissioning and recurring operational costs, becoming increasingly accurate as industry experience accumulates [45].

6.1.2 Levelized Cost of Energy

The Levelized Cost of Energy (LCOE) represents the average electricity price that a power generation project must achieve in order to recover all costs incurred over its entire lifetime. In essence, it corresponds to the break-even electricity price of the project. The LCOE is a fundamental indicator for assessing the economic feasibility of an energy installation and provides a consistent basis for comparing different energy technologies under equivalent financial assumptions.

Mathematically, the LCOE is defined as the ratio between the discounted total costs of the project and the discounted total energy production over its operational lifetime:

$$LCOE = \frac{\sum_{i=1}^T \frac{CAPEX_i + OPEX_i}{(1+r)^i}}{\sum_{i=1}^T \frac{AEP_i}{(1+r)^i}}$$

where the costs are subdivided into CAPEX (capital expenditures), i.e., the costs spent prior to the operation of the project and OPEX (operational expenditures), i.e., the costs associated with electricity production and maintenance of the energy farm. AEP represents the Annual Energy Production of the project, which constitutes the main source of income. The variable T represents the lifetime of the project in years, while r denotes the discount rate.

In this study, electricity costs are evaluated as functions of site-specific parameters. Therefore, the LCOE expression can be reformulated to explicitly include spatial dependence:

$$LCOE(x, y) = \frac{\sum_{i=1}^T \frac{CAPEX(x, y) + OPEX(x, y)}{(1+r)^i}}{\sum_{i=1}^T \frac{AEP(x, y)}{(1+r)^i}}$$

where (x, y) denote the geographical coordinates of the site.

Capital expenditures include all investments associated with project planning, component manufacturing, transport and installation activities. These costs are strongly influenced by site-specific characteristics, such as water depth and the distance from the shore (Figure 41). The offshore distance also impacts operational and maintenance expenses, primarily because greater distances increase travel time and logistical complexity. In contrast, the annual energy production is mainly governed by the local wind resource, which varies geographically and determines the amount of electricity that can be generated at each location.

The values of the LCOE are related to specific projects and therefore the methodology is illustrated through a case study off the Queensland coast, specifically in the region located offshore of Palm Beach. The considered offshore wind farm consists of one hundred 14 MW turbines (corresponding to a total installed capacity of 1.4 GW) mounted on spar-buoy floating platforms. The discount rate (r) for offshore wind projects is generally assumed to fall between 8% and 12%, according to common industry practice. In this study, a value of 10% has been adopted. The operational lifetime of the project T is assumed to be 20 years. To estimate the LCOE for the proposed floating offshore wind farm located off the coast of Palm Beach, Australia, several assumptions are introduced.

The technology considered in this study is based on floating spar-buoy platforms, which are suitable for deep-water applications. Spar buoy platforms can typically operate in water depths ranging from several tens of meters to well beyond 1000 m, making them compatible with the selected locations [46].

Regarding the distance from shore, three scenarios are analysed — 20 km, 45 km and 60 km — with the objective of identifying the most favourable site not only from a technical perspective but also in economic terms. A minimum offset

from the coastline is generally adopted to reduce visual impact and potential environmental or social constraints. At distances beyond approximately 40–45 km, the curvature of the Earth significantly limits the visibility of wind turbines from the coast [47]. Nevertheless, offshore siting criteria may vary depending on national regulations and local planning policies. For the purposes of this study, all three distances are assumed to be technically and legally feasible within the Australian regulatory framework.

Another important consideration concerns differences in regulatory structures, grid connection responsibilities and taxation schemes. In some countries, transmission infrastructure costs may be partially covered by national grid operators, while in others they are borne entirely by the project developer. In this work, grid connection costs are fully included in the LCOE calculation to ensure a comprehensive economic assessment and consistent comparison between the three distance scenarios.

Labour costs represent another country-specific variable that can significantly influence project economics, although they are not explicitly analysed in this study [48]. It should be noted that the CAPEX and OPEX values adopted in the calculations are primarily derived from data reported in high-wage economies. Consequently, overall project costs could differ if implemented in regions with lower labour expenses.

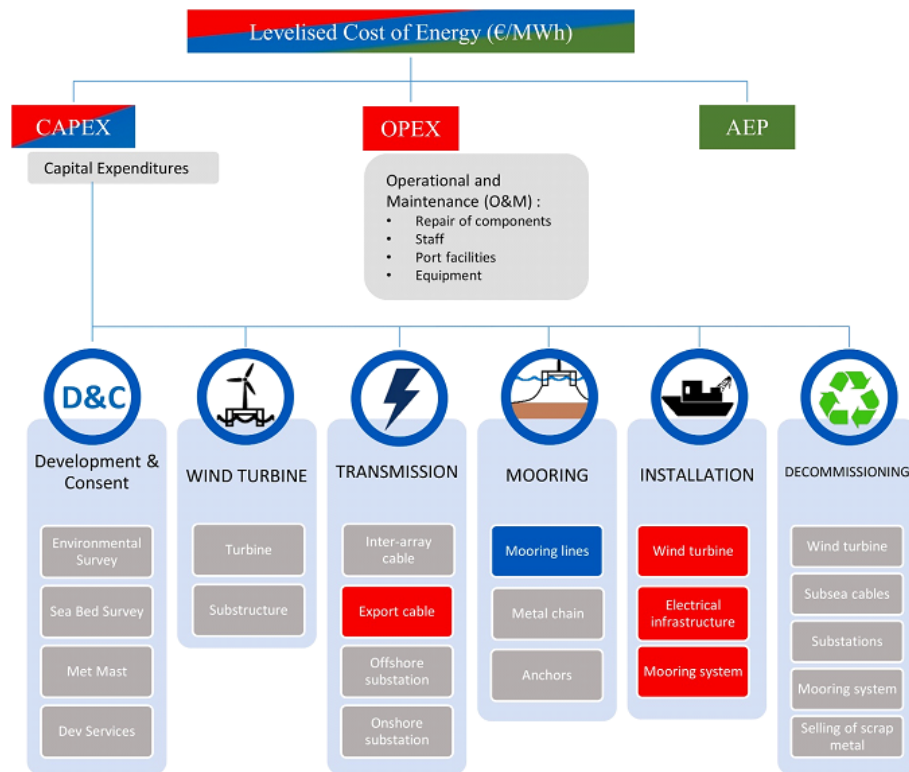


Figure 41: Breakdown of the levelised cost of electricity, separating non-location-dependent components (grey) from site-dependent factors, which vary according to distance from the coastline (red), water depth (dark blue) and local wind conditions (dark green), Martinez & Iglesias, 2022.

6.2 CAPEX

Capital expenditures (CAPEX) represent the costs incurred before the energy farm becomes operational. These include expenses for development and consenting, turbine and substructure, transmission, mooring systems, installation and decommissioning. In this study, capital costs are calculated without accounting for financing or interest-related expenses.

6.2.1 Development and consenting

This phase of the project involves activities such as environmental assessments, seabed investigations and meteorological measurement campaigns, together with project management and development services. Information related to the development and consenting phase (D&C) is generally based on available data from bottom-fixed offshore wind turbine projects. Several studies suggest that this portion represents roughly 5% of the overall CAPEX [49].

The UK government has published a detailed cost distribution for offshore wind developments, outlining how expenses within this phase are allocated. Based on these references, the total expenditure for D&C is estimated to be around 210 k€/MW [50], with the distribution illustrated in Figure 42.

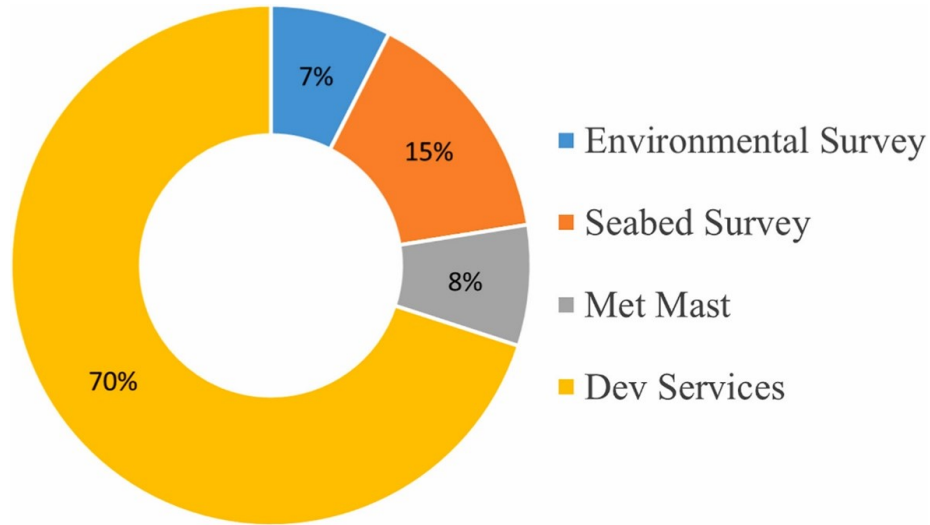


Figure 42: Costs distribution of the development and consenting phase (D&C), Martinez & Iglesias, 2022.

6.2.2 Turbine and substructure

In bottom-fixed offshore wind farms, the turbine together with its supporting structure typically represents about 55% of the total CAPEX [51]. In this con-

figuration, the substructure cost may also include the foundation, making it highly sensitive to water depth.

In contrast, for floating offshore wind systems, the substructure cost is largely independent of depth, since mooring and anchoring expenses are usually treated separately. According to several sources, the average cost of a standard wind turbine is estimated at around 1.6 M€ per MW installed [52]. However, the limited availability of data on floating platforms complicates precise cost assessment. Although pilot projects such as WindFloat and Hywind have been deployed, large-scale industrial production is still required to achieve competitive cost levels.

Based on the material consumption and an estimation of the manufacturing process, a total cost of 8 M€ per turbine for the substructure has been reported [53].

6.2.3 Transmission

High-voltage alternating current (HVAC) is commonly used for transmitting electricity generated by offshore wind farms. It is a cost-effective option for installations located in shallow waters relatively close to the shore, typically between 20 and 60 km [54]. However, HVAC systems are subject to various power losses, including corona effects, skin effects and electromagnetic radiation losses.

Recent research indicates that high-voltage direct current (HVDC) is more suitable for wind farms situated farther offshore, generally beyond 80 km [55],[56]. The uniform distribution of both current and magnetic field in HVDC systems significantly reduces energy losses. Skin effect and radiation or induction losses are essentially eliminated, while the corona effect remains but is less pronounced. Additionally, in AC transmissions, the peak voltage and current are about 1.4 times higher than the average, whereas a conductor of the same size in HVDC can carry more power. The cost per unit length of transmission cables is also generally lower for HVDC systems.

The main drawback of HVDC is that the AC power generated by the turbines must be converted to DC offshore and then back to AC onshore, which increases the cost of terminal stations. In summary, while HVAC remains economically competitive for nearshore projects, HVDC becomes more advantageous beyond a certain distance, reported to be between 55 km [57] and 80 km [58].

The typical energy transmission process is as follows: a wind turbine generates electricity at up to 1 kV AC, which is then stepped up to 11 kV or 33 kV using a transformer, often located in the nacelle. The power is subsequently transmitted to an offshore substation, which further increases the voltage for export to shore. For HVDC systems, the voltage is converted to direct current at an offshore converter and then back to AC once it reaches the onshore grid.

In this study, the costs of both HVAC and HVDC systems are considered, taking into account the required substations and the length of the export cables. The cabling cost for transmitting power to shore C_t can be expressed as shown in the next equation:

$$C_t = d \cdot n_{ex, cab} C_{ex, cab} + n_{off, sub} C_{off, sub} + n_{on, sub} C_{on, sub}$$

In this equation, d represents the distance to the coastline, while the variables n and C correspond to the number and unit costs of the export cables, offshore substations and onshore substations, with the subscripts “ ex, cab ”, “ off, sub ” and “ on, sub ” indicating each respective component. For the example wind farm, these values are derived from a study based on labor costs in the UK, Table 1 [59].

Variable	HVAC	HVDC
$n_{ex, cab}$	3	3
$C_{ex, cab}$ (M€/km)	2.336	1.168
$n_{off, sub}$	3	2
$C_{off, sub}$ (M€/km)	39	142.75
$n_{on, sub}$	–	1
$C_{on, sub}$ (M€/km)	–	84.35

Table 1: Input parameters for the transmission costs. Cavazzi, S., & Dutton, A., 2016.

Figure 43 illustrates how the transmission costs for both HVDC and HVAC systems vary with the distance to shore, showing a break-even point at approximately 56 km. To calculate the total transmission costs, the expenses for the inter-array cabling must also be included alongside the components in previous equation. Optimizing the layout of turbines is a complex task that depends on the specific characteristics of each site. For the purposes of this study the inter-array cables are assumed to be divided into 20 separate strings, each serving 5 turbines. This approach follows similar configurations reported in the literature [60]. The total inter-array cable length for such disposition in the exemplar wind farm is estimated to be 192 km, at 303.5 k€/km.

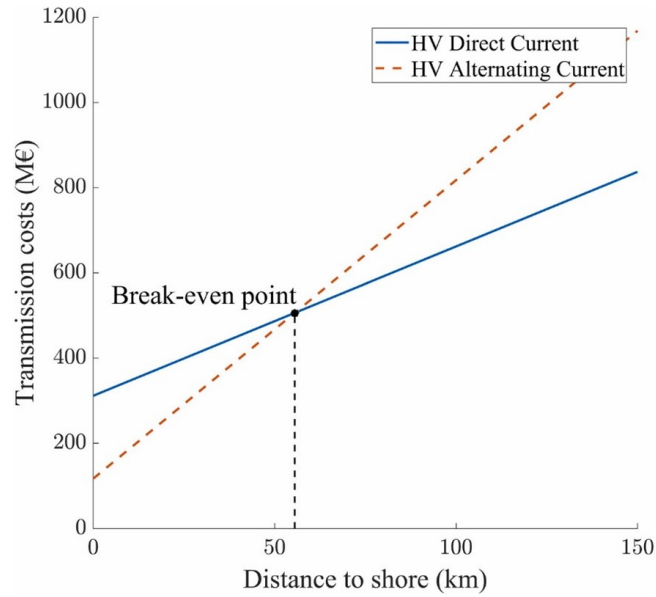


Figure 43: Cabling costs (M€) for the transmission of the electricity to the coast for high-voltage direct current (HVDC) and high-voltage alternating current (HVAC). The break-even point of the two technologies is estimated at a distance to shore of 56 km, Martinez & Iglesias, 2022

6.2.4 Mooring

The mooring of a spar-buoy platform typically relies on several catenary mooring lines, often three per turbine, connected to anchors on the seabed. The choice of anchoring system depends on seabed conditions; Drag Embedment Anchors (DEA) are commonly preferred due to their ability to penetrate the seabed and resist large horizontal loads transmitted by the mooring lines (Figure 44). These anchors are engineered to embed themselves into the seabed and are able to resist the significant horizontal forces transferred through the mooring line resting on the seafloor.



Figure 44: Example of a Drag Embedment Anchor.

