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Assessing the energy potential of Portugal's offshore wind resource

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Master in Mechanical Engineering
Fluids and Energy

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Abstract

The increasing urgency to combat climate change, to secure power supply and to obtain affordable prices, has driven global efforts to transition towards renewable energy sources. Among these, offshore wind energy is emerging as a promising technology due to its capacity to yield strong and consistent wind resources at sea. Although fixed bottom offshore wind farms have seen widespread deployment, their geographical and depth limitations have stimulated the development of floating offshore wind technology, which can access deeper waters with great wind potential. Portugal, with its extensive coastline and favorable wind conditions, is determined to capitalize on this technology and integrate it into its energy transition strategy.

This dissertation provides an in-depth study on the potential of floating offshore wind energy deployment in Portugal. It begins with a thorough literature review of the technological basics, including characteristics of atmospheric flow, evolution of both fixed and floating wind turbine systems, and recent innovations in the sector. Other related issues, like the reduction of greenhouse gas emissions and contributions to sustainable development, are also reviewed alongside the technical challenges of integrating offshore wind into electrical grids.

A detailed analysis of the regulatory and political frameworks governing offshore wind energy is performed, including lessons from leading countries such as the United Kingdom, Germany, and Denmark. Future scenarios for Portugal's adoption and expansion potential of this technology, are also explored. The study then narrows its focus to high-potential areas identified by the Portuguese State, such as Viana do Castelo and Sines, and employs a conventional and widely accepted methodology to assess their suitability for floating offshore wind projects.

The findings highlight the technical and economic feasibility of deploying floating offshore wind farms in these areas, supported by simulations and scenarios that evaluate various turbine technologies and configurations. An economic analysis reveals the potential for cost reduction through economies of scale and technological maturation, while socio-economic and ecological assessments underscore the benefits of job creation and reduced emissions.

The results of this research demonstrate that the floating offshore wind energy map plays a role as a promising and viable avenue for Portugal's renewable energy transition. However, the successful deployment of this technology will require continuous investment, regulatory adaptation, and further research to address emerging challenges and unlock its full potential.

Keywords: Floating Wind Farms, Portugal, Offshore Renewable Resources

Resumo

A urgência crescente em combater as alterações climáticas, assegurar segurança de abastecimento e preços competitivos para a eletricidade, tem impulsionado esforços globais de transição para fontes de energia renováveis. Entre estas, a energia eólica "offshore" está a emergir como uma tecnologia promissora devido à sua capacidade de aproveitar recursos eólicos fortes e consistentes no mar. Embora os parques eólicos "offshore" fixos no fundo do mar tenham sido amplamente implantados, as suas limitações geográficas e de profundidade estimularam o desenvolvimento da tecnologia eólica "offshore" flutuante, que pode aceder a águas mais profundas com um potencial eólico abundante. Portugal, com a sua extensa linha costeira e condições de vento favoráveis, está determinado em utilizar esta tecnologia e integrá-la na sua estratégia de transição energética.

Esta dissertação apresenta um estudo abrangente do potencial da energia eólica "offshore" flutuante em Portugal. Inicia-se com uma revisão aprofundada dos fundamentos tecnológicos, explorando as características do fluxo atmosférico, a evolução dos sistemas de turbinas eólicas fixas e flutuantes, e as inovações recentes no setor. Os benefícios ambientais e sociais, como a redução das emissões de gases com efeito de estufa e as contribuições para o desenvolvimento sustentável, são, também analisados, juntamente com os desafios técnicos da integração da energia eólica "offshore" nas redes elétricas.

É efectuada uma análise detalhada dos quadros regulamentares e políticos que regem a energia eólica "offshore", incluindo lições de países líderes no setor como o Reino Unido, a Alemanha e a Dinamarca. São também explorados cenários futuros acerca do potencial de expansão desta tecnologia em Portugal. A dissertação foca-se depois a áreas de elevado potencial identificadas pelo Estado Português, como Viana do Castelo e Sines, e utiliza uma metodologia convencional e utilizada no setor para avaliar a viabilidade de projectos eólicos offshore flutuantes.

Os resultados destacam a viabilidade técnica e económica da implantação de parques eólicos offshore flutuantes nessas áreas, apoiados por simulações e cenários que avaliam diversas tecnologias e configurações de turbinas. Uma análise económica revela o potencial de redução de custos através de economias de escala e da maturação tecnológica, enquanto as avaliações socioeconómicas e ecológicas sublinham os benefícios da criação de empregos e da redução das emissões de gases poluentes.

Os resultados desta investigação demonstram que a energia eólica offshore flutuante é uma via promissora e viável para a transição energética de Portugal. No entanto, a implementação bem-sucedida desta tecnologia exigirá investimento contínuo, adaptação regulatória e mais investigações para enfrentar os desafios emergentes e desbloquear todo o seu potencial.

Palavras Chave: Parques Eólicos Flutuantes, Portugal, Recursos Renováveis "Offshore"

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Alexandre Fernandes Gonçalves

“*A smooth sea never made a skillful sailor.*”

Franklin D. Roosevelt

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Acronyms list

A-CAES advanced compressed air energy storage

AC alternating current

AbEx Abandonment Expenditures

AEP Annual Energy Production

BESS Battery Energy Storage Systems

CAES Compressed Air Energy Storage

CapEx Capital Expenditures

CET Clean Energy Transition

CfD Contracts for Difference

DC direct current

DevEx Development Expenditures

EIA Environmental Impact Assessment

EIAs Environmental Impact Assessments

EIC EU Innovation Council

ECMWF European Center for Medium-Range Weather Forecasts

EDLC electric double-layer capacitance

EIB European Investment Bank

EMFAF European Maritime Fisheries and Aquaculture Fund

EMFs electromagnetic fields

ESS Energy Storage Systems

EU European Union

FBES Flow battery energy storage

FEED Front-End Engineering and Design

FEUP Faculdade de Engenharia da Universidade do Porto

FES Flywheel energy storage

FCs Fuel Cells

FiT Feed-in Tariff

FWT Floating Wind Turbines

GBFs Gravity Base Foundations

GHG greenhouse gas

GWA Global Wind Atlas

GPS Global Positioning System

HVAC High voltage alternating current

HVDC high voltage direct current

HES Hydrogen Energy Storage

IF Innovation Fund

INEGI Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial

IRR Internal Rate of Return

LCoE Levelized Cost of Electricity

LIDAR light detection and ranging

LNEG Laboratório Nacional de Energia e Geologia

MSP Marine Spatial Planning

MPAs Marine Protected Areas

MVAC medium voltage alternating current

NREL National Renewable Energy Laboratory

NPV Net Present Value

OFTOs Offshore Transmission Owners

OpEx Operational Expenditures

OWF offshore wind farm

OWFs Offshore Wind Farms

PCAD Population Consequences of Acoustic Disturbance

PCMs phase change materials

PNEC2030 Plano Nacional de Energia e Clima 2030

PPA Power Purchase Agreement

PPAs Power Purchase Agreements

PHS Pumped Hydro Storage

QGIS Quantum Geographic Information System

RNA rotor-nacelle assembly

RNC2050 Roteiro para a Neutralidade Carbónica 2050

ROC Renewables Obligation Certificate

ROI Return on Investment

SCES Supercapacitor energy storage

SMES Superconducting magnetic energy storage

SODAR sonic detection and ranging

TES Thermal Energy Storage

TLPs Tension-Leg Platforms

TSO Transmission System Operator

TSOs Transmission System Operators

TNUoS Transmission Network Use of System

UTM Universal Transverse Mercator

VBA Visual Basic for Applications

WAsP Wind Atlas Analysis and Application Program

WFC wind farm capacity

WFA WindFloat Atlantic

GWA Global Wind Atlas

Nomenclature

Item	Description	Units
P_{wind}	Power available in the wind	W
ρ_{air}	Air density	kg/m^3
A	Swept area of the turbine blades	m^2
r	Swept area radius	m
v	Free stream wind speed	m/s
c_p	Power coefficient of the wind turbine	-
η_{max}	Maximum theoretical efficiency of a wind turbine	-
Capacity Factor	Ratio of annual energy output to full capacity	-

Chapter 1

Introduction

1.1 Context

This project, developed by Alexandre Fernandes Gonçalves during the first semester of the 2024/2025 academic year, serves as the final dissertation for the Master's in Mechanical Engineering. The main supervisor from Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial (INEGI), where the dissertation was conducted, was José Carlos Matos, with Bruno Miguel Reis Silva acting as co-supervisor. Paulo José Coelho acted as the co-supervisor at Faculdade de Engenharia da Universidade do Porto (FEUP).

The dissertation was conducted within the Wind Energy Unit of INEGI, a private non-profit association recognized as a public utility. INEGI focuses on scientific research, technological development, technology transfer, advanced consulting, training, and the pre-incubation of technology-based startups. In particular, INEGI's Wind Energy Unit plays a key role in evaluating the potential of national renewable energy sources, particularly wind energy, and in designing wind farms. INEGI's expertise has led to multiple contracts with energy sector companies, equipment production, energy generation, transmission, and distribution, as well as participation in both national and European R&D projects.

1.2 Framework of the dissertation

As the world faces increasingly severe climate change impacts, the urgency to adopt sustainable, endogenous, and competitive energy solutions has intensified. Rising global temperatures, extreme weather events, and the adverse consequences of fossil fuel dependence underscore the need to transition to renewable energy sources. Recent geopolitical developments, particularly the dependence of the European Union (EU) on Russian natural gas, have underscored the urgency to diversify and localize energy sources. European and national energy policies, including the European Green Deal, Fit for 55, and Portugal's

"Plano Nacional de Energia e Clima 2030 (PNEC2030)" and "Roteiro para a Neutralidade Carbónica 2050 (RNC2050)", have established ambitious decarbonization and electrification goals to combat this crisis. Additionally, the Draghi [1] report highlighted the critical role of energy in shaping the competitiveness of EU's economy.

Central to these strategies is the integration of renewable sources of energy, particularly to the power sector, with wind energy emerging as a pivotal technology. Its scalability, declining costs, and technological advancements, especially in offshore installations, position wind power as a cornerstone of the transition to sustainable energy. Offshore wind farms offer unique advantages: vast open spaces, steady wind conditions, and minimal visual or environmental impact on urban areas. Furthermore, larger turbines — reaching up to 15–20 MW — enhance efficiency, contributing to the sector's growing commercial viability and reducing dependence on government subsidies [2, 3].

In Portugal, and as per the PNEC2030, offshore wind energy is considered crucial to achieving ambitious emission reduction goals. The country's historical commitment to sustainability is demonstrated by a 60% reduction in greenhouse gas (GHG) emissions between 1990 and 2019 and, also, per capita emissions lower than the EU average. Guided by the European Green Deal and the Paris Agreement, Portugal aims to reduce emissions by 85–95% by 2050. Offshore wind, though in its early stages of development in Portugal, is a key element of this strategy. The government has initiated the identification of pre-allocated areas for wind farms and capacity auctions to evaluate available technology, environmental constraints, and installable offshore capacities. These measures aim to optimize electricity production while accounting for seasonal variability and mitigating wake effects between turbines [3].

Globally, the offshore wind sector is expanding at an unprecedented rate. As illustrated in Figure 1.1, the global offshore wind installed capacity grew to 35 GW until 2020, primarily in Europe, a milestone that took 30 years to achieve. However, projections indicate a dramatic increase to 205 GW by 2030, more than quintuple of the current capacity [4].

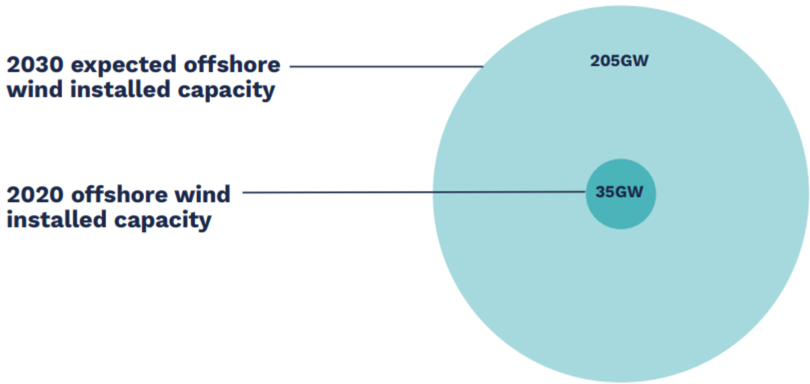


Figure 1.1: Evolution of the Installed Offshore Wind Capacity Worldwide. [4]

Europe's commitment in offshore wind is exemplified by the Oostende target of achieving 120 GW of capacity by 2050. These efforts align with broader climate goals and emphasize the importance of continuous technological innovation. Co-location of wind farms with other renewable energy technologies, such as wave energy, is another promising approach. Such integrations optimize energy yield, reduce spatial and environmental footprints, and align with sustainability objectives.

Portugal's offshore wind initiatives underscore the need for robust infrastructure to support renewable energy integration. Efficient electrical grid connections are vital to transfer energy to where demand is located, while addressing grid congestion and enhancing European interconnections will be critical for managing increased renewable electricity volumes. Additionally, wave-wind interactions, which influence turbine performance, must be studied and modeled to maximize efficiency [5].

Floating offshore wind platforms are another promising frontier, especially for countries with deep offshore waters, like Portugal. These systems provide flexibility in installation while reducing environmental impacts compared to bottom-fixed turbines. Costs for floating platforms are expected to decline by 70% by 2050, further enhancing their commercial feasibility.

Environmental considerations remain a priority. Floating wind platforms, typically located further offshore, minimize coastal ecosystem disruptions. Nonetheless, continuous environmental monitoring and consultation with stakeholders, such as the fishing industry, are essential to ensure sustainable coexistence. This balance between technological innovation and environmental management will determine the long-term success of offshore wind energy development [6, 7, 8].

In general, offshore wind represents an opportunity for Portugal and Europe to accelerate their transitions to renewable energy. As technologies mature and policy support strengthens, offshore wind is set to play an integral role in achieving global climate and energy objectives.

1.3 Goal

This work's main goal is to identify the global potential of offshore wind farms in Portugal. To achieve this objective, several key steps will be undertaken:

- A comprehensive review of the state of the art in offshore wind energy, focusing on the main characteristics of the wind resource and the available technology.
- An examination of the marine areas in Portugal designated for wind farms, including any existing restrictions.
- An analysis of the available sources of climatological information, such as global wind atlases.
- Assessing the geographical availability of the technology, considering the area available, geographical restrictions, and technological limitations.
- The utilization of atmospheric flow simulation tools, particularly the Wind Atlas Analysis and Application Program (WAsP), including the identification and description of WAsP's input data and parameters.
- The planning and execution of various simulations across different areas, taking into account different technologies to estimate energy potential, the significance of the distance between wind turbines, and the impact of turbine size, particularly regarding losses due to the wake effect.
- A high-level assessment of the economic feasibility of offshore wind farms, including cost analysis and investment returns.
- An evaluation of the social and ecological implications, such as potential job creation and reduction of emissions.

1.4 Structure

This dissertation is structured into nine chapters, each contributing to a comprehensive research on assessing the energy potential of offshore wind energy in Portugal.

The first chapter introduces the topic by providing the necessary context, outlining the framework of the study, and defining its objectives. It concludes with an overview of the dissertation's structure, setting the stage for the chapters that follow.

The second chapter delves into the fundamentals of offshore wind energy, including the origins and characteristics of atmospheric flow, offshore wind turbine technologies, and the distinctions between fixed and floating systems. It also examines the environmental and social benefits of offshore wind energy, such as greenhouse gas reduction and sustainable development, while addressing technical challenges related to grid integration.

The third chapter shifts focus to the regulatory and political landscape, analyzing the European and national frameworks governing offshore wind energy. It includes case studies from leading countries, such as the United Kingdom, Germany, and Denmark, highlighting lessons that can be applied to Portugal. The chapter also explores future scenarios for offshore wind energy expansion, including integration with other renewable technologies.

In the fourth chapter, the study narrows its scope to Portugal, presenting a detailed analysis of the country's offshore wind resources. It covers wind characterization, concession areas, and the processes employed by the Portuguese government to identify high-potential sites for offshore wind energy development.

The fifth chapter outlines the methodology for assessing offshore wind energy potential. This includes the selection of study areas, simulations using the Wind Atlas Analysis and Application Program (WAsP), and the design of scenarios to evaluate various turbine configurations and their performance in specific locations.

The sixth chapter presents the application of the methodology and discusses the results. It focuses on high-potential sites such as Viana do Castelo and Sines, analyzing layout scenarios, turbine performance, and local wind behavior. The findings from these simulations provide critical insights into site-specific opportunities and challenges.

The seventh chapter provides an economic analysis, evaluating investment costs, revenue potential, and financing models for offshore wind projects. It explores economies of scale, technological maturation, and competitiveness while assessing the broader socio-economic and environmental impacts of offshore wind energy development.

The eighth chapter examines the socio-economic and ecological aspects of a proposed offshore wind scenario, focusing on job creation, and the contribution to reducing greenhouse gas emissions. It also evaluates the potential to power homes and support sustainable development in the region.

Finally, the ninth chapter concludes the dissertation by summarizing the main findings, drawing key conclusions, and reflecting on the broader implications of the research.

This sequential structure ensures a logical progression from theoretical concepts to practical applications, offering a holistic perspective on offshore wind energy and its potential to contribute to Portugal's renewable energy goals.

Chapter 2

Offshore Wind Farms

This chapter provides an overview of offshore wind energy, covering its fundamentals, main technologies, environmental benefits, and grid integration challenges. It examines atmospheric flow over oceans, turbine designs, fixed and floating foundations, and recent innovations. Also, it highlights offshore wind's role in reducing greenhouse gas emissions and fostering community engagement while addressing challenges in connecting to the electrical grid and utilizing high voltage direct current (HVDC) systems.

2.1 Wind Energy Fundamentals

Wind energy is generated by capturing the kinetic energy of moving air masses with wind turbines. When wind flows past the turbine's blades, lift forces are created on each blade, which causes the rotor to spin. This mechanical energy is then converted into electricity by a generator, either directly or through a gearbox that multiplies rotational speed, embodying the core principle of wind energy technology [9].

The power available in the atmospheric flow, commonly designated as power flux, is influenced by several factors, including the free-stream wind speed, air density, and the swept area. A useful reference value for power flux, derived simply from these independent variables, provides a convenient theoretical baseline, though it is not entirely realistic, as will be seen later, and is defined by the following equation:

$$P_{wind} = \frac{1}{2}\rho A v^3 \tag{2.1}$$

where:

- P_{wind} is the power available in the wind (Watts),
- ρ is the air density (typically 1.225 kg/m^3 at sea level),
- A is the swept area of the turbine blades, $A = \pi r^2$, where r is the swept area radius,
- v is the free stream wind speed (m/s).

The power flux is proportional to the cube of wind velocity, making regions with strong, consistent winds most suitable for wind farms. Air density is another critical factor, where denser air provides more energy, while larger rotors capture greater wind volumes, enhancing energy extraction. These factors collectively determine the energy available from the wind resource [10].

On the other hand, the ability of a wind turbine to yield the energy available in the atmospheric flow, designated as the Power Coefficient and calculated with the expression below, is highly dependent on technological choices - for example, control mechanisms and algorithms or the blade design for the aerodynamic conversion:

$$c_p = \frac{Power\ output\ of\ wind\ turbine}{P_{wind}} \tag{2.2}$$

Furthermore, turbine and wind farm design must account for wake effects, wherein turbulence from one turbine affects the performance of others downstream, impacting overall energy yield. Aerodynamic efficiency and strategic turbine placement are crucial for optimizing wind farm output [11].

In summary, wind energy harnesses the kinetic energy of moving air, first converting it into mechanical energy and then transforming it into electrical power, with the efficiency being determined by wind characteristics and wind farm design. Mastering these principles is crucial for the optimization of wind systems, as well as enhancing their contribution to the global energy transition.

2.1.1 The origins of atmospheric flow

Wind is primarily generated by the uneven heating of the Earth's surface by the sun, driving the movement of atmospheric air masses. Solar radiation heats the Earth more intensely near the equator, causing areas of warm, ascending air and areas of low pressure. Cooler, denser air from higher latitudes flows toward these low-pressure areas, generating wind as air moves from high to low-pressure regions. This dynamic is further enforced by the axial tilt of Earth that causes differential heating and, in turn, drives the convection currents. Warm air rises near the equator and descends at approximately 30° latitude, forming the Hadley Cell circulation pattern. Similar mechanisms operate at higher latitudes, with the Ferrel and Polar cells influencing global wind systems. These global wind patterns, as illustrated in Figure 2.1, form the basis for the distribution of wind resources around the globe [12].

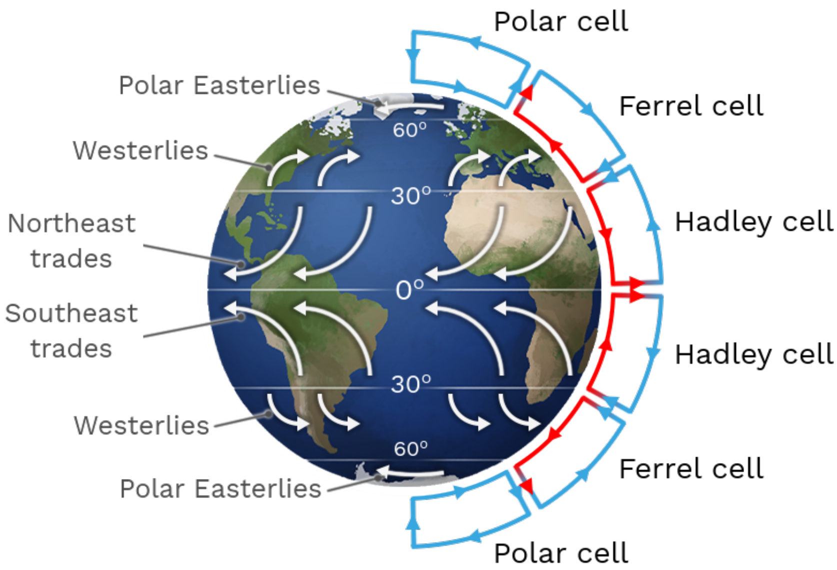


Figure 2.1: Global Wind Patterns. [13]

Earth's rotation also shapes wind patterns through the Coriolis Effect, causing winds to deflect to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. This deflection gives rise to the characteristic circulation of winds around high and low-pressure systems. While these large-scale atmospheric patterns are key to global wind behavior, local factors such as mountains, valleys, and bodies of water also play a significant role. However, over the ocean, wind flows tend to be more consistent and reliable due to the absence of physical obstructions like mountains or buildings, which are typically associated with higher roughness lengths [10, 12, 14].

2.1.2 Particularities of atmospheric flow on the ocean

The atmospheric flow over the ocean develops under conditions very different from those experienced by other winds over land: even with wave or tide action, the sea surface is quite uniform - without topographical features such as mountains or buildings - and thus supports stronger, steadier, and less turbulent winds. No obstacles mean free flow conditions, and as such, offshore is a perfect environment for wind energy applications. Oceanic wind patterns are less interrupted and typically stronger due to reduced surface friction and vast open spaces.

The ocean's thermal properties also play a crucial role in stabilizing atmospheric flow. Unlike land, which heats and cools rapidly, the ocean's high thermal inertia moderates temperature changes, maintaining stable air masses above it. This stability results in more predictable pressure systems and wind patterns compared to the variable winds over land, further enhancing the reliability of offshore winds for energy generation [15].

The Coriolis effect, unhindered by landmasses, steers ocean winds more effectively, producing smoother and more predictable paths. Wind speeds also increase with altitude over the ocean due to the lack of surface friction [16]. In addition, interactions at the coastal boundary, such as low-level jets, influence wind dynamics. While these jets can affect turbine loads, they contribute to less atmospheric turbulence and more organized wind flow compared to land-based systems [17].

The steadiness, strength and predictability nature of oceanic winds, combined with the unobstructed marine environment, makes offshore regions particularly fit for large-scale wind farms. These factors underscore the significant potential of offshore wind energy as a reliable and efficient renewable energy source.

2.1.3 The energy content of the atmospheric flow

Offshore wind energy yields the natural motion of atmospheric air masses, converting kinetic energy from the wind into mechanical and then electrical energy. To understand the energy available from wind, we need to examine the key factors that govern this conversion.

2.1.3.1 Wind Power

As mentioned previously, the power contained in the wind is proportional to the wind speed and the area swept by the turbine blades. Equation (2.1) expresses the power available in the wind:

This expression provides a good backdrop for three important relationships:

1. Wind power increases proportionally to the swept area. The larger the rotor, the more wind it can capture.

2. Wind power increases cubically with the wind speed. Small rises in wind velocity result in big surges of energy.

3. Wind power is further affected by the density of the air which can vary both with altitude, temperature, and humidity.

This fundamental expression sets, together with the Power Coefficient, the stage for calculating how much energy can be theoretically harnessed from the atmospheric flow [18].

2.1.3.2 Betz Limit

The Betz Limit, established by the German physicist Albert Betz in 1919, states that no wind turbine can convert more than 59.3% of the reference kinetic energy in the wind, given by equation (2.1), into work. This is because the air velocity at the wind turbine is much lower than the velocity of the free stream value, v, and thus the reference power over-estimates the real power available in the wind [19]. The advantage of this reference power, although it does not exist in reality, is that it is easily defined based on the independent variables, such as the wind turbine diameter and the undisturbed wind speed.

The maximum theoretical efficiency η_{max} of a wind turbine is thus given by the following equation:

$$\eta_{max} = 0.593 \times P_{wind} \tag{2.3}$$

where P_{wind} is the reference power in the wind, highlighted in equation (2.1).

The 59.3% value, known as the Betz Limit, is derived through a series of theoretical deductions based on the fundamental principles of fluid mechanics. By analyzing the flow of air through the turbine's rotor, as illustrated in Figure 2.2, Albert Betz used the conservation of mass and momentum to describe the behavior of the wind in a streamtube passing through the turbine.

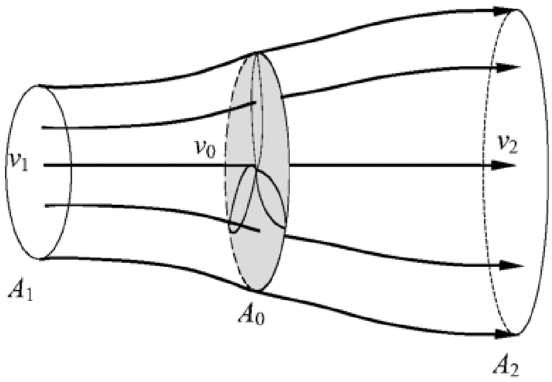


Figure 2.2: Schematic of a streamtube around a wind turbine. [19]

This analysis begins by noting that the air's velocity and cross-sectional area change at different points along the streamtube—upstream, at the rotor, and downstream. From the conservation of mass, the relationship between these variables is established. Betz then applied momentum balance to account for the forces exerted by the airflow on the turbine rotor, calculating the power extracted from the wind as a product of the mass flow rate and the change in the wind's kinetic energy.

Through careful algebraic manipulation of these relationships, Betz found that maximum efficiency occurs when the wind velocity at the rotor is an intermediate value, with the downstream velocity reduced to one-third of the upstream velocity. Under this condition, the theoretical maximum power extracted from the wind equals 16/27, or approximately 59.3%, of the reference power in the wind, Equation 2.1 [19].

In practice, modern wind turbines operate at efficiencies close to 45-50%, which is quite close to the Betz limit, factoring in losses due to mechanical friction, electrical generation, and other inefficiencies. Despite these losses, the Betz limit provides a fundamental constraint for turbine design, helping engineers optimize performance without overestimating the potential energy yield.

In conclusion, understanding the energy content of the atmospheric flow, with the Betz limit as a critical theoretical boundary, provides essential insights into the potential of offshore wind energy. Although the limit constrains the maximum power extraction, it also highlights the importance of practical considerations, such as the efficiency of turbine components, when planning and optimizing wind energy projects. These insights are crucial to ensure the sustainable and efficient growth of offshore wind farms to meet the increasing demand for renewable energy [20].

2.1.3.3 Capacity Factor

The capacity factor of a wind turbine is a critical measure of its efficiency and operational output. It is defined as the ratio between the actual energy the turbine yields over a year and the maximum possible energy it would yield if it were operating at full capacity all year long. It is expressed in the following equation:

$$Capacity\ Factor = \frac{Annual\ Energy\ Output}{Annual\ Energy\ Output\ at\ Full\ Capacity} \tag{2.4}$$

Typically, offshore wind turbines have a higher capacity factor than onshore turbines due to more consistent wind speeds at sea. A capacity factor of 40-50% is common for offshore wind farms, compared to about 25-30% for onshore installations. This metric is vital for understanding the actual energy yield of a wind farm, which is affected by fluctuations in wind speed and turbine downtime due to maintenance or suboptimal conditions [18].

2.1.4 Characterisation of the offshore wind resource

The characterization of the offshore wind resource is crucial for the successful planning and operation of wind farms. Given that offshore wind farms are often located in complex marine environments, various methods are employed to accurately assess wind conditions.

2.1.4.1 Wind Measurement Masts

Wind measurement masts are a reliable method for collecting data on wind conditions at prospective offshore sites. Ideally installed at the hub height of wind turbines, they provide accurate measurements, though constructing tall masts can be costly. Measurements from lower heights can be extrapolated to estimate hub height conditions, and data from multiple elevations are used to determine the wind gradient exponent. These masts typically employ cup anemometers for wind speed, wind vanes for direction, and sensors for temperature and air pressure, [21]. A year-long data collection offers a detailed view of seasonal wind patterns, though data losses may occur due to technical issues or environmental factors.

2.1.4.2 Advanced Measurement Technologies

Modern technologies such as sonic detection and ranging (SODAR) and light detection and ranging (LIDAR) are increasingly used for wind resource assessment. These systems, often supported by buoys in maritime environments, capture three-dimensional wind data and provide measurements at various heights and locations without requiring extensive infrastructure. While not fully replacing traditional masts, they offer a portable and cost-effective alternative that complements conventional methods. The reliability of their data is recognized by financial institutions, making them a viable option for project development [21].

2.1.4.3 Numerical Modeling at the Mesoscale Level

The wind energy industry, especially offshore wind energy, has long recognized the significant value of mesoscale modeling for assessing wind resources and evaluating the energy potential. Using global data from numerical weather predictions, mesoscale models simulate various atmospheric processes that influence wind turbine behavior and performance. This includes factors such as average wind conditions, transient storm systems, weather fronts, turbulence, thermal flows, air-sea interactions, and more [22].

2.1.4.4 Numerical Modeling at the Wind Farms' Level

Despite advancements in mesoscale models, additional detail in wind modeling may still be necessary. This can be achieved through downscaling mesoscale data or supplementing measured data by simulating wind fields and assessing wake effects — areas of reduced wind speed behind obstacles such as turbines. These models are essential for predicting energy yields and optimizing wind farm layouts, providing developers with a comprehensive understanding of site potential and the performance impacts of various configurations [22].

In conclusion, a comprehensive understanding of offshore wind resources combines direct measurement, advanced technologies, and numerical simulations, ensuring more reliable data for enhancing project efficiency and viability.

2.2 Offshore Wind Turbine Technologies

2.2.1 Components of an offshore wind turbine

This section explores the key components of offshore wind turbines, which are designed to harness renewable energy from the wind while coping with the unique challenges of marine environments [23]. The main components of an offshore wind turbine can be categorized into five major systems and some are highlighted in Figure 2.3:

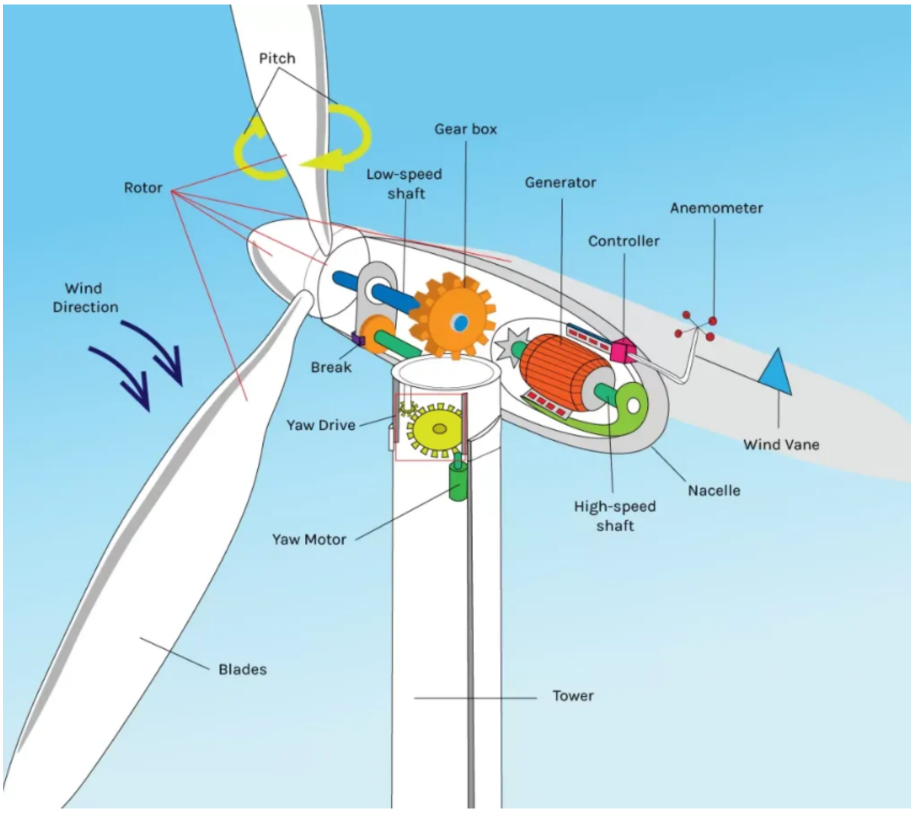


Figure 2.3: Nacelle System and Components. [24]

Blades: These are crucial for capturing wind energy and converting it into rotational motion. Offshore blades are typically longer compared to onshore blades, designed with advanced materials such as glass and carbon fiber composites used to ensure maximum energy capture while improving durability against environmental factors.

Rotor Hub: The rotor hub connects the blades to the main shaft and facilitates blade pitch adjustments, optimizing performance under varying wind conditions and protecting the turbine from excessive loads during high winds.

Nacelle: The nacelle houses important components for operation at the top of the tower, such as the gearbox, generator, brakes, and cooling mechanisms that enhance efficiency and reliability.

Tower: The tower supports the nacelle and rotor system, elevating the turbine to maximize exposure to wind resources while ensuring stability. Various tower designs, such as monopile, jacket, and floating, are suited for different seabed conditions and water depths.

Foundation: The foundation anchors the turbine to the seabed, providing stability against wind and wave forces. Offshore foundations, including monopiles, gravity-based structures, and floating platforms, are designed to ensure long-term operational safety and efficiency.

These five components — blades, rotor hub, nacelle, tower, and foundation — work in synergy to efficiently convert wind energy into electricity, contributing to the advancement of renewable energy technologies.

2.2.1.1 Blades

The blades of wind turbines are essential for yielding wind energy and converting it into rotational motion. Designed for aerodynamic efficiency and durability, they often feature advanced composite materials such as carbon and glass fiber epoxy, which ensure strength, lightness, and fatigue resistance in harsh marine conditions. Blade designs incorporate features like twists, tapers, and protective coatings to optimize performance and mitigate environmental wear, such as leading-edge erosion.

Key components include a spar for structural support, aerodynamic shells for wind interaction, a secure root connection, and systems for lightning protection and sensor monitoring. Modern blades are long and lightweight, with advanced materials like carbon fiber offering significant weight reductions and enhanced stiffness compared to traditional materials. Additionally, blades include mechanisms for pitch adjustments to optimize energy capture. These features collectively ensure efficiency, durability, and reliable energy output in offshore environments [23].

2.2.1.2 Rotor Hub

The rotor hub is an important part of the wind turbine, connecting the blades to the main shaft and facilitating the transfer of aerodynamically generated forces into mechanical energy. Manufactured normally from high-quality cast iron, the hub withstands the dynamic loads of offshore wind conditions and supports the pitch adjustment of the blades for optimal energy capture [25, 26]. In the common three-bladed configuration, the rotor hub ensures aerodynamic balance, reduces mechanical failure risks, and minimizes rotor imbalance, enhancing turbine reliability.

Each blade in the hub has an independent pitch system, allowing for precise control of the rotor speed and continued operation even if one system fails. These systems are critical in the management of over-speed conditions in high winds by protecting the turbine by reducing lift and controlling rotational speeds [23].

The pitch mechanism adjusts blade angles relative to the plane of rotation to optimize energy capture. Like the vast majority of onshore wind turbines in operation today, offshore wind turbines use pitch control, rather than stall regulation, to maintain efficiency across varying wind speeds. Algorithms monitor wind speed and energy output, adjusting the blade's pitch to maximize generation and prevent damage from excessive speeds [27].

Pitch systems in wind turbines use mechanisms such as hydraulic systems, rack-and-pinion designs, or individual motors. Located at the front of the rotor hub, the pitch system relies on toothed gears or belts to modify blade angles, ensuring safe and efficient operation under distinct wind conditions [23].

2.2.1.3 Nacelle

The nacelle is a crucial component of wind turbines, containing essential systems such as the generator, gearbox, and control mechanisms. It safeguards these components from harsh environmental conditions. In offshore turbines, the nacelle's role becomes even more critical due to the challenging marine environment, while also ensuring efficient conversion of mechanical energy into electrical power [23, 24].

