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MÁSTER UNIVERSITARIO EN INGENIERÍA INDUSTRIAL

TRABAJO FIN DE MÁSTER

ESTUDIO TÉCNICO Y ECONÓMICO DE CONEXIÓN DE PLANTA EÓLICA OFFSHORE EN AC

Autor: Belén García San Miguel

Director: Julio Rafael Portillo García

Madrid

Junio de 2024

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título:
Estudio técnico y económico de conexión de planta eólica offshore en AC
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Entidad Colaboradora: ICAI – Universidad Pontificia Comillas.

RESUMEN DEL PROYECTO

1. Introducción

1.1 Planteamiento del problema:

La creciente necesidad de reducir las emisiones de carbono en la producción de electricidad ha impulsado el uso de métodos de generación de energía verde, como las plantas eólicas marinas. Estas instalaciones son clave debido a su eficiencia y capacidad de escalabilidad, lo que las convierte en una herramienta fundamental para mitigar el cambio climático. Sin embargo, el rápido crecimiento de las energías renovables y la incertidumbre en cuanto a los costos representan desafíos significativos para su desarrollo y planificación futura. Este proyecto busca abordar este problema al realizar un estudio técnico y económico de la conexión de una planta eólica offshore en el área de AC.

1.2 Estado de la técnica:

A pesar del significativo desarrollo experimentado por la energía eólica offshore en este período, este avance rápido ha generado desafíos no resueltos y precios elevados. Existen numerosos desafíos tecnológicos que se están abordando mediante la investigación, sin embargo, aún queda un largo camino por recorrer y se requieren esfuerzos continuos para lograr que la producción de electricidad de este tipo sea efectiva, más sostenible y accesible en más ubicaciones. En términos económicos, las empresas que invierten y construyen estas plantas necesitan herramientas que les permitan realizar proyecciones precisas de los costos asociados.

1.3 Objetivo del proyecto:

El objetivo principal de este proyecto es desarrollar una herramienta de cálculo de CAPEX (Capital Expenditure) y OPEX (Operational Expenditure), lo que implicará una ampliación del conocimiento técnico sobre las instalaciones de energía eólica offshore, incluyendo sus componentes y dimensionamiento eléctrico. Además, se seleccionará un caso ejemplo para realizar un diseño completo de una planta eólica offshore, describiendo detalladamente sus partes y llevando a cabo un análisis de pérdidas en los cables como parte de los cálculos. Esta herramienta proporcionará una base sólida para evaluar la viabilidad y planificar el desarrollo de plantas de energía eólica marina de manera más efectiva, al mismo tiempo que contribuirá a expandir el conocimiento sobre el diseño y funcionamiento de este tipo de instalaciones.

Como objetivo técnico adicional, se desarrollará una herramienta para el cálculo de pérdidas en los cables de la red de evacuación. Estas pérdidas son fundamentales para establecer el Leverage Cost of Energy (LCOE). A pesar de que este cálculo no se realiza en este estudio, resulta de interés comparar el porcentaje de pérdidas con respecto a la potencia total generada

en la planta. Este análisis permitirá evaluar el impacto de las pérdidas y asegurarse de que los valores se encuentren dentro de rangos normales para este tipo de tecnología.

2. Metodología

La metodología empleada en este proyecto abarca tres aspectos fundamentales que guían el desarrollo y la evaluación de la conexión de una planta eólica offshore en el área de AC y el análisis económico de esto.

En primer lugar, se realizó una investigación sobre el estado actual de la tecnología en el ámbito de las energías renovables, con un enfoque particular en el diseño eléctrico y mecánico de los componentes, así como en los métodos de transporte de energía (AC vs. DC) (X. Xiang, 2017). Se exploraron los desafíos de sostenibilidad asociados con equipos como las subestaciones GIS con gas SF6 (CIGRE, 2008) y se discutieron los métodos de instalación, como la eólica flotante (Canga-Argüelles, 2021), que impactan significativamente en la viabilidad de las ubicaciones de instalación. Además, se examinaron las potencias de generación y las tensiones de salida de las turbinas eólicas más recientes, con el objetivo de mejorar la efectividad de las plantas en función de los estudios más recientes (Offshore Wind Accelerator, 2022).

En segundo lugar, se llevó a cabo un análisis detallado de la instalación eléctrica de un parque eólico offshore, utilizando un caso de estudio específico ubicado en el Mar del Norte y compuesto por 50 turbinas eólicas. Se desarrolló un diseño de cableado para la red de evacuación, considerando la ubicación de las turbinas, seguido por el diseño de la subestación marina, donde se describieron las partes que la componen, incluyendo las subestaciones a 66 kV y 220 kV, así como los transformadores. Además, se calcularon las secciones de los cables de conexión a la costa y se describió el proceso de conexión a la subestación de tierra utilizando la técnica de perforación direccional horizontal (Orsted, 2022) y la cámara de empalme, (conocida internacionalmente como transiton joint bay TJB).