In this study, the unit cost of such an anchor is assumed to be approximately 123 k€, based on values reported for anchors of comparable capacity [52]. Other options, such as dead-weight anchors, may also be used and can significantly reduce anchoring costs. Spar-buoy mooring lines generally consist of a combination of steel wire and chains, with total lengths increasing with water depth. For instance, in a catenary system, a baseline line length of approximately 500 m for a 100 m water depth is assumed, with an additional 150 m added for every extra 100 m of depth to account for draft and platform stability. Furthermore, additional chain length is included to ensure sufficient seabed friction and long-term durability, typically around 50 m per line [60]. Based on these assumptions, a general expression for the mooring cost C_m of a spar-buoy platform as a function of water depth can be expressed as:

$$C_m = n_{\text{tur}} n_{\text{lines}} [C_{\text{anchor}} + (1.5 h + 410) C_{\text{line}} + 50 C_{\text{chain}}]$$

where n_{tur} is the total number of turbines, n_{lines} is the number of lines per turbine, h is the water depth and C_{anchor} , C_{line} and C_{chain} are the costs per unit of the anchor, mooring line and chain, respectively. Finally, C_{line} and C_{chain} are the costs of the mooring line and chain per unit length, respectively, which are estimated at 48 €/m and 270 €/m [59]. This approach allows the estimation of mooring costs for spar-buoy platforms across different sites, taking into account variations in water depth and seabed conditions. In this study, site-specific water depth values are extracted from the Global Wind Atlas platform for the selected offshore coordinates, ensuring consistency between the wind resource assessment and the bathymetric conditions considered in the economic evaluation.

6.2.5 Installation

The installation of a floating offshore wind farm is a challenging process. The costs related to this phase are at present somewhat uncertain because the technologies and equipment required for installation are still at an early stage of development, leaving room for improvement and cost reductions. In this work, a simplified algorithm is used to evaluate the installation costs of a wind turbine supported by a spar-buoy platform, assuming the use of a tugboat for towing and positioning operations at a cost of 19.5 k€ per day (Figure 45), [60].



Figure 45: Tugboat towing a floating offshore wind turbine platform to the installation site.

The installation costs of the turbines $C_{i,turb}$ can be expressed [59] as :

$$C_{i,turb} = n_{turb} \cdot \left[T_{install} + \frac{2d}{V_{tugboat}} \right] \cdot \frac{C_{tugboat}}{n_{tur,trip}}$$

where n_{turb} is the total number of turbines. $T_{install}$ and d account for the turbine installation time and distance to the coast, respectively. $C_{tugboat}$ represents the charter cost of the vessel and $V_{tugboat}$ its average speed. Finally, $n_{tur,trip}$ is the number of turbines carried per trip. The values of the parameters of the previous equation are listed in Table 2.

T_{install} (days)	2
V_{tugboat} (km/h)	20
C_{tugboat} (k€/day)	19.5
$n_{\text{tur},\text{trip}}$	5

Table 2: Input parameters for the installation costs of the turbines, Cavazzi, S., & Dutton, A., 2016.

The installation cost of the mooring system is assumed to be 240 k€ per turbine [53]. The expenses associated with the installation of the electrical infrastructure are divided into three main components: export cables, inter-array cables and offshore substations.

The installation cost of the export cable can vary considerably depending on technical and site-specific conditions. Reported values for a single trenched cable range between 382 k€/km and 892 k€/km. Due to this wide variability, an average value of 637 k€/km is adopted in this study. This assumption provides a balanced estimate, while acknowledging that future analyses may refine this parameter as more accurate data become available [60].

For the inter-array cabling, the installation cost is assumed to correspond to one-third of the export cable installation cost per kilometre, in accordance with values reported in the literature. The installation cost of the offshore substation, designed for a spar-buoy configuration, is estimated at 20 M€ for the entire wind farm [60].

Based on these assumptions, the overall installation costs including turbine installation, mooring system deployment and electrical infrastructure are estimated for the considered wind farm layout and subsequently evaluated for the different offshore locations analysed in this study.

6.2.6 Decommissioning

As global wind power generation grows, a large number of wind turbines will eventually reach the end of their operational life (EOL). Generally, three main strategies are adopted to manage the EOL of wind farms, which are shown in Figure 46. These include the following: life extension, repowering and decommissioning. Life extension involves extending the operational lifespan of existing turbines, while repowering entails replacing older turbines with new, more efficient models. Decommissioning represents the final stage of a wind farm’s lifecycle and is carried out when the other strategies are not viable. This process involves disconnecting the turbines from the grid, dismantling them along with their supporting structures and equipment, and either burying or marking any items left in place to restore the site to its original condition.

The costs and complexity of decommissioning depend on factors such as lease duration, turbine age, O&M costs and the availability of specialized equipment.

Offshore wind decommissioning is still an emerging field and data on these operations are limited. In Europe, decommissioning activity is expected to grow significantly in the coming years, making it essential for the industry to plan for associated financial liabilities, potential energy production gaps, removal strategies and environmental restoration.

Effective management of decommissioning requires identifying the most costly activities and prioritizing opportunities for safe and efficient cost reduction. Financial planning is therefore a key aspect, including estimating the cost of tasks, operations and lost energy production. While decommissioning in wind energy differs from practices in oil, gas or nuclear sectors, valuable lessons can still be applied. Accurate cost estimation is crucial to enable operators and regulators to plan resources effectively throughout the wind farm's life. Early attention to EOL planning helps close knowledge gaps, improve procedures and establish more efficient and safer decommissioning practices in the wind energy sector.

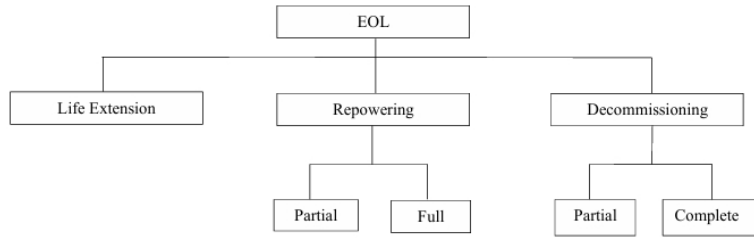


Figure 46: End-of-life (EOL) strategies for offshore wind farms, Shafiee & Animah, 2017.

In many jurisdictions, an offshore energy project cannot be installed unless a decommissioning plan has been formally approved. At present, the costs associated with this phase remain highly uncertain, since no offshore wind farm has yet undergone a full decommissioning process. In general, the procedure is considered to follow the steps of installation in reverse, but with fewer requirements regarding the preservation of individual components. For onshore wind projects, the net cost of decommissioning is typically very low, largely because the recovered scrap metal offsets most of the expenses. Offshore sites, however, involve harsher operating conditions and additional logistical challenges, particularly the need to transport structures back to shore, which leads to higher expected costs. A frequently used approximation is to express decommissioning expenses as a percentage of the installation cost see Table 3.

Wind turbine	70%
Subsea cable	10%
Substation	90%
Mooring system	90%

Table 3: Decommissioning costs as a percentage of the installation costs, BVG Associates. Offshore wind cost reduction pathways-technology work stream. 2012.

Estimating the revenue from scrap metal is also difficult because market prices fluctuate significantly over time. Some studies assume that the value recovered from scrap is roughly comparable to the cost of decommissioning [59]. For example, one assessment for a semi-submersible platform reports a return of about 250 k€, corresponding to approximately 5% of the total CAPEX [53].

6.3 OPEX

Operation and maintenance (O&M) activities represent a substantial portion of the overall expenditure in offshore wind developments. Various studies report that these costs typically make up around 25% of the total life-cycle expenses [61]. O&M costs usually include a fixed component, covering routine repairs, personnel, port infrastructure and necessary equipment and a variable component, largely linked to travel and vessel use.

Because large commercial floating wind farms are not yet in operation, obtaining precise O&M cost estimates remains challenging [62]. As the industry matures, better knowledge of component failure rates and the resources required for maintenance will play a key role in reducing these expenses [63].

In techno-economic assessments, annual OPEX is often modelled as a fixed percentage of the initial CAPEX, following common practice in offshore wind cost analysis. Reported benchmark values generally range between 1.5% and 6% of CAPEX per year, depending on site conditions and maintenance strategies. In this study, a representative value of 3% of CAPEX per year is adopted, which results in a life-cycle O&M contribution consistent with values reported in the literature. It should be noted that, since large-scale commercial floating wind farms are still in an early stage of deployment, accurate estimation of O&M costs remains challenging. As the floating wind industry matures, improved understanding of component reliability and maintenance requirements is expected to contribute to cost reductions.

6.4 Annual Energy Production

The Annual Energy Production (AEP) represents the total amount of electricity generated by the wind farm over one year and constitutes the primary revenue driver in the LCOE calculation. The AEP depends on the rated power of the installed turbines and on the local wind resource, which is typically expressed through the capacity factor (CF). The capacity factor reflects the ratio between the actual energy produced and the maximum theoretical production at rated power over one year. Mathematically, the annual energy production can be estimated as:

$$AEP = P_{\text{rated}} \cdot CF \cdot 8760$$

where P_{rated} is the installed capacity of the wind farm and 8760 represents the number of hours in one year.

In this study, the capacity factor values are obtained from the Global Wind Atlas database, which provides wind resource assessments based on high-resolution atmospheric modelling. The CF is assumed to vary with the distance from the shore (20 km, 45 km and 60 km), as wind conditions generally improve further offshore due to reduced surface roughness and lower turbulence intensity. Consequently, the AEP differs across the considered scenarios, directly influencing the denominator of the LCOE equation.

In order to obtain a more realistic estimate of the net annual energy production, overall system losses are also considered. A total loss factor of 10% is applied to account for wake effects, electrical transmission losses, transformer inefficiencies, availability constraints and other operational losses. Therefore, the net annual energy production used in the LCOE calculation is expressed as:

$$AEP_{\text{net}} = P_{\text{rated}} \cdot CF \cdot 8760 \cdot (1 - 0.10)$$

This adjustment ensures a more accurate representation of the effective energy delivered to the grid.

6.5 Results and Discussion

After defining all the parameters required for the economic assessment, a preliminary site evaluation was carried out using the Global Wind Atlas. In particular, bathymetry and capacity factor (CF) were analysed at the selected project distances of 20 km, 45 km and 60 km from the coast of Palm Beach. The obtained values are reported in Table 4.

Case	Distance [km]	Bathymetry [m]	CF
1	20	71	0.37
2	45	320	0.39
3	60	1036	0.39

Table 4: Summary of the site-specific parameters for each analysed configuration, including distance from shore [km], water depth [m] and corresponding capacity factor (CF), derived from the Global Wind Atlas database.

The total CAPEX was estimated and its individual components are summarised in Table 5. The results clearly indicate that capital expenditures are strongly influenced by the distance from the shore, primarily due to its impact on transmission and installation costs. The highest CAPEX values (approximately 4263 M€) are associated with the most distant site, which is still within the feasible technological range (water depth of about 1000 m). Conversely, locations closer to the coastline exhibit lower overall CAPEX values (approximately 3832 M€).

Costs directly linked to water depth were found to be comparatively less significant than those driven by offshore distance. Within the adopted modelling approach, water depth only affects the required length of the mooring lines. However, mooring system costs are largely dominated by fixed components, meaning that variations in line length have a relatively limited effect on total mooring expenditure. As a result, mooring costs increase from about 49 M€ in shallower areas to roughly 70 M€ in deeper waters.

The wind turbine and its associated floating substructure represent the largest share of total capital costs. Nevertheless, these components also offer the greatest potential for cost reduction, particularly through economies of scale, industrial standardisation, technological optimisation and large-scale manufacturing processes [64], [65], [66].

Transmission costs show the strongest sensitivity to distance from shore. In this study, both HVAC and HVDC transmission options were evaluated, allowing the selection of the most cost-effective solution depending on offshore distance. A break-even distance of approximately 56 km emerges, as evidenced by the transition between the second and third case studies, where transmission costs increase from approximately 11% to 15% of the total CAPEX, as illustrated in Figure 44. Beyond this threshold, transmission infrastructure may become one

of the primary barriers to further offshore deployment.

Installation costs, on the other hand, contribute a relatively small fraction to total CAPEX. Nearshore, they account for roughly 3% of the overall investment and increase only moderately with distance. This proportion is consistent with previous findings for floating offshore wind systems and remains significantly lower than the installation cost share typically observed for bottom-fixed offshore wind turbines [60], [49].

Case	Development [M€]	Turbine + Substructure [M€]	Transmission [M€]	Mooring [M€]	Installation [M€]	Decommissioning [M€]
1	294	3040	315	48	109	47
2	294	3040	491	54	158	52
3	294	3040	638	70	187	56

Table 5: Overview of the analysed configurations, reporting the estimated CAPEX components for each case.

With regard to OPEX, it is important to clarify that, within the scope of this study, operational expenditures were not estimated through a detailed site-specific breakdown. Instead, OPEX was assumed as a fixed percentage of the total CAPEX, in accordance with common practice in preliminary techno-economic assessments of floating offshore wind projects.

This simplified approach implies that the distinction between fixed and site-dependent operational components was not explicitly modelled. In reality, OPEX typically includes both fixed costs (such as scheduled maintenance, component replacement, port facilities, vessels and personnel) and variable costs influenced by site characteristics, including distance to shore. However, since reliable and comprehensive datasets for floating offshore wind systems remain limited, especially when compared to bottom-fixed technologies, a percentage-based assumption was considered appropriate for the level of detail of this analysis.

It should also be noted that actual operational costs may vary depending on additional site-specific factors beyond distance to shore, such as wind and wave conditions, accessibility windows and component failure rates. These aspects, being strongly region-dependent, were not incorporated into the present evaluation and therefore represent a source of uncertainty in the overall economic assessment.

The overall results of the economic evaluation, including total CAPEX, estimated OPEX and annual energy production (AEP), are summarised in Table 6.

Case	Total CAPEX [M€]	OPEX [M€]	AEP [MWh]
1	3853	116	4 083 912
2	4089	123	4 304 664
3	4285	129	4 304 664

Table 6: Summary of the analysed configurations reporting total CAPEX, OPEX and annual energy production (AEP).

Based on the estimated capital and operational expenditures and the corresponding annual energy production (AEP), the Levelized Cost of Energy (LCOE) was calculated for the three considered configurations.

The resulting values are as follows: 139.1 €/MWh for the site located 20 km from the shore, 140.06 €/MWh for the 45 km configuration and 146.8 €/MWh for the 60 km case.

Prior to analysing the obtained LCOE values, the robustness of the results was assessed through a sensitivity analysis. This analysis was carried out by varying key financial, operational and technological parameters of the economic model. In particular, the discount rate was varied to 8% and 12% in order to account for different possible financing conditions. The capacity factor was modified by $\pm 5\%$ relative to the site-specific baseline values derived from the Global Wind Atlas, meaning that the variation was applied proportionally to each reference value rather than as an absolute change in percentage points. Additionally, a CAPEX reduction of 10–15% was considered in order to simulate possible cost reductions associated with technological learning effects, industrial scaling and supply chain optimisation in floating offshore wind deployment. The resulting variations in the Levelized Cost of Energy for the three analysed configurations are reported in Table 7.