- **Main Shaft**: Transfers energy from the rotor hub to the generator, with high durability to withstand mechanical stresses [28].
- **Bearings**: Support the main shaft, minimize friction, and handle high loads in challenging environments [29].
- **Gearbox (if applicable)**: Increases shaft speed for efficient electricity generation, though many offshore turbines now adopt direct-drive systems to reduce complexity [23].
- **Generator**: Converts mechanical energy into electrical energy, often using permanent magnet technology for efficiency and reduced maintenance [30].
- **Brake System**: Stops or slows the turbine during emergencies or excessive winds to prevent damage [24].
- **Yaw System**: Aligns the nacelle to face the wind, enhancing energy capture while minimizing stress on components [23].
- **Cooling and Lubrication Systems**: Manage thermal conditions and minimize wear, extending the nacelle's operational life [31].
- **Control Systems**: Automate turbine operation, optimizing performance and monitoring for maintenance needs [32].

Yaw System

The yaw system ensures the rotor faces the wind, maximizing energy production and minimizing mechanical stress. Sensors track wind direction, triggering yaw motors to adjust nacelle orientation, while brakes stabilize it in steady conditions, as it is represented in Figure 2.4. The system also manages cable twist, periodically untwisting cables to prevent damage [23, 24, 33]. In certain conditions, yaw can help optimize the total energy output of a wind farm by slightly misaligning the nacelle with the wind direction. This strategy reduces wake losses, although it may result in a decrease in wake-free energy output [34].

This integration of nacelle and yaw technologies ensures offshore turbines operate efficiently and safely under variable and extreme conditions.

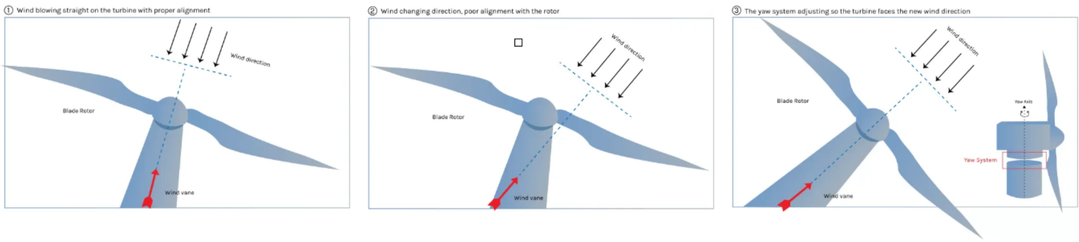


Figure 2.4: Operating Yaw System. [24]

2.2.1.4 Tower

The tower is a fundamental component of wind turbines, supporting the nacelle and rotor above land or sea surface. Typically made of tubular steel, it also houses essential electrical and control systems, provides access for maintenance personnel, and ensures storage for safety equipment. Towers must withstand significant environmental loads, including wind, waves, and currents, with designs tailored to meet severe fatigue and extreme mechanical load requirements [35].

In Floating Wind Turbines (FWT) applications, towers face added complexities due to dynamic interactions from wave and wind forces. These include low-frequency oscillations from the floating substructure and high-frequency responses from the rotor-nacelle assembly (RNA), necessitating innovative designs to enhance structural performance [36].

Emerging integrated designs underline the smooth transition from substructure to tower, reflecting their interconnected roles. Tower reliability directly impacts energy efficiency and fatigue life, making it a key factor in advancing sustainable offshore wind energy [37].

2.2.1.5 Foundation

Foundations are essential elements of offshore wind turbines, securing them in marine environments. The choice of foundation type, whether monopiles, jackets, or floating foundations, involves important technical and financial decisions, often representing 16% to 34% of total project costs [38, 39].

The diverse seabed conditions in offshore wind farms, including variations in water depth and proximity to shore, influence foundation loads. While developers aim to optimize performance by designing foundations individually, economic factors often lead to a preference for standardized foundation types to reduce costs and simplify logistics. This trade-off can shape wind farm layouts to avoid deeper waters or challenging seabed conditions.

Choosing the appropriate foundation is complex, requiring an evaluation of water depth, seabed composition, ocean conditions, and turbine specifications. Secondary factors are the availability of local fabrication and installation vessels, and maintenance strategies. Developers must balance life cycle costs with project risks, making foundation selection a critical early-stage decision [4].

The next section will examine the two primary categories of offshore wind turbine foundations — fixed and floating — describing their technologies and applications along with their respective benefits in the offshore energy industry.

2.2.2 Fixed vs. Floating turbines

As offshore wind energy grows, selecting the right foundation type for turbines becomes an important choice. Offshore wind turbines can be categorized into two main types: Fixed and Floating, each with distinct advantages based on site conditions, particularly water depth and seabed composition [4].

Fixed Offshore Wind Turbines are installed onto rigid structures directly connected to the seabed, typically installed in shallow waters (up to 60 meters deep) on monopiles, jackets, or gravity-based foundations. These turbines are stable, resilient against strong winds and rough seas, and benefit from simpler installation processes. This makes them a cost-effective choice for near-shore wind farms, especially in regions with favorable shallow seabed conditions, such as the North Sea [40].

On the other hand, Floating Offshore Wind Turbines represent an innovative approach, particularly for deeper waters (beyond 60 meters) where fixed foundations are impractical. Floating turbines are anchored by mooring lines to offset foundations, allowing deployment in areas with limited shallow coastal zones or complex seabeds. These turbines access stronger, more consistent winds in deeper waters, potentially increasing energy output. Additionally, floating turbines can be installed farther from shore, reducing visual impacts and minimizing interference with marine activities. They are, however, considerably more complex from a technological perspective, which remains a factor limiting their competitiveness [41].

2.2.2.1 Key Factors in Choosing Fixed or Floating Technologies

The choice between fixed and floating turbines depends on several site-specific factors, with water depth being the most critical. Fixed turbines are cost-effective in shallower waters due to their direct seabed anchorage. Beyond this depth, the cost of fixed foundations, particularly jacket structures, increases significantly, making floating turbines more viable for deeper waters.

Seabed conditions also play a key role in determining the foundation type. Fixed foundations, such as monopiles, gravity-based structures, and suction buckets, require stable, uniform seabeds. Challenging conditions, such as poor soils or rocky grounds, can make fixed foundations less suitable or more costly to install. Floating turbines, anchored via mooring systems, are more adaptable to varied seabed conditions and less affected by geotechnical challenges.

Lastly, wind resources influence the decision. Offshore winds are generally stronger and more consistent in deeper waters, favoring floating turbines for higher energy capture. Fixed turbines are typically preferred in shallow, near-shore locations where installation and maintenance are simpler [4, 40, 41].

2.2.2.2 Current Challenges and Future Prospects

Fixed and floating offshore wind turbines encounter distinct challenges related to construction, installation, and technical aspects, as outlined in Annex A. These challenges become more pronounced as the industry expands into new markets and more demanding environments. Fixed turbines are constrained by water depth and the high costs of complex foundations in deeper waters. However, advances in technology, such as monopiles, have enabled installations in waters as deep as 50–60 meters, a notable improvement from a decade ago.

Floating turbines, while offering access to deep-water wind resources, still face challenges related to cost, stability, and the need for specialized infrastructure for installation, maintenance, and anchoring. Despite these hurdles, the technology is progressing quickly and is expected to become more cost-competitive as it matures, with pilot and demonstration projects paving the way for large-scale deployment.

Looking ahead, both technologies will have their role in the offshore wind energy sector. Floating turbines are expected to unlock new offshore wind resources in previously inaccessible areas, while fixed turbines will remain dominant for shallow, near-shore projects [40, 41].

2.2.3 Fixed Foundations

Fixed foundations are the structural backbone of offshore wind turbines, anchoring them securely to the seabed for stability. Typically used in water depths up to 60 meters, they are ideal for shallow to moderate-depth sites. Their robustness makes them resilient to marine forces and reliable in harsh weather, ensuring straightforward installation and maintenance. This stability has led to widespread deployment, especially in regions with established offshore wind industries [41, 42]. Figure 2.5 exhibits different types of offshore fixed foundation technologies.

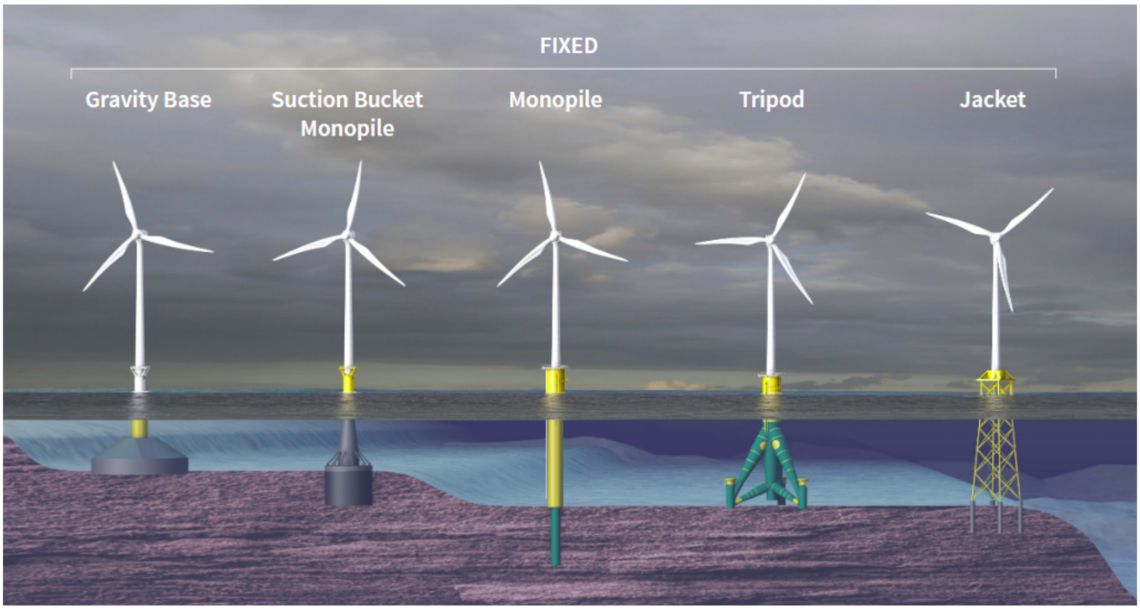


Figure 2.5: Different Fixed Foundation Technologies. [43]

Gravity Base Foundations (GBFs): GBFs are simple, cost-effective foundations that rely on their weight to secure wind turbines to the seabed. Typically used in shallow waters (15-40 meters), they are fabricated onshore and transported using "float and submerge" techniques, minimizing installation costs and environmental impact. Over time, GBFs have evolved to accommodate deeper waters, with third-generation designs supporting larger turbines in up to 35 meters of water. Despite challenges in very deep waters, they remain popular for near-shore installations due to their stability and ease of installation [4, 44].

Suction Bucket Monopiles: These foundations use vacuum pressure to secure the structure to the seabed, offering a quiet and more eco-friendly installation process. Suitable for depths of 10-60 meters, suction bucket monopiles are cost-efficient, easy to remove at the end of their lifespan, and reduce environmental impact during installation. However, they are sensitive to lateral loads and require careful consideration of soil conditions to ensure stability [4, 45].

Monopiles: A common, simple foundation type, monopiles are steel cylinders driven into the seabed, ideal for shallow waters (10-30 meters). They are cost-effective and easy to manufacture but face stability challenges in deeper waters due to lateral loads and soil deformation. Innovations continue to extend their use to deeper waters while maintaining cost-efficiency [4, 45].

Tripod Foundations: Designed for depths of 25-50 meters, tripods feature a central column supported by three legs, providing stability and reducing resonance from wave action. They are easier to manufacture than jacket foundations but require careful fatigue analysis due to their vulnerability to environmental forces. Tripods have proven successful in the German offshore wind market, offering a reliable solution for deeper waters beyond 50 meters [45, 46].

Jacket Foundations: Ideal for depths between 30-100 meters, jackets are lattice structures with multiple legs anchored to the seabed. They distribute loads efficiently and offer stability in deeper waters and varied seabed conditions. Despite being more complex to install, they are more material-efficient in deeper installations and offer better dynamic performance. Jackets are well-suited for challenging marine environments but require careful fatigue analysis to ensure long-term durability [4].

2.2.4 Floating Foundations

Floating offshore wind foundations are a developing technology designed to support turbines in deep waters where fixed foundations are not viable. These platforms maintain stability through gravity stabilization, waterplane stabilization, and mooring lines. They are primarily made from steel and concrete, with concrete gaining popularity due to cost savings and reduced greenhouse gas emissions. While still in the early stages, floating platforms offer significant potential for future offshore wind projects by enabling turbines to be placed in deeper, more remote waters with stronger, more consistent winds. Various designs, represented in Figure 2.6, are being explored, with the choice depending on local conditions and infrastructure needs [8, 47, 48].

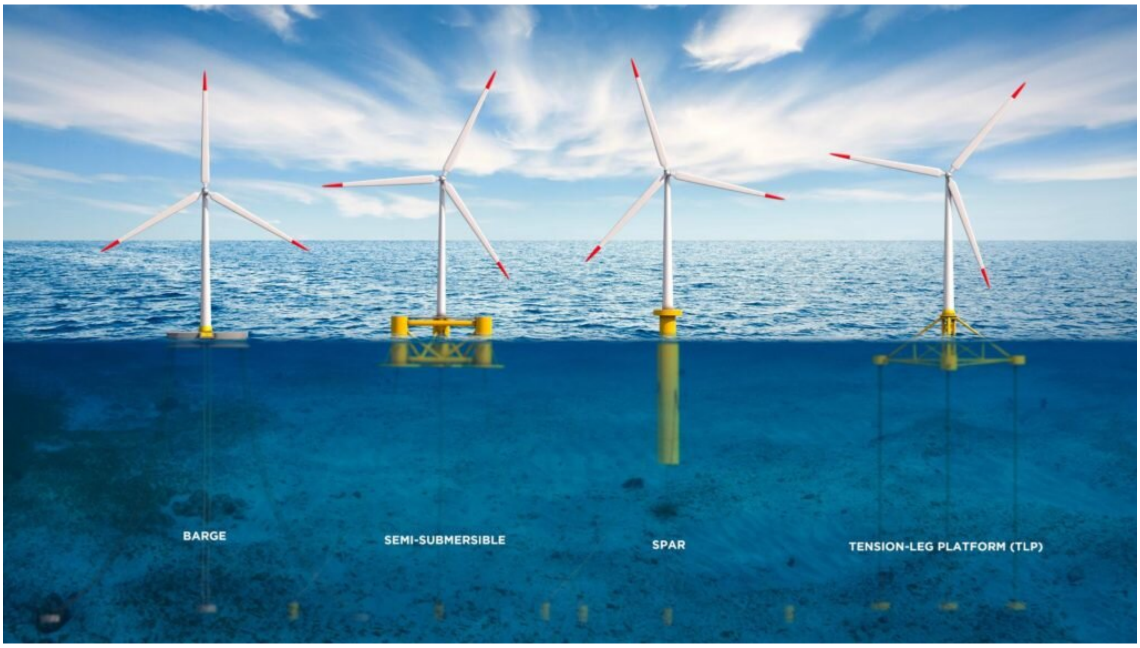


Figure 2.6: Different Floating Foundation Technologies. [49]

Barge Foundations: Barge floating foundations are shallow, wide platforms that distribute weight across the water, offering stability. They can be constructed from steel, concrete, or hybrid materials and are flexible in design. Barge foundations are suitable for water depths starting at 30 meters, providing ease of construction and maintenance. However, their large waterplane area makes them more susceptible to wave-induced motions, requiring robust mooring systems. Despite these challenges, barge foundations are a proven and flexible option for offshore wind turbines [8, 48, 50].

Semi-Submersible Foundations: Semi-submersible floating foundations consist of multiple vertical columns connected by submerged pontoons, offering stability and buoyancy. These structures are adaptable to varying water depths starting at around 40 meters and feature relatively simple mooring systems. However, they are exposed to wave action, which can cause vertical movement and stability issues. Despite fabrication challenges, semi-submersibles remain popular for their depth independence and ease of installation and decommissioning [4, 8, 48, 50].

Spar Foundations: Spar floating foundations are deep-draft, single-cylinder structures that rely on buoyancy and ballast for stability. They are ideal for deep waters starting at 100 meters, offering minimal heave motion. Despite their stability, spar foundations are more complex and costly to fabricate and install. They face challenges with pitch-and-roll motions and fatigue at the tower base but remain an effective solution for deep-water offshore wind projects [4, 8, 48, 50].

Tension-Leg Platforms (TLPs): TLPs are lightweight floating platforms anchored to the seabed with tensioned steel cables. They offer minimal heave and pitch motions, a small seabed footprint, and are suitable for various water depths. However, TLPs require specialized installation vessels and expensive mooring lines, limiting their widespread adoption. Despite their complexity, TLPs offer promising dynamics and operational flexibility for deep-water offshore wind projects [4, 8, 48, 50].

2.2.5 Recent innovations

As the demand for renewable energy increases, the offshore wind industry is advancing rapidly to meet the need for more efficient turbines. Innovations focus on harnessing higher and more consistent offshore wind speeds by developing larger turbines, some exceeding 15 MW capacity and rotor diameters over 200 meters. These larger turbines increase energy capture and improve the economics of offshore wind farms. Additionally, efforts are focused on reducing maintenance costs and improving durability, addressing challenges such as corrosion, wave loads, and extreme weather. Advancements in materials and predictive maintenance systems are improving turbine longevity, positioning offshore wind as a major player in the global clean energy transition.

2.2.5.1 Growing Rotor Diameters

The offshore wind turbine industry is experiencing a significant trend toward increasing rotor diameters, which play a key role in boosting energy capture. By 2023, the average rotor diameter exceeded 134 meters [42], driven by the need to harness more wind energy, particularly in areas with moderate yet more consistent wind speeds. Larger rotors have a greater surface area to sweep, which results in a higher energy yield.

However, larger rotors also pose challenges, such as higher mechanical loads, larger generators, and increased costs for foundations and towers. Therefore, rotor design must balance energy gains with these additional costs and site-specific factors like wind speed. Innovations in rotor technology aim to maximize energy capture while minimizing costs. For example, optimizing the rotor size to minimize the gap between average and rated wind speeds can enhance performance. As turbine sizes continue to grow, the trend of expanding rotor diameters is crucial to achieving the industry's goal of producing more energy at lower costs [42].

Figure 2.7, presented below, illustrates the evolution of offshore wind turbine size and power output over time, highlighting this trend.

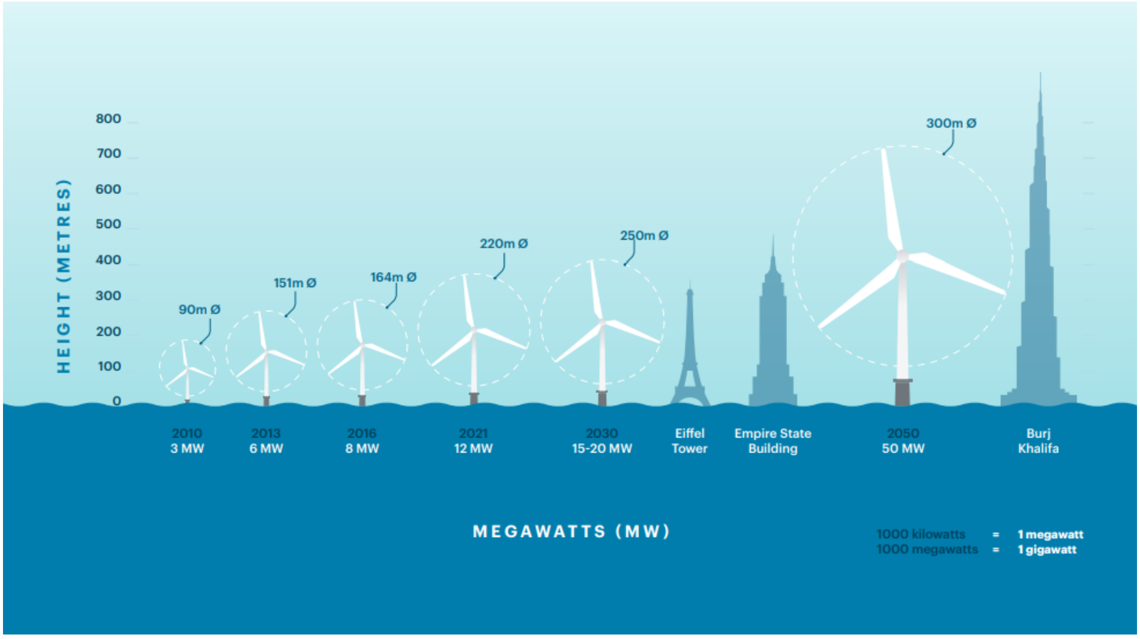


Figure 2.7: Evolution of Wind Turbine Size and Nominal Generating Capacity. [42]

2.2.5.2 Increasing Hub Height

The trend of increasing hub heights in wind turbines is driven by the need to capture stronger and more consistent winds at higher altitudes. Wind speeds increase with height as a result of reduced friction from surface features, allowing turbines at higher elevations to access these faster winds, boosting energy capture and efficiency. In recent years, utility-scale turbines often exceed 100 meters in hub height, which is especially beneficial in areas where wind conditions improve with altitude.

However, increasing hub heights presents challenges, particularly offshore. Offshore wind shear is less significant than onshore, making the economic benefits of taller towers less compelling. The added costs of taller towers, including higher foundation loads and construction expenses, often outweigh the energy gains. Despite this, optimizing the hub height remains crucial for maximizing energy yield, minimizing turbulence, and reducing maintenance costs, which helps improve overall performance and extend operational life [51, 52, 53].

2.3 Environmental and Social Benefits of Offshore Wind Energy

Offshore wind energy, though frequently examined for its environmental challenges and impacts on marine resources as detailed in Annex B, also provides substantial environmental and social benefits. As a clean and renewable energy source, it plays a key role in the transition to sustainable power generation and helps reduce reliance on fossil fuels. Offshore wind farms yield energy with minimal greenhouse gas emissions, contributing to climate change mitigation efforts. Technological advancements have improved efficiency and reduced costs, making it a competitive alternative to traditional energy sources. Additionally, the industry supports job creation, economic growth, and energy security, benefiting societies worldwide. This chapter will explore these positive impacts in detail.

2.3.1 Reduction of GHG emissions

Wind energy in general, and offshore in particular, significantly reduces greenhouse gas (GHG) emissions by replacing fossil fuel based electricity by a clean and renewable energy source that does not rely on burning fossil fuels. Despite some emissions occurring during the production and installation phases of wind turbines, these are minimal compared to the continuous emissions from fossil fuel power plants. For example, coal-fired plants emit around 900 grams of CO_2 per kWh, while offshore wind turbines generate approximately 6 grams of CO_2 per kWh over their lifespan, a reduction of more than 99% compared to coal power generation [54]. This stark contrast highlights the critical role offshore wind energy plays in combating climate change.

Offshore wind farms have the potential to prevent millions of tons of CO_2 emissions annually, with estimates suggesting that some projects could avoid up to 4500 million tons of CO_2 each year [55]. Advances in turbine design and construction, along with the use of carbon-neutral materials, will further reduce emissions from wind energy production, possibly making it nearly emission-free in the future.

Furthermore, research has shown that the environmental cost of wind energy is just 4% of that of coal, making it an economically viable and sustainable energy solution. By incorporating offshore wind power into national grids, countries can significantly reduce their GHG emissions while maintaining a steady electricity supply [56].

2.3.2 Sustainable development

Offshore wind farms contribute to sustainable development by generating clean energy and supporting economic growth, especially in coastal communities. These projects provide both environmental and socioeconomic benefits, combining renewable energy with positive local impacts.

Wind energy, in contrast to fossil fuels, does not require fuel extraction and has very limited environmental impacts, such as a negligible water footprint. Emissions related to the construction and maintenance of turbines are small and are usually compensated for within the first year of operation. Innovations, such as the use of low-carbon steel and recyclable materials, further reduce the environmental impact of wind energy production [57].

Offshore wind farms contribute to the preservation of marine ecosystems by reducing harmful activities such as bottom trawling and dredging. In addition, some projects are designed with artificial reefs, increasing biodiversity and supporting wider conservation goals.

Economically, offshore wind projects drive regional growth, creating jobs in engineering, manufacturing, and logistics. Coastal industries and ports benefit from the expanding wind energy sector, fostering local economic development [58]. Community engagement ensures that wind energy projects meet local needs and foster shared benefits [59].

2.3.3 Public acceptance and community involvement

Coastal communities, directly impacted by offshore wind farm development, play a crucial role in the long-term success of these projects. Their participation is key, as they stand to benefit economically through job creation and state-led initiatives. Ensuring public acceptance and meaningful community involvement requires creating a sense of ownership and shared benefits, not just addressing environmental impacts [59].

Building trust with local stakeholders is essential for success. Early involvement helps align local interests with those of developers. The fishing industry, for example, often shares marine spaces with wind farms, and fostering collaboration between these industries can lead to mutually beneficial outcomes. Clear guidance from local and national governments, including public-private councils and regional plans, can reduce conflicts and streamline the process [58].

State-led initiatives and policies also play a vital role in fostering community acceptance. Government support has boosted public and political support, with offshore wind linked to economic benefits, including job creation and potential cost savings for consumers. These outcomes help build acceptance by demonstrating tangible economic advantages [60].

Community acceptance varies by location, with concerns about visual and environmental impacts often outweighed by the potential for energy security and economic growth, particularly when offshore wind is used for local supply. Public acceptance tends to be higher when communities feel direct benefits [61].

Ultimately, the success of offshore wind farms relies on economic benefits, community engagement, and trust building. Developers and policymakers must prioritize transparent communication, stakeholder involvement, and locally focused strategies to ensure both environmental sustainability and social inclusion.

2.4 Grid Integration Challenges

As the demand for renewable energy grows, integrating offshore wind energy into existing electrical grids presents significant challenges. Transitioning from fossil fuel-based systems to sustainable alternatives requires not only the development of offshore wind farms but also upgrades to grid infrastructure. Although offshore wind energy offers a promising solution for reducing greenhouse gas emissions and promoting energy independence, transporting electricity from offshore to onshore grids involves technical, logistical, and regulatory obstacles.

This chapter will explore the complexities of grid integration, focusing on main issues such as submarine interconnections, the reliability of coastal infrastructure, and the need for advanced technologies to manage wind energy's variability. Addressing these challenges is crucial for successfully incorporating offshore wind into the broader energy system, supporting a sustainable and resilient energy future.

2.4.1 Electrical grid connection

Integrating offshore wind farms into the electrical grid presents challenges, particularly due to their distance from shore. The infrastructure required includes inter-turbine cables, offshore substations, shore cables, onshore substations, and grid connections.

A key challenge is the variable nature of wind energy, which causes fluctuations that can affect grid stability. These fluctuations lead to frequency and voltage deviations if a mismatch between supply and demand occur. Grid operators use advanced forecasting tools to predict wind farm output, helping to balance supply and demand and reduce reliance on backup power sources.

Another issue is potential congestion on transmission lines. Offshore wind farms, often located far from population centers, can overload transmission lines, causing inefficiencies. To address this, substantial investments in grid infrastructure are needed, including the adoption of smart grid technologies to optimize electricity flow and alleviate congestion [62].

In the presence of a high share of non-dispatchable and highly variable generation capacity, storage can play a crucial role in ensuring proper demand-supply balancing. As discussed in Annex C, various storage technologies were evaluated as potential solutions to enhance the demand-supply balance.

Successful integration requires coordination among stakeholders such as grid operators, regulators, and developers. Clear regulatory frameworks and market mechanisms are essential to incentivize wind farm development and investment in clean energy technologies.

Moreover, environmental and social impacts must be considered. Despite being a clean energy source, wind farm construction and operation can affect local ecosystems and communities. Comprehensive environmental assessments and stakeholder engagement are vital to minimize negative impacts [63].

2.4.1.1 Inter-turbine Cables

Inter-turbine cables are vital for the operation of offshore wind farms, especially for floating installations. Unlike static cables used in bottom-fixed turbines, dynamic cables are designed to withstand harsh marine environments, enduring constant movement from ocean waves and currents. These cables reliably transfer energy from floating turbines to the onshore grid, even in challenging conditions [64].

Array cables serve multiple functions, transferring electricity to the offshore substation, providing auxiliary power to turbines during low generation periods, and enabling fiber communications for monitoring. These cables are designed to adapt dynamically, following a lazy wave pattern to accommodate turbine movement. They must withstand the forces of the water column and potential abrasion from the seabed. Cables are typically buried or laid on the seabed, suspending them in deeper waters is still experimental due to practical uncertainties.

Currently, array cables are rated at 66 kV, but future trends indicate that this rating may increase to 132 kV to support larger and more efficient turbines (16 MW and above). This will reduce the number of cables required, improving the efficiency of energy transmission [65]. As illustrated in Figure 2.8 below, offshore wind farms feature a complex network of cables.

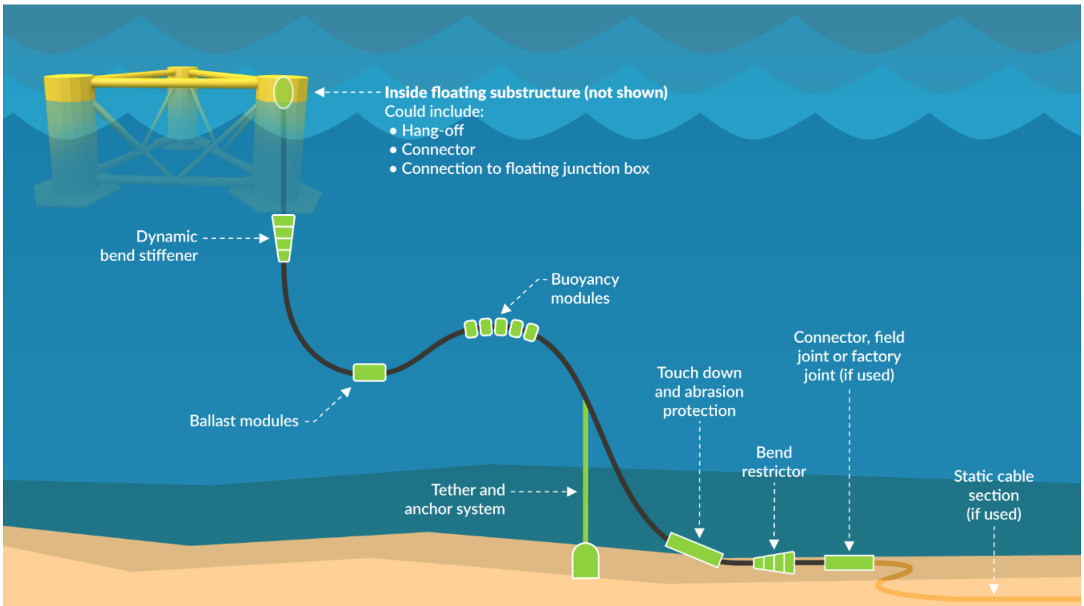


Figure 2.8: Inter-turbine cable dynamics display. [65]

2.4.1.2 Offshore Substations

Offshore substations are vital for improving energy transmission efficiency from wind farms to the onshore grid. Their primary function is to step up the voltage of electricity generated by turbines, minimizing electrical losses during transmission. While smaller, closer-to-shore projects (around 100 MW or less, within 15 km of the coast) may not require substations, larger and more remote offshore wind farms are increasingly incorporating them. These substations typically increase voltage from 30-36 kV to 100-220 kV, reducing the number of subsea export circuits needed. For very distant projects, high-voltage direct current (HVDC) transmission is becoming a more viable option, requiring converter stations both offshore and onshore. Offshore substations house critical equipment like transformers, power factor compensation systems, and switchgear, ensuring efficient and safe power transmission while minimizing losses [66, 67, 68].

2.4.1.3 Export Cables

Export cables are crucial for connecting offshore wind farms to the onshore grid, transmitting generated power, providing auxiliary power, and enabling fiber communications. High voltage alternating current (HVAC) export cables, typically rated at 220 kV, can transmit around 300 MW per three-core subsea cable, with future projects potentially increasing this to 275 kV for better cost efficiency. Smaller near-shore projects may use medium voltage alternating current (MVAC) cables, but these are less common in large commercial-scale farms [69].

For larger offshore projects (over 1 GW and located more than 80-100 km from shore), HVDC cables are preferred as they minimize reactive power losses, improving energy output. HVDC systems, using two single-core cables in a bipolar configuration, are lighter and less costly to install than HVAC systems. Though HVDC requires a higher initial investment, it can reduce overall export cable costs [70]. As shown in Figure 2.9, the initially higher cost of HVDC systems is offset by their lower costs over longer transmission distances.

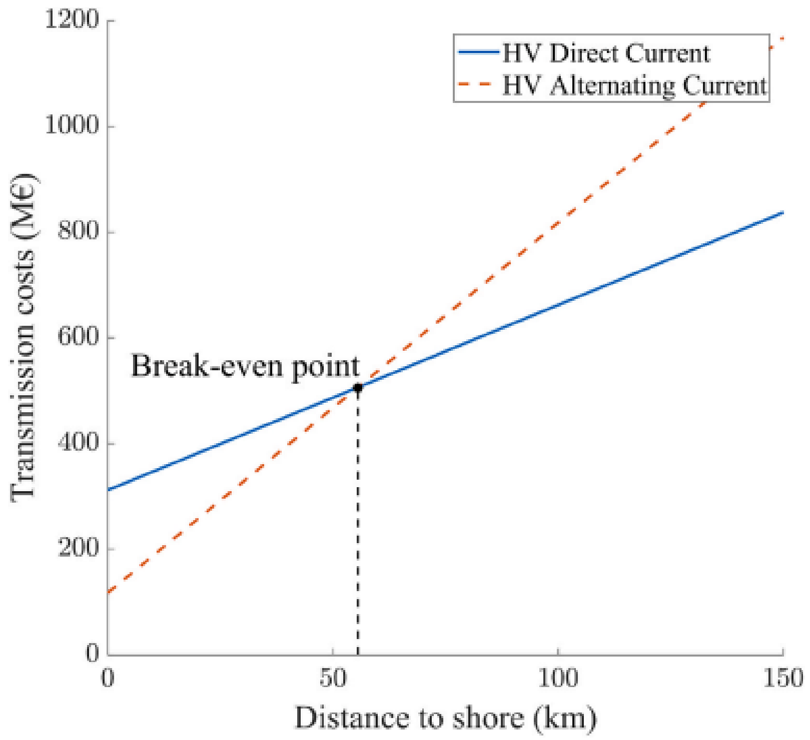


Figure 2.9: Cabling costs: HVAC vs HVDC. [71]

2.4.1.4 Onshore Substation

Onshore substations are essential in the wind energy system, converting power from the wind farm into grid-compatible voltage, often up to 400 kV. For projects using HVDC export cables, these substations also convert power to three-phase alternating current (AC), ensuring safe integration with the grid and providing fault protection [66].

Typically built before offshore work, onshore substations reduce the risk of stranded generation assets. Their components resemble those in offshore substations but without the same space and weight constraints. They also include metering equipment to track exported electricity. To improve installation efficiency, onshore substations are ideally located near the landfall of offshore export cables, although they can be up to 60 km inland. Land requirements are approximately 5 hectares for HVAC systems and 7.5 hectares for HVDC systems. Construction contracts are usually awarded to transmission system suppliers, with civil engineering firms handling much of the work [72].

2.4.2 HVDC Systems

When it comes to transmitting power, there are two primary systems: High Voltage Direct Current (HVDC) and High Voltage Alternating Current (HVAC). Both are used to transmit electricity over long distances, but they have distinct advantages and applications, especially in the context of modern renewable energy projects.

2.4.2.1 Differences Between HVDC and HVAC

- **Power Losses**: HVAC systems experience higher transmission losses due to effects like the "skin" and "corona" effects, especially over long distances. In contrast, HVDC has significantly lower losses, making it more efficient for long-distance power transmission.

- **Cost and Equipment**: While HVAC systems are more cost-effective for short distances, HVDC requires specialized equipment, such as rectifiers and inverters, making it more expensive. However, beyond a certain distance (around 400-500 km), HVDC becomes more economical due to its lower transmission losses.

- **Distance Efficiency**: HVAC is preferred for short distances due to lower initial costs, while HVDC is more efficient for distances over 500-600 km, making it ideal for offshore wind farms or remote energy sources.

- **Grid Synchronization**: HVDC can connect asynchronous grids with different frequencies, unlike HVAC. For example, HVDC is used to connect the UK and mainland Europe, which operate at different frequencies [73].

2.4.2.2 Why HVDC for Offshore Wind Farms?

Offshore wind farms, which are often located hundreds of kilometers from the coast, require a power transmission system that can minimize losses and efficiently transport large amounts of energy over long distances. HVDC is the preferred solution for several key reasons:

- **Efficiency in Long-Distance Transmission**: Offshore wind farms are often located far from shore, where traditional HVAC systems would incur significant energy losses. HVDC is more efficient and cost-effective for transmitting electricity over long distances, typically beyond 400 km, making it the ideal solution for delivering energy to the mainland.

- **Efficient Use of Space and Material**: HVDC cables are smaller in diameter than HVAC cables for the same power capacity, reducing space and material costs for submarine cables, a key factor for offshore wind applications [74].