Como objeto principal del proyecto, se desarrolló una herramienta económica que automatiza el proceso de diseño básico de la planta eólica y el cálculo económico posterior. Esta herramienta permite calcular las secciones de los cables, las distancias, la potencia de los transformadores, y la cantidad de subestaciones y sus respectivas bahías de entrada y salida necesarias para la red de evacuación, basándose en los datos introducidos por el usuario. El desarrollo de la herramienta se basa en la misma metodología utilizada para el dimensionamiento de la instalación eléctrica. Sin embargo, se ha automatizado para eliminar la necesidad de conocer la disposición exacta de las turbinas, lo que hace que el proceso sea más eficiente. Los costos de CAPEX y OPEX se obtuvieron de (X. Xiang, 2017), de (BOE, 2011) y datos proporcionados por el director de tesis.

Finalmente, se realizó un cálculo de pérdidas en los cables de la red de evacuación. Para ello, se utilizó la distribución de vientos en la zona según la curva de Weibull (Figura 1) y la potencia de generación (Figura 2) de las turbinas en función de la velocidad del viento. Con estos datos de entrada y el cálculo previo de la sección de los cables, se adaptó la fórmula de cálculo de pérdidas propuesta por (X. Xiang, 2017) y se elaboró una herramienta en Excel para realizar un cálculo de pérdidas bastante preciso. Posteriormente, se compararon las pérdidas con la potencia total generada.

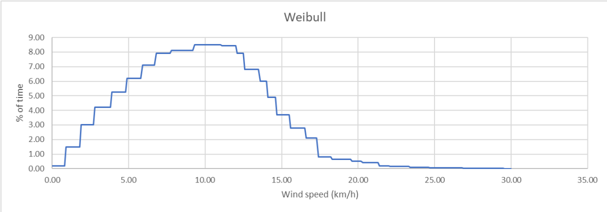

Figura 1: Curva de Weibull. Fuente: Elaboración propia

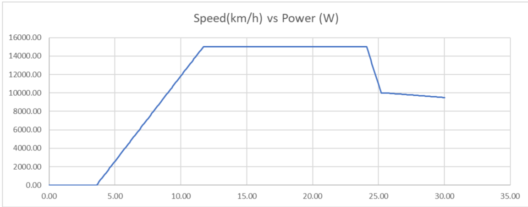

Figura 2: Potencia según la velocidad del viento. Fuente: Elaboración propia

3. Resultados

Los resultados obtenidos de la primera parte del trabajo dedicada al diseño eléctrico de los componentes básicos de la planta de generación eléctrica offshore se muestran en resumen en la Figura 3. En la misma se puede observar:

1. La agrupación de turbinas: número de turbinas agrupadas por circuito.

2. Sección de los cables de la red de evacuación a 66 kV (ABB, 2021).

3. Número de circuitos de entrada a cada subestación.

4. Algunos de los elementos básicos presentes en las bahías de la subestación a 66 kV como pueden ser los interruptores o los transformadores de tensión y de corriente.

5. El número de subestaciones a 66 kV, en este caso, 3. También se observa la corriente nominal (2500 A) y el número de bahías de entrada y salida (4 de entrada y una de salida) por cada subestación (Hitachy Energy, 2024).

6. El número de transformadores para elevar la tensión necesarios, conectando la subestación de 66 kV con la de 220 kV, así como su potencia nominal de 270 MVA (Hitachi Energy, 2023).

7. El número de subestaciones a 220 kV, solo una en este caso. También se observa la corriente nominal (4000 A) y el número de bahías de entrada y salida (3 de entrada y 2 de salida) por cada subestación (Hitachy Energy, 2022).

8. El número de cables de salida de la subestación a 220 kV que la conectan con la costa mediante cables subterráneos, 2 en este caso, así como sus secciones (1000 mm^2 cada uno) (Qifan, 2022).