Scenario	LCOE 20 km [€/MWh]	LCOE 45 km [€/MWh]	LCOE 60 km [€/MWh]
Base case	139.1	140.06	146.8
Discount rate $r = 8\%$	124.4	125.2	131.2
Discount rate $r = 12\%$	154.6	155.7	163.1
Capacity factor -5%	146.4	147.4	154.5
Capacity factor $+5\%$	132.5	133.4	139.8
CAPEX -10%	125.2	126.05	132.1
CAPEX -15%	118.3	119.05	124.75

Table 7: Sensitivity analysis of the Levelized Cost of Energy (LCOE) with respect to key financial, operational and technological parameters.

The sensitivity analysis presented before provides further insight into the robustness of the economic results by evaluating how variations in key financial, operational and technological parameters affect the Levelized Cost of Energy

(LCOE). As expected, the LCOE values show a clear dependence on the considered assumptions. An increase in the discount rate leads to higher LCOE values, reflecting the stronger impact of financing costs on capital-intensive technologies such as floating offshore wind. Conversely, improvements in the capacity factor result in lower LCOE values, highlighting the strong influence of energy production on the overall cost of electricity.

The analysis also shows that reductions in CAPEX, representing potential technological learning effects and industrial cost reductions, have a significant impact on the final LCOE values. In the most optimistic scenario, assuming a CAPEX reduction of 15%, the LCOE decreases by approximately 20 €/MWh compared to the base case. This result confirms the high sensitivity of floating offshore wind economics to capital expenditure and highlights the importance of technological development and supply chain optimisation in improving the competitiveness of the technology.

Despite the variations introduced in the sensitivity scenarios, the relative ranking of the three analysed configurations remains unchanged. The site located 20 km from the shore consistently exhibits the lowest LCOE, while the 60 km configuration remains the most expensive option due to the significant increase in transmission and installation costs associated with greater offshore distances. The 45 km configuration maintains an intermediate position, confirming the overall consistency of the techno-economic comparison carried out in this study. Overall, the sensitivity analysis demonstrates that the economic results obtained in the base-case scenario are robust with respect to reasonable variations in the main input parameters, supporting the validity of the conclusions drawn from the LCOE assessment.

In light of these findings, the analysis now focuses again on the base-case scenario to further examine the techno-economic implications of the different distance configurations. It can be observed that although the 20 km configuration exhibits the lowest LCOE in absolute terms (139.1 €/MWh), the 45 km configuration represents the most advantageous option when considering the overall techno-economic balance of the project. The difference in LCOE between the 20 km and 45 km configurations is minimal (approximately 1 €/MWh), whereas the 45 km case ensures a significantly higher annual energy production, with an increase of 220752 MWh compared to the nearshore scenario.

This additional energy yield substantially improves the project's revenue potential without leading to a meaningful increase in the cost of energy. As previously discussed, total CAPEX is predominantly influenced by transmission and installation costs, which become considerably more significant beyond the break-even distance of approximately 56 km, where HVDC transmission becomes economically (Figure 47). The 45 km configuration remains below this threshold, thus avoiding the sharp escalation in transmission costs observed in the 60 km scenario.

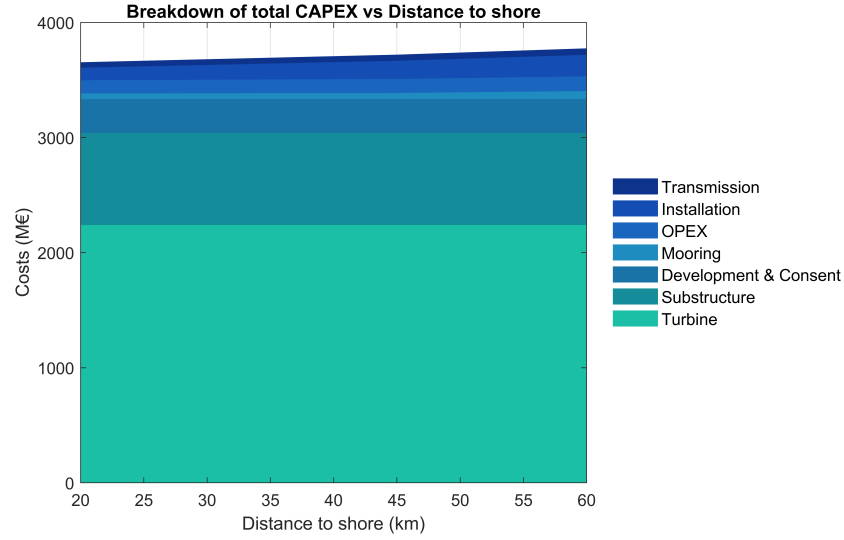


Figure 47: Cost breakdown of the reference wind farm as a function of offshore distance.

The 60 km case, despite producing approximately the same annual energy output as the 45 km configuration, results in a markedly higher LCOE (146 €/MWh). This increase is primarily attributable to the substantial growth in transmission-related capital expenditures associated with greater offshore distances. Therefore, the additional distance does not translate into proportional gains in energy production, leading to a deterioration of economic performance.

Considering the significantly higher annual energy production compared to the 20 km configuration, the minimal variation in LCOE and the avoidance of the transmission cost escalation observed at 60 km, the 45 km configuration emerges as the optimal compromise between economic efficiency, energy yield and overall project feasibility.

6.6 Economic Analysis Conclusion

This work presented a site-specific assessment of the Levelized Cost of Energy (LCOE) for a floating offshore wind farm based on a spar-buoy platform concept located offshore the Palm Beach coast. The analysis included a detailed breakdown of the costs incurred throughout the project lifetime, considering their dependence on key site-specific parameters, namely distance to shore and water depth. In parallel, the annual energy production (AEP) was estimated using the capacity factor, allowing for a realistic evaluation of the theoretical electricity generation at each location.

The cost breakdown shows that the largest share of total CAPEX is associated with the wind turbine and the floating substructure, which represent predominantly fixed expenses within the overall investment. Variable costs are mainly influenced by the distance from shore, as this parameter significantly affects installation and transmission expenditures. The consideration of both HVAC and HVDC transmission technologies enables the identification of the most cost-effective solution depending on offshore distance.

In contrast, water depth was found to have a relatively limited impact on total costs. Within the adopted methodology, water depth only affects the required length of the mooring lines. However, the contribution of line length to overall mooring costs remains relatively small compared to other components, such as anchoring systems. This result suggests that, unlike bottom-fixed offshore wind technologies, floating offshore wind is significantly less constrained by water depth, thereby expanding the range of potentially suitable installation sites.

Regarding the LCOE results, the analysis highlights the dominant role of the wind resource and the resulting annual energy production. The estimated AEP emerges as the primary factor influencing the cost of energy, outweighing other site-specific variables such as distance to shore or water depth. This finding underlines the importance of performing accurate wind resource assessments when evaluating the techno-economic feasibility of floating offshore wind projects.

Taking into account the analysed conditions and the obtained results, the configuration located 45 km from the coast can be identified as the optimal solution. It provides the most balanced trade-off between economic performance and energy yield, combining a higher annual energy production with a competitive LCOE while avoiding the significant increase in transmission costs observed at greater offshore distances. Moreover, this configuration is consistent with the location identified during the earlier design phases of the project, confirming the coherence of the overall development process.

Since the largest share of the total investment is associated with the wind turbine and the floating substructure, the calculated LCOE values show significant potential for future reductions through economies of scale, industrial standardisation, technological optimisation and large-scale manufacturing processes, as

also indicated by the sensitivity analysis. Improvements in turbine design and performance, together with optimised platform configurations, may further increase energy production and contribute to reducing the overall cost of electricity from floating offshore wind systems.

Nevertheless, the LCOE value obtained in this study, approximately 140 €/MWh for the selected area, remains significantly higher than those typically observed for more mature wind energy technologies. According to the International Renewable Energy Agency (IRENA), the global weighted average LCOE for newly commissioned onshore wind projects reached approximately 31 €/MWh in 2024, with values as low as 27–28 €/MWh reported in countries characterised by favourable wind resources and highly developed supply chains, such as China and Brazil [67]. Real project examples confirm the high cost competitiveness achieved by land-based wind technology. For instance, the Fosen Vind wind project in Norway, one of the largest onshore wind developments in Europe with an installed capacity of approximately 1 GW and an annual production of about 3.4 TWh, has been estimated to achieve LCOE values in the range of approximately 35–40 €/MWh [73].

Offshore wind projects based on bottom-fixed foundations generally present intermediate cost levels. IRENA reports a global weighted average LCOE of approximately 73 €/MWh for offshore wind in 2024, although values may vary depending on regional market conditions [67]. In particular, offshore wind costs in China have been reported at around 52 €/MWh, while in markets characterised by higher development and financing costs, such as the United States, LCOE values may exceed approximately 113 €/MWh [67]. Real project examples further illustrate this range. The Hornsea offshore wind projects in the United Kingdom, among the largest bottom-fixed offshore wind farms currently under development, secured strike prices between approximately 63 and 69 €/MWh, highlighting the cost reductions achieved by modern large-scale offshore wind developments [71].

Floating offshore wind, however, is still at an early stage of commercial deployment, which explains the higher cost levels observed in the present analysis. In addition to the standard offshore wind components, floating systems require large floating platforms, dynamic electrical cables capable of accommodating platform motion and complex mooring and anchoring systems designed to ensure stability in deep-water environments. These additional engineering requirements increase both capital costs and installation complexity, while the relatively limited number of commercial-scale projects currently deployed means that industrial supply chains and manufacturing processes have not yet reached full maturity. Recent techno-economic studies estimate current floating offshore wind LCOE values in the range of approximately 130–180 €/MWh, which is consistent with the results obtained in this work [60].

Despite the current cost gap, the historical development of wind energy tech-

nologies suggests that significant cost reductions can occur as deployment increases. Over the last decade, the cost of electricity from onshore wind has decreased by more than 60% globally, mainly driven by technological innovation, increasing turbine sizes, improved capacity factors and economies of scale in manufacturing and installation processes [67]. A comparable trend has been observed for offshore wind based on bottom-fixed foundations. Early offshore wind projects commissioned in the early 2010s exhibited LCOE values often exceeding 140 €/MWh, whereas modern offshore wind farms frequently achieve values between approximately 60 and 80 €/MWh due to technological learning effects, industrial scaling and supply chain maturation [72].

These historical trends highlight the strong influence of technological learning curves in the wind energy sector. As cumulative installed capacity increases, manufacturing processes become more efficient, turbine components become increasingly standardised and installation procedures improve, leading to progressive cost reductions. Floating offshore wind is therefore expected to follow a similar trajectory as the technology moves from pilot and demonstration projects toward large-scale commercial deployment. Consequently, while the LCOE values obtained in this study remain higher than those associated with mature wind technologies, they are broadly consistent with the cost levels typically observed during the early development stages of new energy technologies.

6.6.1 Benchmark with Existing Floating Offshore Wind Farms

A comparison with existing floating offshore wind projects helps contextualise the results obtained in this study and assess their consistency with real industrial applications.

Among the most relevant industrial references, the Hywind concept developed by Equinor represents one of the most advanced and widely documented floating offshore wind technologies currently in operation. In particular, the Hywind Scotland project, commissioned in 2017 in the North Sea near Peterhead, is widely recognised as the first commercial-scale floating offshore wind farm. The project consists of five wind turbines rated at 6 MW each, for a total installed capacity of 30 MW, mounted on spar-type floating foundations similar to the platform configuration adopted in this work. The turbines are installed approximately 25 km offshore in water depths ranging between 95 m and 120 m and are stabilised through a deep ballast system that lowers the centre of gravity of the structure. Operational data from the wind farm have shown particularly strong performance, with an average capacity factor of approximately 54% and peak values reaching about 57% during the 2019–2020 period [68]. From an economic perspective, early project assessments indicate a levelized cost of electricity (LCOE) of approximately 210 €/MWh, reflecting the pioneering nature of the project and the limited industrial maturity of floating offshore wind technologies at the time of installation [69].

Another relevant reference for floating offshore wind development is the WindFloat Atlantic project, located off the coast of Viana do Castelo in Portugal and commissioned in 2020. The project consists of three wind turbines rated at 8.4 MW each, resulting in a total installed capacity of approximately 25 MW. Unlike Hywind Scotland, which adopts a spar-type floating foundation, WindFloat Atlantic utilises a semi-submersible platform developed by Principle Power. This design is characterised by a three-column structure that provides stability through ballast and a catenary mooring system, allowing the platform to be fully assembled in port and subsequently towed to the installation site. The wind farm is located approximately 20 km offshore in water depths of around 100 m and represents one of the first commercial-scale demonstrations of semi-submersible floating wind technology in Europe. Techno-economic studies indicate that early floating offshore wind projects typically exhibit LCOE values in the range of approximately 180-220 €/MWh, reflecting the limited industrial maturity and the additional engineering requirements associated with floating foundations, dynamic electrical cables and complex mooring systems [70].

Overall, the comparison with Hywind Scotland and WindFloat Atlantic confirms that the technological assumptions adopted in this work are consistent with existing industrial applications of floating offshore wind systems. Although the project analysed in this thesis considers a significantly larger installed capacity and different environmental conditions along the Australian coast, the estimated performance indicators and economic results fall within the range observed in early commercial floating wind developments. These comparisons therefore support the plausibility of the proposed project and highlight the potential for further cost reductions as the floating offshore wind sector continues to mature and scale up globally.

7 Hydrodynamic Analysis of a Spar-Type Floating Platform

The understanding of the dynamic behavior of floating structures subjected to wave excitation represents a fundamental step in the study of offshore systems. In the marine environment, the motion of the structure is governed by the interaction between the inertial and stiffness properties of the system and the hydrodynamic forces induced by the wave field. An accurate characterization of this interaction is essential for assessing operational performance, dynamic stability and the overall structural response, particularly under extreme sea states.

For spar-type floating platforms, the dynamic response is strongly influenced by the mass distribution, the deep draft and the hydrodynamic damping characteristics, resulting in motion dominated by specific characteristic frequencies. In this context, frequency-domain analysis provides an effective framework to describe the system's behavior under regular and extreme wave conditions, allowing the physical mechanisms governing the structural response to be identified.

In this chapter, the analysis is developed through a progressive study of the system's dynamic response, focusing exclusively on hydrodynamic performance. The turbine is assumed to be parked and thus aerodynamic effects are not considered, reflecting the conditions typically experienced during extreme sea states. Initially, the behavior of the floating substructure alone is examined to characterize its intrinsic hydrodynamic response through numerical simulations performed with HydroD. Subsequently, the analysis is extended to the complete system, including superstructure masses and inertias, in order to evaluate the modifications introduced in the overall dynamic response and obtain a more realistic representation of the system's behavior under extreme offshore conditions.

This approach highlights the role of the substructure as the main determinant of the system's dynamic signature and emphasizes the importance of hydrodynamic interactions in defining the overall response of floating offshore wind turbines during extreme events.

7.1 Linear Wave Theory and the Six Degree-of-Freedom Equation of Motion

The motion of a floating structure subjected to wave excitation can, in first approximation, be described using linear wave theory, also known as Airy wave theory. This classical approach is widely adopted in offshore hydrodynamics when the wave amplitudes and body motions are sufficiently small to justify linearisation of the governing fluid equations. In this formulation, it is assumed that the waves are small relative to the characteristic dimensions of the structure (wave height $\ll$ body dimensions), that both free surface deformations and body displacements remain sufficiently small to enable linearisation of the Navier–Stokes equations and that the fluid can be treated as incompressible and irrotational, allowing the flow to be represented by a scalar velocity potential [74].