- **Synchronous Independence**: HVDC systems can connect offshore wind farms to different national grids operating at different frequencies, providing flexibility, especially in Europe with multiple asynchronous zones.
- **Blackstart Capability**: HVDC systems have blackstart capability, allowing wind farms to restart production after a blackout without relying on the grid. This feature is crucial for grid restoration, ensuring fast recovery and stability [75].
- **Case Studies**: Projects like NordLink and North Sea Link demonstrate HVDC systems' ability to transport renewable energy over long distances, proving their effectiveness in large-scale offshore wind integration [74].

Considering the various constraints associated with offshore wind farms located far from shore, the typical configuration of such a wind farm connected to the shore via an HVDC system is illustrated in Figure 2.10:

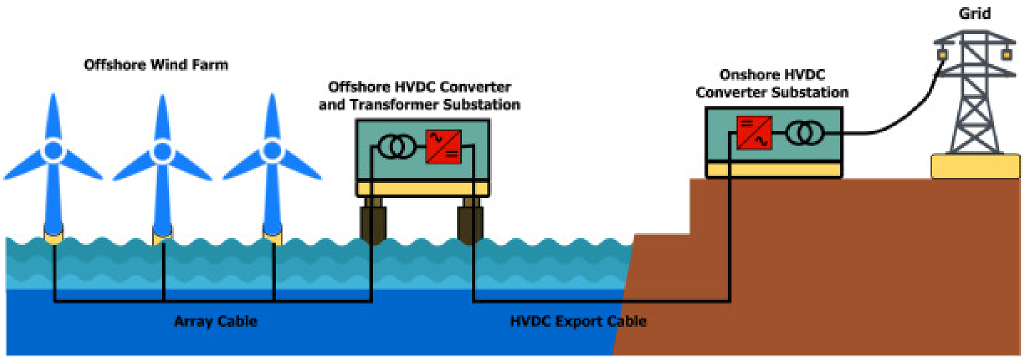


Figure 2.10: Typical configuration of an offshore wind farm connected to shore by an HVDC system. [76]

In conclusion, while HVAC may be a cost-effective solution for shorter transmission distances, HVDC is essential for long-distance, high-capacity renewable energy projects like offshore wind farms. Its reduced transmission losses, capability to connect asynchronous grids, blackstart features, and efficient use of materials make it the preferred choice for modern offshore energy infrastructure [77].

Chapter 3

Regulatory Framework, International Case Studies, and Future Perspectives

This chapter describes the main regulatory, political, and economic features required for the development and expansion of offshore wind energy, with a particular focus on Portugal. It begins by examining the European and national regulatory frameworks, alongside the processes for licensing and maritime concessions, which are crucial for facilitating offshore wind projects. Next, it explores case studies from leading countries, such as the United Kingdom, Germany, and Denmark, to draw valuable lessons that can inform Portugal's approach to offshore wind energy. Finally, it discusses future scenarios for the sector, including growth projections, new projects in Portugal, and the integration of offshore wind with other renewable technologies, highlighting the potential for further expansion and innovation. The chapter aims to provide a comprehensive understanding of the key factors shaping the future of offshore wind energy.

3.1 Regulatory and Political Aspects

3.1.1 European and national regulatory framework

The EU is committed to expanding offshore wind power as part of its strategy for climate neutrality by 2050, as outlined in the European Green Deal. The EU aims for 60 GW of offshore wind by 2030 and 300 GW by 2050, with additional targets for ocean energy, as depicted in Figure 3.1, shown below. However, challenges remain, as only 12 GW was installed by 2020.

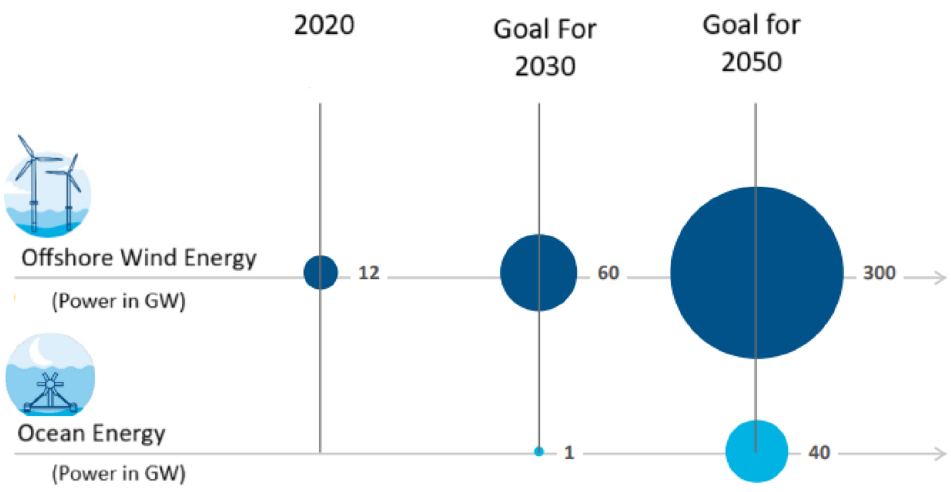


Figure 3.1: European Union's goals for maritime renewables. [78]

The EU promotes the development of offshore renewables through the Marine Spatial Planning (MSP) Directive, which calls for member states to establish maritime spatial plans that designate areas for renewable energy. The European Commission encourages member states to use maritime spatial planning to develop offshore energy resources, ensuring that environmental, social, and economic impacts are considered. This helps to coordinate offshore renewable energy projects with other marine activities such as fishing and shipping, while also promoting public acceptance. The Commission supports national authorities by creating platforms for knowledge exchange and developing guidelines to manage sectoral conflicts. It also encourages cross-border cooperation to optimize shared marine resources [78].

3.1.1.1 Portugal's Offshore Wind Policies

Portugal has aligned its offshore wind energy development with the EU's regulatory framework and climate goals, integrating these into its energy transition strategy. The country's PNEC2030 emphasizes the role of offshore wind in increasing the renewable energy share. Portugal has established working groups to set capacity targets, conduct environmental assessments, and streamline the tender and licensing processes for offshore projects. The government is also addressing spatial conflicts through maritime spatial planning, ensuring sustainable development alongside other maritime activities. Both Portugal and the EU are committed to fostering offshore renewable energy growth through strategic policies and regulatory frameworks, with cross-border cooperation being essential to overcoming challenges and maximizing offshore wind potential [79].

3.1.2 Licensing and maritime concessions

The deployment of offshore wind energy projects in Portugal, as in many other countries, requires a complex and multi-step licensing process, involving several legal, environmental, and maritime rights considerations. Before the installation of wind turbines or other infrastructure at sea, developers must navigate a thorough regulatory framework to ensure that projects are compliant with national and European Union guidelines, including environmental impact assessments, maritime spatial planning, and public consultation.

3.1.2.1 Licensing Process in Portugal

In Portugal, the offshore wind energy development process begins with identifying suitable zones based on wind speed, water depth, and existing maritime uses like fishing and shipping. These zones are defined in the country's Maritime Spatial Plan (MSP), in line with the EU's Directive, ensuring sustainable planning. A first auction is foreseen between developers to assure seabed rights for specific blocks within the before mentioned zones. Developers will conduct their assessments concerning wind resource, geophysical variables, geotechnics, grid impact, as well as a mandatory Environmental Impact Assessment (EIA) evaluating the project's potential environmental impacts, such as on marine ecosystems and biodiversity. After EIA approval, developers can apply for a maritime concession. The process also involves legal requirements for maritime rights and public consultation, ensuring compatibility with other sectors, though this can extend approval timelines. Within the time frame set by the Portuguese State, and if compliant with the technical and financial requirements, the blocks will be considered in a second auction in which they should compete between them. The criteria for awarding is not defined but electricity prices and local content will surely be part of the most relevant.

3.1.2.2 Delays and Challenges

Portugal's strong commitment to renewable energy is hindered by lengthy licensing procedures, posing a significant challenge to the rapid development of offshore wind farms. The process, which involves multiple agencies and extensive environmental and spatial assessments, can take 8–10 years from initial site tendering to project commissioning. This issue is not unique to Portugal; the European Court of Auditors highlights similar bottlenecks across Europe [80].

Portugal's licensing procedures are particularly slow compared to other EU countries. Germany, for example, employs a "one-stop-shop" model that centralizes permitting processes under a single authority, significantly reducing approval times. The Netherlands also boasts a faster process, completing approvals in about four and a half years. Meanwhile, France has faced delays of up to 11 years, and Spain, still refining its licensing framework, lacks commercial experience in marine renewables.

To this end, the European Union has introduced regulatory reforms to try and cut through licensing bottlenecks for renewable energy projects. These reforms have focused on speeding up, simplifying, and making the process more transparent, enhancing cross-border cooperation, and reducing administrative burdens. Streamlined approaches, such as Germany's "one-stop-shop" model, could be of particular benefit in Portugal. This would help Portugal reach its renewable energy goals and contribute to the wider EU goals for the integration of renewable energy sources [78, 79]. The recent establishment of the Mission Structure for "Licensing Renewable Energy Projects 2030" [81] may play an important role in the development of this process.

3.2 Case Studies of Leading Countries

Examining the experiences of leading countries in offshore wind energy is essential for progress. These pioneers have overcome technical, regulatory, and financial challenges, setting the stage for global expansion. By studying their successes, we can learn effective strategies for large-scale deployment, efficient transmission systems, and grid integration. Additionally, understanding the challenges they faced offers valuable lessons for refining future strategies. This case study analysis will provide key insights to guide the development of offshore wind energy moving forward.

3.2.1 United Kingdom

The UK is a global leader in offshore wind energy, with the largest installed capacity of around 14 GW, accounting for 34% of global offshore wind installations. The country's long coastline and strong winds make it ideal for offshore development. The UK government aims for 50 GW of offshore wind by 2030.

Key to the UK's success is its evolving policy framework, starting with the Renewables Obligation Certificate (ROC) system, and later transitioning to the Contracts for Difference (CfD) mechanism in 2017, offering long-term contracts that provide price certainty for developers. The Third-Party Ownership model for offshore transmission helps reduce costs by requiring developers to sell infrastructure to Offshore Transmission Owners (OFTOs) through a competitive process regulated by Ofgem. The Transmission Network Use of System (TNUoS) charge also finances grid expansion but adds to developers' costs.

Summarizing, government policies have facilitated this progress by streamlining project consenting and regulatory approval processes [82, 83, 84].

3.2.2 Germany

Germany, the second-largest offshore wind market globally, aims to reach 15 GW by 2030 and 50 GW by 2035. Although Germany's wind energy strength is largely due to onshore wind, recent efforts have focused on expanding its offshore capacity.

Germany's early support for renewable energy began with the Feed-in Tariff (FiT) system, guaranteeing developers fixed prices for their electricity. Over time, the country transitioned to Power Purchase Agreement (PPA) auctions, promoting competitive pricing and reducing costs for offshore wind projects.

Germany has developed an integrated grid planning model to optimize onshore and offshore wind development. Transmission System Operators (TSOs) like TenneT and 50Hertz are responsible for building and operating offshore transmission infrastructure, creating a networked offshore grid that reduces environmental impact and improves efficiency [82, 83, 84].

3.2.3 Denmark

Denmark has been a pioneer in offshore wind energy, with its 1991 Vindeby project marking the world's first offshore wind farm. Today, Denmark aims to achieve 5 GW of offshore wind capacity by 2030, which will supply 80% of its peak electricity demand. The country's success is due to a stable regulatory framework and centralized site planning, where offshore sites are auctioned to developers through Power Purchase Agreements (PPAs). The Danish Transmission System Operator (TSO), Energinet, builds the offshore grid infrastructure and mitigates risks for developers by compensating for delays.

Denmark is considering evolving its model, potentially transitioning to developer-owned grids to foster competition and lower costs. The government has been crucial in driving Denmark's green transition, supporting initiatives such as the reform of the EU's carbon quota system to boost renewable energy investment. Denmark's economy has grown over 40% since 1990, while reducing carbon emissions significantly, positioning it as a leader in environmental sustainability.

Research and development investments have also been central to Denmark's success in wind technology, helping reduce costs and create a thriving green energy industry. The sector now employs over 31,000 people and is a key driver of Denmark's export economy, with green energy technology, particularly wind turbines, leading exports. Denmark's offshore wind model is being replicated globally, fostering international partnerships with countries like China, the U.S., and South Africa, further solidifying its role as a renewable energy leader.

In conclusion, Denmark's pioneering offshore wind role provides valuable lessons for nations aiming to accelerate their renewable energy transitions through stable policies, innovative grid systems, and international collaboration [83, 85].

3.2.4 Lessons and Innovations from the UK, Germany and Denmark

The UK, Germany, and Denmark present distinct offshore wind development models, each offering valuable lessons in advancing renewable energy. The UK's developer-driven approach and market-based CfD auction system have enabled rapid project deployment, making it the world's leader in offshore wind. Germany's centralized grid planning and early support via FiTs have fostered strong technological development, although grid infrastructure limitations have constrained growth. Denmark's leading position in offshore wind exemplifies a model for how stable regulatory frameworks, central site planning, and government-led initiatives might minimize developer risk and foment international collaboration.

Denmark's success is particularly notable for its early investments in offshore wind, exemplified by the 1991 Vindeby project. The Danish model relies on centralized site planning and PPA - based auctions for efficient resource allocation and minimizes risks for developers. Moreover, Denmark's commitment to environmental sustainability and the country's thriving green energy sector underscore the importance of developing offshore wind in harmony with general climate and economic objectives.

These case studies show how different regulatory, financial, and technological approaches impact offshore wind development. The rapid deployment and competition strategy of the UK, the emphasis on grid integration and environmental management by Germany, and the innovative approach to centralized planning and risk mitigation in Denmark. Together, these examples highlight the need for a tailored policy framework, government support, and international cooperation to accelerate the transition toward renewable energy [82, 83, 84, 85].

3.2.5 Lessons for Portugal

Portugal, with its vast coastline and wind resources, is well positioned to become a major offshore wind energy player. However, it can learn valuable lessons from countries such as Denmark, the UK, Germany, and the Netherlands, which have successfully expanded their offshore wind sectors. These nations demonstrate the importance of scale and competition in driving down costs. Portugal can adopt competitive auctions and encourage diverse developers to reduce wind energy costs.

The offshore transmission model is another area where Portugal can benefit from global experience. Countries like Germany have shifted to centralized, TSO-led grid planning, reducing delays and costs, a model Portugal could implement to streamline its grid integration process. Long-term, visible grid planning is also crucial; Denmark and Germany's forward-looking approaches have provided developers with confidence, and Portugal must similarly plan its offshore wind integration into both onshore grids and potential cross-border connections with Spain.

Regional collaboration, as seen in the North Sea Wind Power Hub, has helped balance renewable energy generation and reduce redundancy. Portugal could explore similar co-operation with Spain or other Mediterranean countries. Denmark's MSP offers another important lesson, as strategic environmental assessments and stakeholder engagement ensure sustainable offshore wind development, a crucial consideration for Portugal's rich bio-diversity coastline [83].

Financial mechanisms, like those in Denmark, help reduce risks for developers. Portugal should consider options such as government-backed guarantees and public-private partnerships to make offshore wind more attractive to investors. Tailoring policies to Portugal's specific conditions, while drawing on successful elements from other countries, will be essential. For example, a more networked or TSO-led model might work better for Portugal than the UK's project-by-project approach.

In conclusion, by fostering competition, adopting long-term planning, ensuring regional collaboration, and tailoring policies, Portugal can accelerate offshore wind deployment and become a leader in renewable energy. With careful, strategic development, offshore wind could be a cornerstone of Portugal's energy future [83, 86, 87].

3.3 Future Scenarios and Expansion Potential

3.3.1 Growth projections

Portugal's offshore wind sector is growing, although recent revisions to the PNEC2030 have adjusted the country's targets. Initially established at 10 GW of installed offshore wind capacity by 2030, the target was reduced to 2 GW in July 2024 due to delays in the supply chain, extended project timelines, and lengthy bureaucratic processes involved in auctions and licensing procedures [79].

Despite this reduction, Portugal remains committed to its broader renewable energy goals, aiming for 80% of its electricity coming from renewables by 2026, with offshore wind playing a key role in the long term. To accelerate progress, the government formed a specialized working group in late 2022 to identify priority areas for offshore wind development, set capacity goals, and prepare tenders for upcoming projects. Although large-scale offshore wind auctions have been delayed, they are expected to progress once these challenges are addressed [88, 89].

3.3.2 Projects in Portugal

Portugal has significant potential in offshore wind energy, with several projects in development. Notable among these are WindFloat 1, a successful prototype, and WindFloat Atlantic (WFA), the first commercial-scale floating wind farm in Europe. Both projects represent important steps forward as the country works to expand its offshore wind capacity.

3.3.2.1 WindFloat 1: The Prototype

WindFloat 1, installed in 2011 off Póvoa de Varzim, was the first project to combine a floating wind turbine with a semi-submersible platform, featuring a 2 MW Vestas V-80 turbine. It successfully demonstrated the potential of floating offshore wind technology, delivering over 17 GWh of energy between 2011 and 2016 and withstanding extreme Atlantic Ocean conditions, including waves over 17 meters tall and winds exceeding 60 knots. Its decommissioning in 2016 also showcased the safe disassembly and relocation of such structures, proving the viability of floating wind technology in deep waters and paving the way for commercial projects [90, 91].

3.3.2.2 WindFloat Atlantic

Building on WindFloat 1's success, the WindFloat Atlantic (WFA) project, installed 20 kilometers off Viana do Castelo, is Europe's first commercial-scale floating offshore wind farm. It consists of three turbines with a total capacity of 25 MW, yielding an amount of electricity equivalent to the demand of 60000 households. WFA introduces cost-effective innovations, such as onshore assembly of turbines using conventional cranes and towing platforms with tugboats, reducing deployment costs. The project received significant financial support, including a €60 million loan from the European Investment Bank and funding from the EU NER300 program and the Portuguese government, advancing floating wind technology and setting the stage for future offshore projects in Portugal [92].

3.3.3 Integration with other renewable technologies

Portugal is also active in developing the offshore energy sector through the introduction of a mix of renewable technologies. In the development of hybrid systems that combine wave, tidal, and solar energy, the prospect of higher and consistent year-round electricity production is brighter than the advancement of offshore wind projects. The matching of resource availability seasonality, such as wind in winter and solar energy in summer, will result in increased energy output and reliability in power supply. This would mean lower costs through combining floating solar panels with offshore wind farms or co-locating grid connections onshore across a number of technologies. Successful tests of floating solar technology in marine settings and showing its potential to complement offshore wind also support this approach [6].

3.3.3.1 The C4 Wave Energy Converter at Aguçadoura

The C4 Wave Energy Converter, to be assembled at Aguçadoura, is a promising project developed by CorPower Ocean to harness wave energy. With a total capacity of 1.2 MW, it is designed to withstand the harsh Atlantic conditions while efficiently extracting energy from ocean waves. Located near the WindFloat Atlantic offshore wind park, the C4 system can integrate seamlessly with the wind farm's power export cable, enhancing energy production. This project illustrates the potential of hybrid renewable systems—combining offshore wind, wave, and solar technologies—to create a balanced and reliable energy supply in Portugal, supporting its renewable energy goals [93].

Chapter 4

Offshore Wind Resource in Portugal and Available Areas

This chapter examines the offshore wind resource potential in Portugal and the areas available for development. It begins with a characterization of wind conditions, including horizontal wind speed maps and productivity estimations, expressed in terms of number of hours equivalent to operation at nominal power. The chapter also explores the process of designating concession areas for offshore wind farms, highlighting the role of the governmental working group and the identification of high-potential zones. Together, these elements provide insight into Portugal's current status for offshore wind energy expansion.

4.1 Wind characterization in Portugal

A good understanding of wind resources is essential in the development of offshore wind energy projects, mainly to provide adequate estimates of energy production for an area of interest. In Portugal, such assessments benefit significantly from the detailed data provided by the national Wind Atlas [94], which compiles key metrics on wind patterns, strengths, and distribution. This chapter delves into the importance of this atlas, focusing on critical wind parameters and their implications for offshore wind farm planning and performance evaluation.

The Wind Atlas is a fundamental tool in the process of offshore wind energy planning. By providing extensive datasets on horizontal wind speed variations across different regions and elevations, the Atlas supports an informed approach to site selection, contributing to an optimized balance of energy output and operational efficiency. In the context of offshore wind, where installations require substantial investment and involve complex logistics, the selection of optimal locations based on high-quality wind data is particularly vital.

Portugal's coastal regions, where prevailing Atlantic winds are robust and relatively consistent, show great potential for offshore wind energy generation. This chapter introduces two figures from the Wind Atlas: one depicts the distribution of average annual horizontal wind speeds expected at 100 m above sea level (Figure 4.1) and the other shows the equivalent number of operational hours at nominal power output (Figure 4.2).

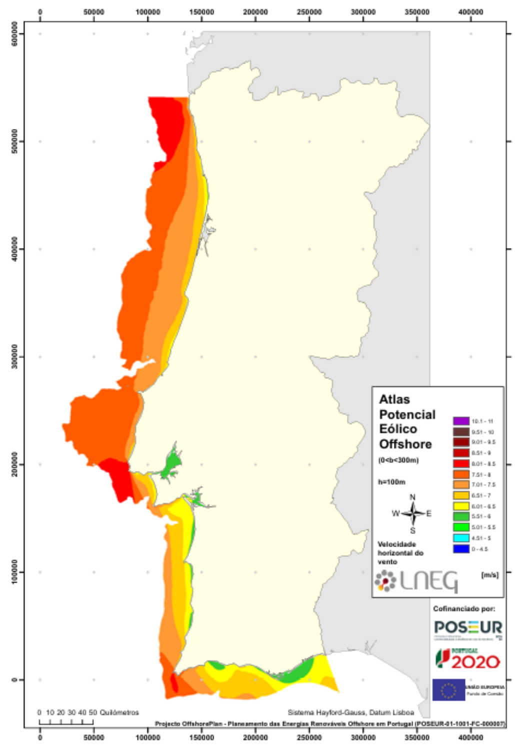


Figure 4.1: Average Horizontal Annual Wind Speed in Portugal at 100m a.s.l. [94]

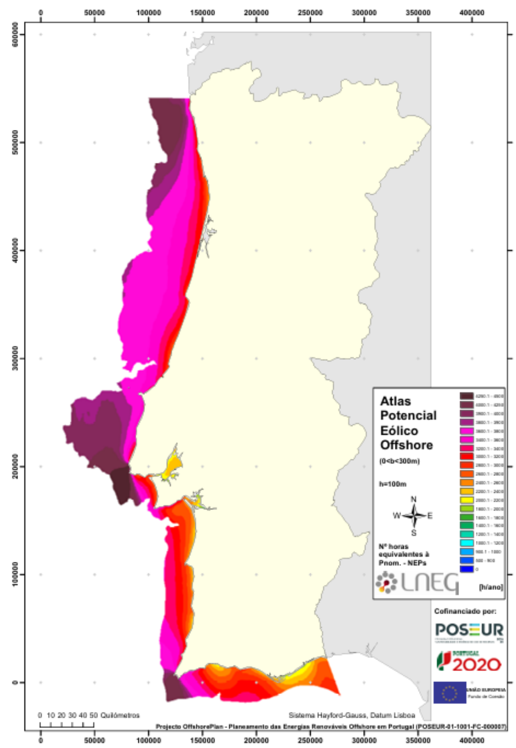


Figure 4.2: Productivity in terms of number of hours of Operation Equivalent to Nominal Power. [94]

4.1.1 Horizontal Wind Speed Map

Figure 4.1, illustrating horizontal wind speed distributions, offers a clear visualization of wind resources available along Portugal's coastline. Horizontal wind speed is a primary determinant of energy potential, directly affecting the operational output of wind turbines in a given area. Generally, higher and sustained wind speeds correlate with increased energy production, making regions with robust wind resources ideal candidates for offshore wind farms.

Analysis of the wind speed map demonstrates significant regional variation, with certain offshore locations exhibiting wind speeds consistently above the national average. In particular, coastal zones adjacent to Viana do Castelo and Figueira da Foz display promising wind characteristics, making them attractive for commercial wind energy projects. This data is instrumental not only for initial site selection but also for guiding investment, infrastructure development, and long-term operational planning.

4.1.2 Productivity in terms of number of hours of Operation Equivalent to Nominal Power

Figure 4.2 displays the productivity in terms of the number of hours of operation equivalent to nominal power for each region, commonly known as Pnom. It is a measure used in offshore wind energy that expresses the actual ability of a wind turbine or a farm to generate electric energy. It characterizes the whole energy produced over some time by the number of hours a turbine should work for at its nominal power to provide the same energy amount. It translates wind speed data into practical operational terms and normalizes productivity across varying wind conditions, thus enabling clear comparisons of performance between turbines or projects.

When selecting optimal locations for offshore wind farms, many wind characterization factors play a crucial role in evaluating the suitability and efficiency of a site. Key metrics such as the average wind speed and distribution, seasonal variability, and the number of hours equivalent to nominal power provide a solid basis for understanding energy yield potential and operational feasibility. Therefore, these wind characterization parameters—particularly those related to speed and duration—are indispensable in guiding effective site selection and enhancing the overall strategic planning for offshore wind energy projects in Portugal. However, it is important to note that when assessing local wind conditions, additional information such as the wind speed vertical profile, wind veer, turbulence intensity, and extreme wind speeds, among others, is essential for site evaluation purposes.

4.2 Concession areas for the operation of offshore wind farms

The establishment of well-defined concession areas is a critical step in developing a structured and sustainable offshore wind sector in Portugal. This structured approach is essential not only for maximizing wind resource efficiency but also for minimizing conflicts across various sectors, including tourism, fishing, and environmental conservation. By delineating concession zones, regulatory authorities provide offshore wind developers with clear boundaries that facilitate simplified permitting processes, regulatory predictability, and ultimately, sustainable energy production.

In setting these concession areas, extensive communication and stakeholder involvement are essential. Transparent dialogue with communities, local businesses, and environmental stakeholders helps mitigate concerns and fosters a more collaborative atmosphere. By including input from various sectors early in the planning phase, the government aims to create a balanced and fair framework that accommodates the interests of impacted groups while also advancing Portugal's renewable energy ambitions.

4.2.1 Formation of the Governmental Working Group

Recognizing the complexity of offshore wind development, the Portuguese State formalized a working group [88] specifically tasked with addressing the unique challenges and opportunities presented by this industry. This multidisciplinary team was entrusted with a comprehensive mandate: to assess optimal locations for offshore wind concession areas, evaluate necessary port and grid infrastructure, and develop a strategic plan for offshore logistics. Their efforts have helped to build a foundational framework for offshore wind development in Portugal, focusing on areas with high wind potential and manageable environmental impacts.

The working group's findings, though iterative and subject to periodic re-evaluation, provide a critical starting point for understanding the interaction between offshore wind energy and other sectors. They illustrate the importance of a multi-sectoral approach, bringing together experts in energy, marine biology, logistics, and environmental sciences to generate a holistic strategy. As a result of the projects developed by the working group, the proposed areas are presented in Figure 4.3 and detailed in Table 4.1:

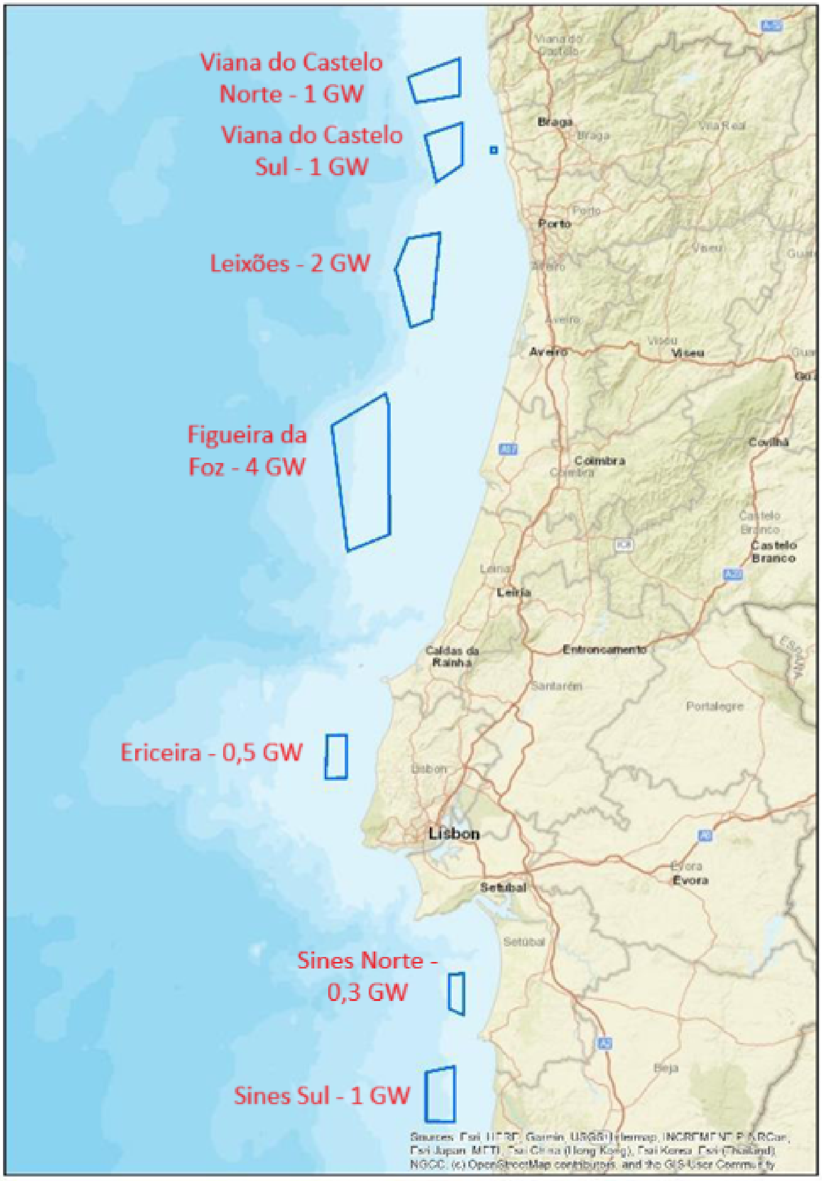


Figure 4.3: Proposed areas and their indicative potential. [88]

Table 4.1: New Areas Proposed for Offshore Wind Energy Exploration in Portugal. [88]

New Proposed Areas	Area [km^2]	Distance to shore [km]	Generating Cap. [GW]	N. of Lots
Viana do Castelo Norte	301	12,8 – 36,1	1,01	2
Viana do Castelo Sul	294	19,4 – 33,2	0,99	2
Leixões	644	41,7 – 59.8	2	4
Figueira da Foz	1325	40,2 – 63,2	4	8
Ericeira	171	13,9 – 23,0	0,5	1
Sines Norte	102	21,3 – 32,0	0,3	1
Sines Sul	287	15,2 – 19,6	1	2
Total	**3124**	—	**9,8**	**20**

Offshore wind energy technologies have evolved significantly in recent years, with floating turbine platforms expanding the geographic scope of feasible wind energy locations. Historically, offshore wind development was largely restricted to shallow coastal waters, often less than 50 meters deep, due to the technical and economic limitations of fixed-bottom turbines. However, recent advancements in floating turbine technology allow for installation in deeper waters, thus increasing the potential exploitation areas and reducing visual impacts on coastal landscapes. This flexibility provides opportunities to move concession areas further offshore, diminishing the potential conflicts with coastal industries while maximizing wind resource capture in high-wind zones.

As technology continues to advance, concession zones will require periodic re-evaluation to align with new capabilities and opportunities. The ability to adapt to these technological shifts is essential for sustaining long-term growth in the sector and optimizing Portugal's offshore wind resources.

4.2.2 Identification of High-Potential Concession Areas

After thorough analysis and evaluation, the working group identified four primary regions that hold significant potential for offshore wind energy development: **Viana do Castelo Norte, Viana de Castelo Sul, Leixões e Figueira da Foz** [95]. Each of these areas was selected based on a range of criteria, including wind resource availability, infrastructure readiness, and environmental impact considerations.

The selection process involved detailed spatial analysis, consultations with local communities, and a thorough review of ecological data. Each of these factors contributed to the identification of these zones as suitable for offshore wind development, balancing wind energy potential with sustainable site selection.

To illustrate the assessment steps, a process diagram (Figure 4.4) can be provided, showcasing how factors like wind speed, proximity to existing grid infrastructure, and local marine biodiversity were prioritized.

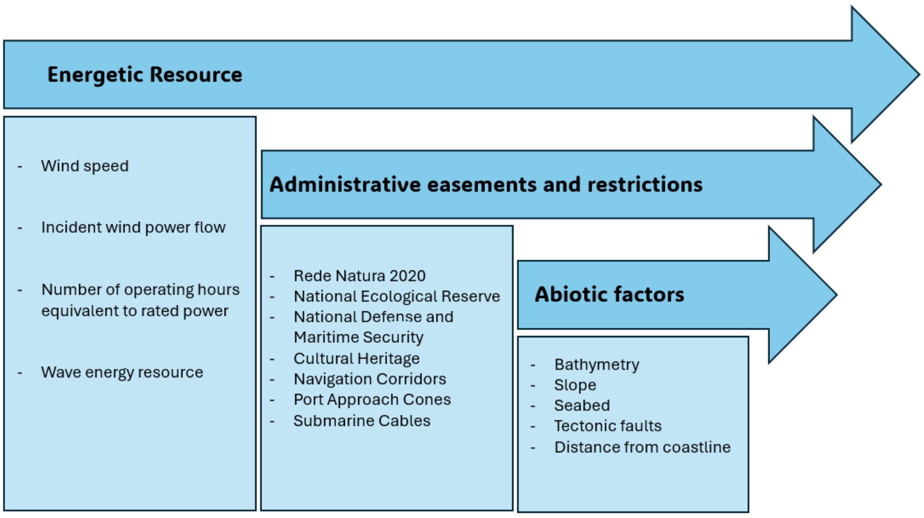


Figure 4.4: Initial process of identifying potential areas for the use of renewable energy. [88]

Additionally, a breakdown of selection criteria (Figure 4.5) will summarize why these areas were chosen.

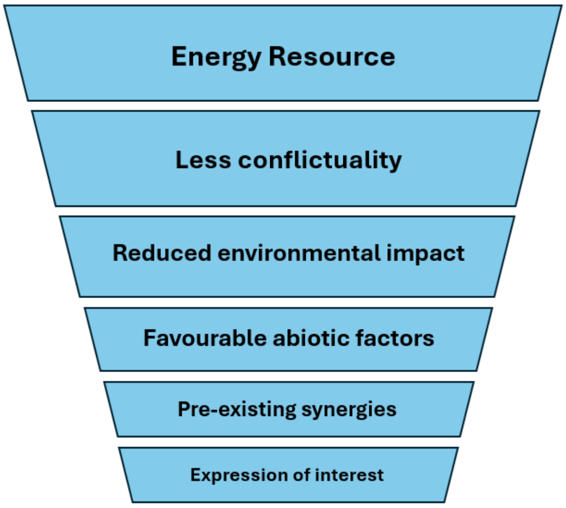


Figure 4.5: Criteria used to select preferred areas. [88]

Chapter 5

Methodology for assessing wind energy potential

This chapter describes the methodological framework adopted to select the areas of interest and to assess the offshore wind energy potential of Portugal, covering the systematic approach, tools, and techniques used to achieve the results presented in subsequent chapters. The methodology was divided into two main areas of focus: simulating atmospheric flow behavior using WAsP and evaluating installable capacity and turbine technology. Each step of the process is documented in detail to ensure transparency and replicability.

5.1 Selection of areas to be studied

In previous sections, the promising regions for offshore wind energy potential in Portugal were identified, based on the recommendations of the government's working group. These areas — Viana do Castelo Norte, Viana do Castelo Sul, Leixões, and Figueira da Foz — were highlighted as optimal locations due to their wind energy potential. However, upon closer examination, it became evident that these areas share highly similar wind regimes, characterized by comparable wind speeds, wind frequency distributions, and power densities. As a result, analyzing these regions would lead to repetitive methodologies and findings.

To introduce greater diversity and complexity into the analysis, two specific areas were selected for study: **Viana do Castelo Norte** and **Sines Sul**. This selection was made to avoid redundancy while ensuring that the analysis encompassed a range of wind dynamics.

The Viana do Castelo Norte area represents the northern regions identified by the working group, while Sines Sul was chosen for its distinct wind regime from the regions on the north and its significant potential for installed power capacity. This contrast provides an opportunity to study offshore wind energy potential in two areas with differing characteristics, offering a more comprehensive understanding of Portugal's offshore wind energy landscape.

This approach reflects a deliberate effort to balance alignment with government recommendations while expanding the scope of the study to include a more diverse range of conditions. Visual comparisons, as wind frequency roses, will be presented below (Figures 5.1 and 5.2) to illustrate the differences in wind regimes between the selected areas [96].