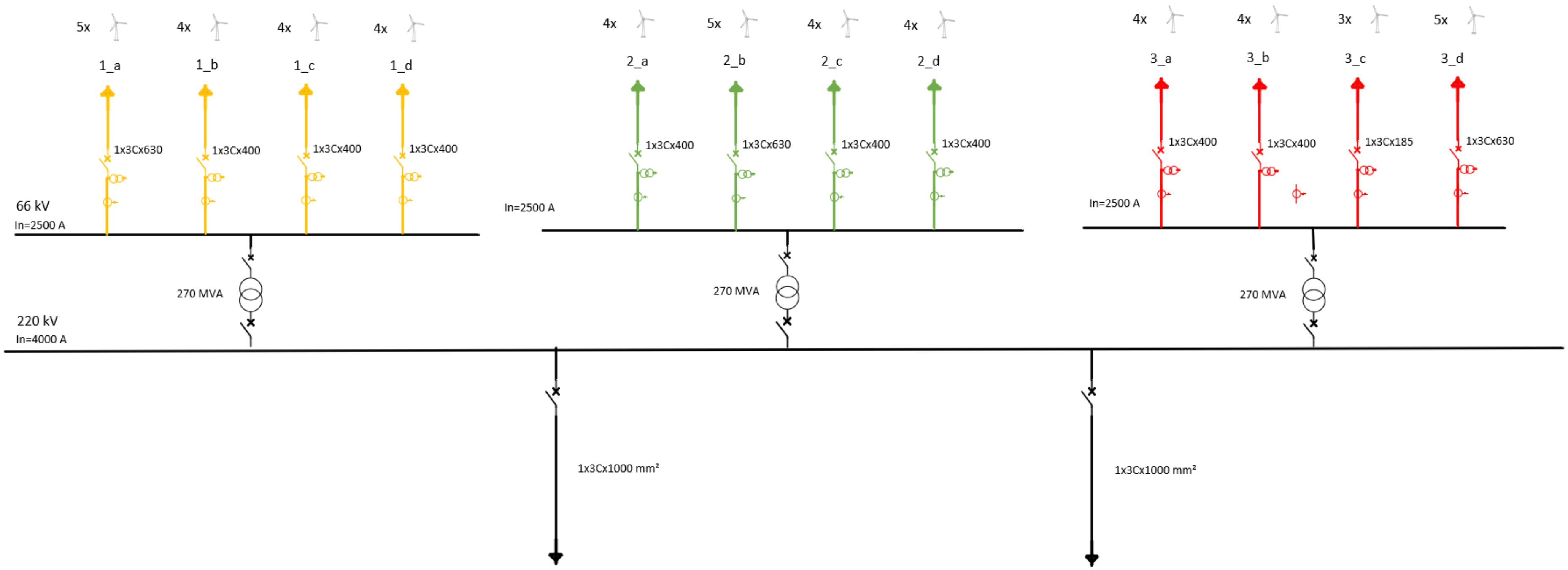

Figura 3: Unifilar simplificado. Fuente: elaboración propia

La segunda parte del cálculo económico, como se mencionó anteriormente, tiene como objetivo obtener los valores del CAPEX y OPEX para una planta eólica offshore en las etapas iniciales del proyecto. Esta herramienta permite, mediante la introducción de algunos datos básicos y genéricos de este tipo de plantas, realizar lo siguiente:

1. Diseño de Componentes Eléctricos: La herramienta realiza un diseño automatizado de los componentes eléctricos necesarios, así como del número de cada uno de ellos (subestaciones y transformadores), y de los cables (longitud y agrupaciones). Este diseño se basa en un menor número de datos de entrada y proporciona un cálculo automatizado de los resultados explicados en la primera parte.

2. Cálculo de Costos (CAPEX y OPEX): A continuación, se obtienen los costos asociados al CAPEX y OPEX al incluir los siguientes datos como inputs:

    - Coste por kilómetro de los cables (X. Xiang, 2017)
    - Coste por MVA de los transformadores (BOE, 2011)
    - Coste por bahía de las subestaciones (BOE, 2011)

Finalmente, para el caso de estudio en cuestión, se obtuvieron los resultados mostrados en la siguiente tabla.

FINAL COSTS		
	CAPEX (k€)	OPEX (k€/year)
Cables	109’052.85	10’566.74
Switchgear	26’000.00	470.00
Transformer	11’340.00	199.26
TOTAL	**146’392.85**	**11’236.00**
TOTAL CAPEX+OPEX (M€)	**157.63**	

4. Conclusiones

Este proyecto se centró en el diseño, dimensionamiento y cálculo del impacto económico de una planta de energía eólica marina en el mar del norte, con 50 aerogeneradores de 15 MW cada uno. Los niveles de tensión fueron establecidos en 66 kV a nivel de aerogenerador y 220 kV a nivel de costa.

Los principales logros incluyen:

1. Cálculo de Componentes Eléctricos: Desarrollo de una herramienta en Excel para calcular subestaciones, cables y transformadores, además de una descripción detallada del método de instalación.
2. Herramienta de Cálculo en Excel: Esta herramienta tiene dos funciones principales:
    - Diseño Eléctrico: Capaz de dimensionar elementos eléctricos y distribuir aerogeneradores con información mínima de entrada.
    - Cálculo de Costos (CAPEX y OPEX): Permite ajustar los costos fácilmente para reflejar los precios actuales del mercado.
3. Estimación de Pérdidas en Cables: Cálculo detallado de pérdidas en la red de evacuación, estimadas en un 3.7% a 66 kV.

Este proyecto demuestra la importancia de realizar pre-cálculos para identificar desafíos y optimizar el diseño y la planificación financiera de proyectos eólicos marinos, asegurando su viabilidad técnica y económica, y contribuyendo al avance de soluciones energéticas sostenibles.

A nivel personal, este proyecto ha ampliado significativamente mi conocimiento sobre la producción de energía eólica y el diseño de componentes eléctricos, proporcionando una comprensión de los costos de inversión y operación de estas plantas, lo que será útil para futuros proyectos y mi carrera profesional.