Under these assumptions, the fluid structure interaction problem can be decomposed into three principal hydrodynamic contributions: the wave excitation forces F_{exc} , which arise from the interaction between incident waves and the structure; the added mass term $A(\omega)$, representing the additional inertia that the structure effectively carries due to the accelerated fluid surrounding it; and the radiation damping component $B(\omega)$, associated with waves generated by the motion of the body itself, which carry energy away from the structure [75]. Although this linear framework neglects viscous effects and large-amplitude nonlinearities, it is capable of providing an accurate representation of the essential hydrodynamic behaviour and isolating the characteristic dynamic signature of the floating body.

The motion of a floating platform can therefore be written in matrix form through the linear equation of motion for the six rigid-body degrees of freedom (surge, sway, heave, roll, pitch and yaw):

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{B}\dot{\mathbf{x}}(t) + \mathbf{C}\mathbf{x}(t) = \mathbf{F}_{\text{wave}}(t)$$

Here, $\mathbf{M} = \mathbf{M}_s + \mathbf{A}_\infty$ denotes the total mass matrix, composed of the structural mass matrix $\mathbf{M}_s$ and the frequency-independent added mass $\mathbf{A}_\infty$; $\mathbf{B}$ represents the radiation damping matrix, which is in general frequency-dependent; $\mathbf{C}$ is the hydrostatic stiffness (restoring) matrix associated with buoyancy and gravitational restoring forces; $\mathbf{F}_{\text{wave}}(t)$ is the vector of wave-induced excitation forces; and $\mathbf{x}(t)$ is the vector of the platform’s generalized coordinates (surge, sway, heave, roll, pitch, yaw) [76], [77].

When transformed into the frequency domain via the Fourier transform, the equation becomes:

$$[-\omega^2 (\mathbf{M}_s + \mathbf{A}(\omega)) + i\omega\mathbf{B}(\omega) + \mathbf{C}] \mathbf{X}(\omega) = \mathbf{F}_{\text{exc}}(\omega)$$

where $\mathbf{X}(\omega)$ and $\mathbf{F}_{\text{exc}}(\omega)$ denote the complex amplitudes of the structural response and the wave excitation, respectively, at a given angular frequency ω .

Each element of $\mathbf{X}(\omega)$ contains both the magnitude and the phase information of the motion in the corresponding degree of freedom (surge, sway, heave, roll, pitch, yaw) relative to the incident wave. Similarly, $\mathbf{F}_{\text{exc}}(\omega)$ contains both force and moment components induced by the waves.

The term $-\omega^2 (\mathbf{M}_s + \mathbf{A}(\omega))$ represents the total inertia of the system, combining the structural mass matrix $\mathbf{M}_s$ with the frequency-dependent added mass $\mathbf{A}(\omega)$, which accounts for the extra inertia induced by the acceleration of the surrounding fluid. The contribution of inertia increases with the square of the wave frequency, making the structure more resistant to acceleration at higher frequencies.

The term $i\omega\mathbf{B}(\omega)$ models the hydrodynamic damping due to waves radiated by the moving structure. The factor $i = \sqrt{-1}$ indicates a 90° phase shift between the velocity and the damping force, while the matrix $\mathbf{B}(\omega)$ varies with frequency to reflect the dependence of energy dissipation on wave period. This damping not only reduces the amplitude of motion but also introduces phase effects that influence the dynamic behaviour across multiple degrees of freedom.

Finally, the term $\mathbf{C}$ accounts for the hydrostatic restoring forces due to buoyancy and gravity, which act to return the platform to its equilibrium position. It behaves analogously to a multi-dimensional spring system, where each degree of freedom has a corresponding stiffness component and off-diagonal terms capture coupling between motions, such as heave–pitch coupling in a spar platform [77].

7.2 Frequency-Domain Representation and the Response Amplitude Operator (RAO)

The Response Amplitude Operator (RAO) represents the amplitude of motion of a floating platform in response to a regular (sinusoidal) wave. It is defined as the ratio between the structural response and the wave amplitude, typically expressed in meters per meter of wave height (for translational motion) or degrees per meter (for rotational motion) [75], [78].

Starting from the linear equation of motion in the frequency domain for the six degrees of freedom:

$$[-\omega^2 (\mathbf{M}_s + \mathbf{A}(\omega)) + i\omega\mathbf{B}(\omega) + \mathbf{C}] \mathbf{X}(\omega) = \mathbf{F}_{\text{exc}}(\omega)$$

we can consider the incident wave as a harmonic excitation with amplitude H , so that the forcing vector can be written as:

$$\mathbf{F}_{\text{exc}}(t) = H \mathbf{F}_{\text{exc}}(\omega) e^{i\omega t}.$$

Assuming a harmonic response of the platform, the solution for the displacement vector can be expressed as:

$$\mathbf{x}(t) = \mathbf{X}(\omega) e^{i\omega t},$$

where $\mathbf{X}(\omega)$ is the complex amplitude of motion at frequency ω . The corresponding velocity and acceleration are obtained by differentiation:

$$\dot{\mathbf{x}}(t) = i\omega \mathbf{X}(\omega) e^{i\omega t},$$

$$\ddot{\mathbf{x}}(t) = -\omega^2 \mathbf{X}(\omega) e^{i\omega t}.$$

Substituting these expressions into the equation of motion yields:

$$[-\omega^2 (\mathbf{M}_s + \mathbf{A}(\omega)) + i\omega\mathbf{B}(\omega) + \mathbf{C}] \mathbf{X}(\omega) e^{i\omega t} = H \mathbf{F}_{\text{exc}}(\omega) e^{i\omega t}.$$

Dividing both sides by H leads to the definition of the RAO vector:

$$\text{RAO}(\omega) = \frac{\mathbf{X}(\omega)}{H} = \frac{\mathbf{F}_{\text{exc}}(\omega)}{-\omega^2 (\mathbf{M}_s + \mathbf{A}(\omega)) + i\omega\mathbf{B}(\omega) + \mathbf{C}}$$

This formulation shows that the RAO is a frequency-dependent transfer function that relates the wave amplitude to the platform response for each degree of freedom. Each element of the RAO vector quantifies the motion per unit wave height, allowing identification of resonances, modal interactions and coupling effects. For instance, a peak in the RAO for heave indicates that the platform's vertical motion is strongly excited at that particular frequency, while off-diagonal terms in the forcing vector can produce coupled responses, such as pitch induced by heave excitation [76], [78].

7.2.1 Natural Frequencies of a Floating Structure

In the study of floating structures, the concept of natural frequency plays a central role in understanding the dynamic response to wave excitation [77]. Each degree of freedom (DOF) of the platform, including surge, sway, heave, roll, pitch and yaw, is associated with a natural frequency at which the system tends to oscillate when displaced from its equilibrium position in the absence of external forcing. These frequencies are determined by the interplay between the system's mass and inertia properties and the restoring forces, which, for a floating body, are primarily hydrostatic in nature [76], [78].

For a spar-type floating substructure, the natural frequencies of motion vary significantly among the different DOFs due to the geometry of the platform. The heave motion, corresponding to vertical translation, typically exhibits a relatively high natural frequency. This is a consequence of the large vertical inertia and the hydrostatic restoring force associated with the submerged volume of the spar. In contrast, pitch, representing rotation about the transverse axis, has a lower natural frequency, as it depends on the distribution of mass along the spar and the transverse hydrostatic stiffness. Roll, the rotation about the longitudinal axis, generally exhibits the lowest frequency among the dominant DOFs, particularly for tall and slender platforms, due to the relatively small restoring moment in the longitudinal direction [75], [77].

The natural frequencies are closely linked to the Response Amplitude Operator (RAO), since peaks in the RAO often occur near these frequencies, indicating resonant amplification of the motion. For instance, a wave with a period close to the natural period of heave will produce a significant vertical displacement, whereas waves matching the natural periods of pitch or roll can generate large rotational motions. Understanding these relationships is crucial for predicting the dynamic behavior of the platform and for identifying the conditions under which resonance may occur.

From a computational perspective, the natural frequencies can be determined by solving the eigenvalue problem associated with the linearized equations of motion. Considering the linearized system in the absence of wave forcing and radiation damping:

$$(\mathbf{M}_s + \mathbf{A}_\infty)\ddot{\mathbf{x}} + \mathbf{C}\mathbf{x} = 0$$

where $\mathbf{M}_s + \mathbf{A}_\infty$ is the total mass matrix including structural mass and the frequency-independent added mass and $\mathbf{C}$ is the hydrostatic restoring matrix [76], [77].

Assuming a harmonic solution of the form:

$$\mathbf{x}(t) = \mathbf{X}e^{i\omega t},$$

the equation reduces to:

$$[-\omega^2(\mathbf{M}_s + \mathbf{A}_\infty) + \mathbf{C}] \mathbf{X} = 0.$$

Non-trivial solutions exist only when the determinant of the coefficient matrix is equal to zero:

$$\det [-\omega^2(\mathbf{M}_s + \mathbf{A}_\infty) + \mathbf{C}] = 0.$$

For a single-degree-of-freedom approximation, the natural frequency can be expressed explicitly as:

$$\omega_n = \sqrt{\frac{C}{M_s + A_\infty}}.$$

Here C is the hydrostatic restoring coefficient for the considered degree of freedom and $M_s + A_\infty$ represents the total effective mass. This form provides an intuitive understanding: the natural frequency increases with greater restoring forces and decreases with larger inertia.

The relationship between the wave frequency ω and the natural frequency ω_n governs the amplitude of the platform response. For a linear system subjected to a harmonic wave excitation with amplitude H , the motion amplitude can be expressed as:

$$X(\omega) = \frac{H F_{\text{exc}}(\omega)}{\sqrt{(C - (M_s + A_\infty)\omega^2)^2 + (\omega B(\omega))^2}}.$$

where $B(\omega)$ represents the radiation damping coefficient. This formulation shows that:

- For $\omega \ll \omega_n$, the platform follows the wave almost rigidly.
- For $\omega \approx \omega_n$, resonance occurs, producing maximum motion.
- For $\omega \gg \omega_n$, inertial effects dominate and the response diminishes.

In practice, understanding this relationship is essential for design and operational assessment, as it allows engineers to predict resonant responses, evaluate coupled motions and optimize the platform's dynamic performance. For a spar-buoy, the dominant natural frequencies correspond to heave, pitch and roll, which define the most critical aspects of the hydrodynamic response. By characterizing these frequencies and their interaction with typical ocean wave spectra, it is possible to anticipate conditions of amplified motion and ensure structural reliability under both regular and extreme sea states [76], [77].

7.2.2 Dominant Degrees of Freedom for a Spar-Type Substructure

In the analysis of a spar-type floating substructure, all six degrees of freedom of the platform, namely surge, sway, heave, roll, pitch and yaw, can theoretically contribute to the motion of the structure under wave excitation [76], [77]. However, the geometric characteristics of a spar buoy, characterised by a deep draft and a slender vertical profile, lead to certain motions becoming dominant, while others remain comparatively small [78]. Understanding which degrees of freedom are most significant is crucial for a focused hydrodynamic analysis and accurate evaluation of the platform's response.

Among the six DOFs, heave, roll and pitch are the primary motions that determine the dynamic behavior of the structure [76], [77]. Heave, representing the vertical displacement of the buoy, is highly sensitive to wave frequency and amplitude. It directly affects platform stability and operational performance and peaks in the heave RAO often indicate resonance conditions where vertical motion is amplified [78]. Accurately characterizing heave is therefore essential for assessing the vertical dynamics and predicting critical responses to wave excitation.

Pitch, the rotation about the transverse axis of the platform, is also a key motion, particularly sensitive to long-period waves and the vertical mass distribution along the spar. Significant pitch motions occur near the natural pitch frequency, which can influence fatigue loads and operational limits [75]. Evaluating pitch RAOs allows engineers to understand how the spar responds to wave-induced moments and how rotational motions couple with vertical displacements.

Roll, corresponding to rotation about the longitudinal axis, generally has smaller amplitudes than heave and pitch. Nevertheless, it becomes important under asymmetric loading conditions or oblique wave directions, where coupled motions can arise [76]. Roll RAOs provide insight into the platform's stability margins and help in designing for safe operation under multi-directional wave conditions.

In contrast, surge, sway and yaw are typically less relevant for a spar buoy. The deep draft and associated hydrostatic restoring forces suppress horizontal translations, while yaw, rotation about the vertical axis, is mostly constrained by the mooring system and rarely contributes significantly under linear wave conditions. Although these motions may be considered in more detailed analyses, the dominant dynamic behavior of a spar-type substructure is captured by heave, roll and pitch, making them the focus of RAO characterization and hydrodynamic evaluation.

7.3 Hydrodynamic Analysis of a Spar-Buoy Platform

The design and analysis of offshore floating platforms require a deep understanding of their dynamic response under wave excitation, particularly during extreme sea conditions. Spar-type platforms, characterized by a deep and slender floating body, exhibit complex hydrodynamic behavior, where mass distribution, inertia and hydrodynamic forces interact to govern the overall structural motion.

This chapter focuses exclusively on the hydrodynamic dynamics of the platform, separating wave-induced effects from the aerodynamic contributions of the turbine, which is assumed to be in a parked condition. After a theoretical overview based on linear wave theory and the six degree of freedom equations of motion, the chapter illustrates how to characterize the natural frequencies, the dominant degrees of freedom and the platform response using the concept of the Response Amplitude Operator (RAO).

The practical part of the chapter presents a progressive simulation of the platform: starting with a detailed substructure model in GeniE, moving on to the hydrodynamic analysis of the substructure in HydroD and finally extending the study to the complete system including the turbine, which is analyzed in SIMA to evaluate how the superstructure modifies the overall dynamic response. This approach allows isolating the intrinsic hydrodynamic behavior of the substructure and understanding its interaction with the additional masses of the turbine, providing a complete and realistic representation of the platform's dynamics under extreme conditions.

The main objective of the chapter is therefore to combine theory and simulation to identify critical design conditions, anticipate potential motion amplification and support the safe and efficient design of spar-type floating platforms for offshore applications.

7.3.1 GeniE

GeniE is a structural analysis software based on the Finite Element Method (FEM), mainly used in the offshore and naval sectors for the modelling and simulation of marine structures. The software allows the creation of detailed three-dimensional models of complex structures, enabling accurate representation of geometry, mass distribution and inertia properties.

Creating a model of a spar-type platform in GeniE involves a logical progression from geometric construction to the generation of a panel model for hydrodynamic analysis. The objective of this phase is to develop the spar-buoy substructure model based on the following design parameters. These parameters are not related to the turbine previously selected, but instead refer to a publicly available reference model, allowing us to visualise and analyse the main characteristics of the platform. The main geometric parameters of the spar-buoy

platform are presented in the Figure 48.