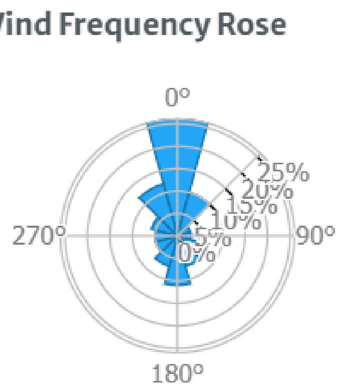


Figure 5.1: Viana do Castelo Norte's Wind Frequency Rose. [96]

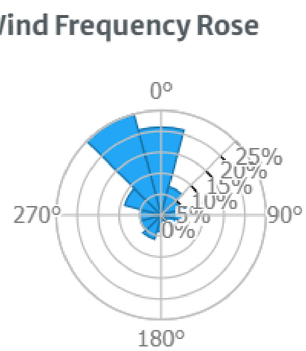


Figure 5.2: Sines Sul's Wind Frequency Rose. [96]

The average annual distribution of mean velocity differs between Viana do Castelo Norte and Sines Sul. Combined with the wind roses provided, this distinction could significantly influence the outcomes of the simulations to be conducted. This distribution is illustrated in Figure 5.3:

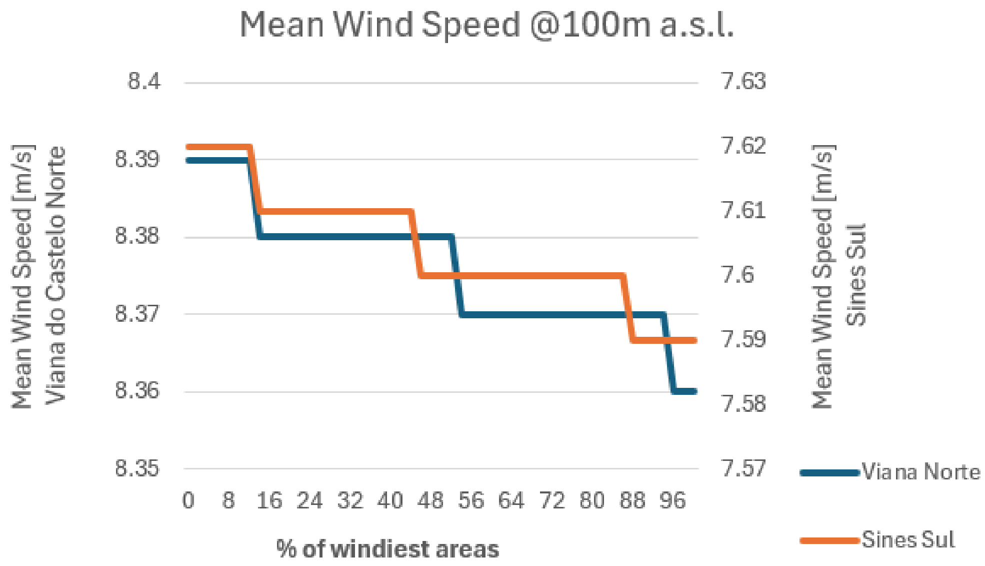


Figure 5.3: Distribution of the Mean Wind Speed at 100 m a.s.l. in Viana do Castelo Norte and Sines Sul. [96]

5.2 Simulating atmospheric flow behavior with WAsP

5.2.1 Identifying and Analyzing Exploration Areas

The first phase involved analyzing predefined areas for offshore wind energy development. Key parameters, such as mean wind speed, wind speed variability, and the number of hours equivalent to nominal power, were used to evaluate the potential of these areas. These metrics, derived from Laboratório Nacional de Energia e Geologia (LNEG) wind resource maps, were presented in Figures 4.1 and 4.2 of the previous chapter, providing an initial understanding of wind resource quality in the designated areas.

To complement the LNEG maps, additional wind behavior data from the Global Wind Atlas (GWA) was consulted, offering detailed insights into diurnal and seasonal wind patterns, as well as wind frequency, speed, and power roses. The GWA datasets are developed using a combination of high-resolution numerical modeling, observational data, and statistical corrections to ensure reliability, particularly in offshore environments. The process begins with global atmospheric datasets, such as those from the European Center for Medium-Range Weather Forecasts (ECMWF), which simulate large-scale wind conditions at a coarse resolution. These datasets are refined through mesoscale modeling, a downscaling process that increases spatial resolution to approximately 3x3 km. This refinement captures critical offshore wind dynamics, including the influence of sea surface temperatures, ocean wave height, and marine boundary layer conditions.

To ensure accuracy, these models are calibrated and validated using observational data from sources such as offshore buoys, satellite scatterometers, and floating LIDAR systems.

Bias correction techniques and long-term climatological analysis further enhance the reliability of the GWA's wind resource data, making it representative of average conditions over 10–30 years. The resulting datasets provide key metrics, including mean wind speed, wind power density, and wind direction distributions at turbine-relevant heights like 50m, 100m, and 150m.

This comprehensive wind resource information was instrumental in designing wind farm layouts, as it highlighted crucial factors such as prevailing wind directions, intensity, and variability. By integrating the high-resolution wind data from the GWA with the initial findings from the LNEG maps, it was possible to create a more detailed and accurate assessment of wind resource potential in the designated offshore areas.

5.2.2 Geographic Mapping and UTM Coordinates

The geographic boundaries of each exploration area were defined using Google Earth Pro, where the perimeter of each region was marked and coordinates were extracted, as it is shown in Figure 5.4. These coordinates were converted into Universal Transverse Mercator (UTM) coordinates to ensure compatibility with mapping and simulation software. UTM coordinates are a planar coordinate system that divides the Earth into zones, each 6 degrees of longitude wide. Portugal falls within Zone 29, which spans 6 degrees west of the Greenwich Meridian. UTM coordinates consist of two main components:

- **Easting**: The distance (in meters) from the central meridian of the zone.
- **Northing**: The distance (in meters) from the equator.

This coordinate system ensures accurate mapping of offshore locations and facilitates precise data alignment in software like WAsP.

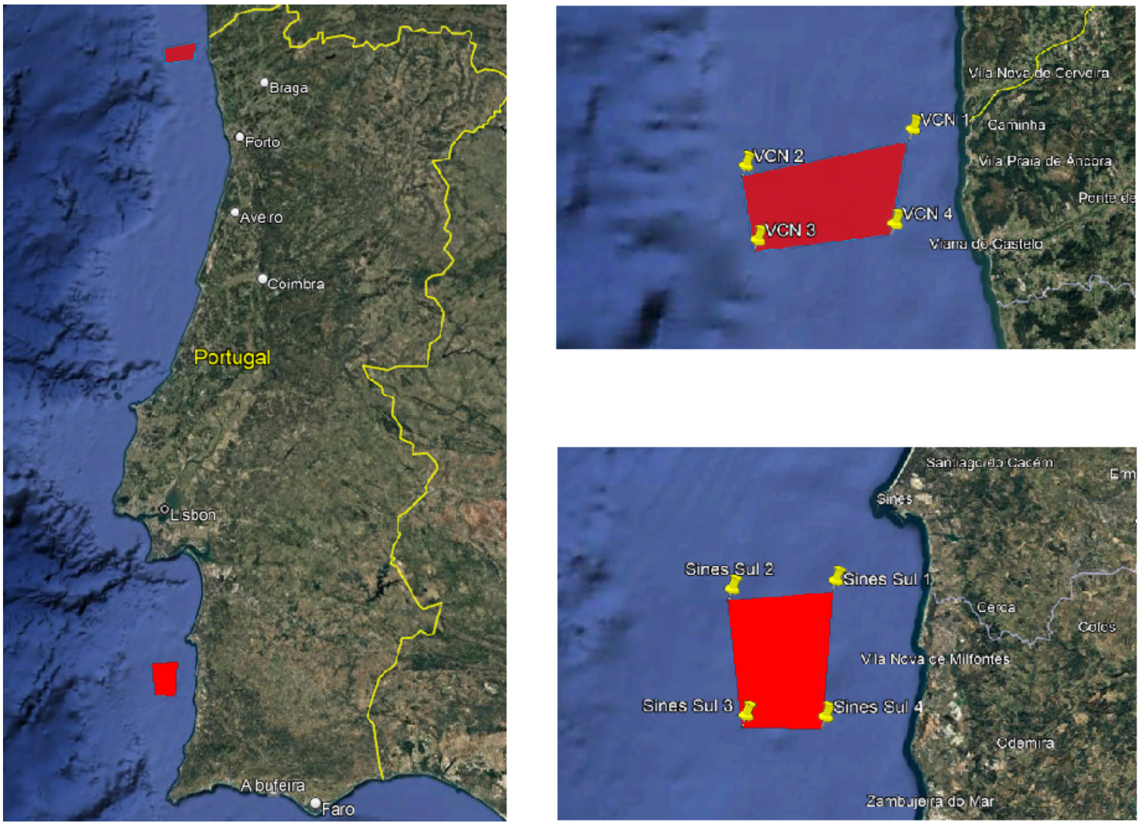
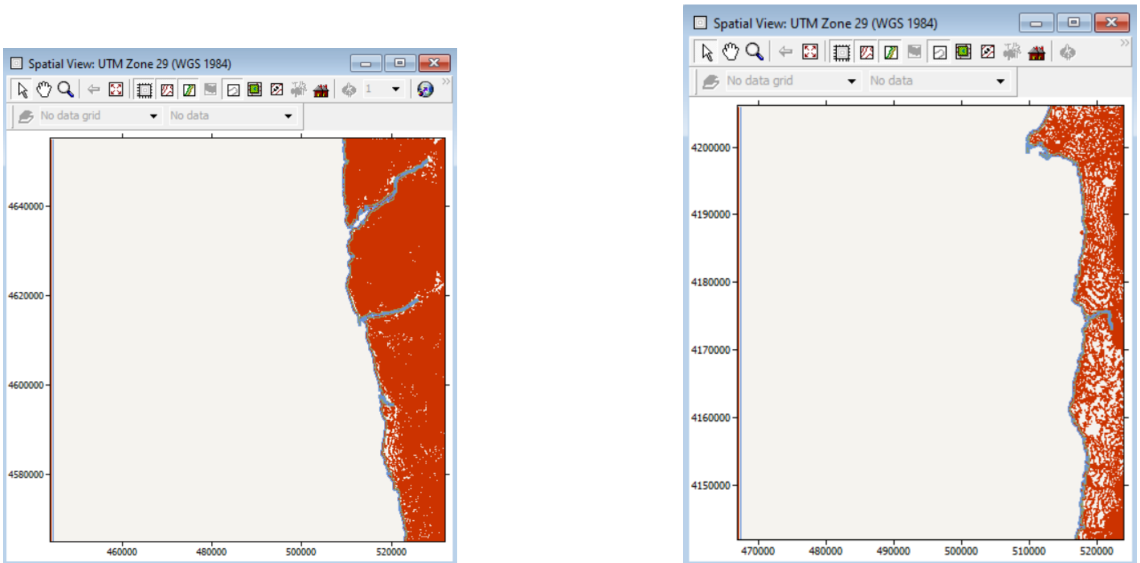


Figure 5.4: Areas to be studied projected in Google Earth Pro.

5.2.3 Defining and Delimiting the Exploration Area

Defining the boundaries of the exploration area was a critical step, as it directly influenced the accuracy of the climate report generated for the region. The designated area included not only the wind farm site but also an additional surrounding zone. This buffer area was incorporated to account for wind inflow from surrounding regions, improving the reliability of the climate report by capturing a broader range of wind patterns.

The resulting maps, represented below in Figure 5.5, created using the WAsP Map Editor, accurately represent the perimeter of the site and ensured all simulations were constrained to the appropriate geographic limits. This step ensured the data used for simulations reflected real-world conditions for the entire area under study.



(a) Digital Representation of the Map regarding Viana do Castelo Norte

(b) Digital Representation of the Map regarding Sines Sul

Figure 5.5: Resulting Maps

As observed in the presented Vector Maps, the ocean area is uniformly colored, with no vectors indicating variations in roughness length. This is expected, as the entire ocean surface is characterized by a uniform roughness length assumed to be zero.

5.2.4 Generating Turbine Site Locations

To position turbines within the exploration area, a systematic approach was developed to ensure turbine layouts met specific design criteria. Using Visual Basic for Applications (VBA) in Excel, multiple configurations of turbine placements were generated dynamically. Each layout adhered to different constraints:

- **Spacing Requirements**: Ensuring adequate distances between turbines to minimize wake losses.
- **Boundary Adherence**: Guaranteeing that turbines remained within the designated exploration area.
- **Variation in Layouts**: Generating different configurations to explore performance trade-offs.

The layouts created included:

- **Uniform Alignments**: Rows aligned along East-West and North-South directions.
- **Offset Patterns**: Alternating rows offset to reduce wake interference.
- **Rotated Configurations**: Layouts rotated at varying angles to match prevailing wind directions.

5.2.5 Simulations Using WAsP

The turbine site layouts were imported into WAsP (Wind Atlas Analysis and Application Program) for simulation. WAsP is a specialized tool for wind resource assessment and energy production estimation, allowing for detailed analysis of wind farm performance. Inputs to WAsP included:

- **Digital Maps**: Representing the offshore exploration area and its surroundings.
- **Climate Data**: Wind speed and frequency distributions for the area, derived from global wind resources and adjusted using site-specific data.
- **Turbine Specifications**: Technical parameters of the selected turbine models (detailed in the next section).

Simulations were run for each layout to calculate key performance indicators:

- **Energy Production**: Annual energy output for the entire wind farm.
- **Wake Losses**: Quantification of energy reduction due to turbine interference.
- **Capacity Factor**: Efficiency of the turbines under local wind conditions.

These results were compared to identify optimal configurations for energy yield and efficiency.

5.3 Installable capacity and technology used

5.3.1 Government-Defined Capacity

The installable capacity for each exploration area was defined by the working group established by the Portuguese Government. For the Viana do Castelo Norte region, the capacity was set at 1 GW, as well as for the Sines Sul region, based on an assessment of site-specific conditions, grid integration potential, and alignment with national renewable energy goals. This capacity served as a boundary condition for all simulations, determining the number of turbines deployed and influencing the layout design.

5.3.2 Selection of Turbine Models

The selection of turbine models for this study aimed to ensure broad applicability and unbiased results by avoiding the use of brand-specific turbines. Instead, three de-characterized models with rated capacities of 8 MW, 12 MW, and 16 MW were developed. These sizes reflect the trend in offshore wind energy toward larger turbines, enabling an analysis of the technical and economic impacts of increasing turbine scales.

5.3.2.1 Model Development in WAsP

Genereic turbine models were generated using the WAsP Turbine Editor, with input data prepared in Excel. Two key performance curves were generated according to the methodology presented in Annex D:

1. **Wind Speed-Power Curve**: Describing the turbine's power output at various wind speeds.
2. **Wind Speed-Thrust Coefficient Curve**: Representing aerodynamic loading as a function of wind speed.

Additional parameters were specified for each model:

- **Hub Height**: Reflecting typical offshore configurations for optimized energy capture.
- **Rotor Diameter**: Determining swept area and energy potential.
- **Rated Power**: Defined for each model (8 MW, 12 MW, and 16 MW).
- **Control System**: A pitch control system was selected for all turbines to manage power and protect the system under variable conditions.

The additional parameters of each turbine are specified in Table 5.1, presented below:

Table 5.1: Parameters of the Selected Wind Turbine Models

Turbine Model	Rotor Diameter [m]	Hub Height [m]	Rated Power [MW]
8 MW	177	119	8
12 MW	220	136	12
16 MW	251	163	16

The turbine files were then generated in WAsP and configured for subsequent simulations.

5.3.2.2 Implications of the Turbine Model Selection

The deliberate choice to de-characterize the turbine models and adopt a generalized approach ensures that the findings of this study are broadly applicable and not limited to the performance characteristics of specific turbine brands. The selected turbine capacities (8 MW, 12 MW, and 16 MW) align with the industry's trajectory toward larger turbines, enabling this study to provide valuable insights into the technical and economic implications of turbine scaling in offshore wind energy.

This methodical and transparent approach to turbine model selection and creation ensures the reliability and generalizability of the simulation results, contributing to the broader understanding of offshore wind energy system optimization.

5.3.3 Performance Evaluation

The performance of the selected wind turbine models was assessed through simulations conducted in WAsP, where key parameters were analyzed to evaluate the efficiency and productivity of each simulated scenario. These parameters were chosen to provide a comprehensive understanding of the turbines' operational performance and include:

1. **Total Net AEP** [**GWh**]: As defined by WAsP, the Annual Energy Production (AEP) is the total energy output expected from a wind turbine or wind farm, calculated after considering wake losses.

2. **Proportional Wake Losses** [%]: The percentage of energy lost due to wake effects, which occur when turbine airflow is disrupted by upstream turbines.

3. **Capacity Factor** [%]: The ratio of the annual energy output with the energy output over a year if the wind turbines operated at its rated capacity all year long.

4. **Number of Hours at Nominal Capacity**: The total number of hours per year in equivalent terms at its full capacity.

These metrics provide a holistic evaluation of the turbines, highlighting the impact of turbine size and layout on energy production, efficiency, and operational behavior. Each parameter's significance lies in its ability to measure specific aspects of turbine performance, from energy output to efficiency losses.

5.4 Scenarios Design and Configuration

This section outlines the different turbine layout scenarios analyzed in the study to evaluate the impact of turbine placement on energy production, wake losses, and overall efficiency. The configurations are designed based on varying spacing [97, 98], orientations, and offsets, with the goal of optimizing performance under the prevailing wind conditions in both Viana do Castelo Norte and Sines Sul.

5.4.1 Scenarios Explored in Viana do Castelo Norte

The Viana do Castelo wind farm was analyzed under three distinct scenarios to evaluate the impact of turbine placement on energy production, wake losses, and operational efficiency. Given that the prevailing wind direction is predominantly from the North-South axis, the layout of the turbines was deliberately designed to be perpendicular to this axis (aligned in the East-West direction) to minimize wake losses. The spacing of the turbines was carefully considered, with the downwind spacing defined in the Y direction (corresponding to the Northing coordinates in the UTM coordinate system) and the crosswind spacing defined in the X direction (corresponding to the Easting coordinates in the UTM coordinate system). Both spacings were expressed as multiples of the rotor diameter (D) to achieve optimal performance.

Each scenario description conducted in Viana do Castelo Norte is complemented by a digital representation of the region and the turbine locations. This facilitates a more comprehensive understanding of the wind farm's spatial configuration, orientation, and the proportion of the available area utilized. The digital representations corresponding to the three wind turbine types are presented in Annex E.

5.4.1.1 Scenario A: Baseline Configuration

- **Turbine Alignment**: Turbines are aligned in the East-West direction.
- **Spacing Configuration:**
  - Crosswind (X) Distance: 5 × D
  - Downwind (Y) Distance: 10 × D
- **Description**: This scenario represents a standard layout where turbines are spaced moderately in both the downwind (Y) and crosswind (X) directions. The 5 × D spacing in the X direction aims to balance land usage, while the 10 × D downwind distance provides sufficient separation between rows to minimize wake overlap. This straightforward alignment avoids any staggered turbine placement and serves as the baseline for comparison.

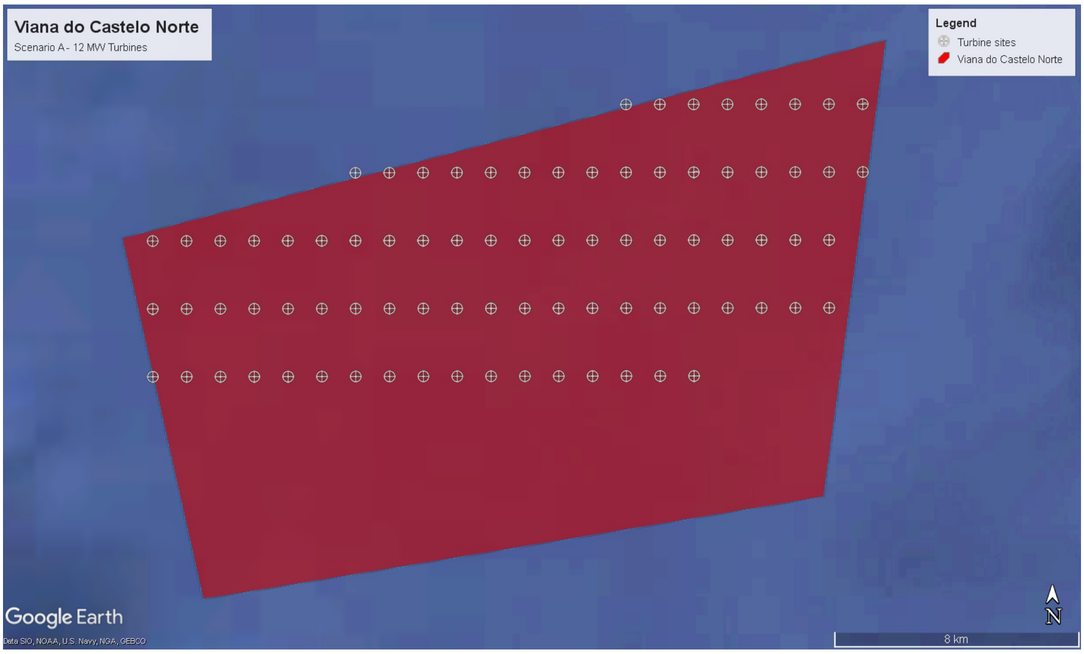


Figure 5.6: Digital Representation of Scenario A (12MW Wind Turbines).

5.4.1.2 Scenario B: Increased Downwind Spacing

- **Turbine Alignment**: Turbines are aligned in the East-West direction.
- **Spacing Configuration:**
  - Crosswind (X) Distance: 5 × D
  - Downwind (Y) Distance: 15 × D (increased from Scenario A)
- **Description**: This scenario modifies the baseline layout by increasing the downwind (Y) spacing from 10 × D to 15 × D, while keeping the crosswind (X) spacing at 5 × D. The increased downwind spacing allows for greater wake recovery between rows of turbines, reducing wake losses and improving energy capture efficiency. This configuration is particularly beneficial for scenarios where wake effects in the Y direction are the primary limiting factor on performance.

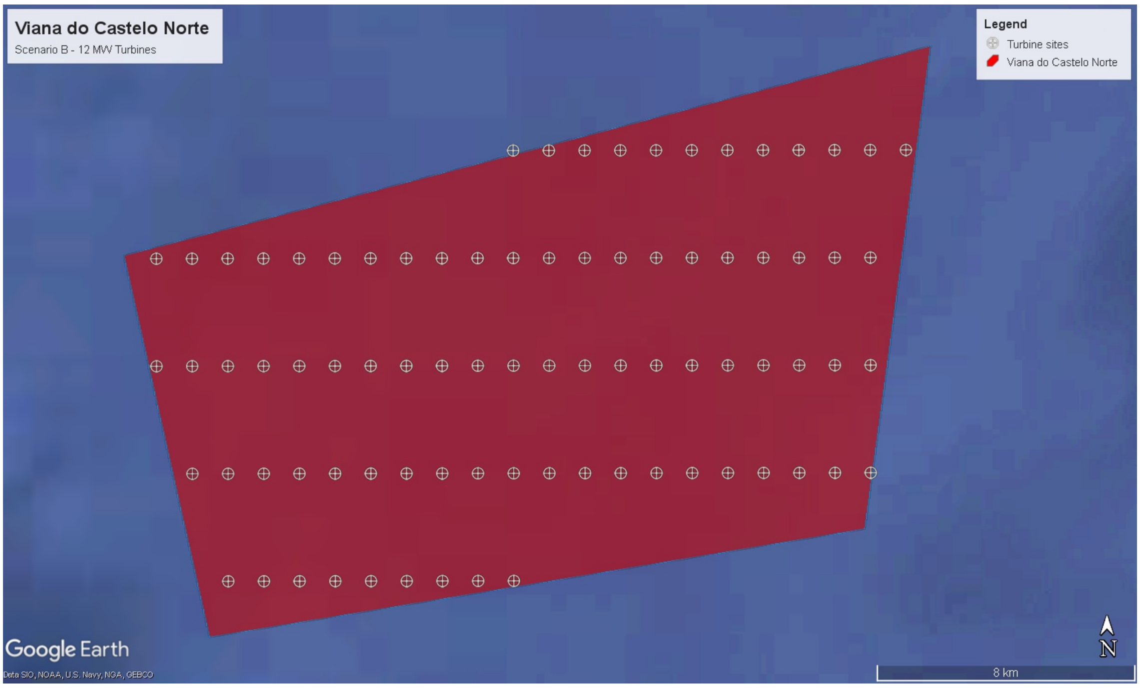


Figure 5.7: Digital Representation of Scenario B (12MW Wind Turbines).

5.4.1.3 Scenario C: Offset Row Configuration

- **Turbine Alignment**: Turbines are aligned in the East-West direction.
- **Spacing Configuration:**
  - Crosswind (X) Distance: 5 × D
  - Downwind (Y) Distance: 15 × D
  - Special Feature: Odd and even rows of turbines are offset in the X direction.
- **Description**: Building on Scenario B, this configuration retains the same crosswind and downwind spacing (5 × D and 15 × D, respectively) but introduces an offset in the X direction between odd and even rows. The staggered layout ensures that turbines in one row are not directly downwind from turbines in the preceding row. This configuration was designed to investigate whether offsetting rows could reduce the cumulative impact of wake losses under prevailing wind conditions and potentially enhance overall park efficiency.

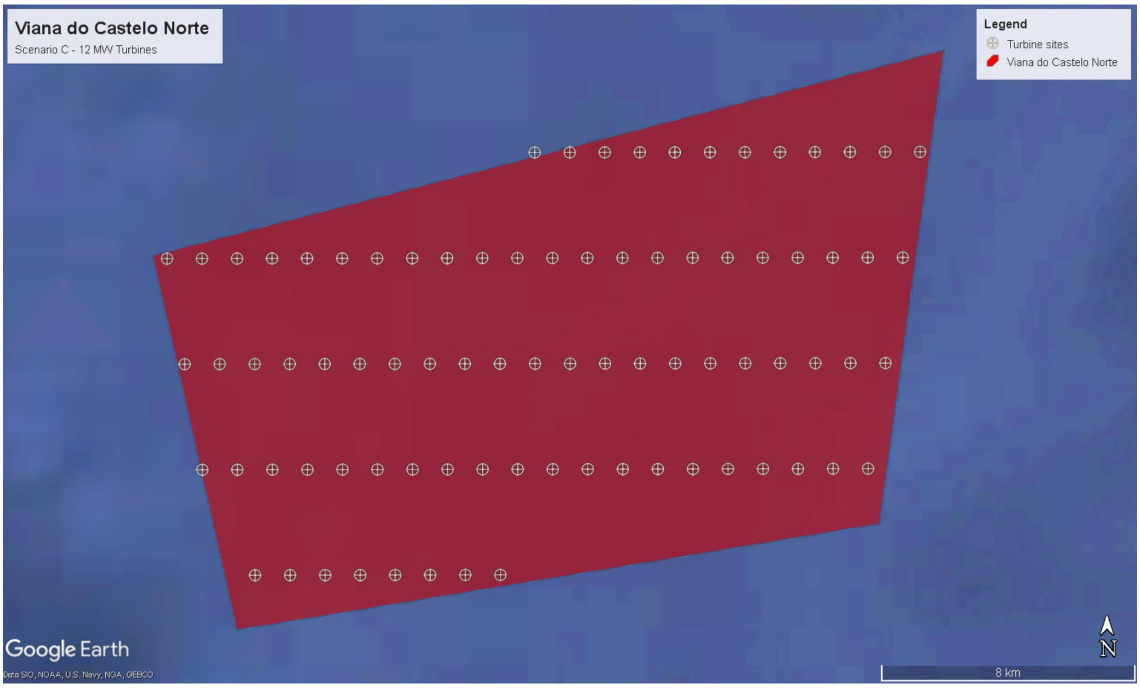


Figure 5.8: Digital Representation of Scenario C (12MW Wind Turbines).

5.4.2 Scenarios Explored in Sines Sul

The Sines Sul wind farm was analyzed under four distinct scenarios to explore how turbine placement, alignment, and rotation influence energy production and wake losses. With prevailing winds predominantly from the North (N) and North-Northwest (NNW), the layouts were specifically designed to optimize performance by minimizing wake interference while accounting for the region's variable wind directions.

Each scenario description conducted in Sines Sul is complemented by a digital representation of the region and the turbine locations. This facilitates a more comprehensive understanding of the wind farm's spatial configuration, orientation, and the proportion of the available area utilized. The digital representations corresponding to the three wind turbine types are presented in Annex F.

5.4.2.1 Scenario A: Baseline Configuration

- **Turbine Alignment**: Turbines are aligned in the East-West direction.
- **Spacing Configuration:**
  - Crosswind (X) Distance: 5 × D
  - Downwind (Y) Distance: 14 × D
- **Description**: This scenario features a standard layout with turbines evenly spaced, maintaining a 5 × D spacing in the crosswind direction and 14 × D in the downwind direction to balance land use and minimize wake overlap. It serves as the baseline for evaluating performance under prevailing wind conditions.

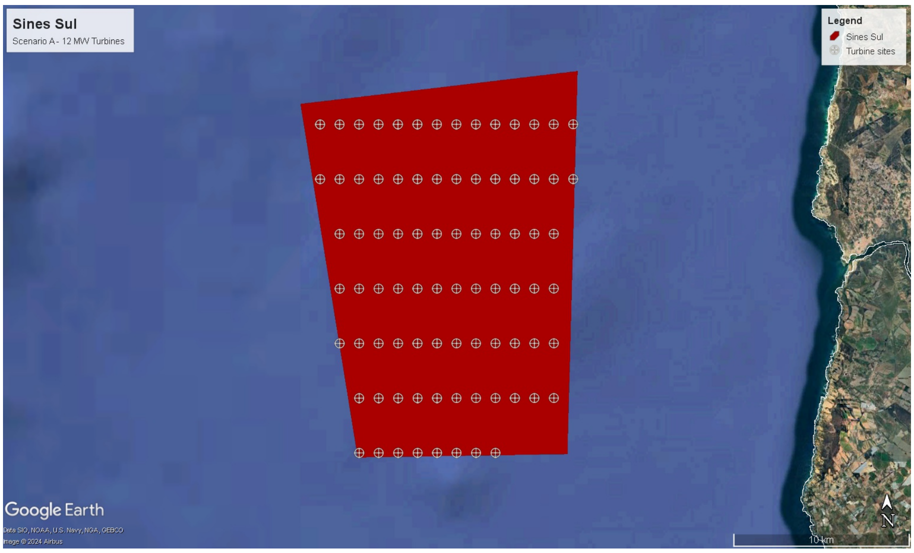


Figure 5.9: Digital Representation of Scenario A (12MW Wind Turbines).

5.4.2.2 Scenario B: Offset Row Configuration

- **Turbine Alignment**: Turbines are aligned in the East-West direction.
- **Spacing Configuration:**
  - Crosswind (X) Distance: 5 × D
  - Downwind (Y) Distance: 14 × D
  - Special Feature: Odd and even rows are offset in the X direction to minimize turbine alignment directly downwind of one another.
- **Description**: This scenario introduces a staggered row configuration, building on Scenario A. By offsetting rows in the X direction, the alignment of turbines directly downwind from each other is increased. This layout aims to test whether staggered rows can mitigate wake losses and enhance park efficiency, especially given the variability in the wind direction from N and NNW.

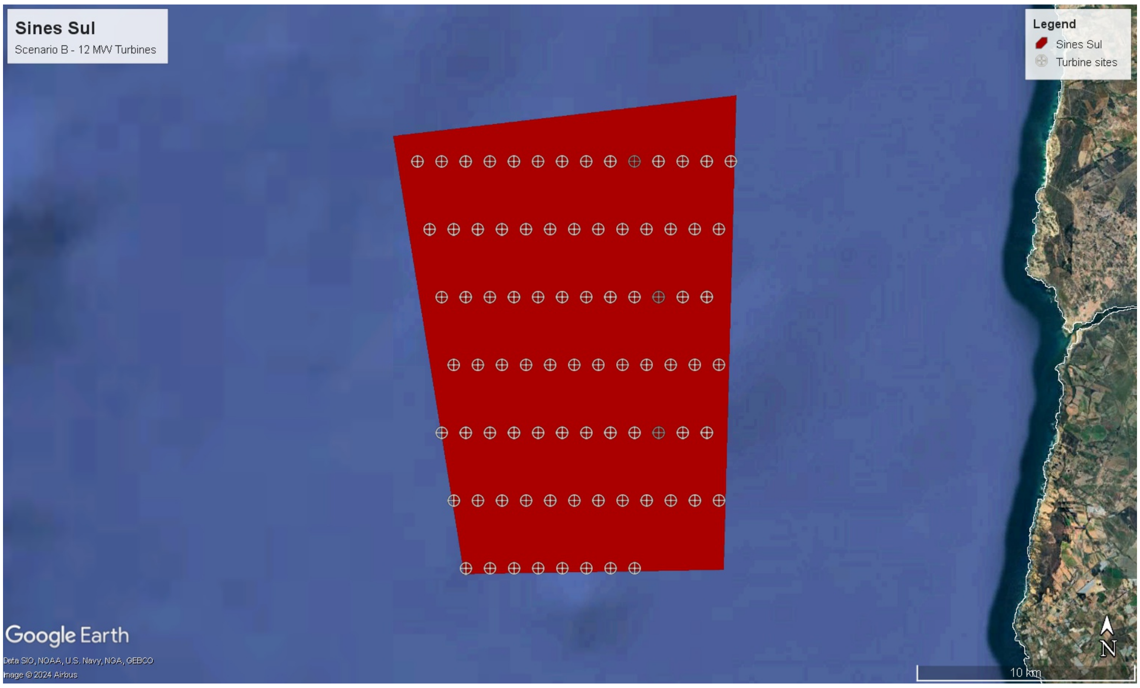


Figure 5.10: Digital Representation of Scenario B (12MW Wind Turbines).

5.4.2.3 Scenario C: 25° Counter-Clockwise Rotation

- **Turbine Alignment**: The entire offshore wind farm is rotated 25° counter-clockwise relative to Scenario A.
- **Spacing Configuration:**
  - Crosswind (X) Distance: 5 × D
  - Downwind (Y) Distance: 14 × D
- **Description**: In this scenario, the wind farm layout is rotated by 25° counter-clockwise from the baseline Scenario A, to better align with the prevailing wind directions from N and NNW. This adjustment is designed to reduce the direct impact of wakes in the primary wind direction, potentially improving energy capture and reducing wake losses across the park.

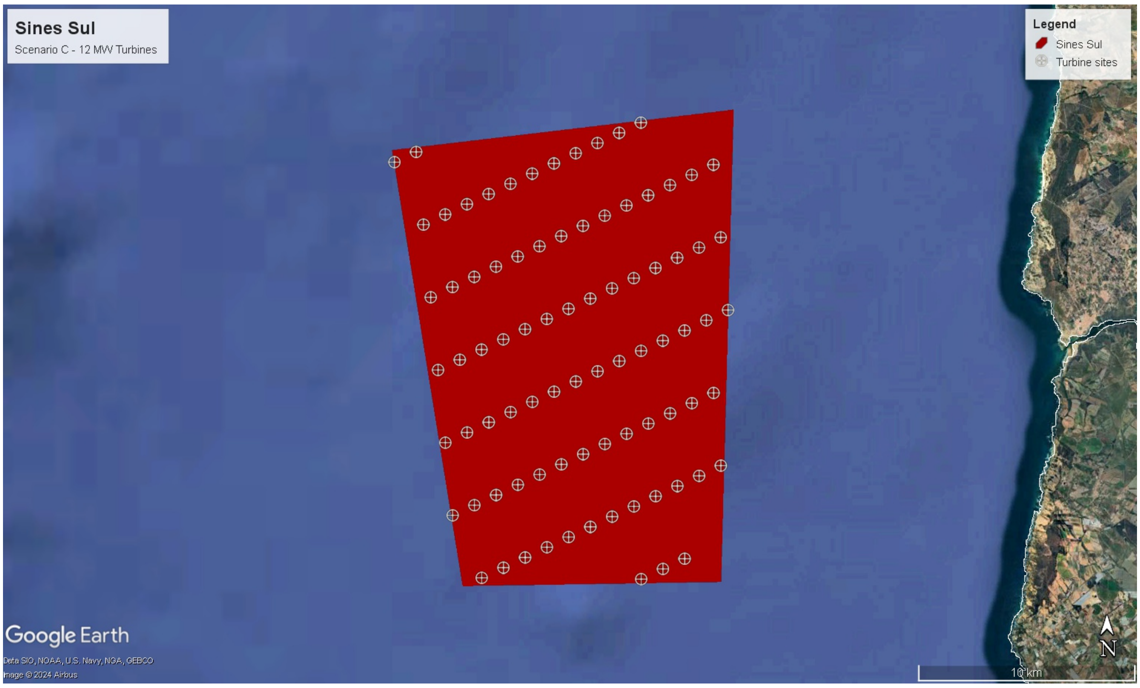


Figure 5.11: Digital Representation of Scenario C (12MW Wind Turbines).

5.4.2.4 Scenario D: 12.5° Counter-Clockwise Rotation

- **Turbine Alignment**: The entire offshore wind farm is rotated 12.5° counter-clockwise relative to Scenario A.
- **Spacing Configuration:**
  - Crosswind (X) Distance: 5 × D
  - Downwind (Y) Distance: 14 × D
- **Description**: Similar to Scenario C, this scenario involves rotating the wind farm layout, but with a smaller adjustment of 12.5° counter-clockwise. This moderate rotation aims to partially align the turbines with the prevailing wind directions while maintaining some of the benefits of the baseline East-West configuration. The goal is to evaluate whether this intermediate rotation offers a better trade-off between energy production and layout efficiency compared to the larger rotation in Scenario C.