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TECHNICAL AND ECONOMIC STUDY OF THE CONNECTION OF AN OFFSHORE WIND FARM IN AC

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Director: Portillo Garcia, Julio Rafael

Collaborating Entity: ICAI – Universidad Pontificia Comillas.

PROJECT ABSTRACT

1. Introduction

1.1 Problem Statement:

The growing need to reduce carbon emissions in electricity production has driven the use of green energy generation methods, such as offshore wind farms. These installations are crucial due to their efficiency and scalability, making them fundamental tools for mitigating climate change. However, the rapid growth of renewable energy and the uncertainty regarding costs present significant challenges for their development and future planning. This project aims to address this issue by conducting a technical and economic study of the connection of an offshore wind farm in the AC area.

1.2 State of the art:

Despite the significant development experienced by offshore wind energy during this period, this rapid advancement has generated unresolved challenges and high prices. Numerous technological challenges are being addressed through research; however, there is still a long way to go, and continuous efforts are required to make electricity production from this source more effective, sustainable, and accessible in more locations. Economically, companies that invest in and build these plants need tools that allow them to make accurate cost projections.

1.3 Project Objective:

The main objective of this project is to develop a calculation tool for CAPEX (Capital Expenditure) and OPEX (Operational Expenditure), which will involve expanding technical knowledge about offshore wind energy installations, including their components and electrical sizing. Additionally, a case example will be selected to perform a complete design of an offshore wind farm, detailing its parts and conducting a cable loss analysis as part of the calculations. This tool will provide a solid foundation for evaluating the feasibility and planning the development of offshore wind power plants more effectively, while also contributing to expanding knowledge about the design and operation of such installations.

As an additional technical objective, a tool will be developed for calculating losses in the evacuation network cables. These losses are fundamental for establishing the Levelized Cost of Energy (LCOE). Although this calculation is not performed in this study, it is of interest to compare the percentage of losses concerning the total power generated in the plant. This analysis will allow assessing the impact of losses and ensuring that the values are within normal ranges for this type of technology.

2. Methodology:

The methodology employed in this project encompasses three fundamental aspects that guide the development and evaluation of the connection of an offshore wind farm in the AC area and its economic analysis.

First, a study of the current state of technology in the field of renewable energies was conducted, with a particular focus on the electrical and mechanical design of components and energy transport methods (AC vs. DC) (X. Xiang, 2017). The sustainability challenges associated with equipment such as GIS substations with SF6 gas (CIGRE, 2011) were explored, and installation methods such as floating wind turbines (Canga-Argüelles, 2021) that significantly impact the viability of installation locations were discussed. Additionally, the generation capacities and output voltages of the latest wind turbines were examined to enhance plant effectiveness based on the most recent studies (Offshore Wind Accelerator, 2022).

Second, a detailed analysis of the electrical installation of an offshore wind farm was carried out using a specific case study located in the North Sea, comprising 50 wind turbines. A cabling design for the evacuation network was developed, considering the location of the turbines, followed by the design of the offshore substation. This included describing the components of the substation, such as the 66 kV and 220 kV substations and the transformers. Cable cross-sections for the connection to the shore were calculated, and the process of connecting to the onshore substation using horizontal directional drilling (Orsted, 2022) and the Transition Joint Bay, TJB was described.

As the main objective of the project, an economic tool was developed to automate the basic design process of the wind farm and subsequent economic calculations. This tool enables the calculation of cable cross-sections, distances, transformer power, and the number of substations and their respective input and output bays required for the evacuation network, based on user-entered data. The development of the tool is based on the same methodology used for the electrical installation sizing but has been automated to eliminate the need for exact turbine layout knowledge, making the process more efficient. CAPEX and OPEX costs were obtained from (X. Xiang, 2017) (BOE, 2011) and data provided by the thesis supervisor.

Finally, a calculation of losses in the evacuation network cables was performed. The wind distribution in the area was used according to the Weibull curve Image 1 and the power generation curve of the turbines based on wind speed according to Image 2. With these input data and the previously calculated cable cross-section, the loss calculation formula proposed by (X. Xiang, 2017) was adapted, and an Excel tool was developed to perform a precise loss calculation. Subsequently, the losses were compared to the total generated power.