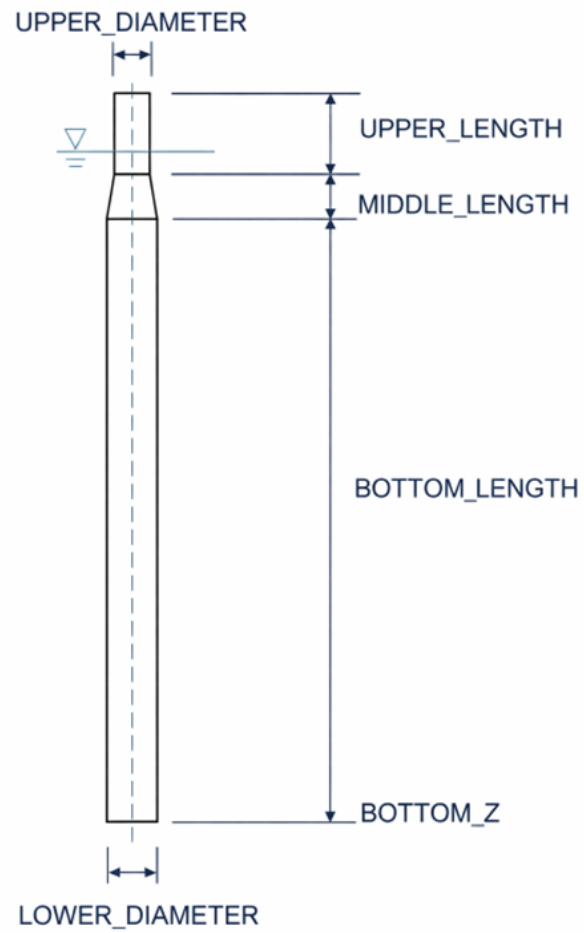


Figure 48: Geometric scheme of the spar-buoy substructure showing the main dimensional parameters used for the modelling.

Design parameters	Value [m]
UPPER_LENGTH	14
MIDDLE_LENGTH	8
BOTTOM_LENGTH	108
UPPER_DIAMETER	6.5
BOTTOM_DIAMETER	9.4
BOTTOM_Z	-120

Table 8: Design parameters of the spar-buoy substructure.

Taking into account the data reported in the previous table, the spar-buoy substructure model was developed in GeniE following a structured and systematic procedure. The modeling process begins with the creation of a new workspace in Full Mode, where the selection of the Dual Assembly option is recommended for structures that may subsequently integrate both shell and beam elements. During the initial configuration stage, the fundamental structural properties are defined, including the material (e.g., S355 structural steel), the plate thickness and the mesh density, which directly influences the numerical resolution and accuracy of the model. A crucial step in this phase is the definition of the Wet Surface property. This attribute enables the software to identify the structural surfaces that will be subjected to hydrodynamic pressure in the subsequent analysis performed in HydroD.

The geometric model of the spar is constructed by introducing a series of guiding points along the vertical axis, corresponding to the main geometric transitions of the structure, such as the bottom cylindrical section, the conical transition region and the upper cylindrical segment. These reference points are then used to generate the shell geometry through the Circular Cone/Cylinder tool. The bottom closure of the spar is created by defining a circular guiding curve and applying the Cover Curves function to generate the closing plate.

Particular attention is given to the orientation of the shell elements. The surface normals must be verified and, if necessary, reversed to ensure that the wetted side is correctly oriented outward toward the surrounding fluid. This step is essential to guarantee a correct interpretation of hydrodynamic pressures in the subsequent analysis. Once the geometric model is completed, the mesh and wet surface properties are assigned to all shell elements. The plates are then grouped into a Named Set (e.g., PanelModelSet), allowing the isolation of the panel model for hydrodynamic analysis.

To finalize the GeniE workflow, a Mesh Activity is created together with a Dummy Hydro Load Case. The latter is required to enable HydroD to recognize the wetted surfaces of the model. Finally, the model is exported in .FEM format, providing the structural input required for the subsequent frequency-domain hydrodynamic analysis. The model developed is shown in the following Figure 49.

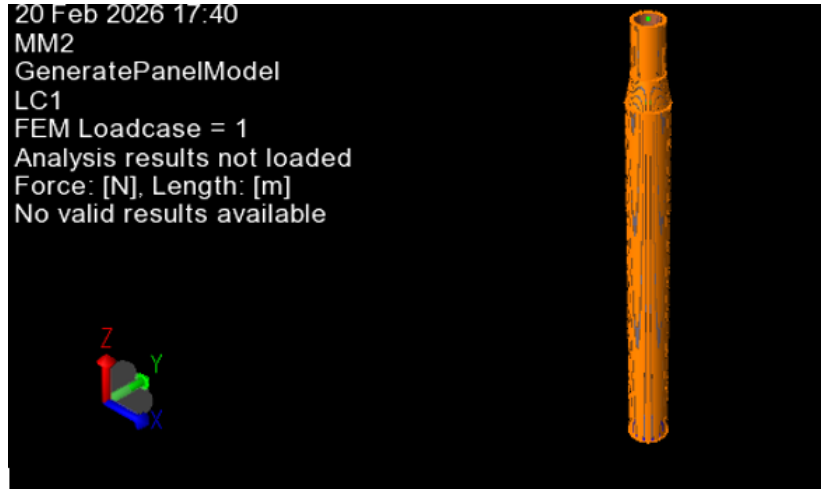


Figure 49: Three-dimensional geometric model of the spar-buoy substructure developed using GeniE, showing the overall geometry and structural configuration of the floating platform.

7.3.2 HydroD

HydroD is a specialized hydrodynamic analysis software developed for the frequency domain evaluation of offshore floating structures subjected to wave excitation. Widely used in offshore engineering, it enables the computation of fundamental hydrodynamic coefficients such as added mass, radiation damping and wave excitation forces, which are essential for predicting the dynamic behavior of marine systems.

The software is based on linear potential flow theory and solves the boundary value problem associated with wave-structure interaction by discretizing the wetted surface of the body into panels. Starting from the panel model generated in GeniE, HydroD identifies the submerged surfaces and evaluates the fluid-structure interaction effects for each of the six degrees of freedom, allowing a complete characterization of the platform response in the frequency domain. Among its main outputs are the Response Amplitude Operators (RAOs), which describe the relationship between wave excitation and structural motion, enabling the identification of natural frequencies, resonance phenomena and dominant motion modes. In addition, the software provides hydrostatic properties such as buoyancy, restoring stiffness and equilibrium conditions.

After importing the panel model of the spar substructure from the .FEM file generated in GeniE, the hydrodynamic modelling was carried out within a newly created HydroD workspace, where a Wadam frequency-domain analysis was initialized. Particular attention was devoted to the definition of the frequency set, since this directly affects the quality and interpretation of the RAOs. Two com-

plementary ranges were adopted. The first covered wave periods from 1 s to 60 s with a step of 5 s, providing a broad overview of the global dynamic behaviour of the system. The second, narrower interval ranged from 28 s to 33 s with a refined step of 0.5 s, specifically introduced to increase the resolution of the results around the expected natural period of the spar-buoy substructure.

It is important to clarify that, although most ocean waves in real offshore conditions typically range between 5 s and 25 s, the wider period interval was intentionally selected for numerical and interpretative purposes. The objective was not to represent realistic sea states beyond this range, but rather to accurately capture and illustrate the RAO peaks in the vicinity of the natural frequency, ensuring a precise identification of the resonance behaviour of the structure.

A mass model was introduced by specifying the total mass and the damping matrix. The total mass of the system was defined as 8184112 kg, the value was derived directly from the geometry of the structure, in particular from the calculation of the displaced water volume. By applying Archimedes' principle, the submerged volume was evaluated and multiplied by the seawater density (1025 kg/m^3), ensuring that the structural mass was coherent with the buoyancy force required for equilibrium.

In addition, a critical damping matrix was implemented by introducing a damping ratio equal to 5% for the degrees of freedom associated with the RAOs of interest. The inclusion of this damping contribution is essential to obtain a more realistic dynamic response of the structure, particularly in the vicinity of the natural frequencies.

Physically, the damping matrix accounts for energy dissipation mechanisms that are not fully captured by potential-flow hydrodynamics alone, such as viscous effects, structural damping and additional hydrodynamic losses. Numerically, it prevents unrealistically high resonance peaks in the RAOs and allows a more representative estimation of the platform motions under wave excitation, especially around the resonance region where the response would otherwise be overpredicted.

The model developed using the selected software is presented in the following Figure 50.

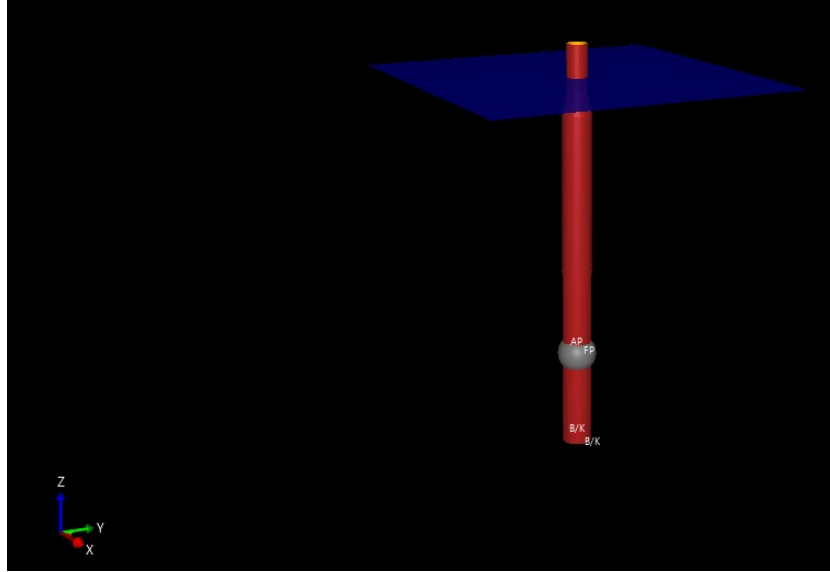


Figure 50: Three-dimensional panel model of the spar-buoy substructure developed in HydroD, showing the discretized wetted surface, reference axes and waterplane level used for the hydrodynamic frequency-domain analysis.

The equilibrium configuration was defined by imposing the correct waterline position and hydrostatic balance, allowing the computation of restoring forces and the natural periods of the system. The hydrodynamic analysis was performed in the frequency domain assuming a rigid-body behaviour with six degrees of freedom, although the present discussion focuses primarily on the heave, pitch and roll motion.

Once the environmental and physical parameters were established, the Wadam analysis was executed to compute the hydrodynamic coefficients governing the floating body response. The resulting data provide the basis for evaluating the dynamic behaviour of the spar platform and for subsequent motion analyses of the complete offshore wind system.

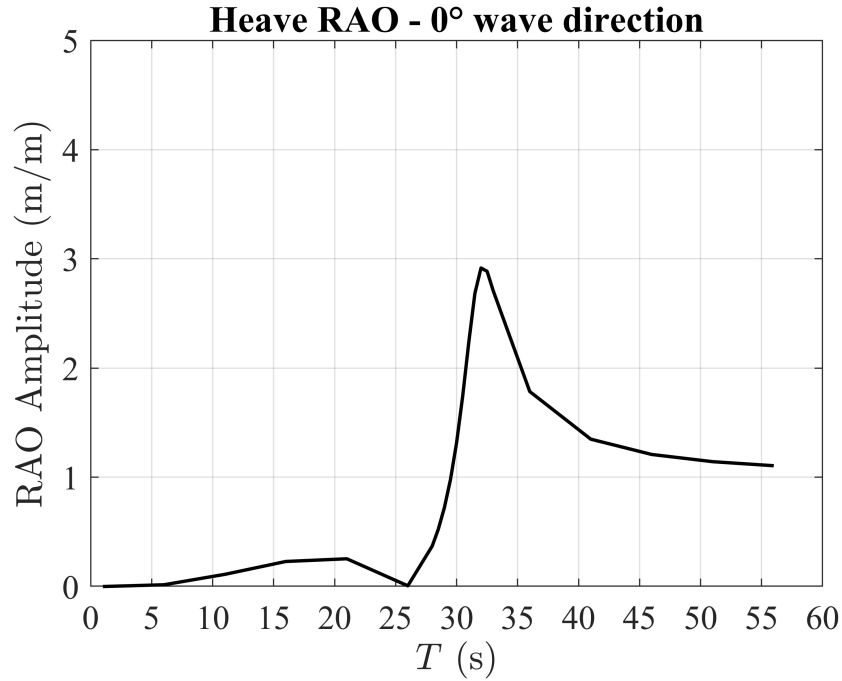


Figure 51: Heave RAO of the spar-buoy platform for 0° wave direction, showing the resonance peak at the natural heave period.

The previous figure illustrates the heave Response Amplitude Operator (RAO) of the spar-buoy platform for regular waves propagating in the 0° direction, expressed as the ratio between the heave motion amplitude and the incident wave amplitude (m/m) as a function of the wave period.

The curve shows a clear and dominant resonance peak at approximately 32–33 s, which corresponds to the natural heave period of the system. At this period, the RAO reaches a maximum value close to 2.9, indicating a significant amplification of the vertical motion, with the platform heave approaching nearly three times the incident wave amplitude. For shorter wave periods (below about 20 s), the RAO remains very small, confirming that the structure exhibits limited response when the excitation frequency is far from resonance due to its large inertia and deep-draft configuration. As the wave period increases beyond the resonance region, the RAO progressively decreases and gradually approaches a value close to unity, reflecting a quasi-static behaviour in which the platform tends to follow the wave surface elevation. The overall trend is consistent with the expected dynamic characteristics of a spar-type floating structure under linear wave excitation.

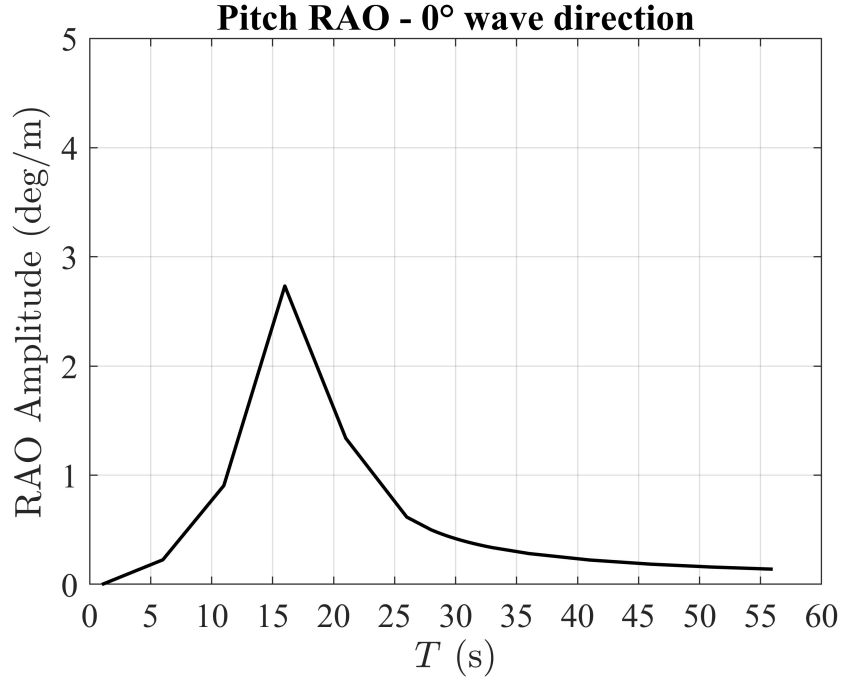


Figure 52: Pitch RAO of the spar-buoy platform for 0° wave direction, highlighting the resonance peak at the natural pitch period.