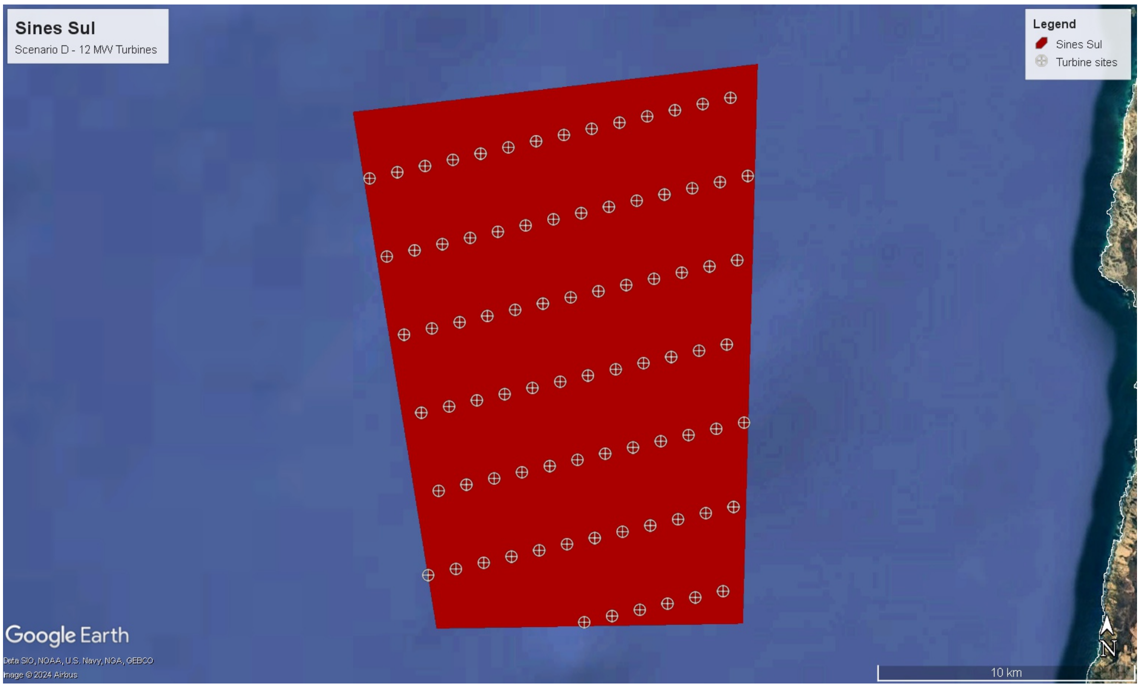


Figure 5.12: Digital Representation of Scenario D (12MW Wind Turbines).

By analyzing these four scenarios, the study aims to identify the optimal layout and configuration for the Sines Sul wind farm, considering the specific wind conditions of the region and the trade-offs between wake losses and energy production efficiency.

5.4.3 Bathymetry Data Processing

The bathymetry data for the offshore wind turbine sites were acquired and processed using Quantum Geographic Information System (QGIS) software. This process involved multiple steps to ensure the accurate determination of seabed depths at the designated turbine locations, a critical parameter influencing various technical and economic aspects of the project, such as cable sizing and overall installation costs.

5.4.3.1 Acquisition of Bathymetric Data

Initially, a bathymetry map encompassing the areas of interest was obtained. This map provided a comprehensive dataset consisting of numerous points, each containing information regarding the seabed depth. However, the raw dataset required manipulation and refinement to derive the specific depth information relevant to the turbine sites.

5.4.3.2 Rasterization of Bathymetric Data

The raw bathymetric data points were processed using the "Rasterize" tool in QGIS. This tool converts point data into a raster format by dividing the map into a grid of cells, each representing a specific depth value. The resolution of the raster map, determined by the size of the grid cells, was chosen based on a balance between the desired level of detail and computational efficiency. Smaller grid cells offered greater detail but required more processing time, whereas larger cells reduced detail but sped up the analysis. The chosen value balanced these factors, ensuring a thorough and reliable analysis of the bathymetric data while maintaining efficiency.

5.4.3.3 Integration of Turbine Location Data

After generating the rasterized bathymetry map, the next step involved uploading the wind turbine site locations into QGIS. This dataset was overlaid onto the raster map to associate each turbine site with the corresponding seabed depth. The tool "Sample Raster to Points" in QGIS was employed for this purpose. This tool enabled the extraction of depth values at each turbine site by sampling the rasterized bathymetric data.

5.4.3.4 Data Export and Utilization

The extracted bathymetry data was then exported from QGIS in a text file format. This file was subsequently transferred to Microsoft Excel for further analysis and integration into project planning. The seabed depth data were collected for subsequent processing to evaluate whether the depth would have a significant impact on the economic aspects of the project. While not immediately identified as a decisive factor, this information holds potential utility in refining parameters such as the length and specifications of subsea cables required for the wind turbine installations.

By following these methodological steps, the bathymetry data were effectively processed and prepared, providing a foundation for future technical and economic assessments of the wind turbine sites.

Chapter 6

Application of the Methodology and Results

This chapter applies the proposed methodology to two regions: Viana do Castelo Norte and Sines Sul. For each, it analyzes layout scenarios, compares turbine models, and examines turbine performance by location. Additionally, Sines Sul includes an analysis of local wind conditions, providing insights into regional wind patterns and the performance of the project's turbine sites.

6.1 Viana do Castelo Norte

The analysis of wind farm configurations in Viana do Castelo Norte produced key insights into the impact of turbine models and layout scenarios. The results of the simulations are summarized in Table 6.1, showcasing three different turbine models and three layout scenarios.

Table 6.1: Comparison of Scenarios for Different Turbine Models in Viana do Castelo Norte

Turbine Model	**No. of Turbines**	**Scenario**	**AEP [GWh]**	**Wake Losses (%)**	**Capacity Factor (%)**	**Hours at Nominal Capacity**
8 MW	**125**	A	3899	8.67	44.5	3899
		B	4022	6.22	45.9	4022
		C	3972	7.39	45.3	3972
12 MW	**83**	A	3953	7.13	45.3	3953
		B	4067	5.06	46.6	4067
		C	4029	6.02	46.2	4029
16 MW	**62**	A	3988	6.16	45.9	3988
		B	4071	4.52	46.8	4071
		C	4038	5.39	46.4	4038

***Note**: The total installed capacity is approximately 1.0 GW for all scenarios.*

The turbine models evaluated (8 MW, 12 MW, and 16 MW) were chosen to maintain a global installed capacity of 1 GW across all scenarios. The focus here is on comparing their performance and the resulting implications for wind farm design.

6.1.1 Analysis of Layout Scenarios

When comparing the scenarios, the differences in layout configurations reveal significant impacts on energy production and efficiency:

- **Scenario A**: Scenario A adopts a baseline layout with moderate spacing of 5 × D in the crosswind (X) direction and 10 × D in the downwind (Y) direction. While this configuration provides a balanced use of space, it exhibits higher wake losses compared to other scenarios. The limited recovery distance in the downwind direction contributes to increased turbulence and reduced energy capture for turbines located further downstream. This scenario represents a starting point but highlights the need for more refined layouts to improve performance.

- **Scenario B**: By increasing the downwind spacing to 15 × D while maintaining the 5 × D crosswind spacing, Scenario B significantly reduces wake interference. The extended recovery distance between rows allows for more effective dissipation of turbulent airflow, resulting in lower wake losses and higher AEP. This improvement is observed consistently across all turbine models, demonstrating the importance of optimizing row spacing. However, the benefits of this layout must be balanced against the increased costs associated with longer cable lengths and additional material requirements, which could impact overall project viability.

- **Scenario C**: Scenario C builds on Scenario B by introducing a staggered arrangement, offsetting rows in the crosswind direction. The goal of this configuration is to further minimize direct wake propagation to downstream turbines. However, the results show that this layout underperforms compared to Scenario B. The offset arrangement creates uneven wake effects, and increased turbulence can propagate to turbines in adjacent rows. This finding suggests that while staggered designs can be beneficial in specific conditions, they require careful tuning to avoid unintended performance losses.

The comparative analysis underscores the effectiveness of Scenario B in achieving the highest AEP and lowest wake losses. The layout's extended downwind spacing emerges as a critical factor in optimizing energy production. However, the economic implications of adopting Scenario B, including increased installation complexity and material costs, must be carefully considered to ensure the project's financial viability. Scenario A provides a less costly but less efficient alternative, while Scenario C highlights the potential risks of introducing additional complexity without guaranteed benefits.

6.1.2 Comparison Across Turbine Models

A key observation is the variation in the number of turbines required for each model. As the rated power of turbines increases, fewer turbines are needed to achieve the same total installed capacity. This shift has significant implications:

1. **Increased AEP**: Larger turbines exhibit a consistent increase in AEP compared to smaller ones. This trend aligns with the technological shift towards larger rotor diameters, which capture more energy from the wind, as discussed in the State of the Art chapter. It is interesting to note, however, that the increase in AEP is not uniform across all upgrades. For instance, the transition from an 8 MW turbine to a 12 MW turbine results in a more significant boost in energy production compared to the upgrade from a 12 MW turbine to a 16 MW turbine. This suggests that for this specific area with a maximum global installed capacity of 1 GW, the trend of increasing AEP with higher-rated turbines may begin to stagnate beyond a certain point.

2. **Reduced Wake Losses**: It was observed that the increase in turbine size did not lead to a proportional increase in wake losses. Larger wind turbines actually showed a reduced wake loss effect compared to smaller turbines. This suggests that the relationship between turbine size and wake losses is not linear, and that other factors, such as operational efficiency in varying wind conditions and the design of turbine spacing, also play a significant role in minimizing wake effects.

3. **Flexibility in Design**: The availability of turbine models with varying power ratings introduces flexibility in project planning. This adaptability allows for customized designs tailored to the site's unique characteristics and constraints.

6.1.3 Behavioral Insights: Turbine Performance by Location

The analysis of individual turbine sites provides crucial insights into the behavior of wake losses and their impact on Annual Energy Production (AEP). By visualizing these parameters, it becomes possible to identify areas within the wind farm that exhibit superior or inferior performance and understand the underlying factors influencing these variations. The layout adopted in this analysis is using a 12 MW turbine model and Scenario A.

6.1.3.1 Wake Losses

The distribution of wake losses across turbine sites, as depicted in Figure 6.1, reveals clear spatial patterns within the wind farm. Turbines located in the first row, particularly those facing the predominant wind direction from the north, experience the least wake interference. This is a logical consequence of their unobstructed position, which allows the turbines to harness wind energy without the disruptive turbulence caused by upstream turbines.

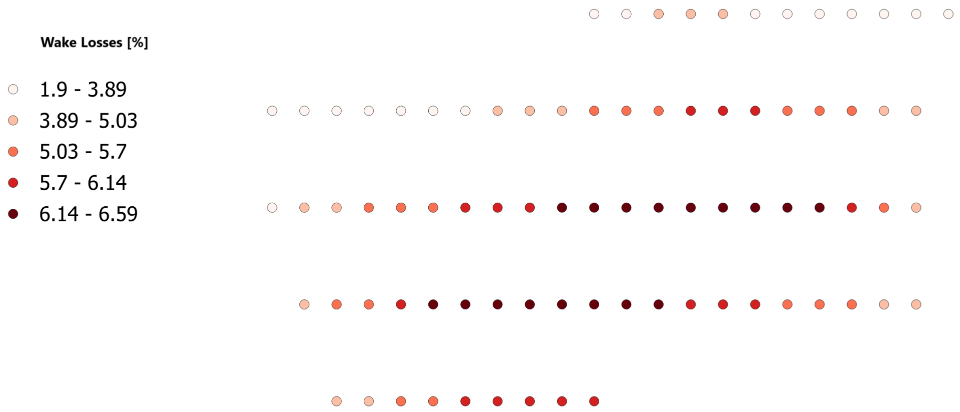


Figure 6.1: Wake Loss Distribution Across Turbines.

As expected, turbines positioned in subsequent rows exhibit progressively higher wake losses. The cumulative wake effects created by turbines in the preceding rows reduce wind speed and increase turbulence for downstream turbines. Notably, turbines situated in the central area of the wind farm endure the highest wake losses, given their exposure to the combined wakes of multiple upstream turbines.

Interestingly, turbines located in the last row, toward the southern boundary of the wind farm, show a slight decrease in wake losses. This phenomenon may be attributed to occasional winds from the south, which mitigate the overall impact of wake effects from northern winds. Additionally, turbines positioned at the edges of the wind farm consistently display lower wake losses compared to those at the center. This highlights the influence of external, undisturbed wind flows along the periphery of the wind farm.

This observation underscores the importance of iterative design and optimization in wind farm layout planning. By carefully assessing and mitigating wake effects, it is possible to minimize losses in areas most affected by turbulence, thereby enhancing the overall performance of the wind farm.

6.1.3.2 Annual Energy Production (AEP)

The AEP analysis, as illustrated in Figure 6.2, aligns closely with the trends observed in wake losses. Turbine sites that experience higher wake losses exhibit a corresponding reduction in AEP. This relationship emphasizes the critical role of minimizing wake interference to maximize energy generation.

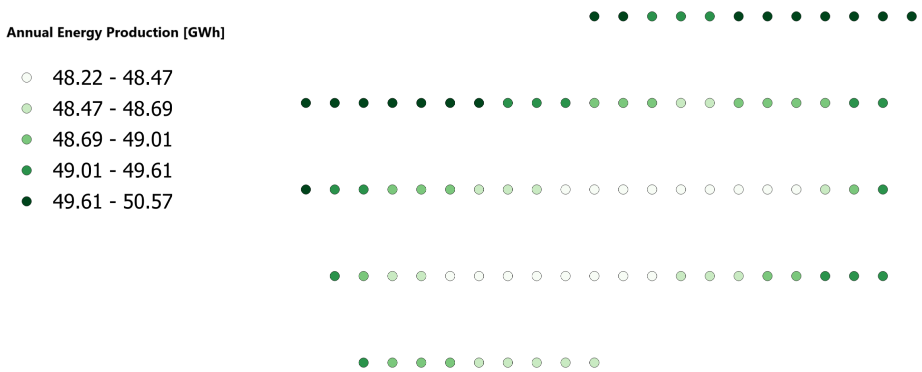


Figure 6.2: Annual Energy Production Distribution Across Turbines.

Turbines in the first row, benefiting from unimpeded wind flow, consistently achieve the highest AEP values. Conversely, turbines located further downstream, particularly those in the middle of the wind farm, suffer from diminished wind resources due to cumulative wake effects, leading to lower energy production. Similarly, the slight improvement in AEP observed in the last row reflects the reduced wake impacts and occasional beneficial influence of winds from the south.

The turbines at the edges of the wind farm demonstrate higher AEP compared to those in central locations. This is a direct result of their reduced exposure to wake interference, as they partially benefit from external wind flows that bypass the interior turbines.

6.1.3.3 Implications for Wind Farm Design

The spatial variability in wake losses and AEP across the wind farm highlights the importance of site-specific considerations in turbine layout design. Optimizing the arrangement of turbines can significantly mitigate wake effects, particularly in the central and downstream areas of the farm, where performance losses are most pronounced. Iterative simulations and analyses are essential to identify and implement configurations that strike a balance between maximizing energy production and minimizing wake losses.

By incorporating these insights into the design process, wind farm developers can enhance the overall efficiency and economic viability of their projects. This approach ensures that turbine sites with the greatest potential for high performance are prioritized, while strategies are implemented to minimize the adverse impacts of wake effects on less favorable locations.

6.2 Sines Sul

The analysis of wind farm configurations in Sines Sul highlighted the unique challenges posed by the site's wind characteristics. Table 6.2 summarizes the results for different turbine models and layout scenarios, emphasizing the influence of layout and turbine choice on energy production, wake losses, and overall efficiency.

Table 6.2: Comparison of Scenarios for Different Turbine Models in Sines Sul

Turbine Model	**No. of Turbines**	**Scenario**	**AEP [GWh]**	**Wake Losses (%)**	**Capacity Factor (%)**	**Hours at Nominal Cap.**
8 MW	**125**	A	3468	9.75	39.6	3468
		B	3432	10.63	39.2	3432
		C	3460	10.06	39.5	3460
		D	3459	9.94	39.5	3459
12 MW	**83**	A	3565	8.03	40.8	3565
		B	3530	8.94	40.4	3530
		C	3561	8.28	40.8	3561
		D	3558	8.31	40.8	3558
16 MW	**62**	A	3643	7.23	41.9	3643
		B	3611	8.04	41.5	3611
		C	3637	7.41	41.8	3637
		D	3634	7.46	41.8	3634

Note: The total capacity is approximately 1.0 GW for all turbine models and scenarios.

6.2.1 Analysis of Layout Scenarios

The layout scenarios designed for Sines Sul reflect an effort to optimize turbine placement in response to the site's wind conditions and available space. Key observations from the scenarios are as follows:

- **Scenario A**: In this baseline configuration, turbines are aligned in an East-West direction with uniform spacing of 5 $\times$ D in the crosswind direction and 14 $\times$ D in the downwind direction. This scenario provides a balanced arrangement but exhibits moderate wake losses.

- **Scenario B**: Adding offsets in the X direction between odd and even rows, Scenario B aims to disrupt wake propagation. However, the results reveal that this offset introduces uneven wake effects, leading to higher wake losses compared to other configurations. Similar to findings from Viana do Castelo Norte, this layout proves to be less effective, underscoring the need for cautious implementation of staggered designs.

- **Scenario C**: A rotation of 25º counterclockwise adjusts the layout to better align with the prevailing NNW and N wind directions. Despite this logical alignment, the results show that this configuration does not perform as well as expected.
- **Scenario D**: A more modest 12.5º counterclockwise rotation is applied in Scenario D. This configuration was specifically designed to align perpendicularly to the most prevalent wind direction (between NNW and N). Despite this alignment, the results show that it still underperforms compared to Scenario A.

The analysis shows that the wake losses in Sines Sul are significantly higher than in Viana do Castelo Norte, due to the more varied wind directions. While Scenarios C and D initially seemed promising, the results highlight the complexities of adapting layouts to diverse wind patterns. Scenario A stands out as the simplest yet most robust option for this site.

6.2.2 Comparison Across Turbine Models

The choice of turbine models in Sines Sul provides additional insights into their impact on wind farm performance:

1. **Increased AEP**: As seen in Viana do Castelo Norte, larger turbines (12 MW and 16 MW) deliver higher AEP compared to smaller turbines (8 MW). Unlike the earlier site, however, the increase from 12 MW to 16 MW turbines in Sines Sul remains significant, suggesting that the trend of diminishing returns with higher-rated turbines has not yet materialized here. This observation may be attributed to the wind conditions and layout efficiencies at this site.
2. **Wake Losses Across Models and Scenarios**: Across all turbine models, Scenario B consistently shows the highest wake losses due to the staggered X-offset arrangement. This is consistent with the findings from Viana do Castelo Norte. However, wake losses in Sines Sul are generally higher for all scenarios, which can be attributed to the site's diverse wind directions. This complexity makes the optimal turbine and layout combination more challenging to identify.
3. **Impact of Wind Patterns**: The dominance of NNW and N winds, as shown in the site's wind roses, initially suggested that Scenarios C and D (with their rotations) would reduce wake interference. However, the results indicate the opposite: the rotated layouts appear to exacerbate turbulence and wake effects, particularly under changing wind conditions. This discrepancy highlights the need for deeper analysis into site-specific aerodynamic factors.

The findings highlight the importance of customizing wind farm layouts to suit local conditions. In Sines Sul, the complex wind patterns and higher wake losses challenge the assumption that rotated or offset designs inherently lead to better performance. The next section explores the hypothesis explaining why Scenario A achieved better results, despite initial expectations suggesting otherwise.

6.2.3 Analysis of Local Wind Report

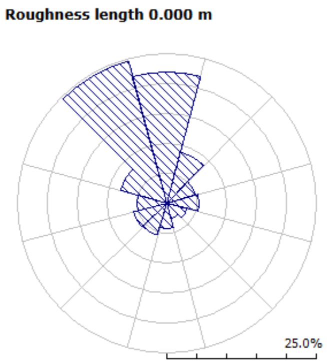
To understand why Scenario A delivered unexpectedly better results in Sines Sul, it is crucial to analyze the local wind characteristics. Using WAsP, the wind report utilized in the simulations was generated. This report, derived from the Global Wind Atlas, provides detailed insights into wind behavior at various heights and roughness lengths, forming the foundation of the simulations, as described in Chapter 5.

6.2.3.1 Roughness Length and Its Role

The roughness length parameter was set to 0 for all simulations. This value represents the absence of wind-slowing obstacles under neutral atmospheric conditions, as is typical for offshore environments. While oceanic conditions such as wave height, length, water depth, and tidal variations can influence roughness length [99], studies indicate that these factors generally exert minimal sensitivity on mean wind and turbulence under standard conditions [100]. Therefore, adopting a roughness length of 0 is a reasonable approximation for offshore wind farms.

6.2.3.2 Wind Regime Analysis at Roughness Length 0

The wind regime is represented using a Weibull distribution, as seen in Figure 6.3, which characterizes wind speed variations through three key parameters:



		Sec. 1 0°	Sec. 2 30°	Sec. 3 60°	Sec. 4 90°	Sec. 5 120°	Sec. 6 150°	Sec. 7 180°	Sec. 8 210°	Sec. 9 240°	Sec. 10 270°	Sec. 11 300°	Sec. 12 330°
Height 10.0 m	A [m/s]	7.3	5.8	5.0	5.6	5.9	6.6	6.9	6.7	6.2	5.6	5.4	7.6
	k	2.27	2.10	1.82	2.00	1.61	1.72	1.93	1.88	1.51	1.48	1.32	2.15
	U [m/s]	6.49	5.15	4.49	4.93	5.32	5.89	6.15	5.95	5.57	5.07	5.01	6.72
Height 50.0 m	A [m/s]	8.7	6.9	6.0	6.6	7.1	7.9	8.2	8.0	7.4	6.7	6.5	9.0
	k	2.48	2.28	1.99	2.18	1.75	1.88	2.11	2.04	1.65	1.62	1.44	2.35
	U [m/s]	7.70	6.10	5.32	5.84	6.31	6.99	7.29	7.06	6.60	6.02	5.95	7.96
Height 100.0 m	A [m/s]	9.4	7.5	6.6	7.2	7.8	8.6	9.0	8.7	8.1	7.4	7.2	9.8
	k	2.73	2.51	2.18	2.40	1.92	2.06	2.32	2.25	1.81	1.77	1.57	2.58
	U [m/s]	8.40	6.66	5.81	6.38	6.88	7.63	7.95	7.71	7.21	6.56	6.49	8.69
Height 150.0 m	A [m/s]	9.9	7.8	6.7	7.9	8.3	8.7	9.2	9.1	8.5	7.5	7.3	9.8
	k	2.67	2.22	1.95	2.22	1.78	1.84	2.03	2.16	1.80	1.74	1.56	2.39
	U [m/s]	8.77	6.91	5.93	6.97	7.35	7.76	8.19	8.05	7.53	6.65	6.59	8.71
Height 200.0 m	A [m/s]	10.1	8.4	7.0	8.2	8.6	9.0	9.3	9.3	8.6	7.6	7.4	9.6
	k	2.67	2.22	1.83	2.00	1.75	1.75	1.88	2.07	1.76	1.71	1.56	2.28
	U [m/s]	9.01	7.40	6.18	7.26	7.68	7.99	8.24	8.25	7.64	6.75	6.67	8.54
Freq. [%]		21.8	8.8	4.9	5.4	3.5	2.7	4.2	5.6	5.7	5.0	8.0	24.5

Figure 6.3: Wind Report at Roughness Length of 0 m.

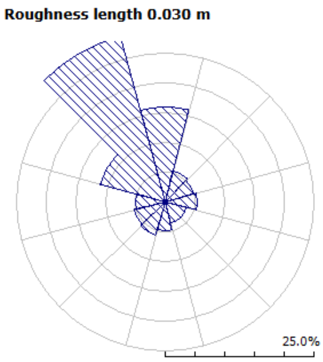
1. **Scale Parameter (A)**: This indicates the characteristic wind speed, with larger values representing distributions shifted towards higher wind speeds.
2. **Shape Parameter (k)**: This governs the peakedness of the distribution:
    - k<1: Distribution is heavily skewed, with a long tail towards higher wind speeds.
    - k=2: Distribution resembles a Rayleigh distribution, typical for locations with consistent winds.
    - k>2: Distribution becomes narrower, reflecting more consistent wind speeds around the mean.
3. **Mean Wind Speed (U)**: The average wind speed for the distribution.

For Sines Sul, the sections of primary interest are 1 (North) and 12 (North-Northwest), corresponding to the dominant wind directions. At 150 m—close to the hub heights of 12 MW and 16 MW turbines—the analysis reveals an intriguing pattern. Although the wind roses identify NNW as the most frequent wind direction, the North direction exhibits higher values for all three Weibull parameters. This suggests that winds from the North are not only stronger but also more consistent. This consistency may explain why Scenario

A, which aligns with the North-South axis, achieved better results than the rotated layouts initially expected to perform better.

6.2.3.3 Impact of Roughness Length Variations

While the simulations assume a roughness length of 0, it is insightful to compare wind regimes under varying roughness lengths. Analyzing the wind regime with a roughness length of 0.030 m, demonstrated in Figure 6.4 below, this comparison reveals notable differences, particularly in Section 12, where the wind demonstrates higher frequency, consistency, and intensity. These changes highlight the sensitivity of wind behavior to roughness length variations.



		Sec. 1 0°	Sec. 2 30°	Sec. 3 60°	Sec. 4 90°	Sec. 5 120°	Sec. 6 150°	Sec. 7 180°	Sec. 8 210°	Sec. 9 240°	Sec. 10 270°	Sec. 11 300°	Sec. 12 330°
Height 10.0 m	A [m/s]	4.8	3.7	3.6	3.9	4.0	4.8	4.7	4.6	3.9	3.7	4.2	5.4
	k	1.65	1.43	1.58	1.64	1.30	1.59	1.54	1.38	1.21	1.21	1.29	1.93
	U [m/s]	4.28	3.40	3.22	3.48	3.68	4.30	4.24	4.17	3.68	3.47	3.85	4.82
Height 50.0 m	A [m/s]	6.8	5.4	5.1	5.5	5.8	6.8	6.7	6.5	5.7	5.4	6.0	7.6
	k	2.02	1.74	1.94	2.00	1.58	1.94	1.88	1.69	1.47	1.47	1.58	2.37
	U [m/s]	5.99	4.77	4.51	4.88	5.16	6.02	5.95	5.84	5.16	4.87	5.40	6.75
Height 100.0 m	A [m/s]	8.1	6.4	6.1	6.6	7.0	8.1	8.0	7.9	7.0	6.6	7.3	9.1
	k	2.50	2.16	2.40	2.48	1.95	2.40	2.33	2.08	1.82	1.81	1.95	2.94
	U [m/s]	7.17	5.71	5.40	5.84	6.18	7.21	7.12	6.99	6.18	5.82	6.46	8.08
Height 150.0 m	A [m/s]	9.1	7.4	6.5	7.7	7.9	8.7	8.9	8.8	7.9	6.9	7.8	9.8
	k	2.73	2.30	2.18	2.51	1.96	2.30	2.31	2.21	2.07	1.85	2.06	3.08
	U [m/s]	8.06	6.57	5.78	6.81	7.03	7.75	7.93	7.76	7.03	6.15	6.94	8.80
Height 200.0 m	A [m/s]	9.9	8.3	7.1	8.4	8.7	9.2	9.6	9.4	8.5	7.2	8.3	10.3
	k	2.82	2.25	2.04	2.24	1.90	2.06	2.18	2.12	2.00	1.77	1.99	2.89
	U [m/s]	8.81	7.39	6.32	7.45	7.70	8.16	8.50	8.34	7.50	6.39	7.31	9.17
Freq. [%]		15.9	5.4	4.9	5.4	3.6	3.7	4.8	5.7	5.4	5.1	11.3	28.9

Figure 6.4: Wind Report at Roughness Length of 0.030 m.

When considering wind originating from the East, Northeast, or even North, the question arises whether the distance from the shore — where roughness length is much higher — is sufficient to dissipate turbulence before reaching the wind farm.

This highlights the importance of critically assessing the influence of roughness length. While the simulations assume idealized offshore conditions, real-world factors such as shoreline proximity and wind direction could introduce variability that impacts the observed performance. Transparency in acknowledging these limitations is vital to ensure robust and reliable conclusions.

6.2.4 Behavioral Insights: Turbine Performance by Location

The analysis of turbine performance in Scenario A for the 12 MW model highlights the distribution of wake losses and Annual Energy Production (AEP) across the Sines Sul wind farm. By visualizing and interpreting these trends, key insights into wake behavior and energy performance can be drawn.

6.2.4.1 Wake Losses

The wake loss distribution, as shown in Figure 6.5, exhibits a clear spatial pattern throughout the wind farm:

Figure 6.5: Wake Loss Distribution Across Turbines.

1. **First Row Performance**: Turbines positioned in the first row experience the lowest wake losses, ranging between 2.42% and 5.69%. This result is expected due to the high frequency of north (N) and north-northwest (NNW) winds, which are the dominant wind directions in Sines Sul. These turbines are exposed to undisturbed wind flows, leading to minimal wake interference.

2. **Progressive Increase in Wake Losses**: Moving downstream through the rows, there is a consistent increase in wake losses. By the fourth row, turbines begin to exceed 10% wake losses, which is relatively high. This trend reflects the cumulative wake effects generated by upstream turbines, where wind speeds are reduced, and turbulence intensity increases.

3. **Impact of Limited Space**: Unlike Viana do Castelo Norte, where the wind farm layout could span a wider East-West direction, Sines Sul's spatial constraints necessitate the addition of more rows to accommodate the 1 GW total capacity. This layout configuration inherently exacerbates wake interference and contributes to the higher wake losses observed in this region.

4. **Edge Turbine Behavior**: Turbines located along the edges of the wind farm demonstrate relatively smaller wake losses compared to the central turbines. This is due to the occasional influence of less frequent winds from other directions, which provide undisturbed wind flows to the peripheral turbines.

6.2.4.2 Annual Energy Production (AEP)

The observed wake loss distribution has a direct impact on Annual Energy Production (AEP), presented in Figure 6.6:

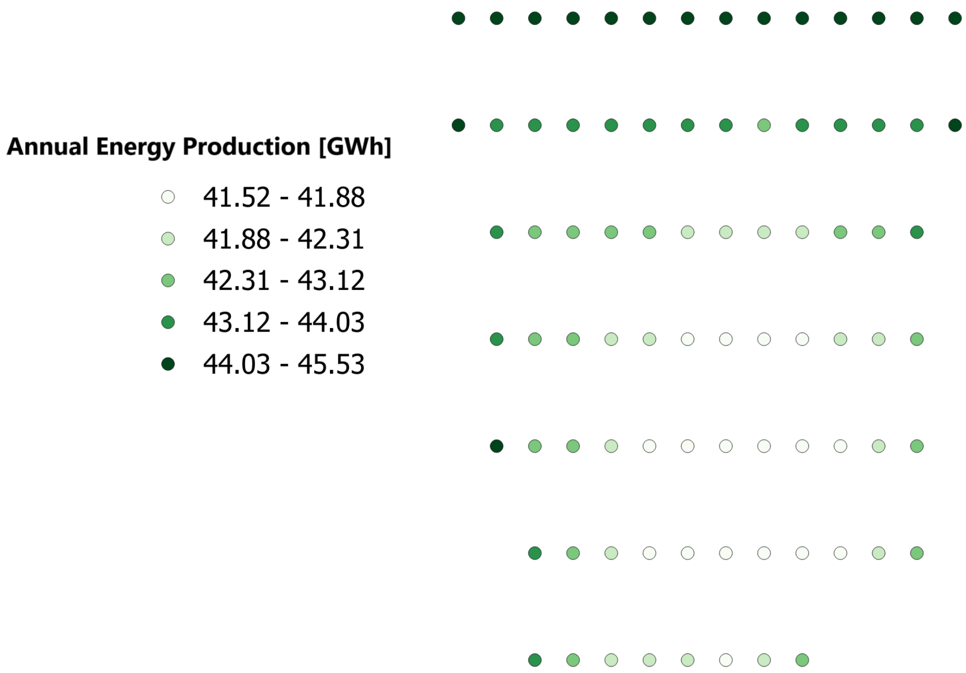


Figure 6.6: Annual Energy Production Distribution Across Turbines.

1. **First Row Advantage**: Turbines in the first row achieve the highest AEP values, as they benefit from unobstructed wind flows with minimal wake interference.

2. **Central and Downstream Performance**: Turbines situated in the middle of the wind farm, particularly those in the downstream rows, exhibit a significant reduction in AEP. This decrease aligns with the elevated wake losses caused by cumulative turbulence from upstream turbines.

3. **Edge Turbines**: As observed with wake losses, turbines positioned at the edges of the wind farm tend to achieve higher AEP values compared to central turbines. These locations partially benefit from external wind flows that bypass the central wake effects.

6.2.4.3 Implications for Wind Farm Design

The findings from Sines Sul underscore the challenges associated with designing wind farm layouts in areas with limited spatial flexibility. The necessity of adding more rows to meet the 1 GW capacity target increases wake losses, particularly for turbines located further downstream. This highlights the importance of optimizing wind farm configurations to minimize wake effects while accommodating spatial constraints.

An interesting observation is that, despite the wake losses, the ratio of increasing the turbines' rated power and Annual Energy Production (AEP) continued to grow significantly in Sines Sul — unlike in Viana do Castelo Norte. This suggests that higher power-rated turbines, despite being larger, allow for better wake effect dissipation compared to smaller turbines. When lower-rated turbines are used, the need for more turbines exacerbates wake losses, especially when the wind conditions do not favor the geometry of the available area.

For regions where the wind comes predominantly from a single direction— such as the high-frequency winds from N and NNW in Sines Sul, and the winds from N in Viana do Castelo Norte — achieving better results depends heavily on the geometry of the available area. If the layout can expand perpendicularly to the wind's axis, fewer turbines will need to be placed downstream, significantly reducing wake losses and enhancing overall performance. This insight highlights the importance of aligning wind farm designs with both wind regime characteristics and spatial constraints to maximize efficiency.

Chapter 7

Economic analysis

This chapter analyzes the financial viability of offshore wind farms, covering key aspects such as investment costs, long-term returns, and risk management. It explores financing models like public-private partnerships and green bonds, as well as the role of economies of scale in reducing costs.

7.1 Investment analysis

The viability of offshore wind projects relies on a detailed investment analysis that covers key financial components, including Development Expenditures (DevEx), Capital Expenditures (CapEx), Operational Expenditures (OpEx), and Abandonment Expenditures (AbEx). Accurate cost estimation is critical to prevent overspending and ensure the project stays within budget. Each financial aspect must be carefully planned to avoid unforeseen expenses, ensuring the project's overall feasibility.

In addition to precise cost planning, a realistic revenue estimate is essential to avoid overstating the project's economic performance. The projected income from energy production should match the operational capabilities of the wind farm. To assess the financial health of the project, metrics such as Payback Period, Return on Investment (ROI), and Internal Rate of Return (IRR) help determine the potential returns, allowing stakeholders to make informed decisions and plan strategically.

7.1.1 Costs

Understanding the cost structure of offshore wind projects is paramount for ensuring financial viability and sustainability. Each category of costs plays a critical role in the overall investment analysis, and a detailed examination of Development Expenditures (DevEx), Capital Expenditures (CapEx), Operational Expenditures (OpEx), and Abandonment Expenditures (AbEx) will illuminate their importance [101].

7.1.1.1 DevEx

Development Expenditures (DevEx) cover all costs incurred during the early stages of an offshore wind project, which are critical for minimizing risks and ensuring long-term viability. These expenditures can vary based on regional regulations and site conditions but typically include several key activities.

Key steps in DevEx include site identification, where areas for wind farm development are assessed for wind resources and environmental impacts; the Front-End Engineering and Design (FEED) phase, where technical uncertainties are addressed, and the concept design is developed; and wind farm design, which integrates data from FEED studies and environmental surveys. Additionally, stakeholder engagement is vital for gaining support and navigating regulatory approval, while procurement ensures timely contracting for project components. Effective management of DevEx is essential to avoid delays, unforeseen costs, and risks during later stages of the project, laying a solid foundation for the wind farm's successful development [102].

7.1.1.2 CapEx

Capital expenditures (CapEx) cover all costs incurred before a wind farm becomes operational, crucial for evaluating the project's financial viability. These costs include installation and setup, excluding ongoing operation and maintenance.

Key CapEx components include turbine and substructure costs, which depend on materials and foundation types (fixed or floating), and mooring systems, essential for floating platforms and tailored to site conditions. Electrical infrastructure costs are influenced by the choice between HVAC and HVDC systems, with each option suited to different project scales and distances. Installation costs can vary based on methods and equipment, including the use of specialized vessels for turbine transportation. Understanding CapEx is vital for assessing the project's financial health, enabling informed decision-making and strategic planning for successful development [103].

7.1.1.3 OpEx

Operating expenditures (OpEx) encompass the ongoing costs of managing an offshore wind farm during its operational life, crucial for ensuring efficiency and safety over its 20 to 25-year lifespan. Effective OpEx management is vital for maintaining financial viability and optimizing returns.

Key components of OpEx include day-to-day operations, involving routine maintenance and spare parts; condition monitoring to assess equipment health and minimize downtime; logistical support, such as renting operational bases and using crew transfer vessels; and maintenance activities, ranging from minor repairs to major repairs requiring external contractors. Additionally, improvements and technological upgrades throughout the wind farm's life enhance efficiency and lifespan. Proper management of OpEx is essential for ensuring sustained performance and maintaining competitiveness in the renewable energy market [102, 103].