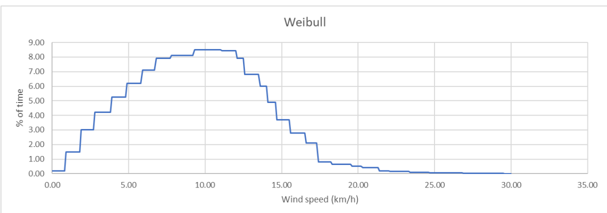

Image 1: Figure 1: Weibull curve. Source: Self-elaboration

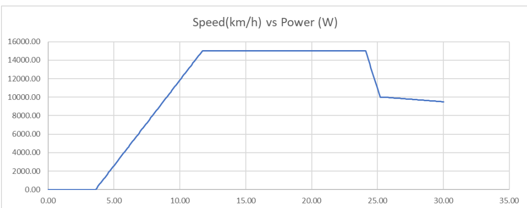

Image 2: Power output. Source: Self-elaboration

3. Results:

The results obtained from the first part of the work dedicated to the electrical design of the basic components of the offshore power generation plant are summarized in Image 3. The following can be observed:

1. Grouping of Turbines: Number of turbines grouped per circuit.

2. Cross-Section of Cables: Evacuation network cables at 66 kV (ABB, 2021).

3. Number of Input Circuits: Number of input circuits to each substation.

4. Basic Elements in Substation Bays: Some of the basic elements present in the 66 kV substation bays, such as switches or voltage and current transformers.

5. Number of 66 kV Substations: In this case, 3. Also shown are the nominal current (2500 A) and the number of input and output bays (4 input and 1 output) per substation (Hitachy Energy, 2024).

6. Number of Step-Up Transformers: Needed to connect the 66 kV substation to the 220 kV substation. Their nominal power is 270 MVA (Hitachi Energy, 2023).

7. Number of 220 kV Substations: Only one in this case. Also shown are the nominal current (4000 A) and the number of input and output bays (3 input and 2 output) per substation (Hitachy Energy, 2022).

8. Number of Output Cables: Number of cables exiting the 220 kV substation connecting it to the shore via underground cables, in this case, 2, and their cross-sections (1000 mm² each) (Qifan, 2022).

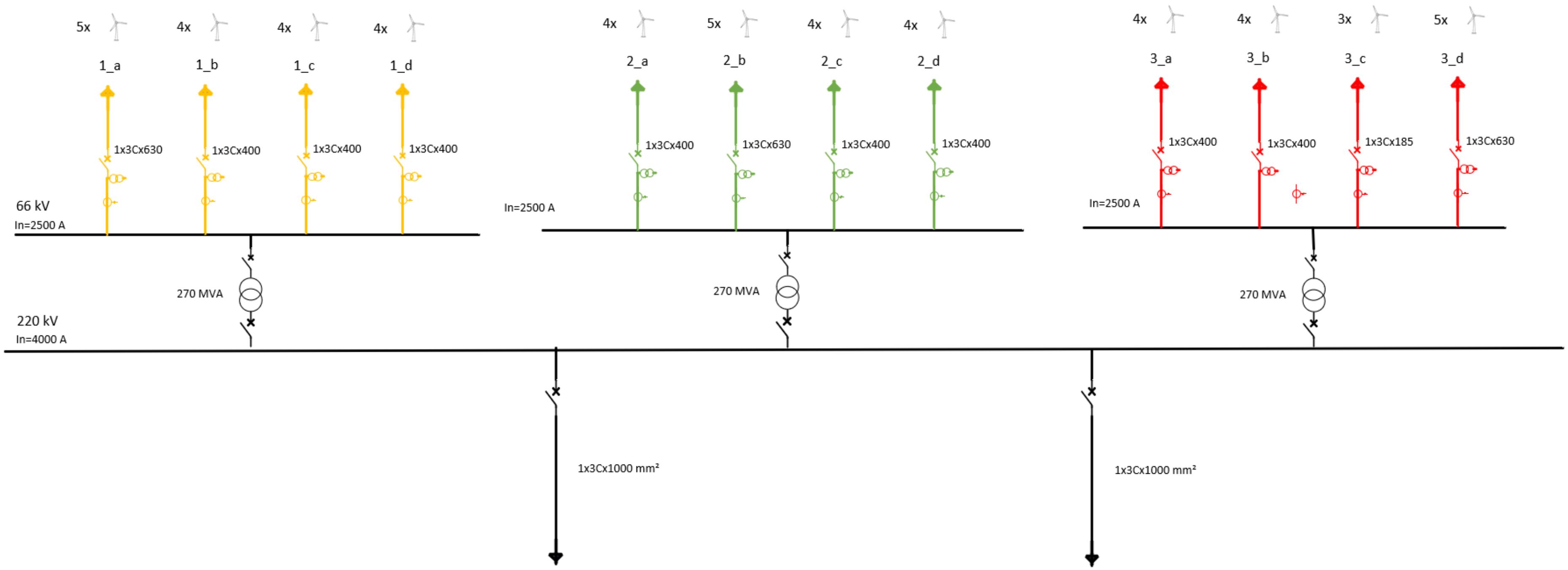

Image 3: Simplified SLD. Source: Self-Elaboration.

The second part of the economic calculation, as previously mentioned, aims to obtain the CAPEX and OPEX values for an offshore wind farm in the initial stages of the project. This tool allows, through the introduction of some basic and generic data for this type of plants, to perform the following:

1. Electrical Components Design: The tool performs an automated design of the necessary electrical components, as well as the number of each (substations and transformers), and the cables (length and groupings). This design is based on a smaller number of input data and provides an automated calculation of the results explained in the first part.