Figure 52 illustrates the pitch Response Amplitude Operator (RAO) of the spar-buoy platform for regular waves propagating in the 0° direction. The RAO is expressed as the ratio between the rotational pitch motion and the incident wave amplitude (deg/m) as a function of the wave period.

The curve exhibits a clear resonance peak at a wave period of approximately 15–16 s, which corresponds to the natural pitch period of the floating system. In this region, the platform reaches its maximum rotational response, with a peak RAO value close to 2.7 deg/m, indicating a significant amplification of the pitch motion when the excitation period approaches the natural frequency. This behaviour is consistent with spar-type floating structures, where the pitch dynamics are governed by the interplay between mass distribution, hydrostatic restoring moment and hydrodynamic loading. For shorter wave periods, the pitch RAO remains very small, showing that the platform experiences limited rotational motion under high-frequency wave excitation. As the wave period increases beyond the resonance region, the RAO progressively decreases, tending toward very low values for long periods. This reflects a quasi-static behaviour in which the structure follows the wave profile without significant rotational amplification. Overall, the trend confirms the expected dynamic response of the spar platform and demonstrates that the resonance peak is realistically bounded due to the damping contribution included in the numerical model.

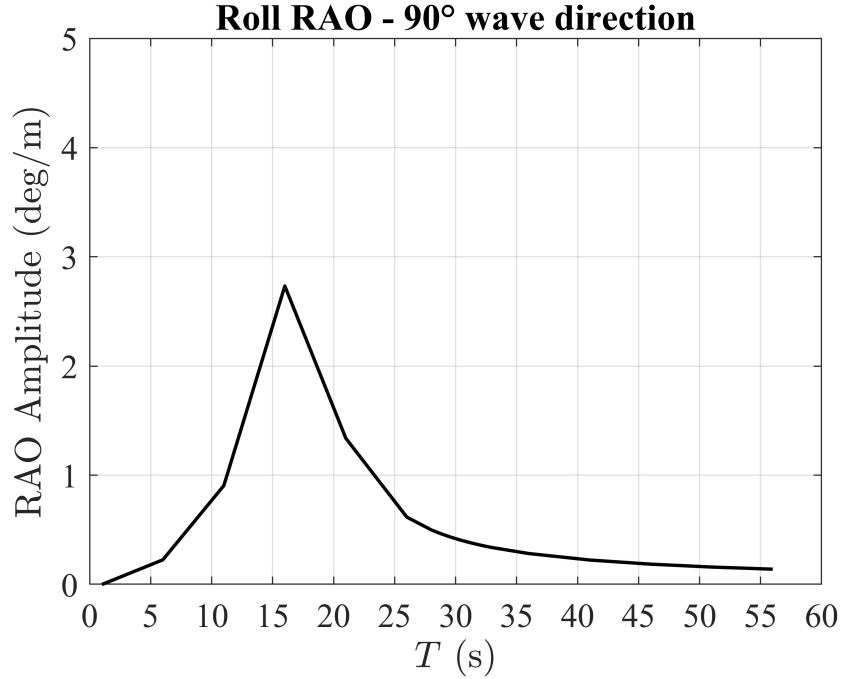


Figure 53: Roll RAO of the spar-buoy platform for 90° wave direction, showing the resonance peak at the natural roll period.

The prior figure illustrates the roll Response Amplitude Operator (RAO) of the spar-buoy platform for regular waves propagating in the 90° direction. The RAO is defined as the ratio between the roll rotational motion and the incident wave amplitude (deg/m) as a function of the wave period.

The curve exhibits a pronounced resonance peak at a wave period of approximately 15–16 s, which corresponds to the natural roll period of the floating structure. At this resonance condition, the roll motion reaches its maximum amplitude, with a peak RAO value close to 2.7 deg/m, indicating a significant rotational amplification when the wave excitation period approaches the natural frequency of the system. This behaviour is characteristic of spar-type floating platforms, where roll dynamics are governed by the balance between mass distribution, hydrostatic restoring moments and hydrodynamic forces.

For shorter wave periods, the roll response remains limited, as high-frequency waves are not able to effectively excite large rotational motions due to the inertia of the system. As the wave period increases beyond the resonance region, the RAO progressively decreases and tends toward low values, reflecting a quasi-static response in which the structure follows the wave profile without substantial rotational amplification. The smooth decay of the curve and the finite resonance peak confirm a realistic prediction of the roll dynamic behaviour,

with the resonance amplitude properly moderated by the additional damping included in the hydrodynamic model.

7.4 Hydrodynamic Analysis of a Spar-Buoy wind Turbine

Following the definition of the project site offshore near Palm Beach, the selection of the floating spar-buoy foundation and the identification of the most suitable turbine configuration for the proposed offshore wind farm, the next step of this work focuses on the hydrodynamic analysis of the floating system.

As discussed in the previous chapters, the selected offshore area is located 45 km far from the coast of Palm Beach with moderate wind and wave conditions. These characteristics make the adoption of a floating solution necessary and require a detailed assessment of the platform's dynamic response to wave excitation. Ensuring the stability and reliability of the floating structure under different sea states is essential to validate the feasibility of the proposed offshore wind farm.

To achieve this objective, numerical simulations have been carried out using SIMA, a time-domain simulation software developed by SINTEF Ocean and widely used in offshore engineering for the analysis of floating structures. SIMA enables the evaluation of the hydrodynamic behaviour of offshore systems subjected to environmental loads and is particularly suitable for modelling floating offshore wind turbines supported by spar-buoy platforms. In the present analysis, the geometric model of the spar-buoy previously defined and described in the earlier sections has been adopted. Concerning the wind turbine, its main characteristics have been derived from a reference model provided in the technical documentation of the simulation software. Similarly, the mooring system configuration has been defined based on setups reported in the literature and in the application examples included in the software.

It is important to clarify that the hydrodynamic model implemented in SIMA does not represent the exact commercial turbine selected during the preliminary design phase, namely the Siemens Gamesa SG 14-222 DD. Due to the lack of publicly available detailed geometric data and structural parameters for this turbine, it was not possible to reproduce its exact configuration within the numerical model.

For this reason, a validated reference model representative of a generic large-scale offshore wind turbine in the 14 MW class installed on a spar-buoy floating platform has been adopted. This approach allows the numerical simulations to capture the main hydrodynamic and dynamic characteristics of floating offshore wind turbines while ensuring consistency with validated configurations available in the scientific literature and in the software documentation.

However, this modelling simplification implies that some properties of the real turbine, such as the exact mass distribution, inertia characteristics and aerodynamic loading conditions, may differ from those of the reference model adopted in the simulations. As a consequence, the computed natural frequencies and motion responses of the floating system may slightly deviate from those that

would be obtained using the exact turbine configuration.

Nevertheless, the adopted model remains representative of the overall dynamic behaviour of a floating offshore wind turbine of comparable size and rating. Therefore, the results obtained in this study should be interpreted as representative of the hydrodynamic response of a floating offshore wind turbine in the 14 MW class rather than as a precise dynamic representation of the specific turbine selected in the preliminary design phase.

The numerical model developed in SIMA for the hydrodynamic analysis of the floating offshore wind turbine is shown in Figure 54.

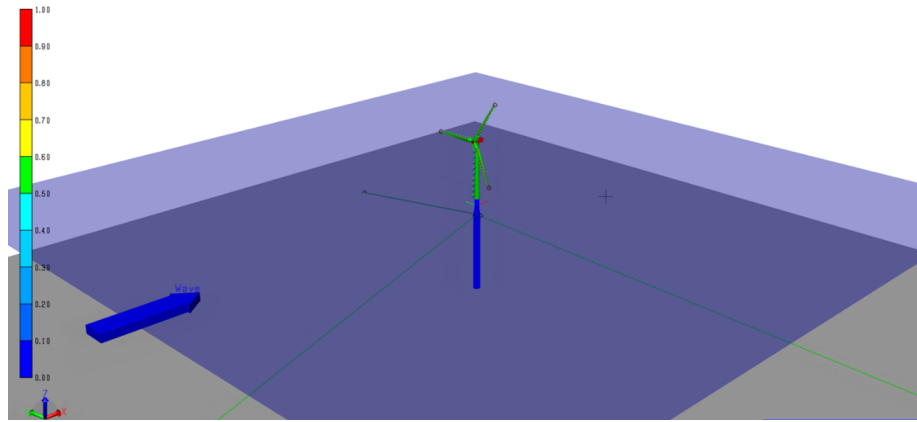


Figure 54: Overview of the floating offshore wind turbine model developed in SIMA for hydrodynamic analysis.

In this study, the software has been employed to perform a hydrodynamic analysis of the selected floating wind turbine configuration, considering only the wave action and neglecting aerodynamic loading from the wind, that is, under parked conditions. The objective is to evaluate the dynamic response of the system and verify its stability under real and extreme waves conditions representative of the chosen offshore site. Particular attention is given to the main motions of the platform, such as surge, heave and pitch, as these parameters directly influence turbine performance, structural integrity and mooring system loads.

The environmental conditions have been defined using the JONSWAP wave spectrum, which provides a realistic representation of irregular sea states and allows the distribution of wave energy to be described as a function of frequency. This approach ensures that the simulations accurately reflect the metocean conditions expected at the selected offshore location.

Two main categories of sea states have been analysed:

- Real wave conditions, representing realistic environmental scenarios ex-

pected during normal turbine operation;

- Extreme wave states, introduced to evaluate the system response under worst-case conditions and to verify the robustness and stability of the floating configuration.

All hydrodynamic analyses are performed with a simulation duration of 2000 s. This time window allows that a sufficiently large number of wave cycles are included in the analysis, thereby improving the statistical reliability of the obtained results. The hydrodynamic simulations performed in SIMA provide a detailed understanding of the dynamic behaviour of the floating offshore wind turbine and allow the identification of the most critical conditions in terms of platform motion and structural loads. These results form the basis for the evaluation of system performance and support the technical validation of the proposed floating offshore wind farm design.

7.4.1 Compensating Force

During the development of the numerical model in SIMA, a compensating vertical force was introduced to ensure a correct static equilibrium configuration of the floating spar-buoy prior to performing the hydrodynamic simulations. After defining the floating body and the associated mooring system, the structure initially exhibited a residual vertical imbalance caused by the interaction between gravity, buoyancy and mass distribution.

To identify the appropriate magnitude of the compensating force, a preliminary simulation was carried out under near-calm sea conditions. A wave input characterized by a significant wave height equal to 1×10^{-5} m and a peak period of 100 s was applied, as shown in Figure 55. These parameters were selected to represent an almost still-water condition, allowing the vertical behaviour of the platform to be observed without significant hydrodynamic excitation. This approach made it possible to isolate the residual vertical imbalance of the system and accurately determine the force required to achieve equilibrium.

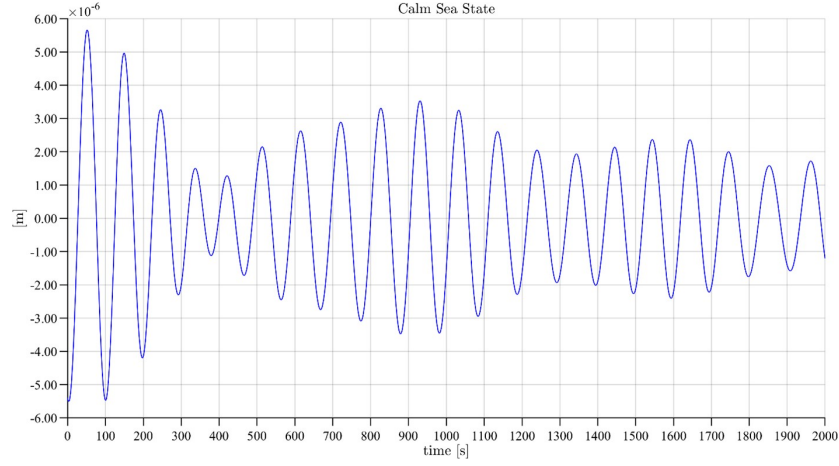


Figure 55: Time history of total wave elevation under near-calm sea conditions ($H_s = 1 \times 10^{-5}$ m, $T_p = 100$ s) used for the calibration of the compensating force.

To correct this imbalance, a constant vertical force was applied using the “Specified Force” component in SIMA. The force was defined along the global Z-axis and applied at the reference point of the floating body. The calibrated magnitude of the compensating force was set equal to 1.16×10^6 N, corresponding to the residual vertical load required to balance the net difference between structural weight and buoyancy. This value ensures that the platform reaches its intended hydrostatic equilibrium position before the beginning of the dynamic analysis. The effectiveness of this modelling step can be observed in the Z-translation time history shown in Figure 56.

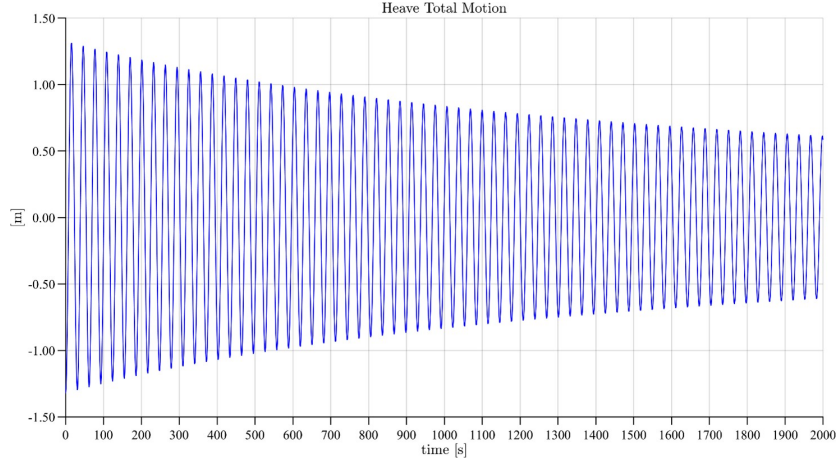


Figure 56: Time history of the vertical motion of the floating system during the initial equilibrium phase under calm sea conditions following the application of the compensating force (1.16×10^6 N).

The plot represents the vertical motion (heave) of the floating platform during the initial phase of the simulation. It is possible to observe a transient response in the first part of the simulation, followed by a gradual stabilization of the oscillations around the equilibrium position. The decreasing amplitude indicates that the system converges towards a dynamically stable configuration, confirming that the compensating force successfully balances the vertical loads without introducing artificial drift or instability.

This validation step is fundamental to guarantee numerical reliability, as it ensures that subsequent hydrodynamic analyses under JONSWAP wave excitation are performed starting from a physically consistent and balanced configuration of the floating offshore wind system.

7.4.2 Real sea state

After verifying the correct hydrostatic equilibrium of the floating spar-buoy system, the hydrodynamic response of the platform was analysed under real sea conditions representative of the selected offshore site. To evaluate the realistic sea conditions at the selected site, the wave reanalysis dataset was downloaded from the Copernicus Marine Service covering the period from 1 January 2004 to 31 December 2024. The dataset was subsequently analysed in order to derive the one-year return sea state representative of the location. In probabilistic terms, it represents the environmental condition associated with an annual exceedance probability of 1. This parameter is commonly used in offshore engineering to describe typical operational or moderate extreme conditions for the design and analysis of offshore structures.