7.1.1.4 AbEx

Abandonment expenditures (AbEx) refer to the costs incurred during the decommissioning of an offshore wind farm at the end of its operational life. Although large-scale decommissioning has yet to occur, insights can be drawn from the decommissioning of smaller projects, though uncertainty remains regarding specific processes and costs.

Key aspects of AbEx include the removal of turbines and transition pieces, with foundations cut below seabed level to avoid environmental disruption. Cable removal is another crucial step, with cables being repurposed or responsibly disposed of to offset costs. Environmental monitoring post-decommissioning ensures compliance with regulations, and some farms may be repowered, reusing existing infrastructure to reduce AbEx costs. While decommissioning details are still evolving, understanding these potential costs is essential for financial planning and risk management as the industry matures [102].

7.1.2 Revenues

In offshore wind farms, revenue generation is crucial for assessing financial viability. The primary source of revenue comes from the sale of electricity, influenced by factors like market demand, regulatory frameworks, and pricing mechanisms.

Offshore wind projects can also tap into supplementary revenue streams such as leasing agreements, carbon credits, and partnerships with other energy sectors, providing investors and stakeholders with insights into their economic viability and long-term sustainability.

7.1.2.1 PPAs

Power Purchase Agreements (PPAs) are critical for the economic stability of offshore wind projects, offering long-term financial predictability by setting a fixed price for electricity. These agreements provide reliable revenue streams, which are essential for securing financing and attracting investors.

PPAs facilitate investment decisions by reassuring financiers about the project's viability, enhancing its bankability. The increasing trend in PPAs, with 36.7 GW of renewable energy contracted in 2022, reflects the growing demand for stable, sustainable energy sources. Additionally, PPAs can include the sale of environmental attributes like Guarantees of Origin, further supporting corporate sustainability goals. In summary, PPAs are vital for securing funding and advancing renewable energy transitions [104].

7.1.2.2 Market Prices for Electricity

Electricity from offshore wind farms is sold in competitive markets, with prices influenced by demand, supply, and regulatory frameworks. These prices fluctuate throughout the day and seasons, reflecting real-time changes in consumption and generation patterns. Factors such as high demand during peak hours or oversupply during favorable weather conditions can impact prices, while the integration of renewable energy sources like offshore wind can drive prices down by displacing fossil fuels.

Three primary pricing mechanisms are used for wind power: fixed-price, quota price, and green price mechanisms. The fixed-price mechanism stabilizes early-stage development but lacks competition, potentially hindering long-term efficiency. The quota price mechanism mandates renewable energy consumption but may limit price growth and industrial development. The green price mechanism, which encourages cost reduction, requires strong public support for renewable energy. As offshore wind grows, there is a need for a more suitable pricing mechanism that reflects modern energy market dynamics, which is crucial for developers and investors to optimize project viability [105].

7.1.2.3 Contracts for Difference (CfD)

Contracts for Difference (CfD) are financial mechanisms designed to reduce investment risks and financing costs for large-scale renewable energy projects, including offshore wind farms. By providing a stable revenue framework, CfDs lower the cost of electricity generation, with studies indicating reductions of approximately 30%. This mechanism has been internationally recognized and widely implemented in several European countries, such as Denmark, the United Kingdom, Italy, and France, with Poland and Lithuania recently adopting CfDs for offshore wind financing [106].

The CfD model operates by establishing a fixed “strike price” for electricity, agreed upon during the contract period. If the market price for electricity falls below this strike price, the CfD counterparty — typically a government-backed entity — compensates the renewable energy generator for the difference. In contrast, if the market price exceeds the strike price, the generator pays the surplus back to the CfD counterparty.

This stability not only supports climate protection and energy security goals but also strengthens the renewable energy supply chain. Given these advantages, the CfD model has gained widespread support from wind farm operators, manufacturers, and financial stakeholders alike, underscoring its vital role in driving the global expansion of offshore wind energy [106, 107].

7.1.2.4 Incentives and Subsidies

Incentives and subsidies are essential for boosting investment in the offshore wind sector, improving the economic viability of projects and attracting developers and investors. Various incentives, including EU mechanisms, are crucial for renewable energy development across member states. Recently, governments have increased direct financial support to stimulate investment, such as the UK's increase in the price paid for offshore wind-generated electricity from £44 per MWh to £73 per MWh to attract energy firms [108].

These measures are vital, especially as rising construction costs due to inflation and higher interest rates have made the financial landscape more challenging. Despite these pressures, electricity from offshore wind is expected to remain more affordable and less vulnerable to price fluctuations compared to gas-fired power.

7.1.3 Financial Indicators

Financial indicators are crucial for evaluating the economic viability of offshore wind projects. Metrics like payback period, return on investment (ROI), and internal rate of return (IRR) provide insights into potential returns and help stakeholders make informed financing and management decisions. Additionally, Levelized Cost of Electricity (LCoE) plays a key role in comparing offshore wind with other renewable energy sources, offering a standardized measure of cost per unit of electricity generated over the project's lifecycle.

These indicators are essential for securing funding, ensuring project sustainability, and showcasing the long-term economic benefits of offshore wind energy. As the sector grows, thorough financial analysis becomes vital to navigate renewable energy markets and build confidence among investors and policymakers.

7.1.3.1 Payback Period

The payback period is a key financial metric that shows how long it takes to recover the initial investment, reflecting the time needed to reach breakeven. A shorter payback period is more attractive, especially in capital-intensive sectors like renewable energy.

To calculate it, divide the initial investment by the average annual cash flows. While it helps investors assess project viability, the payback period has limitations, such as not accounting for the time value of money. Understanding it allows investors to gauge risks and determine when they can expect returns on offshore wind projects [109].

7.1.3.2 Return on Investment (ROI)

Return on Investment (ROI) is a performance measure used to evaluate the efficiency or profitability of an investment or to compare multiple investment options. It directly measures the return generated by an investment relative to its cost. Key factors influencing ROI include the initial investment amount, ongoing maintenance costs, and the cash flow generated by the investment [110].

The ROI is calculated using the following formula:

$$ROI = \frac{Current\ Value\ of\ Investment - Cost\ of\ Investment}{Cost\ of\ Investment} \tag{7.1}$$

The result is typically expressed as a percentage or a ratio, providing a clear indicator of the investment's performance.

7.1.3.3 Internal Rate of Return (IRR)

The internal rate of return (IRR) is a key financial metric that estimates an investment's profitability by identifying the discount rate that makes the Net Present Value (NPV) of all cash flows equal to zero. It represents the expected annual growth rate of an investment.

Calculating IRR is similar to NPV, but focuses on finding the rate at which the present value of future inflows matches the initial investment. A higher IRR makes an investment more attractive. IRR is vital in capital budgeting, helping investors compare and rank investment options. The investment with the highest IRR is often seen as the best choice for potential returns [111].

Together with other financial metrics, IRR provides a comprehensive view of a project's economic potential, guiding decisions on capital allocation and risk management.

7.1.3.4 Levelized Cost of Electricity (LCoE)

The Levelized Cost of Electricity (LCoE) is a critical financial metric used to evaluate the average cost of electricity generation over the entire lifespan of an energy project. It determines the per-unit cost of electricity, enabling comparisons between different energy technologies, such as wind, solar, and nuclear power, regardless of disparities in lifespan, capital costs, or project sizes.

The LCoE is calculated using the formula:

$$LCoE = \frac{\sum_{t=1}^{T} \frac{Total\ Costs_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}} \tag{7.2}$$

where $Total\ Costs_t$ represents the sum of all costs incurred in year t, including investment, maintenance, and operational expenses, E_t is the energy produced in year t, r is the discount rate, and T is the project's lifespan.

This metric is indispensable for assessing project viability and competitiveness, aiding companies, investors, and policymakers in identifying cost-effective options. LCoE is also instrumental in the global energy transition, helping to compare the cost-effectiveness of renewable technologies with conventional fossil-fuel alternatives. For instance, government subsidies or fluctuating fuel costs can influence the financial attractiveness of energy projects, and LCoE serves as a guiding metric for such evaluations [112].

Current LCoE values exhibit significant regional variations due to site-specific factors like wind resources, water depth, and distance to shore. For floating offshore wind projects, the lowest LCoE values (approximately 95 €/MWh) are observed in areas with abundant wind resources, such as the North Sea, off Great Britain and Ireland. In contrast, regions like the Gulf of Biscay and southern Iberian Peninsula experience higher LCoE values exceeding 160 €/MWh, primarily due to less favorable wind resources and increased distances to shore [113]. Figure 7.1 provides an approximate representation of the LCoE across various regions in Europe and Northern Africa.

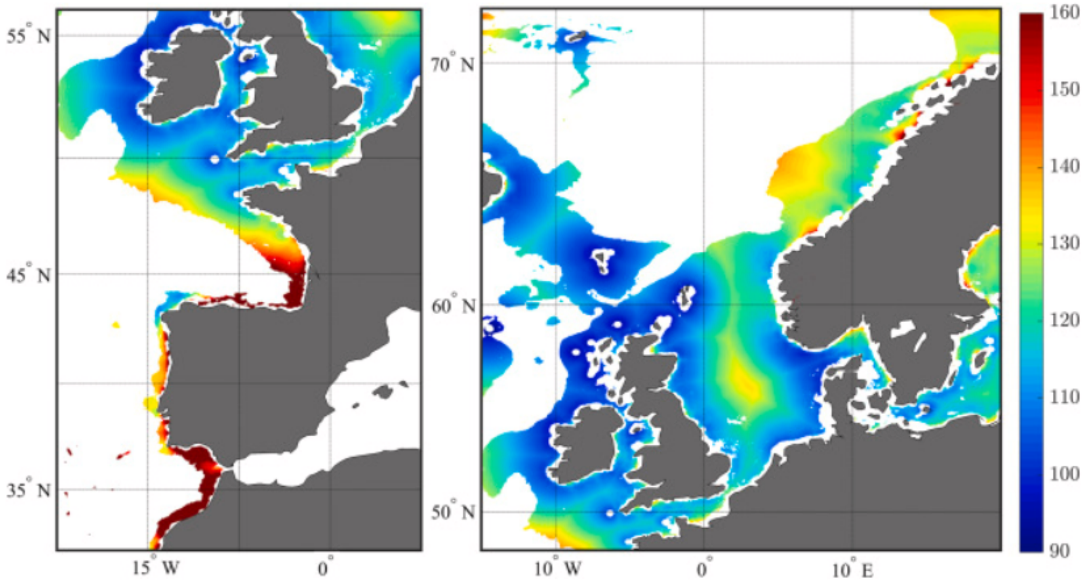


Figure 7.1: Floating wind LCoE (€/MWh). [113]

Analyzing the LCoE map distribution reveals that wind farms projected in the regions between Viana do Castelo and Figueira da Foz are likely to have similar LCoE values, approximately 140 €/MWh. In contrast, areas further south near Sines show a slight increase in LCoE, with estimated values around 160 €/MWh.

While the Levelized Cost of Electricity is a fundamental metric for evaluating and comparing energy projects, it is most effective when used alongside other parameters.

Combining LCoE with additional analyses, such as project-specific economic, environmental, and risk assessments, provides a more comprehensive understanding of a project's overall viability and long-term impact [114].

7.2 Financing Models

Offshore wind projects require significant capital, and their financing models are key to ensuring economic viability. Various mechanisms, including government subsidies, renewable energy auctions, and private investment, play an essential role. The European Union (EU) actively promotes clean energy through initiatives like Horizon Europe, Innovation Fund, and InvestEU, which provide financial support for offshore wind development.

Government subsidies reduce upfront costs and improve project attractiveness. For example, the EU offers several funding programs such as:

- **Horizon Europe Cluster 5**: Supports innovations in energy, with a €15.1 billion budget for offshore renewables.
- **EU Innovation Council (EIC)**: Funds high-impact innovations, including offshore energy, with a €10.1 billion budget.
- **LIFE Clean Energy Transition (CET)**: A €527 million program to support the transition to sustainable energy, including offshore renewables.
- **European Maritime Fisheries and Aquaculture Fund (EMFAF)**: Funds sustainable maritime resource use, including €20 million for offshore renewables.
- **BlueInvest**: Supports blue economy SMEs, including offshore renewables, with €6 million in funding.
- **Innovation Fund (IF)**: A €38 billion fund supporting low-carbon projects, including offshore renewables.
- **EU Renewable Energy Financing Mechanism**: Promotes cross-border cooperation on renewable projects, supporting offshore wind.

Renewable energy auctions also play a crucial role by allowing competitive bidding for offshore wind projects. These auctions reduce costs and boost investment, especially when coordinated across regions. Private investment is encouraged by financial institutions like the European Investment Bank (EIB), which provide low-cost financing, improving the bankability of offshore projects.

In conclusion, the combination of public subsidies, structured auctions, and private sector investment creates a strong financial framework for offshore wind, ensuring profitability and supporting the EU's green energy goals [115, 116].

7.3 Economy of scale

In this section, we'll explore how increasing the installed capacity in offshore wind projects can significantly reduce costs, making the industry more competitive with traditional energy sources. Two key factors play a central role in driving these cost reductions: mass production and technological maturation.

7.3.1 Series Production

As with many industries, transitioning from small-batch to mass production leads to cost reductions due to economies of scale, where production efficiency improves, and materials and labor are optimized. In offshore wind energy, this shift is occurring as turbines and wind farms increase in size and production volumes. Larger projects and turbines reduce the number of turbines and foundations needed, resulting in overall cost savings.

Recent research by National Renewable Energy Laboratory (NREL) shows that upsizing turbines and wind plants can reduce the Levelized Cost of Energy (LCoE) by over 23% compared to typical offshore wind farms installed in 2019. This reduction stems from fewer components, substructures, and maintenance needs, simplifying projects and lowering costs [117].

7.3.2 Technological Maturation

As technology advances, improvements in design, materials, and manufacturing further reduce costs. In offshore wind, innovations like enhanced installation vessels, more efficient electrical systems, and the use of digital tools for optimizing operation and maintenance (O&M) processes contribute to significant cost savings. For instance, upsizing turbines can reduce O&M costs by 33%, as larger turbines require fewer maintenance trips and repairs. Additionally, as wind farms scale, economies of scale in export systems and infrastructure help distribute costs more efficiently [118].

7.3.3 Impact on Competitiveness

Cost reductions are making offshore wind energy more competitive. Experts predict a 24–30% decrease in costs by 2030, with further reductions by 2050. Floating wind technology, still in early development, is expected to see costs fall to €53-76/MWh by 2030 and further to €30-50/MWh by 2040 as production scales and technology matures [119, 120].

Concluding, by leveraging economies of scale through both larger projects and more efficient mass production, along with ongoing technological advancements, the offshore wind sector is rapidly reducing its costs. With that, the Levelised Cost of Electricity has a clear trend to decrease with the increase of the cumulative capacity installed globally, as shown below, in Figure 7.2. This trend is crucial to making offshore wind energy more competitive with other forms of energy production, positioning it as a key player in the transition to a more sustainable global energy system.

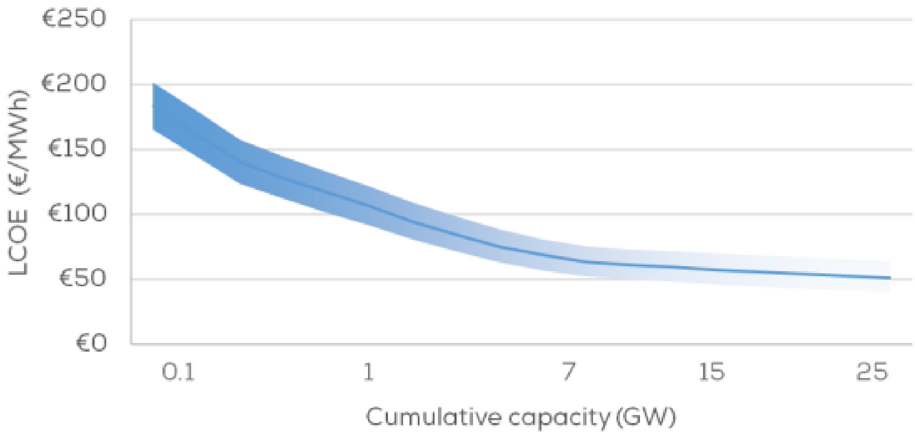


Figure 7.2: Floating wind LCOE according to cumulative installed capacity worldwide. [118]

Chapter 8

Socio-Economic and Ecological Analysis of a Proposed Scenario

In this section, we present a socio-economic and ecological analysis of a proposed scenario for an offshore wind farm project. This scenario has been carefully selected based on predefined parameters and conditions, identified through prior evaluations as one of the most favorable options in terms of energy production and key performance indicators.

8.1 Wind Farm Characterization

The example under consideration is located in Viana do Castelo Norte and features turbines with a rated power of 12 MW, arranged in an East-West alignment (Scenario B). Table 8.1, shown below, incorporates all the details of the wind farm characterization.

Table 8.1: Parameters of the Projected Scenario

Parameter	**Value**	**Unit**
Wind Farm Area	301	km^2
No. of Turbines	83	-
Unitary Power	12	MW
Total Power Offshore Farm	996	MW
Equivalent Production Hours	4067	h
Annual Energy Production	4067	GWh/yr
Capacity Factor	46.6	%

By focusing on this scenario, we aim to assess its economic feasibility by evaluating key financial metrics, costs, and potential revenues. The results will provide insights into the project's viability and its competitiveness within the renewable energy market.

8.2 Financial Assumptions

To proceed with the economic evaluation of the proposed scenario, a set of financial assumptions is defined. These assumptions include interest rates, annual cost escalation, taxes, and electric tariffs, which are essential for determining key economic parameters. The details of the financial assumptions are presented in Table 8.2:

Table 8.2: Financial Assumptions for Economic Analysis

Parameter	**Value**	**Unit**
Interest ratio	8	%
Increase in sale price (yr)	2	%
Annual cost increase (Operating Expense Inflation Factor)	2	%
Taxes, fees	35	%
Government incentives	0	%
Yearly depreciation of taxes and fees	0	%
Electric tariff	17.1	c€/kWh
Incentives	0	%
Land Lease	0	€
Royalties	0	€

8.3 Cost Estimations

To evaluate the economic feasibility of the offshore wind farm project, the total costs associated with the project are divided into several categories, which encompass all stages of the project lifecycle. These include costs related to project development, equipment, installation, operations, and eventual decommissioning. The detailed cost estimations are presented in Table 8.3.

It is important to emphasize that multiple sources of information were consulted during the cost estimation process. While some of the costs are not well defined in existing literature, and recent references were limited, a selection of relevant articles provided valuable insights. These cost estimations were carefully derived based on the data and methodologies found in the consulted articles [113, 121, 122].

Table 8.3: Estimated Costs for the Offshore Wind Farm Project

Item	**Costs**	**Unit**
Project development	190.9	M€
Turbine and Floating Platform Cost	2888.4	M€
Onshore substation	117.4	M€
Connection to the grid	259.4	M€
Offshore substation	245.3	M€
Offshore substation installation	32.9	M€
AC collector substation	185.0	M€
Cable array (33 kV)	1.50	M€
Cable offshore (220 kV)	10.2	M€
Cable onshore (220 kV)	1.46	M€
Mooring	21.9	M€
Anchors	37.8	M€
Substructure installation cost	42.4	M€
Turbine installation cost	102.4	M€
Ports and staging	27.7	M€
Operations	0.029	M€
O&M	55.1	M€
Port and staging cost	0.023	M€
Decommissioning	137.5	M€

The key project characteristics, such as the number of turbines, floating platform type, water depth, and distances to key infrastructure, were considered for the calculation of the costs. These parameters are summarized below in Table 8.4:

Table 8.4: Key Parameters of the Offshore Wind Farm

Parameter	**Value**
No. of Turbines	83
Floating Platform	Semi-Submersible
Mean Water Depth	110 m
Distance to Coast	15 km
No. of Anchors per Turbine	4
No. of Mooring Lines per Turbine	4
Distance to Offshore Substation	5 km
Distance to Shore Substation	5 km

To provide a comprehensive cost breakdown, the costs are categorized into four main groups: Development Expenditure (DevEx), Capital Expenditure (CapEx), Operational Expenditure (OpEx), and Abandonment Expenditure (AbEx). Additionally, Contingencies have been included to account for uncertainties. Table 8.5 presents the cost breakdown for the project.

Table 8.5: Cost Breakdown of the Offshore Wind Farm Project

Category	**Cost (M€)**	**Percentage**
DEVEX	190.9	4.0%
CAPEX	3973.8	83.6%
OPEX	55.2	1.2%
ABEX	137.5	2.9%
Contingencies	397.4	8.4%
Total	**4754.76**	**100%**

It is important to highlight that contingencies were set as 10% of the CapEx value, ensuring that unforeseen costs during project implementation are appropriately covered.

The total cost of the project amounts to 4,754.76 M€, and the cost breakdown, represented in Figure 8.1, in a pie diagram, highlights the weight of each cost component within the project.

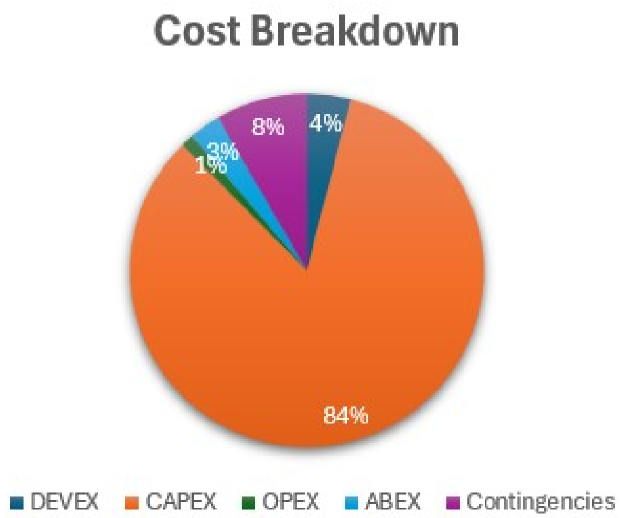


Figure 8.1: Cost Breakdown of the project.

This cost distribution underscores the capital-intensive nature of offshore wind projects, where technological and logistical challenges significantly influence the upfront investment requirements.

The breakdown of the CapEx for the offshore wind farm project reveals that a significant portion of the total investment is allocated to specific components. As shown in Table 8.6, the Turbine and Floating Platform costs dominate the CapEx, accounting for nearly 73% of the total.

Table 8.6: CapEx Breakdown for the Offshore Wind Farm Project

Component	**Cost (M€)**	**Percentage**
Turbine and Floating Platform	2888.4	72.69%
Onshore substation	117.4	2.95%
Connection to the grid	259.4	6.53%
Offshore substation	245.3	6.17%
Offshore substation installation	32.9	0.83%
AC collector substation	185.0	4.66%
Cable array (33 kV)	1.50	0.04%
Cable offshore (220 kV)	10.2	0.26%
Cable onshore (220 kV)	1.46	0.04%
Mooring	21.9	0.55%
Anchors	37.8	0.95%
Substructure installation cost	42.4	1.07%
Turbine installation cost	102.4	2.58%
Ports and staging	27.7	0.70%

Additionally, substation costs (including onshore, offshore, and AC collector substations) contribute a substantial share of the CapEx, collectively accounting for approximately 14%. This highlights the importance of electrical infrastructure in ensuring the efficient transmission and distribution of electricity from offshore to onshore locations. Other components such as the cable array, mooring, anchors, and ports and staging have a relatively minor impact on the overall CapEx, but they are still essential for the successful development and operation of the wind farm.

With all the detailed cost estimations, the Annual Energy Production, and the defined financial assumptions, we now have a comprehensive understanding of the project's economic inputs. These key parameters lay the foundation for calculating the essential economic indicators, which will be presented and analyzed in the following chapter.

8.4 Potential Impact on Employment, Environment, and Housing

When developing a project of this scale, it is essential to evaluate its potential impacts on employment creation, environmental benefits, and the number of households that could be powered by the generated energy. These factors, dependent on the wind farm capacity (WFC) underscore the broader socio-economic and ecological significance of the initiative. The following methodologies and formulas were employed to quantify these impacts:

8.4.1 Employment Creation

The implementation of such projects generates both direct and indirect employment opportunities [121], which can be defined as follows:

- **Direct Jobs:** These are roles directly associated with the project, including the manufacturing of key components, wind farm planning and development, installation, and operations and maintenance. The estimation of direct jobs is based on the formula:

$$DJ = 9.2 \times WFC[MW] \tag{8.1}$$

- **Indirect Jobs:** These are jobs related to the supply chain, such as material processing (e.g., concrete and steel) and services required during the project lifecycle. Indirect jobs are calculated as follows:

$$IJ = 7.5 \times WFC[MW] \tag{8.2}$$

8.4.2 Greenhouse Gases and Emissions

Reducing greenhouse gas emissions is a critical environmental benefit of floating wind farms. The project's carbon footprint, measured in terms of CO_2 and SO_2 emissions (tons per year), is calculated using the following formulas:

- **Carbon Dioxide (CO_2):**

$$CO_2 = 1431.4 \times WFC[MW] \tag{8.3}$$

- **Sulfur Dioxide (SO_2):**

$$SO_2 = 33.3 \times WFC[MW] \tag{8.4}$$

These calculations provide valuable insights into the environmental implications of transitioning to renewable energy sources [121].

8.4.3 Number of Homes Powered

One of the most tangible benefits of a floating wind farm is its ability to supply energy to households. Based on previous studies [121], the number of homes powered during a year by a wind farm can be estimated using the formula:

$$HP = 714.3 \times WFC[MW] \tag{8.5}$$

This metric highlights the direct societal advantages of renewable energy investments, demonstrating their potential to provide clean and sustainable power to communities.

By quantifying these impacts, stakeholders can make informed decisions that balance economic opportunities, environmental benefits, and social contributions. These assessments further emphasize the importance of renewable energy projects in driving sustainable development.

8.5 Results

In this section, we will present the results of the analysis for the offshore wind farm project, focusing on key economic and socio-ecological aspects. The Economic Results will explore the financial performance of the project, including a sensitivity analysis to assess how variations in key parameters affect the outcomes. Following that, the Socio-Ecological Impacts will examine the potential social and environmental consequences of the project, providing a comprehensive view of its broader implications.

8.5.1 Economical Results

This section details the process used to calculate the financial parameters for the offshore wind farm project. To obtain these results, several steps were followed to calculate key metrics such as Payback Period, Internal Rate of Return (IRR), Return on Investment (ROI), and Levelized Cost of Energy (LCoE).

First, the Net Revenue was calculated by multiplying the yearly Annual Energy Production (AEP) by the defined electric tariff. The calculation also accounted for a 35% tax rate, which was deducted from the total revenue. Additionally, since the yearly values of the electric tariff and Operational Expenditure (OpEx) are sensitive to inflation, these values were adjusted accordingly.

With the total investment and the yearly revenue values in hand, the Payback Period, IRR, and ROI were computed. These financial indicators provide insights into the project's profitability and its expected returns.

For the LCoE calculation, the values were updated to the Net Present Value (NPV) using the defined discount rate of 8%. This adjustment allowed for the calculation of the LCoE using the standard formula, resulting in the final value for the project's LCoE.

The results of these calculations are presented in Table 8.7:

Table 8.7: Project's Financial Indicators

Item	Value	Unit
Payback Period	10	Years
IRR	9.03	%
ROI	76.81	%
LCoE	134.9	€/MWh

The financial indicators suggest that, despite the project's capital-intensive nature, it is both profitable and relatively low-risk. The Payback Period of 10 years, which is half of the project's 20-year life, is a positive sign, as it indicates that the initial investment will be recovered relatively early, ensuring quicker returns. The IRR of 9.03% shows a moderate return, which is attractive if it exceeds the cost of capital. The ROI of 76.81% indicates a strong return on investment, suggesting that the project will generate nearly 77% more than its initial cost, making it financially viable.

The LCoE of 134.9 €/MWh aligns with industry expectations, confirming that the project's energy production cost is competitive.

Overall, these indicators point to a financially sound and profitable project, with a quick payback and high returns over its lifespan.

8.5.1.1 Sensitivity Analysis

This section evaluates how changes in key parameters impact the project's financial performance. Sensitivity analysis is crucial for understanding the robustness of the results and identifying factors that significantly influence the project's profitability and feasibility.

Government Incentives/Financing

To explore the impact of government incentives, a sensitivity analysis was conducted assuming a 10% reduction in total investment costs due to funding. The resulting changes in financial indicators are as follows in Table 8.8:

Table 8.8: Financial Indicators

Item	Value	Unit
Payback Period	9	Years
IRR	10.51	%
ROI	92.48	%
LCoE	122.6	€/MWh

This analysis highlights the significant positive impact of government incentives on the project's financial performance. A reduction in investment costs shortens the Payback Period to 9 years, increases the IRR to 10.51%, and raises the ROI to 92.48%, all of which enhance the project's economic attractiveness. Moreover, the LCoE decreases to 122.59 €/MWh, further improving cost-competitiveness.

These findings emphasize the role of incentives and funding mechanisms in fostering the development of capital-intensive renewable energy projects, particularly those with emerging technologies. As technological advancements mature over time, such projects are expected to become less reliant on external support.

Distance between Turbines

The distance between turbines is an intriguing parameter to evaluate in a sensitivity analysis, as it could potentially impact the project's financial indicators. However, as previously demonstrated, the costs associated with inter-turbine cables contribute only a minimal fraction of the overall capital expenditure (0.04% of the total CapEx). This limited impact suggests that variations in turbine spacing are unlikely to significantly influence the financial outcomes of the project. Nonetheless, it remains a factor worth considering for completeness in assessing all design parameters.

Water Depth and Distance to Shore

For the analyzed scenario, the mean water depth was set at 110 m, and the distance to shore was 15 km. To evaluate the sensitivity of these parameters, an alternative scenario was considered with an increased water depth of 250 m and a distance to shore of 50 km. The resulting financial indicators are as indicated in Table 8.9:

Table 8.9: Financial Indicators

Item	**Value**	**Unit**
Payback Period	10	Years
IRR	8.87	%
ROI	75.11	%
LCoE	136.5	€/MWh

As observed, these changes had minimal impact on the financial indicators. The Payback Period remained unchanged at 10 years. The IRR decreased slightly from 9.03% to 8.87%, and the ROI dropped marginally from 76.81% to 75.11%. The LCoE increased by only 1.6 €/MWh, reflecting a modest cost rise.

While increasing water depth and distance to shore adds costs to the project—primarily due to more expensive mooring systems, higher installation costs, longer mooring lines, and increased travel distances for operations—these changes did not significantly affect the project's overall financial performance. This highlights the project's resilience to variations in these parameters.

Electric Tariff

In the projected scenario, the electric tariff was defined as 171 €/MWh. To evaluate its impact, a sensitivity analysis was performed by reducing the tariff to 120 €/MWh. Since the LCoE is independent of revenue, it remains unaffected. However, the other financial indicators show significant changes, highlighted in Table 8.10:

Table 8.10: Financial Indicators

Item	**Value**	**Unit**
Payback Period	15	Years
IRR	4.81	%
ROI	24.08	%

The results demonstrate a substantial impact on the financial indicators. The IRR dropped from 9.03% to 4.81%, the ROI declined sharply from 76.81% to 24.08%, and the Payback Period increased to 15 years, indicating a much longer time to recover the initial investment.

This analysis underscores the project's high dependence on the electric tariff. A significant decrease in the tariff would severely diminish the project's profitability and extend the time required for financial returns, highlighting the importance of maintaining favorable tariff conditions for the project's viability.

Discount Rate

In the analyzed scenario, the discount rate was defined as 8%. To evaluate its impact, a sensitivity analysis was conducted by increasing the discount rate to 10%. Since other financial indicators are independent of the discount rate, this analysis focuses solely on the LCoE, which is directly affected. The resulting value is as follows in Table 8.11:

Table 8.11: Financial Indicators

Item	**Value**	**Unit**
LCoE	152.8	€/MWh

The results reveal a significant impact on the LCoE due to the 2% increase in the discount rate. The LCoE rose from 134.9 €/MWh to 152.8 €/MWh, representing a 13% increase. This highlights the critical role the discount rate plays in determining the LCoE, as higher discount rates increase the present value of future costs, making the project appear more expensive on a per-unit energy basis.

Project's Lifetime

In the base scenario, the project's lifetime was set to 20 years. To evaluate its impact, the lifetime was increased to 25 years. The resulting financial indicators are presented in Table 8.12:

Table 8.12: Financial Indicators

Item	**Value**	**Unit**
Payback Period	10	Years
IRR	10.15	%
ROI	118.10	%
LCoE	125.61	€/MWh

The results show notable changes in the indicators. While the Payback Period remains unaffected, the IRR increased from 9.03% to 10.15%, and the ROI rose significantly from 76.81% to 118.10%, reflecting a substantial improvement in overall profitability. Additionally, the LCoE decreased from 134.9 €/MWh to 125.6 €/MWh, further enhancing the project's cost-competitiveness.

This analysis highlights the positive impact of extending the project's lifetime. As technological advancements improve turbine durability, longer lifespans will likely become standard, offering substantial financial and economic benefits to similar projects.

8.5.2 Socio-Ecological Impacts

The project demonstrates significant socio-ecological benefits, as highlighted in Table 8.13, below:

Table 8.13: Socio-Ecological Impacts

Item	**Value**	**Unit**
Direct Jobs	9200	-
Indirect Jobs	7500	-
CO_2	1431400	tons/year
SO_2	33300	tons/year
Homes Powered	714300	-

These indicators underscore the project's value for both the population and the environment. By creating an estimated 9,200 direct and 7,500 indirect jobs, the project significantly contributes to economic development and social well-being. The reduction of 1.43 million tons of CO_2 and 33,300 tons of SO_2 emissions annually represents a critical step in mitigating environmental impact and improving air quality. Furthermore, the project's ability to power 714,300 homes highlights its contribution to energy accessibility and sustainability.

These results illustrate how the project goes beyond financial metrics to deliver substantial socio-ecological benefits, addressing critical population and environmental needs.

Chapter 9

Conclusions

This dissertation explores the potential of offshore wind energy as a key component of Portugal's renewable energy strategy, situated within the global transition to sustainable energy systems. The urgent need to tackle climate change and reduce dependence on fossil fuels has promoted the need for innovative technologies in the harnessing of renewable energy in a more efficient way. Offshore wind energy, already deployed in a number of countries, represents a promising pathway for this transition. While its application has been traditionally constrained by water depths and technological limitations, the emergence of floating offshore wind farms has expanded its viability, enabling exploration in deeper and more dynamic marine environments.

Portugal, with its extensive maritime resources and favorable wind conditions, presents a unique opportunity to adopt this technology. Although the sector is still in its maturity phase and associated with high initial costs, technological advancements and economies of scale are expected to reduce these barriers, positioning floating offshore wind as a competitive renewable energy source in the near future.

This research provides a comprehensive analysis of the technological, environmental, economic, and regulatory dimensions of floating offshore wind energy. It examines the state of offshore wind turbine technology, contrasting fixed and floating systems, and evaluates recent industry innovations. A key focus was placed on Portugal's evolving regulatory framework, which needs to adapt to the complexities of this emerging sector. International experiences from leading countries in this domain, such as the United Kingdom, Germany, and Denmark, presented a number of best practices that could help inspire Portugal.

Site-specific evaluations were conducted on areas that were pointed out for offshore wind farms by the Portuguese State, namely the regions of Viana do Castelo and Sines. Further, detailed simulations have been performed in order to optimize turbine layouts, assess performances for different technologies, and analyze local wind conditions. An economic analysis examined installation costs, revenue potential, financing models, and the broader socio-economic and environmental impacts of developing wind farms in these areas.

The findings reveal the substantial potential of floating offshore wind energy in Portugal. Simulations demonstrated great performance indicators for the proposed wind farms, with significant Annual Energy Production (AEP) and Hours at Nominal Capacity, and acceptablue values for wake losses. When comparing the two study areas, Viana do Castelo Norte performed better, due to its more consistent wind regime, which resulted in superior overall outcomes. These results underscore Portugal's favorable natural conditions for offshore wind energy, despite the challenges associated with early-stage technology development. However, the sector's growth requires careful management, including collaboration among stakeholders such as industry, local communities, and policymakers.

Future research will be crucial in overcoming current obstacles and fully realizing the potential of floating offshore wind energy. Exploring synergies with other renewable energy sources, such as wave and solar energy, could further enhance the efficiency and resilience of integrated energy systems. Continued innovation in turbine design, installation methods, and grid integration will also be vital in reducing costs and improving the feasibility of large-scale deployment.

From a financial perspective, the study's results are highly promising. The Levelized Cost of Energy (LCoE) values align with expectations from existing literature and predicted future trends. Additionally, the financial parameters indicate that, although capital-intensive, these projects can be profitable. This underscores the economic viability of floating offshore wind energy as a sustainable solution and as a promising avenue for renewable energy, with Portugal being well-positioned to take advantage of this opportunity. To play a leading role in the global expansion of this transformative technology, Portugal must take strategic action, reinforcing its commitment to sustainable development and a clean energy future.

9.1 Further Work

As offshore wind technology continues to evolve, future research should focus on exploring areas previously discarded due to technological limitations. Considering recent developments in floating offshore wind systems, reassessment of such sites regarding their development feasibility could be useful. In addition, further studies could focus on optimizing the selected areas for offshore wind farms, such as Viana do Castelo and Sines, to identify the most suitable technologies, turbine layouts, and grid integration strategies. These factors, along with other critical parameters, must be carefully defined to ensure the smooth development of these sites.