2. Cost Calculation (CAPEX and OPEX): Subsequently, the costs associated with CAPEX and OPEX are obtained by including the following data as inputs:

   - Cost per kilometer of cables (X. Xiang, 2017)
   - Cost per MVA of Transformers (BOE, 2011)
   - Coste per bay of the switchgears (BOE, 2011)

Finally, for the specific case study, the results shown in the following table were obtained.

FINAL COSTS		
	CAPEX (k€)	OPEX (k€/year)
Cables	109’052.85	10’566.74
Switchgear	26’000.00	470.00
Transformer	11’340.00	199.26
TOTAL	**146’392.85**	**11’236.00**
TOTAL CAPEX+OPEX (M€)	**157.63**	

4. Conclusions:

This project focused on the design, sizing, and economic impact calculation of an offshore wind power plant in the North Sea, featuring 50 wind turbines, each with a capacity of 15 MW. The voltage levels were set at 66 kV at the wind turbine level and 220 kV at the shore level.

The main achievements include:

1. Electrical Components Calculation: Development of an Excel tool to calculate substations, cables, and transformers, along with a detailed description of the installation method.
2. Excel Calculation Tool: This tool has two main functions:
    - Electrical Design: Capable of sizing electrical components and distributing wind turbines with minimal input information.
    - Cost Calculation (CAPEX and OPEX): Allows for easy adjustment of costs to reflect current market prices.
3. Cable Loss Estimation: Detailed calculation of losses in the evacuation network, estimated at 3.7% at 66 kV.

This project demonstrates the importance of conducting pre-calculations to identify challenges and optimize the design and financial planning of offshore wind projects, ensuring their technical and economic viability, and contributing to the advancement of sustainable energy solutions.

On a personal level, this project has significantly expanded my knowledge of wind energy production and the design of electrical components, providing an understanding of the investment and operation costs of these plants. This experience will be valuable for future projects and my professional career.

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1 INTRODUCTION AND MOTIVATION

The urgent need to decarbonize electricity production has led to a significant surge in green energy generation methods. Climate change, driven by the extensive use of fossil fuels, has necessitated a transition to renewable energy sources to reduce greenhouse gas emissions and mitigate global warming. Among these renewable sources, wind turbine power plants have garnered significant interest due to their substantial potential for efficiency and scalability. Wind energy is abundant, renewable, and emits no greenhouse gases during operation, making it a key component in the transition towards sustainable energy systems.

Wind power technology has advanced rapidly over the past few decades. Modern wind turbines are now capable of converting wind energy into electricity more efficiently than ever before. Offshore wind farms, in particular, are becoming increasingly popular due to several key advantages. Offshore wind turbines can be much larger than their onshore equivalents, which allows them to capture more energy. The wind speeds offshore are generally higher and more consistent, leading to a greater energy yield. Additionally, offshore wind farms can be situated near coastal population centers, reducing the need for long-distance electricity transmission.

This project focuses on the electrical aspect of offshore wind power plants. The primary objective is to estimate the initial investment costs and the subsequent maintenance and operation expenses of an offshore wind generation plant. This is particularly relevant given the increasing number of such projects currently in development. In the early phases, comprehensive data on equipment and plant design are often unavailable. Therefore, developing a calculation tool to provide cost estimates based on basic project data is highly valuable. Such a tool can help investors and engineers make informed decisions ensuring the financial viability of offshore wind projects.

Furthermore, understanding the current state of technology is crucial for developing this tool. Consequently, this project will include a study of a sample offshore generation plant. This study will help illustrate how basic electrical design calculations are performed in such plants and identify the essential components involved. Key factors such as cable section calculation, electrical infrastructure, equipment selection and connection strategies will be analyzed to provide a comprehensive understanding of the financial and technical aspects of offshore wind energy projects.

Through this comprehensive approach, the project aims to provide a robust framework for cost estimation, aiding in the efficient planning and implementation of future offshore wind power plants. With this, this project will contribute to the broader goal of increasing the adoption of renewable energy technologies, thereby supporting global efforts to combat climate change and promote sustainable development.

2 STATE OF THE ART

Before delving into the case study on the electrical design of components and the economic analysis of installation, operation, and maintenance costs for an offshore plant, it is important to establish an understanding of the current state of offshore technology. This section provides a broad overview of the present-day offshore wind technology, as well as future forecasts. Understanding the current state and the challenges faced by this technology is crucial, especially as we are in the era of energy transition, seeking accessible energy sources for societies. Offshore energy development aims to achieve a robust and economically viable solution to the challenges the modern society faces in terms of energy development. Due to its higher efficiency, significant investments are being made to develop new technologies and enhance existing ones, aiming to maximize the adoption of these plants. This section will encompass the power capacities of current turbines, optimal generation and distribution voltages to minimize losses, environmental challenges posed by gases in some electrical equipment, and mitigation strategies. Additionally, it will address current installation methods and the pursuit of alternatives to expand installations to the greatest possible extent.