From the statistical analysis of the retrieved dataset, the following values were obtained for the selected location:

- Significant wave height: $H_s = 3.2$ m;
- Peak wave period: $T_p = 10.6$ s.

These parameters were then used to define the representative annual sea state considered in the subsequent hydrodynamic analyses.

The irregular nature of the imposed sea state is illustrated in Figure 57, which shows the time history of the total wave elevation generated using the JONSWAP spectrum. The non-periodic behaviour and variable amplitude confirm the stochastic characteristics of the applied wave loading.

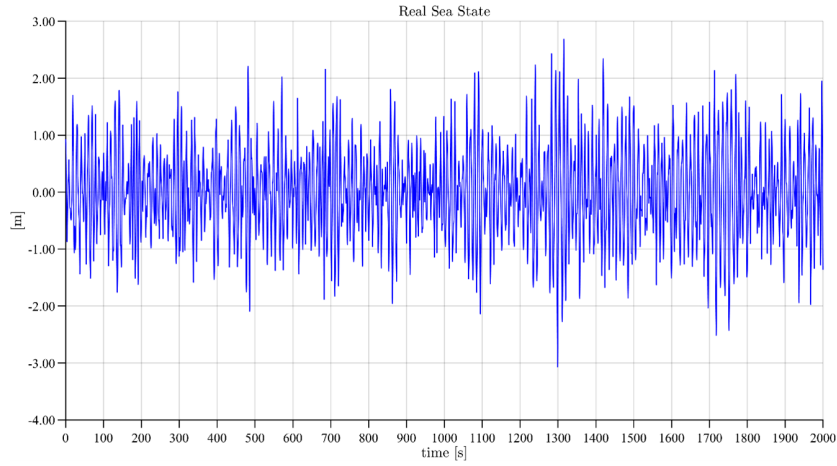


Figure 57: Total wave elevation time history generated using the JONSWAP spectrum ($H_s = 3.2$ m, $T_p = 10.6$ s), showing the irregular nature of the imposed real sea state.

The next figure shows the heave response of the floating structure under real sea state conditions. The motion exhibits an oscillatory behaviour around the equilibrium position, which confirms that the hydrostatic restoring forces and buoyancy provide a stable vertical response of the system.

At the beginning of the simulation, a short transient phase can be observed, associated with the adjustment of the structure to the wave excitation and the initial conditions of the numerical model. After this initial period, the response evolves into a stationary oscillatory regime, where the motion amplitude fluctuates due to the irregular nature of the incoming waves.

The heave displacement remains generally within a limited range, with most oscillations occurring approximately between ± 1.5 m, while only occasional peaks

approach larger values. This behaviour is typical of floating offshore structures subjected to irregular wave conditions, where the response is governed by the combined effects of wave excitation forces, hydrostatic restoring forces, hydrodynamic damping and the inertia of the system.

Overall, the results indicate that the vertical motion of the structure remains bounded and dynamically stable, suggesting that the platform is able to respond to the imposed sea state without exhibiting excessive heave motions.

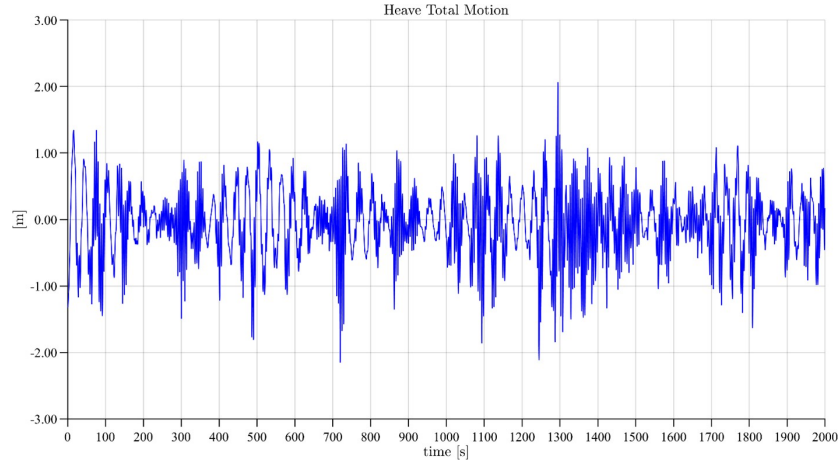


Figure 58: Time history of the vertical motion (heave motion) of the floating structure under irregular wave conditions representative of the considered real sea state.

Figure 59 shows the surge total motion of the floating structure under real sea state conditions. The response exhibits a clear oscillatory behaviour around the equilibrium position, reflecting the horizontal excitation induced by irregular waves propagating in the considered direction.

At the beginning of the simulation, a short transient phase can be observed as the system adjusts from the initial conditions to the imposed wave forcing. After this initial adjustment, the motion evolves into a stationary oscillatory regime, where the surge displacement varies continuously due to the stochastic nature of the irregular wave field.

Compared with the vertical motion, the surge response shows larger amplitude variations, which is typical for floating offshore platforms. Horizontal motions are generally less constrained by hydrostatic restoring forces and are mainly governed by the combined effects of wave drift forces, hydrodynamic damping, platform inertia and the restoring contribution of the mooring system.

The oscillations remain bounded within a limited range, indicating that the

mooring system provides an effective restoring force in the horizontal direction, preventing excessive excursions of the structure. Overall, the results confirm that the platform maintains stable horizontal dynamics under the considered real sea state conditions.

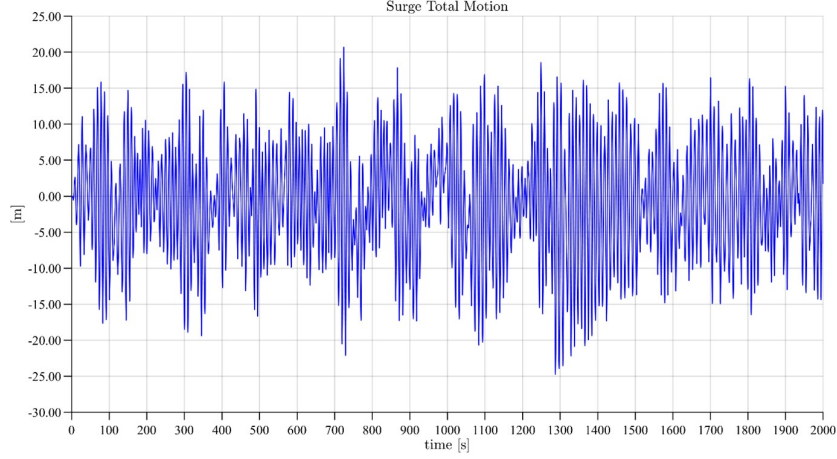


Figure 59: Time history of the horizontal motion (surge motion) of the floating structure under irregular wave conditions representative of the considered real sea state.

The figure below shows the pitch motion of the floating structure under real sea state conditions. The response exhibits an oscillatory behaviour around the equilibrium position, driven by the irregular wave excitation acting on the structure.

At the beginning of the simulation, a short transient phase is observed as the system adjusts from the initial conditions to the applied hydrodynamic loads. After this initial period, the response reaches a stationary oscillatory regime, where the pitch angle varies continuously due to the stochastic nature of the irregular wave field.

Compared with the other degrees of freedom, the pitch motion represents one of the most significant rotational responses of the platform. This behaviour is typical for floating offshore structures subjected to head-sea wave conditions, where surge and pitch are generally the most excited degrees of freedom. The oscillations remain bounded within a limited angular range, indicating that the platform maintains stable dynamic behaviour under the considered environmental conditions.

Overall, the observed pitch response is governed by the combined effects of wave excitation forces, hydrostatic restoring moments, hydrodynamic damping and the inertia of the floating system.

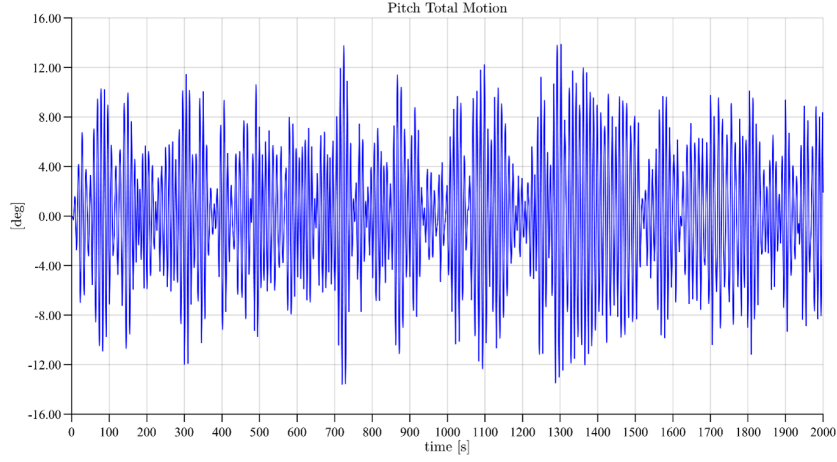


Figure 60: Time history of the Y-rotation (pitch motion) of the floating structure under irregular wave conditions representative of the considered real sea state.

7.4.3 Extreme sea state

To conclude the hydrodynamic analysis, the behaviour of the floating structure must also be evaluated under extreme wave conditions. In order to define such conditions, it is necessary to determine the values of significant wave height (H_s) and peak wave period (T_p) representative of severe sea states at the selected offshore location.

For this purpose, wave reanalysis data obtained from the Copernicus Marine Service were analysed and the 50-year return sea state was estimated. The 50-year return sea state represents the environmental condition that is statistically expected to be exceeded on average once every 50 years at the considered site. Such conditions are commonly adopted in offshore engineering to assess the response of floating structures under extreme environmental loading.

Based on this analysis, the extreme sea state adopted in the simulations is characterized by a significant wave height $H_s = 7$ m and a peak wave period $T_p = 13$ s, which are used to evaluate the platform response under severe wave conditions.

The irregular characteristics of the imposed sea state are illustrated in Figure 61, which presents the time history of the total wave elevation generated using the JONSWAP spectrum. The non-periodic behaviour and the variability in wave amplitude clearly highlight the stochastic nature of the applied wave excitation.

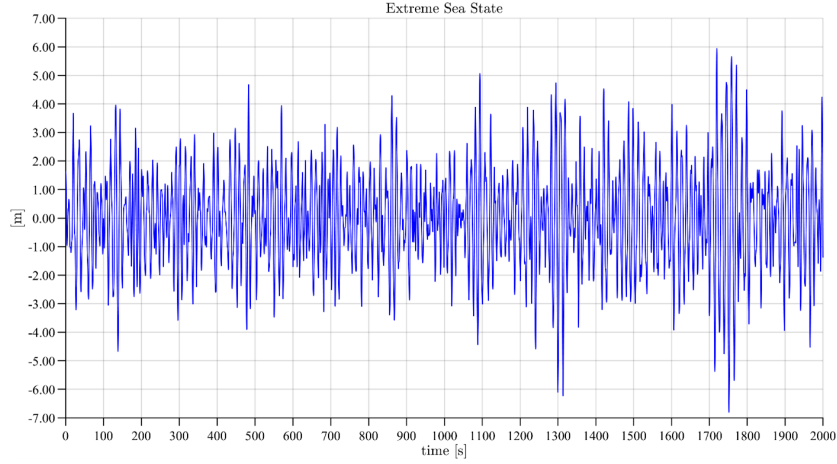


Figure 61: Total wave elevation time history generated using the JONSWAP spectrum ($H_s = 7$ m, $T_p = 13$ s), showing the irregular nature of the imposed extreme sea state.

The next figure shows the heave motion of the floating structure under extreme sea state conditions. The response exhibits a non-periodic oscillatory behaviour, reflecting the stochastic nature of the imposed wave field. Compared with the operational sea state, the heave motion shows larger amplitude fluctuations, which is expected due to the increased wave energy associated with the extreme environmental conditions. Nevertheless, the vertical displacement remains bounded around the equilibrium position, indicating that the platform maintains a stable dynamic response even under severe wave loading.

This behaviour is consistent with the typical characteristics of spar-type floating structures, where the large draft and the strong hydrostatic restoring forces limit excessive vertical motions. The heave response is therefore mainly governed by the balance between wave excitation forces, hydrostatic restoring effects and hydrodynamic damping acting on the system.

It can also be observed from the time history that the heave amplitude remains significantly lower than the corresponding wave height, even under extreme conditions. This indicates that the platform does not follow the wave profile directly but instead exhibits a filtered dynamic response, which is typical for spar configurations due to their large inertia and long natural periods. Such behaviour is desirable, as it contributes to reducing excessive vertical motions and improving the overall stability of the floating system.

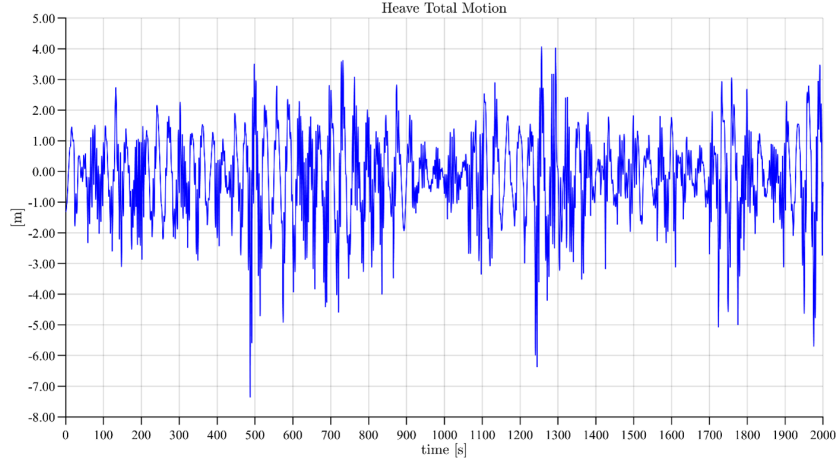


Figure 62: Time history of the vertical motion (heave motion) of the floating structure under irregular wave conditions representative of the considered extreme sea state.

The Figure 63 shows the surge motion (horizontal translation along the longitudinal axis) of the floating structure under extreme sea state conditions. The surge response exhibits a non-periodic oscillatory behaviour, reflecting the stochastic nature of the imposed wave field. Compared with the operational sea state conditions, the surge motion shows significantly larger amplitude excursions, which is expected due to the increased wave energy associated with the extreme environmental loading. The motion oscillates around the equilibrium position with peak displacements reaching several tens of meters, highlighting the dominant influence of low-frequency wave excitation and mooring system dynamics on the horizontal response of the platform.

This behaviour is typical of spar-type floating structures, where the surge motion is mainly controlled by the restoring forces provided by the mooring system and by hydrodynamic damping. Unlike heave, which is strongly limited by hydrostatic restoring forces, surge tends to exhibit larger excursions due to the relatively lower horizontal stiffness of the mooring system. The observed response therefore reflects the dynamic balance between wave excitation forces, mooring restoring forces, inertia effects and hydrodynamic damping acting on the floating platform.

Despite the large excursions observed in the time history, the motion remains bounded and dynamically stable, indicating that the mooring system is capable of maintaining the platform around its equilibrium position even under severe environmental conditions.