Additionally, there is a need for re-evaluating the economic analysis using more precise, up-to-date industry values. As costs and financial parameters evolve, access to accurate and current data will provide clearer insights into the feasibility and competitiveness of floating offshore wind energy.

Another area of future work could involve analyzing the electricity market in light of the ongoing transformation due to the integration of renewable energy. Understanding the evolving market dynamics, pricing mechanisms, and grid integration challenges will be crucial for ensuring the financial viability of offshore wind projects and maximizing their contribution to the energy system.

In conclusion, the offshore wind energy sector is vast and rapidly evolving, requiring continuous research and discussion. Further work in these areas will be essential to fully unlock the potential of floating offshore wind and ensure its successful integration into Portugal's energy future.

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Appendix A

Challenges in the Construction and Deployment of Offshore Wind Farms

Offshore wind energy is becoming a key solution in the global shift towards renewable energy, with Portugal recognizing its potential due to favorable coastal conditions. However, significant technical, environmental, and economic challenges must be addressed for successful deployment.

Offshore wind turbines face harsh marine environments, requiring durable materials and robust engineering. Challenges such as turbine reliability, grid integration, and maintenance logistics need ongoing research. Floating offshore wind turbines, especially in deeper waters off Portugal's coast, face additional challenges in cost, material durability, and operational risks, which need refinement before commercial adoption [123, 124].

Environmentally, while offshore wind offers a cleaner alternative to fossil fuels, it can impact marine ecosystems, biodiversity, and wildlife. Effective environmental assessments and mitigation strategies are necessary to ensure sustainability without compromising ecological integrity [125].

To fully harness offshore wind's potential, Portugal must overcome these technical and environmental barriers, advancing technology for long-term viability.

A.1 Construction, installation and technical challenges

In this section, we will examine the technical and environmental challenges faced in the construction and installation of offshore wind energy projects. Offshore wind farms, particularly Floating Offshore Wind Turbines and Traditional Fixed-base structures, present unique obstacles that must be navigated to ensure efficient deployment and long-term operational success.

A.1.1 Subsea Terrain and Geotechnical Considerations

A major challenge in constructing offshore wind farms is navigating the complex underwater landscape, including deep trenches, rocky formations, and large boulders. Advanced technologies like sonar and seismic reflection surveying are crucial for accurately mapping these obstacles. This mapping helps identify suitable locations for turbine foundations and reduces potential installation delays [126].

A.1.2 Corrosion and Material Integrity

The harsh marine environment poses a threat to the structural integrity of turbines and their foundations. Offshore installations are susceptible to corrosion, fatigue, and erosion, exacerbated by factors such as biofouling. To combat these issues, innovations in materials and protective coatings are crucial. Developing and implementing advanced materials that can withstand these challenges will be key to ensuring the long-term viability of offshore wind farms [123].

A.1.3 Environmental Dynamics and Modeling

A comprehensive understanding of oceanic conditions is vital for the successful operation of offshore wind farms. The interplay of wind, waves, and currents necessitates robust atmospheric models and data assimilation methods to accurately predict operational conditions. Extensive field studies are essential to validate these models, enabling operators to make informed decisions regarding turbine placement and operational strategies [123].

A.1.4 Installation Procedures and Logistics

The installation of offshore wind turbines involves key steps like floating turbines to the site, mooring, ballasting, and cable installation. Ports with deep harbors are essential for these operations, and their proximity to the site impacts costs and logistics, especially with chartering vessels and crews. The mobility of Floating Offshore Wind Turbines offers greater adaptability, with technologies like detachable electrical connections enabling efficient power distribution and turbine adjustments, leading to cost savings and improved wind farm efficiency [95, 125].

A.1.5 Supply Chain Challenges

The offshore wind sector faces rising capital and material costs, which pose significant challenges for project development. Offshore wind projects are capital-intensive and highly sensitive to fluctuations in capital costs, driven by surging interest rates and increased investment risk due to engineering challenges. These rising costs have led to the cancellation of several projects in Europe and the U.S. Additionally, material costs, including steel, copper, and freight, have increased due to supply chain disruptions following the

COVID-19 pandemic. Although some inflationary pressures have eased, material prices remain high, complicating project financing and implementation [126, 127].

A.1.6 Planning and Grid Connection Challenges

The successful operation of offshore wind farms relies on effective connection to existing electrical infrastructure, but in Portugal, as in much of Europe, planning and connection issues are delaying offshore wind projects. These challenges, especially for onshore wind initiatives, stem from fragmented approval processes that require approvals from multiple under-resourced authorities. This bureaucratic bottleneck leads to delays and cost overruns. In response, the European Union's Wind Power Action Plan aims to streamline these processes to enable faster offshore wind deployment. Additionally, capital costs, including hardware, electrical infrastructure, and substation expenses, heavily influence the overall cost of offshore wind energy. Effective planning and infrastructure investment are key to integrating offshore wind into Portugal's national grid and achieving renewable energy goals [127].

A.1.7 Maintenance and Operational Challenges

Once installed, offshore wind farms face maintenance and operational challenges due to the deep-water environment, which complicates logistics. Vessels must navigate rough seas and adverse weather, leading to delays and higher servicing costs. Additionally, the longer distances for cabling in deep-water installations increase expenses, requiring careful planning for cable laying and maintenance. Overcoming these challenges is essential for the successful development of offshore wind energy in Portugal, enhancing sustainability and resilience while meeting the growing demand for renewable energy sources [125].

Appendix B

Environmental challenges and impact on marine resources

Offshore wind energy is becoming a key component of global renewable energy strategies, offering significant environmental and energy benefits. However, its development presents ecological and logistical challenges that must be carefully managed. Offshore projects are more complex than onshore installations, involving large infrastructure and extensive construction activities, such as shipping, dredging, and seabed preparation. These operations can disturb marine environments, requiring a balance between energy production and ecosystem protection.

Ecologically, offshore wind farms are often located in biologically rich shallow waters, which provide critical habitats for marine species. Infrastructure can disrupt these habitats, affecting species like seabirds, fish, and marine mammals. Additional concerns include visual and noise impacts on coastal communities and conflicts with activities like fishing, shipping, and tourism. The challenge of connecting offshore farms to mainland grids, particularly in deeper waters, further complicates projects due to technical and financial demands.

To mitigate these issues, coordinated efforts between countries are essential. Streamlining regulatory frameworks, sharing environmental data, and adopting innovative technologies, such as quieter construction methods and eco-friendly designs, can help reduce the ecological footprint of offshore wind energy. This section explores the environmental challenges of offshore wind development, focusing on its impact on marine ecosystems, wildlife, and human activities, aiming to balance renewable energy advancement with marine conservation [66].

B.1 Visual Impact

A significant challenge in offshore wind energy development is the visual impact on coastal landscapes. As turbines grow larger and more widespread, their visibility from shore can extend over considerable distances, raising concerns for coastal communities. Research indicates that turbine towers can be visible from 30 to 42 km, with blades and navigation lights visible up to 39 km under certain conditions. As turbine technology advances, the visual impact may increase further.

The perception of this visual impact is subjective, with some viewing turbines as symbols of progress, while others find them intrusive. Studies show that individuals' attitudes toward renewable energy and the surrounding environment influence their opinions on the aesthetics of offshore wind farms. The distance from shore also affects perception: turbines within 16 km are highly visible, while those beyond 30 km are less discernible.

Balancing aesthetic concerns with the broader environmental and economic benefits of offshore wind energy is crucial. Coastal communities may worry about impacts on tourism, local identity, or property values, making careful planning and siting essential. In conclusion, managing the visual impact of offshore wind farms requires thoughtful planning, public engagement, and innovative technologies to preserve the visual quality of coastal environments while promoting renewable energy development [66, 128].

B.2 Noise Impact

Offshore Wind Farms (OWFs) generate noise pollution during installation, operation, and decommissioning, which can significantly impact marine species, particularly mammals and fish. While birds are primarily affected by background noise, marine animals face more direct harm, and the effects vary across species and locations. More research is needed to assess the long-term and cumulative impacts of OWFs noise.

- **Installation Phase** The installation of OWFs, especially pile driving, produces loud, disruptive noise that can damage hearing and disrupt behaviors of marine mammals, such as harbor seals and porpoises, displacing them from affected areas. Noise mitigation techniques like bubble curtains can reduce these impacts [66, 129, 130].

- **Operational Phase** During operation, continuous noise from turbines affects marine life by interfering with communication and predator detection. While sound levels are lower, they can still cause behavioral changes in species like European seabass. Long-term exposure could affect reproductive success or survival rates [66, 130].

- **Decommissioning Phase** Decommissioning, involving heavy machinery and underwater cutting, generates noise that can displace marine species, though further studies are needed to understand its full impact [130] [66].

- **Operational Phase** During operation, continuous noise from turbines affects marine life by interfering with communication and predator detection. While sound levels are lower, they can still cause behavioral changes in species like European seabass. Long-term exposure could affect reproductive success or survival rates [66, 130].

- **Decommissioning Phase** Decommissioning, involving heavy machinery and underwater cutting, generates noise that can displace marine species, though further studies are needed to understand its full impact [66, 130].

B.2.1 The Need for Further Research

Despite growing knowledge, uncertainties remain about species-specific responses and the cumulative effects of noise. Some species, like European plaice, show little response, while others, like European seabass, exhibit significant changes. Further research and the development of comprehensive environmental assessments, alongside noise mitigation techniques like bubble curtains and ramp-up procedures, are necessary to protect marine ecosystems. Ongoing monitoring and research are crucial to refining strategies and ensuring the sustainable development of offshore wind energy [129, 131, 132, 133].

B.3 Electromagnetic field effects

Offshore wind farms (OWFs), particularly those using deepwater, floating turbines, require extensive subsea cabling to transmit electricity to the grid. These cables, including inter-array and export cables, emit electromagnetic fields (EMFs) due to the electric currents, generating both magnetic and electric fields. The impact of these fields on marine life is an emerging area of research, but significant gaps in understanding remain regarding their effects on marine organisms.

B.3.1 EMF Generation and Characteristics

The primary source of EMFs in OWFs is the subsea cables that transmit electricity from the turbines, typically using three-phase AC cables. These cables generate low-intensity magnetic fields, ranging from microtesla (µT) to picotesla (pT), within several meters. Floating offshore wind farms, requiring longer transmission distances, may use HVDC cables, which produce stronger magnetic fields over a wider area. EMFs from OWFs range between 1 and 100 µV/cm, similar to the bioelectric fields of prey species, potentially attracting electroreceptive predators like elasmobranchs. The intensity of these EMFs depends on factors like cable type, conductor distance, and power levels.

B.3.2 Marine Species' Sensitivity to EMFs

Several marine species, including elasmobranchs (sharks and rays), bony fish, crustaceans, marine turtles, and cetaceans, are sensitive to EMFs, using them for navigation, orientation, and prey detection. Elasmobranchs, for example, can detect electric fields as low as 0.005 µV/cm and avoid fields above 10 µV/cm. The impact of EMFs varies among species, but overall, the impact on species' fitness and migration is often minimal.

B.3.3 Potential Ecological Impacts

The most likely effects of EMFs from OWFs are behavioral and physiological changes in marine organisms, particularly electro-receptive species. For instance, species like the European eel and Baltic herring show altered migration patterns when exposed to subsea cables. However, the overall significance of these effects is debated, with some studies reporting minimal impact on fish behavior. In benthic species, long-term exposure to static magnetic fields from offshore wind farm (OWF) cables has shown minimal physiological impacts, with studies on mussels revealing no significant differences in survival or reproductive success under these conditions [66, 133, 134].

B.3.4 Knowledge Gaps and Future Research

Despite extensive studies, the understanding of EMFs effects on marine ecosystems remains incomplete. Effects are species-specific, with varied responses even within similar groups, and research is often limited by technical constraints such as difficulty in measuring low-intensity EMFs in the marine environment. Long-term, in-situ studies are essential to assess the full impact, particularly for floating OWFs, which may expand anthropogenic EMFs in the water. Understanding how different species interact with these fields, especially those migrating through areas with subsea cabling, is crucial to minimize ecological disruptions from offshore wind energy expansion [133, 134].

B.4 Impact on Benthos, Fish, Marine Mammals and Habitat Alterations

The establishment and operation of offshore wind farms (OWFs) significantly impact local habitats and marine life. Turbine installation alters seabed characteristics and ecological interactions, with increased turbidity during construction affecting marine flora and fauna. Additionally, the introduction of hard substrates creates new habitats, changing species composition and abundance.

B.4.1 Impact on Benthos

Offshore wind farms significantly impact benthic communities, which include organisms residing on the seabed. The construction of turbine foundations creates new artificial substrates, attracting specific species and altering existing community dynamics. Studies show that food availability for fish and other organisms can increase dramatically in wind farm areas, with some documenting up to a 60-fold rise in food resources. This enriched environment benefits non-mobile species like mussels and barnacles, while larger fish may also be drawn to these areas. Although increased turbidity during construction may temporarily affect local vegetation, these effects are generally short-lived, allowing new ecological relationships to form [66, 135].

B.4.2 Impact on Fish

Offshore wind turbines impact fish populations by creating artificial habitats that often lead to greater fish abundance and diversity, similar to artificial reefs. Species like sand eels have shown significant population increases within wind farm zones, likely due to enhanced food availability and fishing restrictions. However, responses vary by species, with some attracted to the turbines and others showing minimal changes in behavior or distribution. Long-term studies indicate that effects on fish assemblages differ by location, with increased densities of certain species observed during feeding and spawning seasons [66, 133].

B.4.3 Impact on Marine Mammals

The effects of offshore wind farms on marine mammals can be both positive and negative. During construction, underwater noise and physical disturbances can cause avoidance, but some species, like porpoises, may rebound as the wind farms become operational. The artificial habitats created by turbine foundations can enhance food availability, potentially leading to neutral or positive outcomes. However, the long-term impacts on reproduction and population health remain uncertain, emphasizing the need for further research into the ecological effects of offshore wind energy development [66].

B.5 Impact on Birds and Migration Routes

Offshore wind farms (OWFs) can significantly impact bird populations by altering flight paths and migration routes. While collision risks exist, specific data on migratory birds is limited. Studies show that birds, like Eurasian curlews, often adjust flight altitudes or avoid wind farms, reducing collision risks. Turbine design and bird approach angles influence mortality rates, with many birds avoiding OWFs by changing direction kilometers away. Research suggests that seabird collisions are rare, with strong avoidance behaviors leading to fewer fatalities than expected. However, OWFs can act as barriers to migration, especially during breeding seasons, emphasizing the need for continued monitoring, particularly in Portugal [133, 135, 136].

B.6 Changes to Atmospheric and Oceanic Dynamics

Offshore wind farms (OWFs) significantly impact both atmospheric and oceanic dynamics. The wake effect from turbines reduces wind speed by up to 70-90%, influencing local weather and sediment dynamics, and can lead to increased precipitation in certain areas. The turbines also enhance vertical mixing in surrounding waters, creating upwelling effects that modify hydrographic conditions and reduce wave heights. This can lead to changes in wave energy, including increased energy downstream. Additionally, OWFs influence sediment transport and turbidity levels, which can affect marine ecosystems by reducing visibility for sensitive species, though it may also reduce predation risks for fish. Construction methods, such as trenching, further alter seabed dynamics and turbidity. While atmospheric effects are generally moderate, the broader consequences for marine ecosystems warrant further investigation [133, 134, 137].

B.7 Impact on Fisheries, Tourism and Other Activities

The increasing interest in offshore wind farms (OWFs) as a renewable energy source has raised significant concerns regarding their potential impacts on various sectors, notably fisheries and tourism. These concerns revolve around the complex interactions between established activities like fishing and emerging industries like offshore renewable energy. As we explore these impacts, it becomes evident that comprehensive planning and stakeholder engagement are essential for achieving a balanced approach.

B.7.1 Fisheries

Fisheries play a critical role in coastal economies, and their coexistence with offshore wind farms (OWFs) presents challenges, particularly regarding space utilization. The exclusion of fisheries from OWFs can have significant economic and social consequences, especially for regions with bottom-contacting fishing fleets, such as northern Europe and the Mediterranean, where small-scale fisheries are vital. The vulnerability of fish stocks further complicates the issue. On the positive side, OWFs can provide new habitats for fish, such as shelter and foraging opportunities in the North Atlantic. However, these benefits must be balanced against the loss of traditional fishing grounds, and not all OWFs offer the same ecological advantages. In some cases, wind farms are located in areas already closed to trawl fisheries, reducing conflict but limiting fishing opportunities [137, 138, 139, 140].

B.7.2 Tourism

Tourism, especially maritime and coastal leisure activities, can be significantly impacted by the development of offshore wind farms (OWFs), particularly in regions with narrow continental shelves. In the Mediterranean, where tourism is a key economic sector, concerns about the visual impact of wind farms on coastal landscapes are common. Activities like sailing, scuba diving, and whale watching rely on scenic views, and studies estimate that the presence of wind farms could lead to substantial welfare losses, such as €203 million per season in Catalonia, as local residents fear that the wind farms may deter visitors and negatively affect businesses and recreation [137].

B.7.3 Other Activities and Spatial Conflicts

The development of offshore wind farms (OWFs) introduces challenges with other maritime activities, such as shipping and aquaculture. The Mediterranean Sea, a busy shipping region, faces potential disruptions in traffic and navigational safety due to wind farms. Additionally, aquaculture competes for space with OWFs, creating a conflict of interest. Collaborative planning is crucial to address these challenges. As offshore wind development progresses, it is essential to engage with regional fishing industries and other stakeholders to minimize impacts on fisheries, tourism, and maritime activities. Responsible turbine siting, visual impact consideration, and stakeholder involvement are key to ensuring the sustainable coexistence of offshore wind energy and coastal industries [137, 139].

B.8 Lessons learned and Recommendations for the future

B.8.1 Integrated Environmental Impact Assessments

A key lesson from offshore wind farm (OWF) projects is the importance of thorough Environmental Impact Assessments (EIAs) to assess the potential impacts on biodiversity, sensitive species, and habitats during all phases of development. Comprehensive and independent evaluations help ensure that environmental, social, and economic effects are fully understood. Long-term monitoring of cumulative impacts on marine life and maritime activities is crucial for refining mitigation strategies and improving future predictions. A regional and transnational approach, as suggested by European experience, ensures impacts are assessed across borders, reflecting the interconnected nature of marine ecosystems [137, 141].

B.8.2 Adaptive and Data-Driven Planning

The OWF industry has benefited from advances in data collection and predictive models, but early studies often underestimated the area of potential biological effects, especially regarding underwater noise impacts on marine species. Technologies like passive acoustic monitoring, radar, and Global Positioning System (GPS) tracking have proven more effective than traditional methods in tracking species and detecting behavioral changes. A data-driven approach, combining empirical field data and predictive models, is essential to address knowledge gaps and improve risk assessments. For example, gradient design studies have helped understand spatial displacement, particularly for species like harbor porpoises [141].

B.8.3 Sustainable Marine Spatial Planning

A key recommendation for future OWF projects is prioritizing MSP with a focus on conservation, especially within Marine Protected Areas (MPAs). This includes incorporating buffer zones around OWF sites and migration corridors to mitigate impacts on vulnerable species, like seabirds, which face collision risks and displacement. MSP should also consider socio-economic factors, addressing the impacts on fisheries, tourism, and local economies to protect regional identities and livelihoods [137, 141].

B.8.4 Technological Innovations and Mitigation Strategies

As the OWF industry expands, technological innovations, such as noise reduction during pile-driving and floating wind turbines, are key to minimizing environmental impacts. While floating turbines reduce noise pollution, they introduce new challenges, such as entanglement risks. Learning from onshore wind and oil platform industries can improve mitigation strategies, particularly for bird collisions and underwater noise. Ongoing research, including testing mitigation measures like exclusion zones for marine mammals, is essential to ensure effectiveness [141].

B.8.5 International Collaboration and Knowledge Transfer

Lessons from Europe and other regions with established OWF industries emphasize the importance of international collaboration. Emerging sectors like the U.S. can benefit from these experiences by adopting best practices and refining regulatory frameworks. Sharing knowledge can improve ecological assessments and mitigation strategies, while pilot projects in sensitive areas allow for better approaches before full-scale development. Adopting precautionary principles and supporting global conservation goals, will balance economic benefits with environmental preservation [137, 141].

B.8.6 Continuous Monitoring and Research

A key recommendation for future OWF developments is the creation of robust monitoring programs to track both short-term and long-term impacts on marine ecosystems. Given the limited understanding of population-level effects from behavioral changes like displacement due to underwater noise, ongoing research is essential to refine models such as the Population Consequences of Acoustic Disturbance (PCAD). Studies should also consider cumulative impacts across multiple wind farms, which will become increasingly important as the industry expands. In conclusion, while the offshore wind industry has significant potential for contributing to the renewable energy transition, further technological and environmental advancements, along with adaptive, transnational planning, are needed to balance energy needs with marine ecosystem preservation [141].

Appendix C

Technologies for Grid Stability

Wind energy's intermittent nature presents challenges for maintaining grid stability, particularly as we transition to cleaner energy sources. To ensure a reliable power supply despite fluctuating wind conditions, transmission system operators have adopted stricter grid requirements and enhanced weather forecasting to better predict wind farm output and balance supply and demand.

C.1 Solutions to achieve a more resilient energy network

Energy Storage Systems (ESS) are increasingly seen as a viable solution to store excess energy during high wind periods and release it when production drops. While economic barriers remain, technological advancements are making ESS more feasible for grid stability. Other strategies, such as turbine de-loading, are also being explored to manage grid stability. This appendix will explore these solutions in detail, focusing on how energy storage and innovative approaches can improve the reliability of wind energy and contribute to a more resilient energy network [142].

C.1.1 Pumped Hydro Storage

Pumped Hydro Storage (PHS) is a well-established energy storage technology that operates similarly to a large battery. It uses two water reservoirs at different elevations to store and generate energy. When there is excess power in the grid, water is pumped from the lower reservoir to the upper one, storing energy in the form of gravitational potential. When energy is needed, the stored water is released back down through turbines, generating electricity [143].

PHS is widely used in wind power management due to its large-scale capacity, with a global installed capacity of over 160 GW as of 2021. Its efficiency ranges between 70-85%, and it offers a long lifespan of more than 40 years. However, PHS is constrained by factors such as the need for suitable geographical sites, high capital costs, and long construction times. Despite these challenges, it remains a key technology for stabilizing grids with variable renewable energy sources like wind power [142].

C.1.2 Compressed Air Energy Storage

Compressed Air Energy Storage (CAES) is a well-established mechanical energy storage system that utilizes excess electricity to compress air and store it in pressurized spaces, such as natural underground structures like caverns, abandoned mines, or artificial vessels. When needed, the compressed air is released and expanded through turbines connected to electricity generators, providing power when demand is high.

CAES systems offer significant power and energy capacity with an efficiency of around 71% [144]. Despite these advantages, CAES has some limitations. It has a lower power density when compared to gas, heat, and electricity storage systems, and its site requirements are quite specific. Furthermore, CAES systems often have longer discharge times and shorter cycling capabilities, making them more suitable for applications where energy needs to be stored over longer periods [142].

C.1.3 Thermal energy storage

Thermal Energy Storage (TES) provides a practical solution for storing energy for later use in heating or cooling applications. It enables renewable energy storage when production doesn't align with demand and allows consumers to take advantage of off-peak electricity tariffs. TES systems store energy either as sensible heat, where the temperature of a material is raised, or as latent heat, where phase change materials (PCMs) store energy during a phase transition, like melting.

Sensible heat storage involves increasing the temperature of liquids or solids with high heat capacities, such as water or ceramics, which later release heat when the temperature decreases. On the other hand, latent heat storage systems, often using PCMs, absorb heat during the phase change process, storing more energy per unit volume than sensible heat systems [145].

In certain systems, like advanced compressed air energy storage (A-CAES), TES also plays a role by cooling compressed air and recovering the heat during storage to enhance energy recovery during expansion [146].

C.1.4 Flywheel energy storage

Flywheel energy storage (FES) is a mechanical energy storage technology that stores energy as kinetic energy by spinning a flywheel at high speeds. Energy is charged into the system by operating the flywheel as a motor to accelerate the wheel, and discharged by slowing it down to generate electricity. FES systems are highly efficient, with excellent cycle stability and power density. They are particularly useful in applications like power quality management, damping, and mitigating rapid fluctuations in wind power [142].

Flywheels offer quick response times and can maintain continuous operation by storing energy in motion. However, they have some limitations, such as lower energy density, short operational times, and high self-discharge losses due to friction and other factors. The use of magnetic bearings in a vacuum helps minimize these losses. Compared to alternatives like batteries, FES has lower energy storage capacity and can be more costly due to maintenance and safety concerns [147].

C.1.5 Supercapacitor energy storage

Supercapacitor energy storage (SCES) systems, also known as ultracapacitors or double-layer capacitors, are advanced electrochemical storage technologies distinguished by their high power density and efficiency. Unlike conventional capacitors that utilize solid dielectrics, supercapacitors employ an electrolytic fluid between two electrodes, allowing for a more compact design. They can achieve efficiencies of up to 90% and require minimal maintenance, making them attractive for various applications.

When integrated with wind turbines, supercapacitors play a vital role in managing rapid fluctuations in energy output, effectively smoothing the energy supply. They operate using two mechanisms: electric double-layer capacitance (EDLC), which stores energy through charge separation, and pseudocapacitance, which involves reversible electrochemical reactions. The key components of supercapacitors include electrodes, electrolytes, and separators, with carbon-based materials increasingly favored for electrodes due to their cost-effectiveness and sustainability [142].

However, supercapacitors do have limitations; they generally have lower energy density compared to batteries and exhibit faster self-discharge rates. Despite these drawbacks, their unique properties make them essential for applications requiring quick charge and discharge cycles [148].

C.1.6 Superconducting magnetic energy storage

Superconducting magnetic energy storage (SMES) systems are advanced energy storage technologies that utilize a superconducting coil to store energy in a magnetic field. The energy storage process involves a direct current (DC) flowing through the superconducting coil, which must be cryogenically cooled below its critical temperature to achieve superconductivity. This cooling allows the system to operate with almost no electrical resistance, leading to minimal energy losses during storage [142].

SMES systems are known for their rapid response times, typically in the milliseconds range, making them highly effective for applications that require quick bursts of energy. They exhibit high power density and cycle efficiency, with energy conversion efficiencies around 95%. These characteristics make SMES particularly useful in conjunction with wind turbines to enhance power quality and improve dynamic stability within the electrical grid.

However, despite their efficiency and performance advantages, SMES systems face several challenges. They are sensitive to temperature fluctuations, which can impact their reliability. Additionally, common superconducting materials, such as mercury, vanadium, and niobium-titanium, have limitations related to energy density and economic viability. Currently, SMES technology has not been widely deployed or commercialized, mainly due to high costs and specific operational requirements [149, 150].

C.1.7 Hydrogen energy storage

Hydrogen Energy Storage (HES) is an emerging and versatile technology suitable for energy storage applications due to its high energy capacity. One of the significant advantages of hydrogen is its potential integration with offshore wind farms, particularly when hydrogen is produced offshore. Traditional hydrogen production methods include grey hydrogen, derived from fossil fuels, and blue hydrogen, which utilizes natural gas in combination with carbon capture and storage. However, the environmental impact of grey hydrogen and the costs associated with carbon capture have led to a growing interest in producing hydrogen through electrolysis, commonly known as green hydrogen production.

The process of hydrogen production via electrolysis uses excess or off-peak electricity to split water into hydrogen and oxygen. This hydrogen can be stored in various forms, including compressed gas, liquefied gas, metal hydrides, or carbon nanostructures, depending on the technical, economic, or environmental characteristics of the available technologies [142].

Hydrogen can then be converted back into electricity through fuel cells, which exhibit good dynamic behavior and rapid start-up capabilities, even under partial loads. However, it is important to note that rapid fluctuations can lead to accelerated degradation of the fuel cell stacks. HES offers the benefit of long-term energy storage with no self-discharge, boasting a useful life cycle of approximately 15 years and around 20,000 charge and discharge cycles at 100% depth of discharge.

Despite these advantages, hydrogen-based energy storage is characterized by relatively low energy efficiency, with an overall efficiency of about 42%. This low efficiency stems from the individual processes involved: the electrolyzers operate at around 70% efficiency, while fuel cells achieve approximately 60% efficiency. Additional energy losses occur during the transport and compression stages, further impacting the overall efficiency. As a result, the round-trip efficiency of hydrogen energy storage may be as low as 30%, although its high energy density can partially offset these losses [151, 152].

C.1.8 Battery energy storage systems

Battery Energy Storage Systems (BESS) represent a well-established form of electrochemical energy storage that is widely used in various applications, particularly as the demand for renewable energy continues to rise. With the increased integration of renewable sources, especially wind and solar energy, BESS has emerged as one of the most cost-effective solutions for managing the intermittent and variable nature of these energy sources. These systems play a crucial role in mitigating the short-term variability that characterizes renewable energy production, thus enhancing grid stability.

BESS is often employed to provide combined or "stacked" services to the grid, creating economic incentives for their adoption. These systems can respond quickly, with reaction times measured in milliseconds, enabling them to track load changes effectively and improve overall system stability. The technology is particularly suitable for applications that require backup power for seconds to hours [142].

Batteries are generally classified into two main categories: primary and secondary batteries, with secondary batteries being rechargeable. A BESS typically consists of multiple individual cells connected in series and parallel configurations. Each cell comprises an anode, cathode, and electrolyte, where electrochemical reactions take place during the charging and discharging processes, allowing the battery to absorb and supply power to the grid.

While BESS offers significant advantages, including high energy density, the technology is not without its limitations. The lifespan of batteries can be restricted by the frequency and depth of discharges, with the number of cycles also impacting longevity. Additionally, battery storage systems typically exhibit lower power density and are more suited for applications requiring prolonged continuous discharge. Frequent high-rate charging and discharging can lead to accelerated degradation, further emphasizing the need for careful management in their application [153].

C.1.9 Flow battery energy storage

Flow battery energy storage (FBES) represents a unique and innovative type of secondary battery technology. Unlike conventional batteries, which store energy directly in the electrode materials, flow batteries utilize an electrolyte solution that contains one or more dissolved electro-active species to store energy. This configuration allows flow batteries to store large quantities of energy by simply increasing the volume of the electrolyte, independent of the size of the electrochemical cell itself.

Flow batteries, particularly redox flow batteries, have garnered attention in the literature for their advantages, including high efficiency, low cost per unit of energy, and extended operational lifetimes. These characteristics make them especially valuable for applications such as peak-hour load leveling and enhancing the stability of the grid when connected to renewable energy sources [142].

The operational principle of flow batteries involves the continuous flow of the electrolyte through the electrochemical cell, where chemical energy is converted directly to electricity. This design allows for rapid recharging by simply replacing the spent electrolyte with fresh liquid, akin to refilling a fuel tank in internal combustion engines. Additionally, the spent electrolyte can be processed separately to recover the electro-active materials, contributing to the sustainability and efficiency of the system [154].

C.1.10 Fuel cells

Fuel Cells (FCs) are electrochemical devices that convert the chemical energy of fuels—primarily hydrogen—into electricity and heat through an electrochemical reaction. In a typical fuel cell, hydrogen gas is supplied to the anode side, where it undergoes oxidation, releasing electrons and forming protons. The electrons flow through an external circuit, generating electricity, while the protons move through an electrolyte to the cathode side.

At the cathode, oxygen (usually from the air) reacts with the protons and electrons to produce water and heat. This process results in high efficiency and low pollutant emissions, which has fueled significant interest in fuel cell technology. Additionally, fuel cells require minimal maintenance, making them an attractive option for various applications, including transportation and stationary power generation [155].

Appendix D

Wind Turbine Specifications for Simulations

This appendix discusses in depth the wind turbine models used for the simulations, specifically three turbine models with rated powers of 8 MW, 12 MW, and 16 MW. The turbine files were generated using the WAsP Turbine Editor, a specialized tool designed for creating detailed turbine characteristics based on input data. This process was deliberately undertaken to de-characterize the turbines and avoid the potential bias that might arise from using specific models or brands, which could impact the results. To achieve this, a range of turbines were considered to generate the data, ensuring that the turbine characteristics used in the simulations were not limited to any single manufacturer or design.

The curves used in the turbine models were developed based on a specific methodology to ensure a representative and unbiased dataset. Regarding the thrust coefficient (Ct), an average value was calculated from the manufacturers' provided curves. For the power curve, the power coefficient curves were averaged, and rotor diameter values were defined while ensuring a consistent specific area. This approach allowed the creation of generalized turbine characteristics, providing flexibility and avoiding any undue influence from particular turbine designs.

For each turbine model, the following parameters were input into the WAsP Turbine Editor to generate the turbine files:

1. **Wind Speed-Power Curve**: The wind speed-power curve represents the relationship between wind speed and the electrical power output of the turbine. This curve is critical for determining the amount of electricity a turbine will produce under different wind conditions. By inputting the appropriate data, the software generates the power output at various wind speeds, which is essential for the simulation of turbine performance in real-world conditions.

2. **Wind Speed-Thrust Coefficient Curve**: This curve defines the relationship between wind speed and the thrust coefficient, which represents the mechanical thrust

forces exerted on the turbine as a function of wind speed. The thrust coefficient is important for understanding the structural loads and mechanical stresses the turbine experiences, which influence the design and longevity of the turbine.

3. **Rated Power**: The rated power of each turbine was specified in the WAsP Turbine Editor, which corresponds to the maximum electrical output that the turbine can generate under optimal wind conditions. This parameter is essential for simulating the operational limits of each turbine in the offshore wind farm configurations.

4. **Hub Height**: The hub height, defined as the height of the turbine's rotor above the ground or sea level, was entered for each turbine. The hub height is a critical factor in determining the amount and consistency of the wind resource available to the turbine. Higher hub heights allow turbines to access stronger and more consistent winds, which improves their efficiency.

5. **Rotor Diameter**: The rotor diameter, which is the distance from one tip of the turbine blade to the other, was also specified for each turbine. The rotor diameter is a key determinant of the swept area of the turbine blades, which directly impacts the amount of wind energy that can be captured and converted into electrical power.

6. **Pitch Control Mechanism**: Each turbine was modeled with a pitch control mechanism, which is used to adjust the angle of the blades in response to changing wind conditions.

The turbine data and curves generated by the WAsP Turbine Editor are presented in the following Figures D.1, D.2 and D.3 for each of the three turbine models:

Figure D.1: 8 MW Turbines' Data.

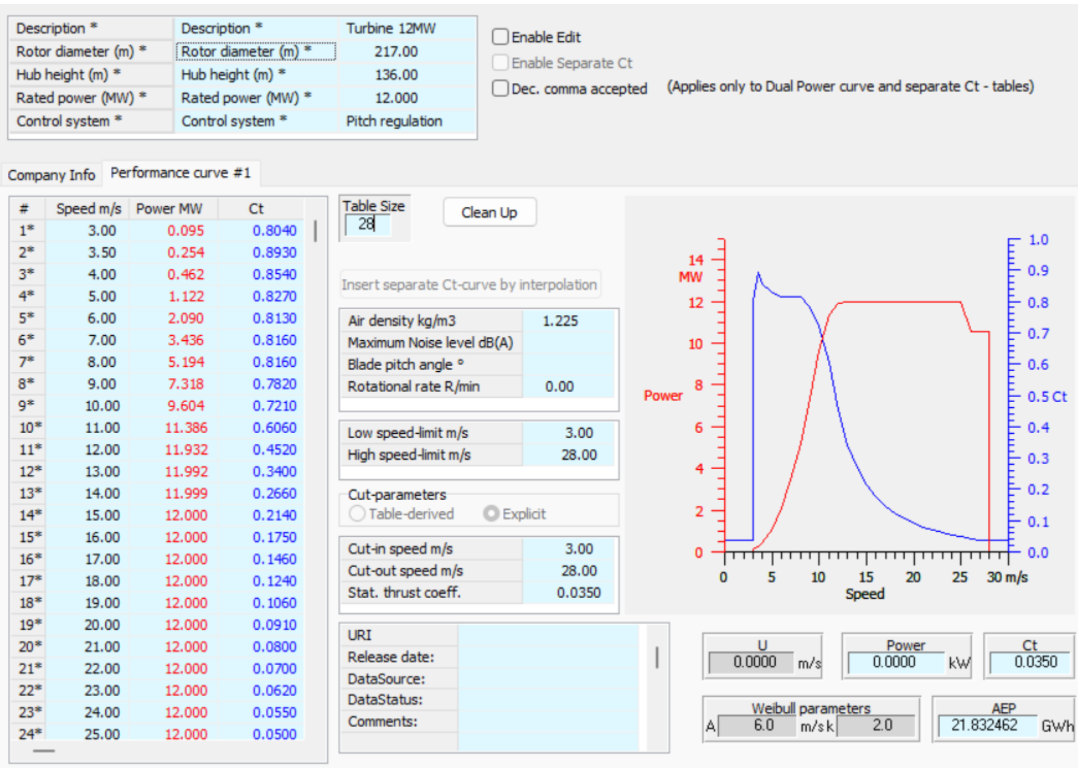

Figure D.2: 12 MW Turbines' Data.

Figure D.3: 16 MW Turbines' Data.

These images provide a visual representation of the performance characteristics of each turbine, showing the wind speed-power and wind speed-thrust coefficient relationships. The data generated by the WAsP Turbine Editor were crucial for accurately simulating the energy production and mechanical loads of each turbine model, enabling a more precise assessment of offshore wind potential in the selected study areas. This process ensured that the turbine characteristics were generalized and not influenced by specific commercial models or brands, providing a neutral foundation for the simulation results.