2.1 WIND TURBINES

2.1.1 Power capacity of wind turbines and voltage range of power transmission

When it comes to describing the current state of offshore wind energy and its technology, one of the key aspects is discussing the production capacity of the turbines and the transmission voltage ranges used, from the turbine itself to the onshore station where the electricity is integrated into the grid.

The collection system is composed by inter-array cables to gather energy from the wind turbines. These turbines deliver electrical output at about 690V. Using a step-up transformer, located at the base of the tower of every wind turbine, the voltage is elevated up to 66 kV.

The power generated by the entire system is gathered at an offshore substation, where transformers further elevate the collection system's voltage up to 150-250 kV for transmission purposes, facilitating the interconnection with the onshore grid (Padmavathi Lakshmanan , Ruijuan Sun, and Jun Liang, 2021).

Regarding the capacity of the wind turbines in current projects, they range from 8 to 12 MW, with the most common capacities, and even up to 15 MW in some of the more recent projects.

Examining the advancements in offshore wind technology, particularly focusing on turbine power output and the voltage at the array cable stage, reveals significant growth trends. By 2040, offshore wind technology is projected to contribute 5% of the global electricity generation share. Offshore wind farm capacities are also expected to increase substantially, from an average size of 310 MW in 2010 to an anticipated average of 3 GW in the near future. The capacity and size of wind turbines have shown consistent growth, advancing from 3.6 MW in 2008 to 12 MW in 2019, with projections indicating turbine sizes will reach 15-20 MW by 2030 (Leonard Weimer, 2023).

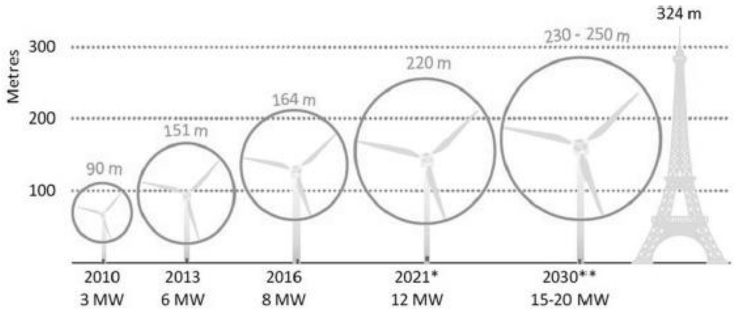

Figure 1: Incremental growth in size and capacity of wind turbines for offshore over time. Source: Hitachi Energy.

This leads to stepping up the array cable voltage in AC to enable efficient power collection and transmission. As generator power increases, transmission losses also rise. Consequently, increasing the array cable voltage can result in cost savings and a reduction in the Levelized Cost of Energy (LCOE).

Currently, the highest voltage level for array systems is 66 kV, and thus, most array system components are not designed for voltages exceeding 66 kV. This posed a new challenge for companies and manufacturers. In response, the Offshore Wind Accelerator (OWA) conducted a study to determine the optimal AC array voltage for the next generation of bottom-fixed wind turbines. The objective was to establish a global standard for this voltage level, inform stakeholders, and perform comprehensive technical, cost-benefit, and risk analyses (Offshore Wind Accelerator, 2022).

The main findings between the studied possibilities (90 kV, 110 kV, 132 kV and 150 kV) across a range of different turbine sizes (14 MW, 17 MW and 20 MW) and several offshore wind farm sizes and configurations common in industry; was that 132 kV is the best option. The main reasons are:

- 132kV array systems offer the best cost efficiency due to cheaper cables and wind turbine switchgear compared to 150kV, with existing equipment standards facilitating international buy-in.

- Equipment and accessories for 132kV are either available or in development from various suppliers, expected to be competitively priced due to economies of scale.

- Time to market for 132kV SF6-free compact switchgear and array cables/accessories is quicker than 150kV, with existing commercial products and ongoing research and development by multiple manufacturers into 132kV technologies.

This study concludes that both 132 kV dry array cables and 132 kV wet array cables provide cost savings over 66 kV array cables. The transition piece design and layout are compatible with 132 kV technology and can accommodate a three-circuit breaker arrangement using standard 150 kV (and thus 132 kV) SF6-free switchgear in a feasible configuration. The offshore substation implementation is viable as 132 kV switchgear is already available, including SF6-free variants. Although 220/132 kV transformers are not common, they are standard for power distribution and transmission voltages.

Based on the findings, it can be concluded that 132 kV is the most beneficial voltage for the future of offshore wind energy. Increasing the voltage is essential for enhancing the efficiency of this technology, enabling higher power transmission at the lowest possible cost. Consequently, it is crucial to emphasize that forthcoming offshore technology projects will be executed at 132 kV, demonstrating both technological and economic viability in the market.