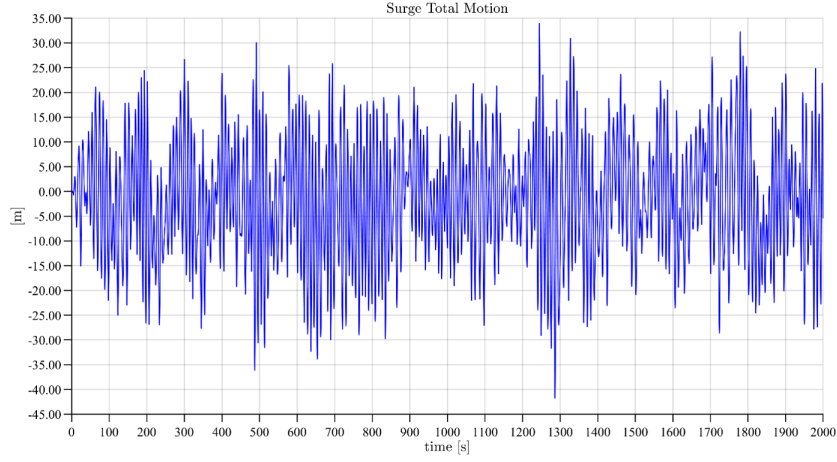


Figure 63: Time history of the horizontal motion (surge motion) of the floating structure under irregular wave conditions representative of the considered extreme sea state.

The following figure shows the pitch motion of the floating structure under extreme sea state conditions. The rotational response exhibits a strongly non-periodic oscillatory behaviour, reflecting the stochastic nature of the imposed wave field. The pitch motion oscillates around the equilibrium position and shows significant amplitude variations over time, which are associated with the superposition of multiple wave components with different frequencies contained in the irregular wave spectrum.

From the time history it can be observed that the maximum pitch excursions reach values of approximately $\pm 20^\circ$, indicating that the structure experiences relatively large rotational motions due to the increased wave-induced moments acting on the platform under severe environmental loading. The presence of groups of larger oscillations can also be observed in the signal, which are typical of irregular sea states and arise from the constructive interference of wave components within the JONSWAP spectrum.

Compared with the operational sea state conditions, the platform response in this extreme scenario is significantly more energetic, with larger pitch amplitudes and more pronounced oscillation groups. This behaviour is consistent with the higher wave energy associated with the extreme environmental conditions, which leads to stronger excitation moments acting on the floating structure.

Nevertheless, the pitch motion remains bounded around the equilibrium position throughout the simulation, indicating that the restoring mechanisms of the system are effective even under severe wave loading. In spar-type floating structures, the pitch dynamics are mainly governed by the balance between wave excitation moments, hydrostatic restoring, hydrodynamic damping and the sta-

bilizing contribution of the mooring system.

Overall, the results indicate that although the extreme sea state produces significantly larger rotational motions compared with the operational conditions, the platform maintains a stable dynamic behaviour, confirming the capability of the system to withstand severe environmental loading without exhibiting unstable responses.

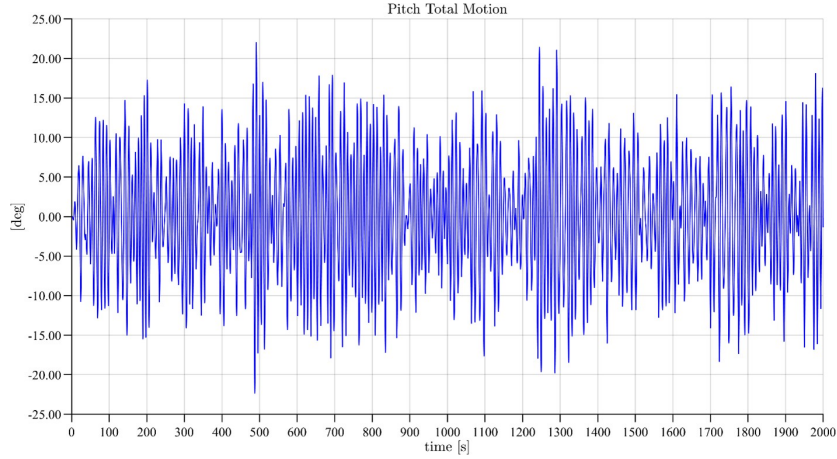


Figure 64: Time history of the horizontal motion (pitch motion) of the floating structure under irregular wave conditions representative of the considered extreme sea state.

7.4.4 Discussion of Hydrodynamic Results

The simulations carried out in this section allow an evaluation of the dynamic response of the floating spar-buoy wind turbine under different wave conditions. The analysis first considered near-calm sea conditions in order to correctly calibrate the compensating force and verify that the system was able to reach a stable equilibrium configuration. This preliminary step is important because it ensures that the subsequent simulations start from a physically consistent condition.

After the equilibrium phase, the behaviour of the platform was analysed under a representative real sea state characterized by a significant wave height of approximately 3.2 m and a peak period of about 10.6 s. As expected for an irregular wave field generated through a JONSWAP spectrum, the platform motions show a non-periodic behaviour. The heave, surge and pitch responses fluctuate over time due to the superposition of wave components with different frequencies. However, the amplitude of the motions remains relatively limited, indicating that the platform is able to maintain a stable dynamic response under typical operating conditions.

The response of the system was also investigated under a more severe sea state, characterized by a significant wave height of 7 m and a peak period of 13 s. In this case the platform experiences larger oscillations, as a consequence of the higher wave energy acting on the structure. The time histories clearly show an increase in the amplitude of the motions, particularly in surge and pitch. Nevertheless, the overall behaviour of the system remains stable and no excessive or unstable motions are observed.

These results highlight the advantages of the spar-type configuration for floating offshore wind applications. Thanks to its large draft and to the low position of the centre of gravity, this type of platform is able to limit rotational motions and provide good hydrodynamic stability. Overall, the simulations suggest that the considered configuration is suitable for operating in the environmental conditions typical of the selected offshore area, both during normal operating conditions and during more severe sea states.

Beyond the purely hydrodynamic interpretation of the results, the platform response observed in the simulations also has relevant implications for the long-term techno-economic performance of the floating wind system. In particular, the amplitude of the platform motions under irregular wave excitation may influence the cyclic loading experienced by several structural and station-keeping components.

Even though the present analysis considers the turbine in parked condition and neglects aerodynamic loading, wave-induced motions such as heave and pitch can still generate fluctuating forces within the system. Heave oscillations lead to variations in the tension of the mooring lines and in the dynamic export cables, while pitch motions can introduce additional bending moments at the tower base and at the interface between the tower and the floating substructure. Over time, these cyclic loads may contribute to the progressive accumulation of fatigue damage in critical components of the structure.

From a lifecycle perspective, fatigue accumulation represents a key factor affecting the reliability and maintenance requirements of floating offshore wind turbines. Components such as mooring lines, tower-substructure connections and dynamic electrical cables are particularly sensitive to repeated loading cycles associated with platform motions. Increased fatigue loading may therefore require more frequent inspection campaigns, preventive maintenance operations or potential component replacement during the operational lifetime of the system.

These aspects have direct implications for the economic performance of floating offshore wind farms. Increased maintenance requirements and inspection activities contribute directly to higher operational expenditure (OPEX) throughout the project lifetime. In addition, maintenance operations or unexpected structural issues may require temporary turbine shutdowns during inspection or re-

pair campaigns. Such shutdown periods reduce the operational availability of the turbine and consequently decrease the annual energy production (AEP) of the wind farm.

Since the Levelized Cost of Energy (LCOE) depends both on the total lifecycle costs and on the amount of electricity generated over the lifetime of the project, the combined effect of increased OPEX and reduced AEP can lead to a higher effective LCOE. For this reason, the relatively moderate motion amplitudes observed in the present simulations represent a favourable characteristic of the analysed spar-type configuration. By limiting excessive pitch and heave oscillations, the platform can reduce fatigue loading on key structural components, contributing to improved system reliability, lower maintenance requirements and potentially improved long-term economic performance.

8 Conclusion

This thesis investigates the feasibility of developing a floating offshore wind farm along the Queensland coast in Australia through an integrated analysis including site selection, wind resource assessment, techno-economic evaluation and hydrodynamic modelling of a floating wind turbine platform. The main objective was to verify whether the selected location and the technological choices adopted throughout the study could represent a realistic solution for offshore renewable energy production.

The site selection process, based on the analysis of wind resource data and bathymetry, as well as on the evaluation of environmental and regulatory constraints imposed by the Australian government, made it possible to identify a suitable offshore area located approximately 45 km from the coast of Palm Beach, with a total extent of about 215 km². Within the selected area, data obtained from the Global Wind Atlas indicate an average wind speed of approximately 7.64 m/s at 100 m hub height and a water depth of around 320 m.

Considering the environmental conditions of the site and the objective of maximizing energy production, a spar-buoy floating platform was selected as the most suitable foundation concept for the wind turbine. The Siemens Gamesa SG 14-222 DD turbine, with a rated power of 14 MW, was adopted as the reference turbine for the wind farm design. Taking into account the turbine dimensions and the spacing requirements necessary to minimize wake losses, the available area allows the installation of approximately 104 turbines. According to wind resource data obtained from the Global Wind Atlas, the selected site is characterized by a capacity factor of approximately 0.39. Under these conditions, the expected annual energy production of each turbine is approximately 43 GWh, resulting in a total estimated wind farm production of about 4.4–4.5 TWh per year.

This level of electricity generation could potentially supply approximately 50% of the annual electricity demand of the city of Brisbane, highlighting the significant role that floating offshore wind energy could play in supporting the regional energy transition and increasing the share of renewable energy within the local electricity mix.

Following the technical design of the wind farm, a techno-economic assessment based on the Levelized Cost of Energy (LCOE) was conducted in order to evaluate the economic feasibility of the proposed project. The analysis considered the full cost structure of the offshore wind farm throughout its lifetime, including CAPEX, OPEX and the expected annual energy production derived from the estimated capacity factor. Particular attention was given to the influence of key site-specific parameters, such as distance from shore and water depth, on the overall project economics.

The results highlight that the largest share of total CAPEX is associated with

the wind turbine and the floating substructure, which represent predominantly fixed costs within the project. Conversely, variable costs are mainly influenced by the distance from shore, which significantly affects both installation and electrical transmission costs. The analysis also shows that water depth has a relatively limited impact on the overall project cost, since it primarily affects mooring line length and therefore only a small portion of the total investment. This confirms one of the main advantages of floating offshore wind technologies, namely the possibility of operating in deep-water environments without a significant increase in costs.

Regarding the economic results, the analysis indicates that annual energy production (AEP) plays a dominant role in determining the final LCOE value, as it is strongly influenced by the wind resource available at the site. Consequently, locations characterized by stronger and more consistent wind conditions can significantly improve the economic performance of floating offshore wind projects.

Taking into account the analysed configurations, the results show that the 45 km offshore configuration represents the most favourable solution, providing the best compromise between installation costs, transmission infrastructure and annual energy production. In this configuration, the Levelized Cost of Energy (LCOE) is estimated at approximately 140.05 €/MWh, confirming the economic viability of the proposed wind farm within the current technological and market conditions. Although this value remains higher than those typically associated with onshore wind and bottom fixed technologies, it is consistent with the current cost range reported for floating offshore wind projects, reflecting the early stage of technological development.

In addition to the economic evaluation, the thesis included a hydrodynamic analysis of a spar-type floating platform, which was selected as the most suitable configuration for deep-water offshore wind applications. The analysis first investigated the dynamic behaviour of the platform in the frequency domain through the evaluation of the Response Amplitude Operators (RAOs), allowing the identification of the main motion characteristics of the floating structure.

Subsequently, time-domain simulations were performed using irregular wave conditions generated through a JONSWAP spectrum, representing both operational and extreme sea states. Under realistic operating conditions ($H_s = 3.2$ m and $T_p = 10.6$ s), the platform exhibits moderate oscillatory motions in surge, heave and pitch, demonstrating stable behaviour under typical environmental conditions. When subjected to more severe conditions ($H_s = 7$ m and $T_p = 13$ s), the amplitude of the motions increases due to the higher wave energy; however, the system remains dynamically stable and no critical responses are observed.

These results confirm the good hydrodynamic performance of the spar-type configuration, which benefits from a large draft and a low centre of gravity that help reduce rotational motions and improve platform stability. The hydrodynamic

analysis therefore validates the technological choices made in the earlier stages of the project, demonstrating that the selected floating foundation is suitable for the environmental conditions expected at the chosen offshore site.

Overall, the results of this study highlight several key insights regarding the feasibility of floating offshore wind deployment along the Queensland coastline. In particular, the analysis demonstrates that:

- The offshore area located approximately 45 km from the Palm Beach coast presents favourable wind resource availability and bathymetric conditions, making it a suitable candidate for floating offshore wind development.
- Annual energy production represents the dominant factor influencing the Levelised Cost of Energy, highlighting the critical importance of accurate wind resource assessment in floating offshore wind projects.
- Among the analysed configurations, the site located 45 km offshore provides the most favourable balance between installation costs, transmission infrastructure requirements and overall energy yield.
- The hydrodynamic simulations confirm that the selected spar-buoy platform exhibits stable dynamic behaviour under both operational and severe sea states, supporting the suitability of this floating foundation concept for deep-water offshore wind applications.

Despite the encouraging results obtained in this study, several limitations should be acknowledged. The techno-economic assessment was based on simplified assumptions for operational expenditures, which were estimated as a fixed percentage of CAPEX rather than derived from a detailed modelling of maintenance strategies, logistics operations and long-term operational activities. Furthermore, due to the limited availability of publicly accessible structural and design data for the selected commercial wind turbine model, the hydrodynamic simulations were conducted using a representative turbine configuration derived from reference models available within the simulation software. In addition, the hydrodynamic analysis focused primarily on wave-induced responses of the floating platform and did not include a fully coupled aero-hydro-servo-elastic representation of the wind turbine system. Although these simplifications are appropriate for a preliminary feasibility assessment, they introduce a certain degree of uncertainty in the overall evaluation of the system's dynamic behaviour and economic performance.

Future research could build upon the findings of this study by extending the analysis in several directions. In particular, the implementation of fully coupled aero-hydro-servo-elastic simulations would enable a more comprehensive representation of the complex interactions between aerodynamic loads, platform dynamics and turbine control systems. Further investigations could also address the optimisation of wind farm layout and electrical infrastructure, with the objective of minimising the Levelized Cost of Energy while accounting for wake

interactions and grid connection constraints. In addition, more detailed techno-economic analyses incorporating site-specific operational costs, uncertainty assessments and sensitivity to key financial parameters could further strengthen the robustness and reliability of the economic evaluation.

In conclusion, the combined outcomes of the techno-economic and hydrodynamic analyses confirm the feasibility of the proposed floating offshore wind project. The results demonstrate that the assumptions adopted during the feasibility assessment are consistent with the performance indicators obtained from the subsequent analyses. In addition, the study highlights the potential of floating offshore wind technologies to support the diversification of energy production and contribute to the reduction of reliance on fossil fuels. In this context, the proposed project may represent a relevant opportunity for the Government of Queensland to further explore the development of floating offshore wind as part of its future renewable energy strategy. Nevertheless, further investigations and potential design optimisations could enhance the overall performance and economic viability of the proposed system.

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