Appendix E

Digital Representation of Scenarios in Viana do Castelo Norte

This Annex presents the digital representations of the scenarios conducted in Viana do Castelo Norte.

E.1 Scenario A

E.1.1 8 MW Wind Turbines

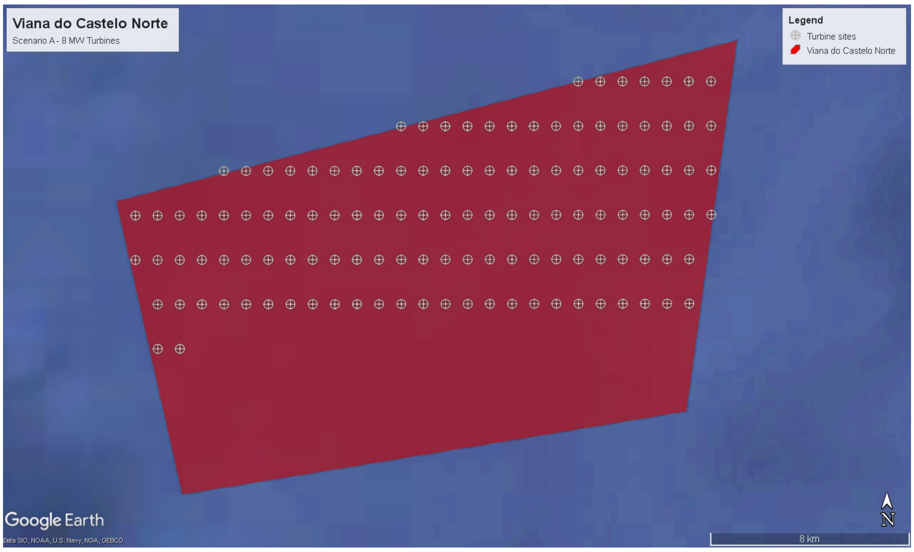

Figure E.1: Digital Representation of Scenario A (8MW Wind Turbines).

E.1.2 12 MW Wind Turbines

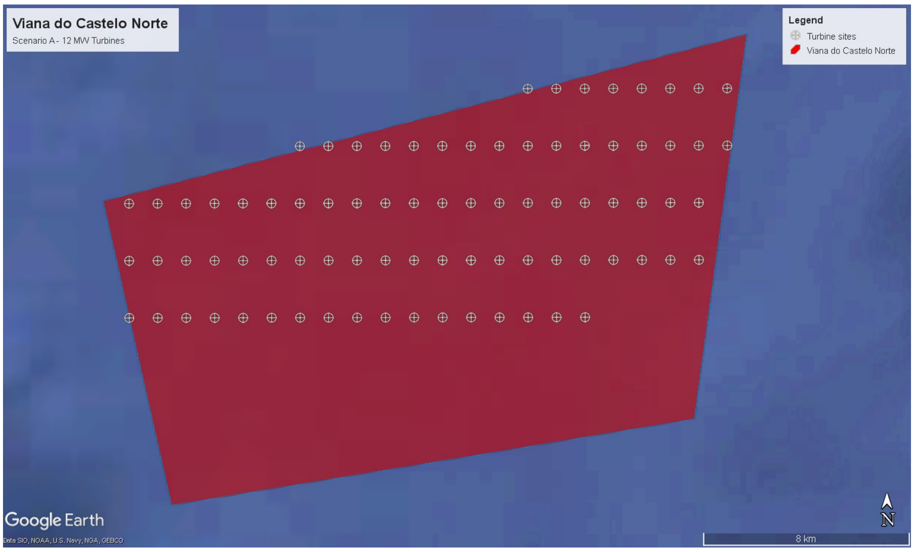

Figure E.2: Digital Representation of Scenario A (12MW Wind Turbines).

E.1.3 16 MW Wind Turbines

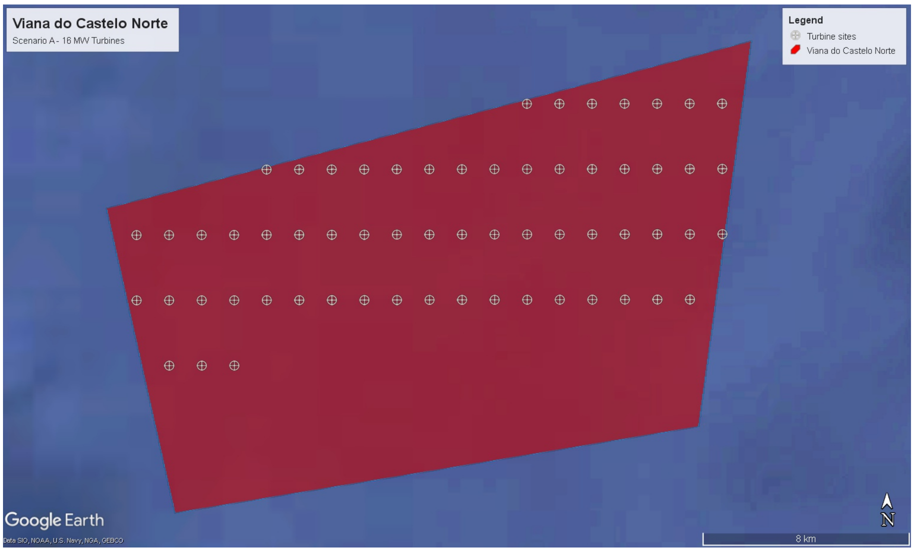

Figure E.3: Digital Representation of Scenario A (16MW Wind Turbines).

E.2 Scenario B

E.2.1 8 MW Wind Turbines

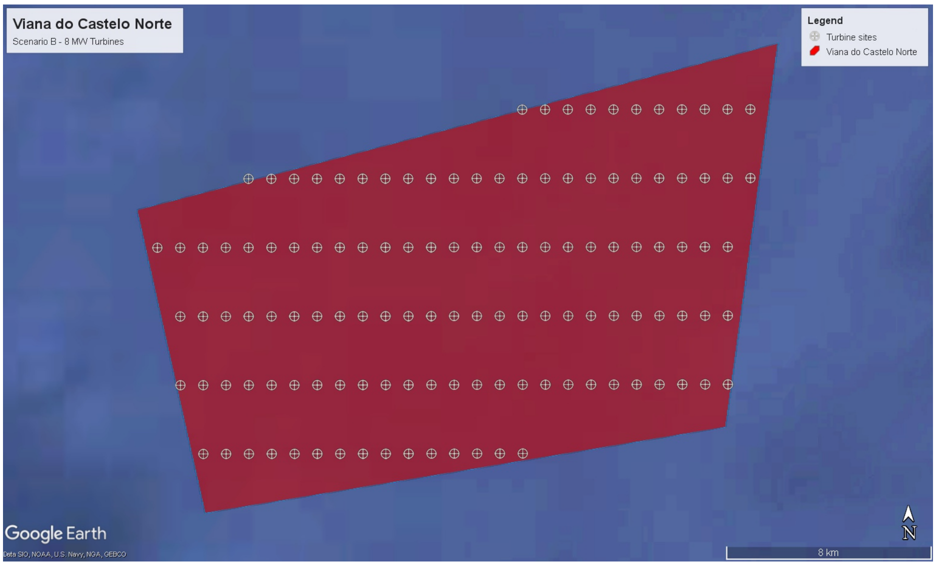

Figure E.4: Digital Representation of Scenario B (8MW Wind Turbines).

E.2.2 12 MW Wind Turbines

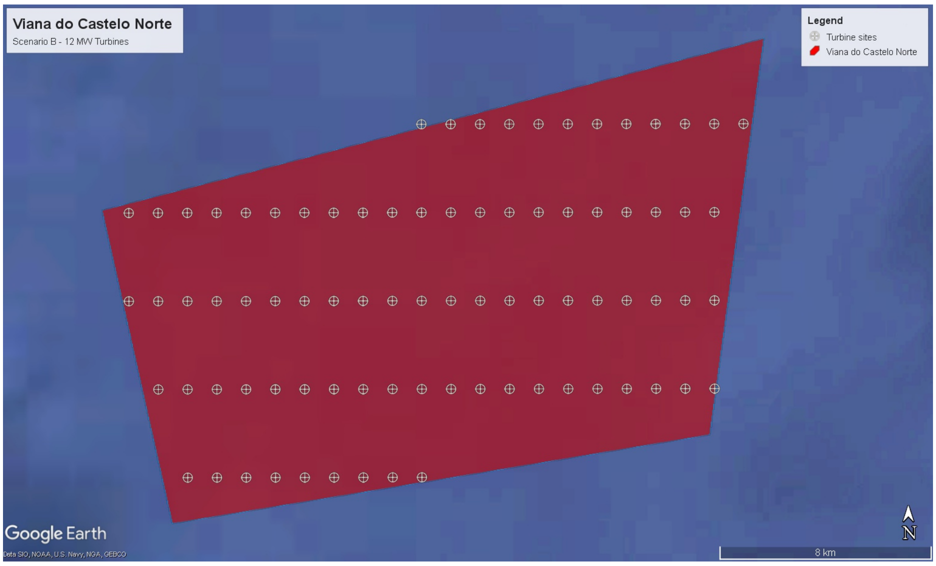

Figure E.5: Digital Representation of Scenario B (12MW Wind Turbines).

E.2.3 16 MW Wind Turbines

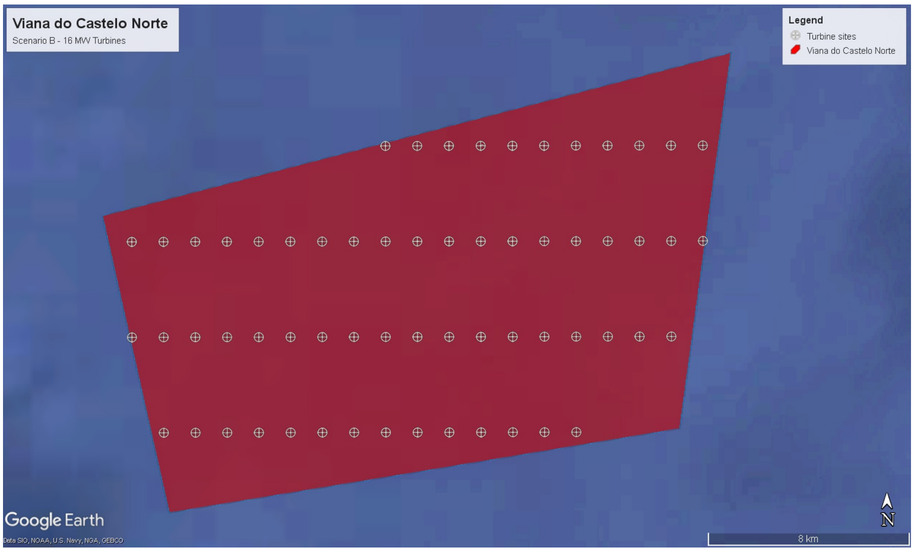

Figure E.6: Digital Representation of Scenario B (16MW Wind Turbines).

E.3 Scenario C

E.3.1 8 MW Wind Turbines

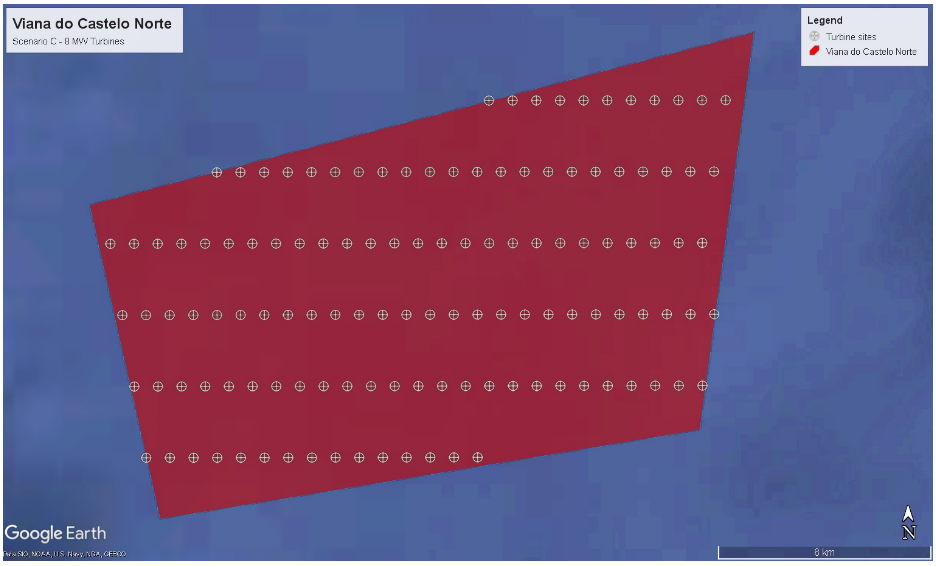

Figure E.7: Digital Representation of Scenario C (8MW Wind Turbines).

E.3.2 12 MW Wind Turbines

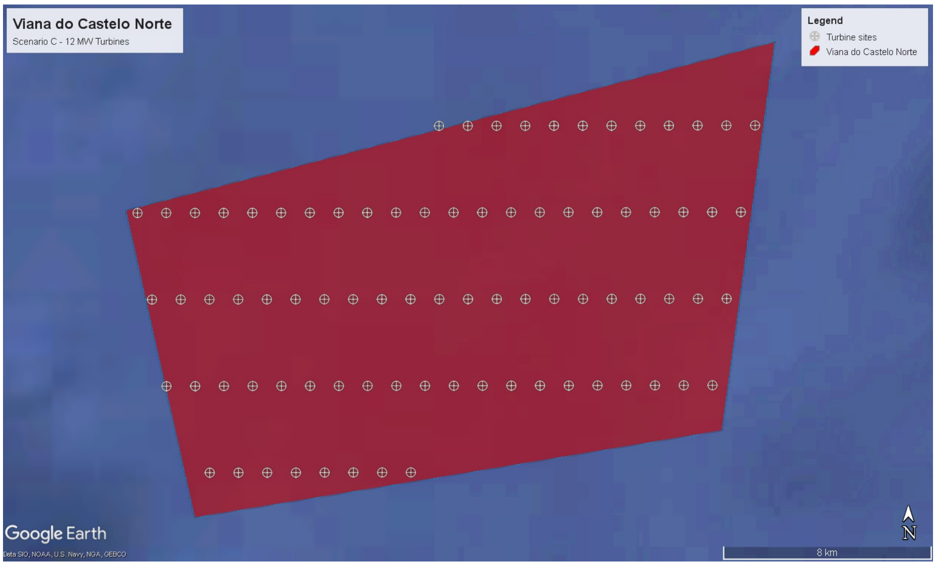

Figure E.8: Digital Representation of Scenario C (12MW Wind Turbines).

E.3.3 16 MW Wind Turbines

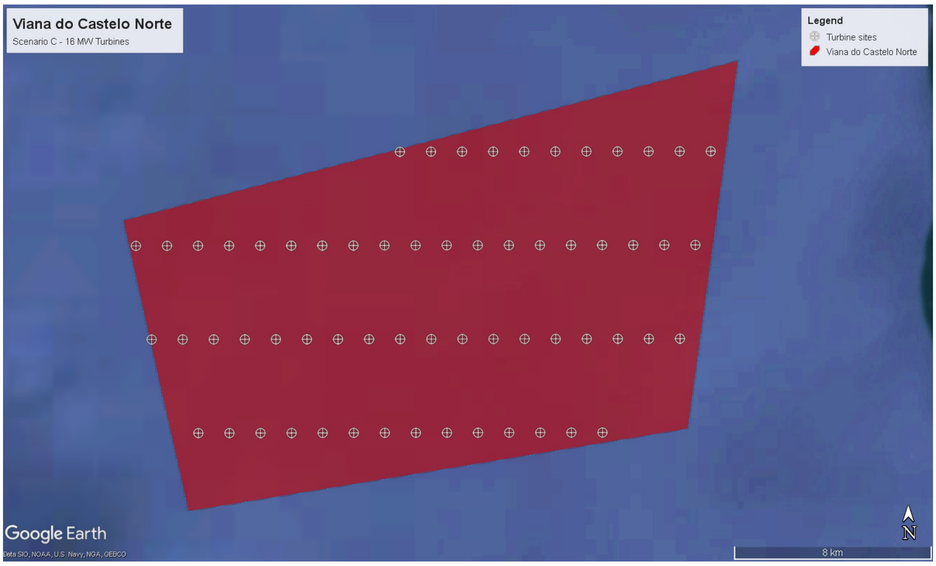

Figure E.9: Digital Representation of Scenario C (16MW Wind Turbines).

Appendix F

Digital Representation of Scenarios in Sines Sul

This Annex presents the digital representations of the scenarios conducted in Sines Sul.

F.1 Scenario A

F.1.1 8 MW Wind Turbines

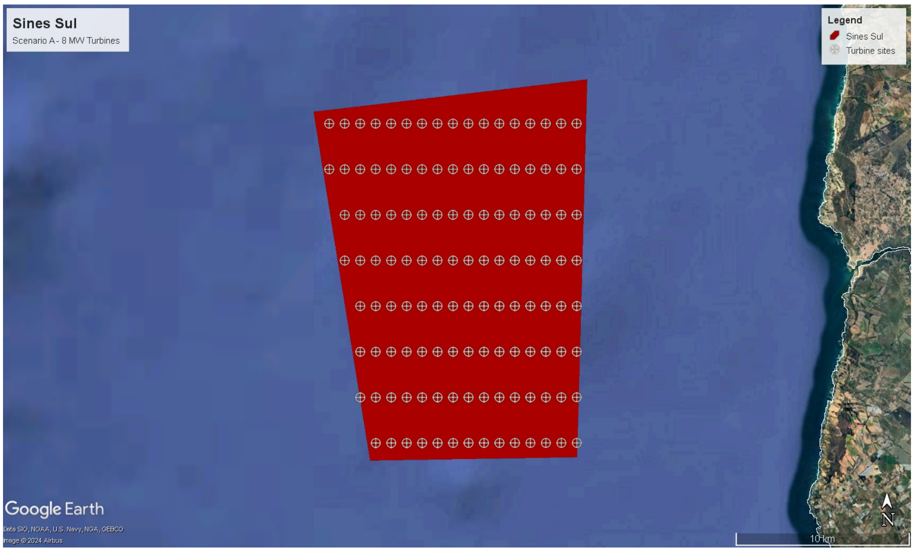

Figure F.1: Digital Representation of Scenario A (8MW Wind Turbines).

F.1.2 12 MW Wind Turbines

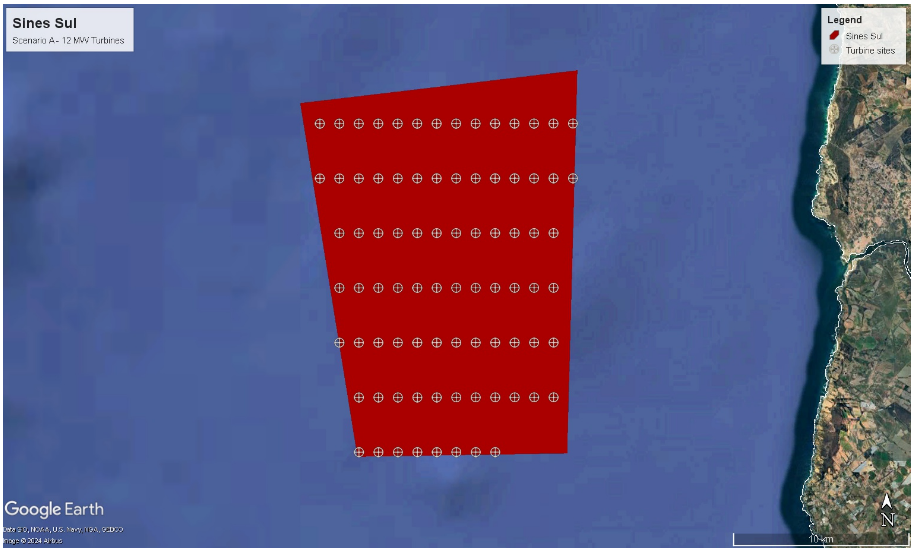

Figure F.2: Digital Representation of Scenario A (12MW Wind Turbines).

F.1.3 16 MW Wind Turbines

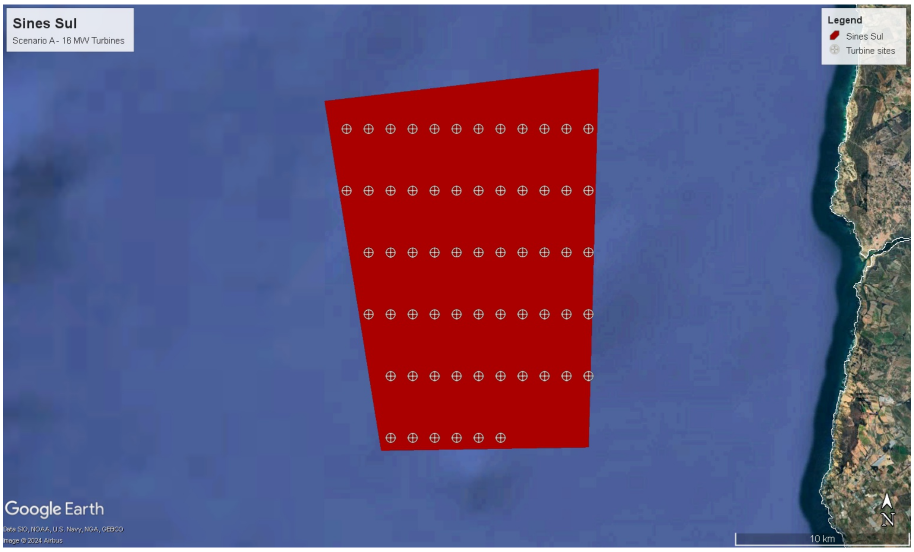

Figure F.3: Digital Representation of Scenario A (16MW Wind Turbines).

F.2 Scenario B

F.2.1 8 MW Wind Turbines

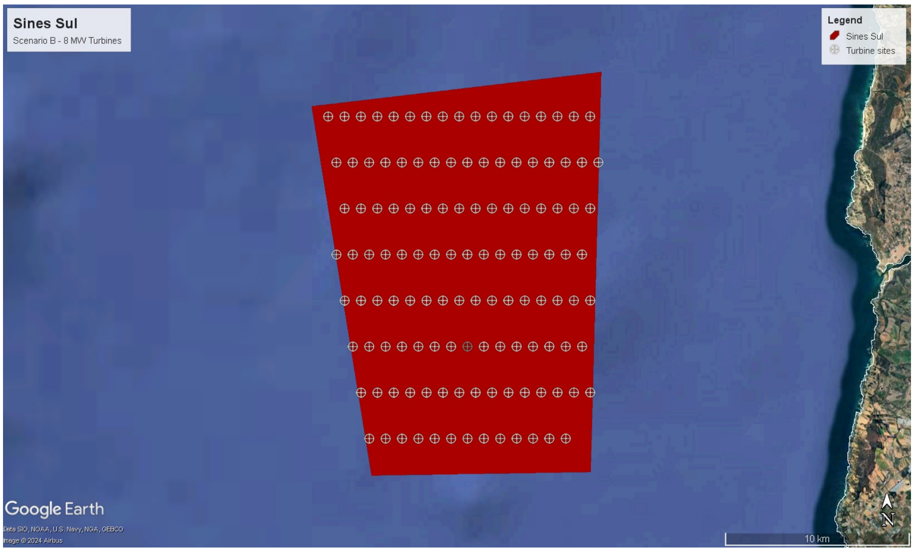

Figure F.4: Digital Representation of Scenario B (8MW Wind Turbines).

F.2.2 12 MW Wind Turbines

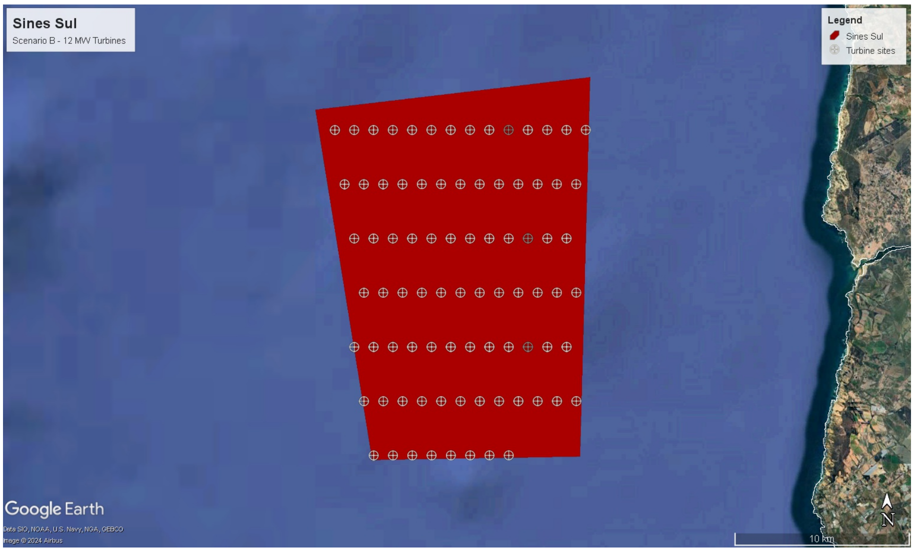

Figure F.5: Digital Representation of Scenario B (12MW Wind Turbines).

F.2.3 16 MW Wind Turbines

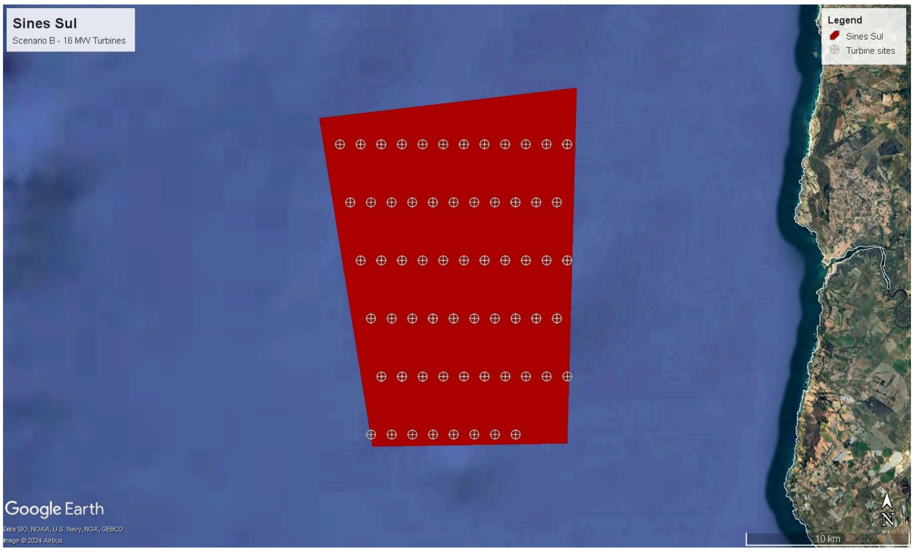

Figure F.6: Digital Representation of Scenario B (16MW Wind Turbines).

F.3 Scenario C

F.3.1 8 MW Wind Turbines

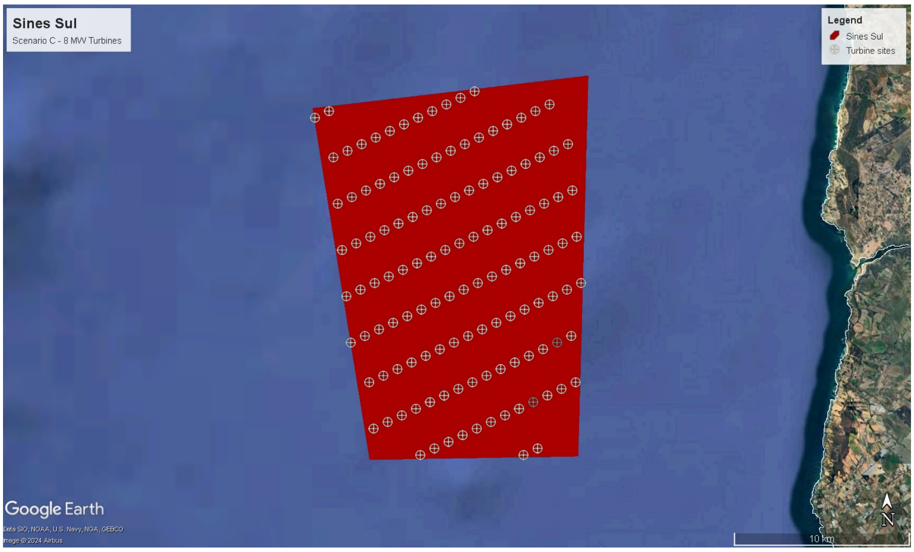

Figure F.7: Digital Representation of Scenario C (8MW Wind Turbines).

F.3.2 12 MW Wind Turbines

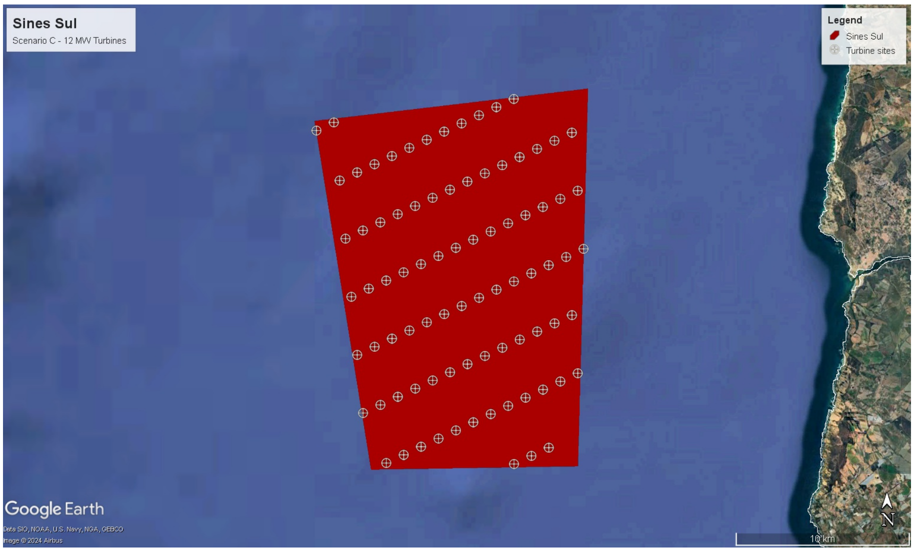

Figure F.8: Digital Representation of Scenario C (12MW Wind Turbines).

F.3.3 16 MW Wind Turbines

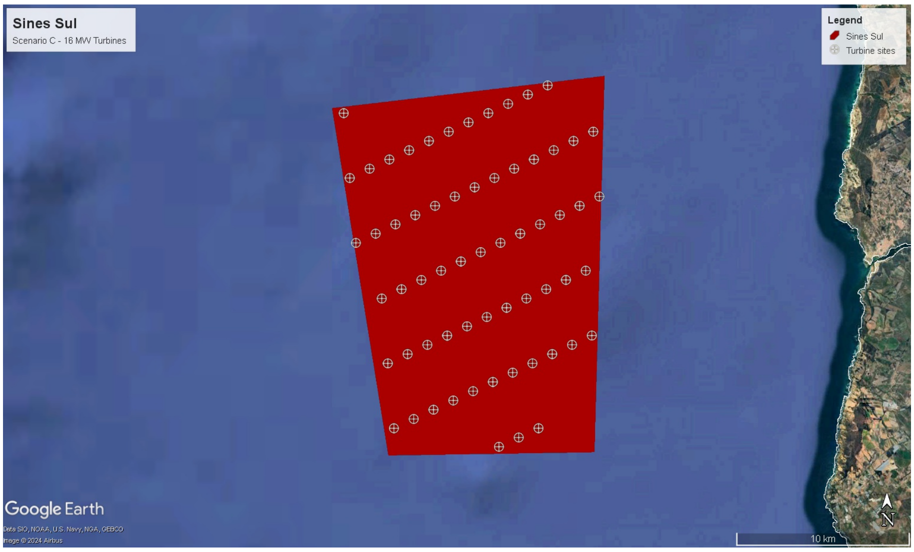

Figure F.9: Digital Representation of Scenario C (16MW Wind Turbines).

F.4 Scenario D

F.4.1 8 MW Wind Turbines

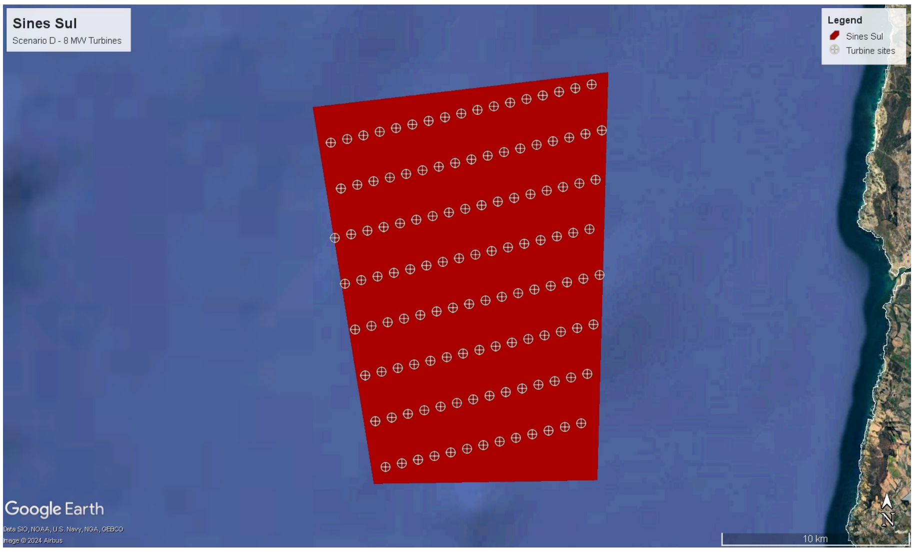

Figure F.10: Digital Representation of Scenario D (8MW Wind Turbines).

F.4.2 12 MW Wind Turbines

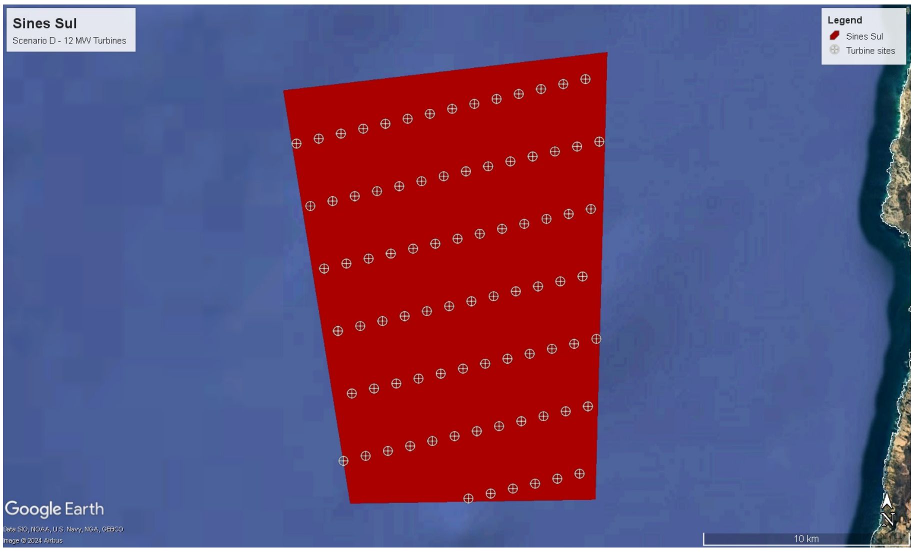

Figure F.11: Digital Representation of Scenario D (12MW Wind Turbines).

F.4.3 16 MW Wind Turbines

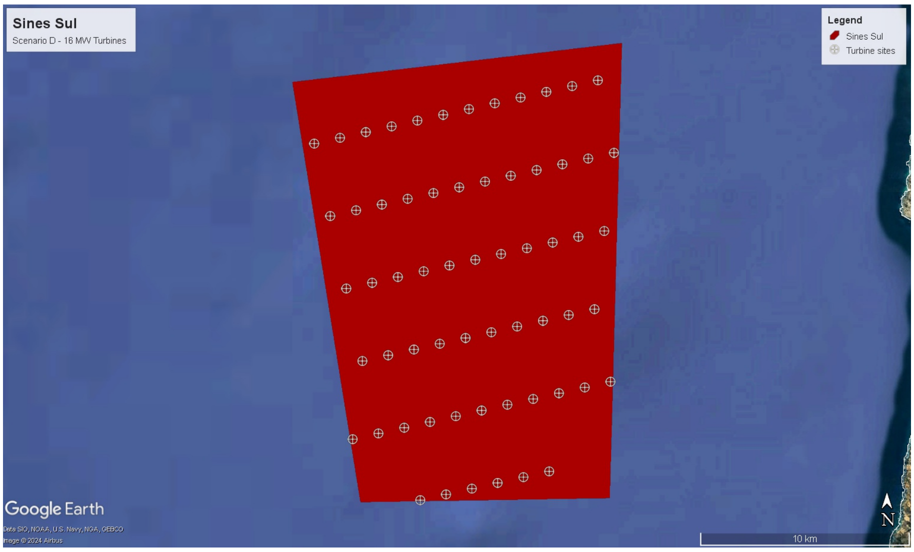

Figure F.12: Digital Representation of Scenario D (16MW Wind Turbines).