Advantages of 132 kV:

- **Lower array losses/cabling costs**: This is a critical factor. Using cable sections of the same diameter range as those in 66 kV installations (up to around 800 mm²), twice the power can be transferred per array cable, reducing the number of cables required for the same power. The losses in a cable due to resistance can be shown in (1):

$$P_{losses} = R * I^2 = R * \left(\frac{P}{U}\right)^2 \tag{1}$$

This illustrates that when the voltage is doubled, losses decrease by 75% for a fixed power and resistance.

- Lower typical **short circuit levels** result in reduced stress on all electrical components, but this implies a more complex protection system.

- A greater **distance for direct connection** allows for the possibility of not installing an offshore substation, particularly for short distances. According to Figure 2, transitioning to a 132 kV configuration expands the distance at which foregoing an offshore substation becomes more economically advantageous.

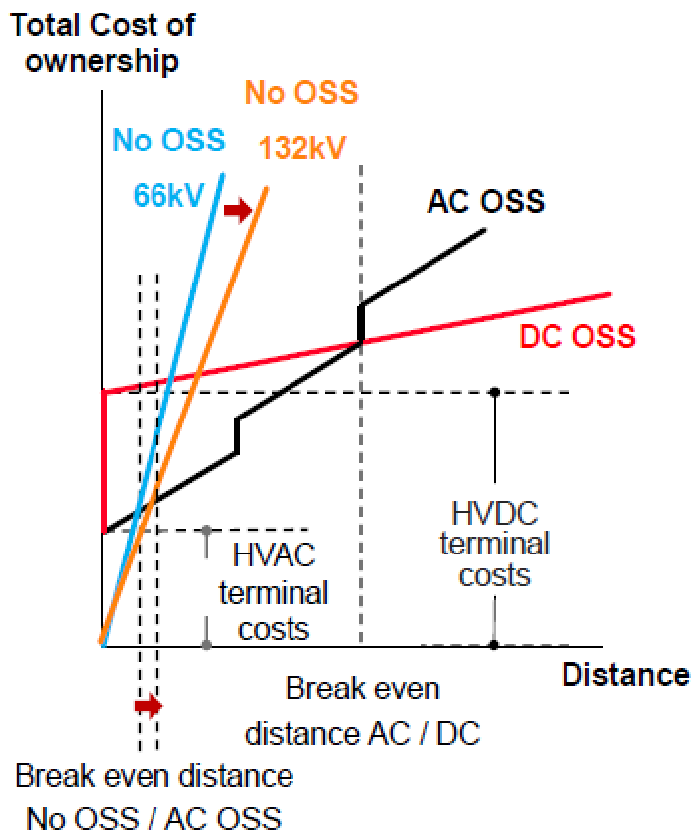

Figure 2: Break even distance of no OSS vs OSS in AC. Source: Hitachi Energy

This change has some technical implications on the system components:

- **Switchgear (GIS):** As mentioned earlier, the reduction in short circuit levels associated with 132 kV operation leads to lower amperage requirements for most heavily loaded components, thereby reducing the need for complex solutions. Although lower-voltage Gas-insulated switchgear (GIS) may require more space per unit, a decrease in the total number of units can yield an overall space reduction of about 30%, balancing out the larger individual space requirements and resulting in a net space-saving benefit.

- **Power transformer:** With a reduced ratio between the array grid and the export system, the use of autotransformers (ratios in the range of 1:2) becomes feasible. These autotransformers offer advantages such as weight, material, and cost reduction, as well as lower energy losses during operation (both idle and under load conditions). However, they lack isolation between circuits, which may necessitate additional winding configurations.

The trend towards larger turbines and wind farms, necessitating higher transport voltages, doesn't solely impact AC connections. Wind farms connected via DC are also evolving in this aspect. The cost of inverters remains notably high. While losses in cables with DC connection are significantly lower compared to those in AC connections, they become non-negligible with extended lines and high voltages. Maximizing transport capacity is essential to ensure the installation's economic viability. The most effective approach to achieve this is through voltage increment. Hence, the ongoing transition from 350 kV to 500 kV in transmission voltage directly addresses these factors.

2.1.2 Installation

The advantages of installing wind turbines at sea are evident, as previously mentioned: wind speed and available space. However, the foundation and installation of all structures comprising wind farms are undeniably more complex and come with significantly higher costs.

In marine environments, there are conditions such as waves, terrain instability, ocean currents, and high wind gusts, which significantly influence installation, unlike on land surfaces. Foundations can be categorized as either fixed or floating. Although there's been considerable effort in advancing floating structures, the reality is that operational offshore wind farms currently have for the most part shallow foundations.

Exploring both fixed and floating foundation options is compelling. Developing installations in deeper coastal areas would vastly expand the spectrum of potential locations for offshore wind farms, such as along the Spanish coastlines.

Figure 3 shows the installation methods for both fixed and floating offshore wind farms.

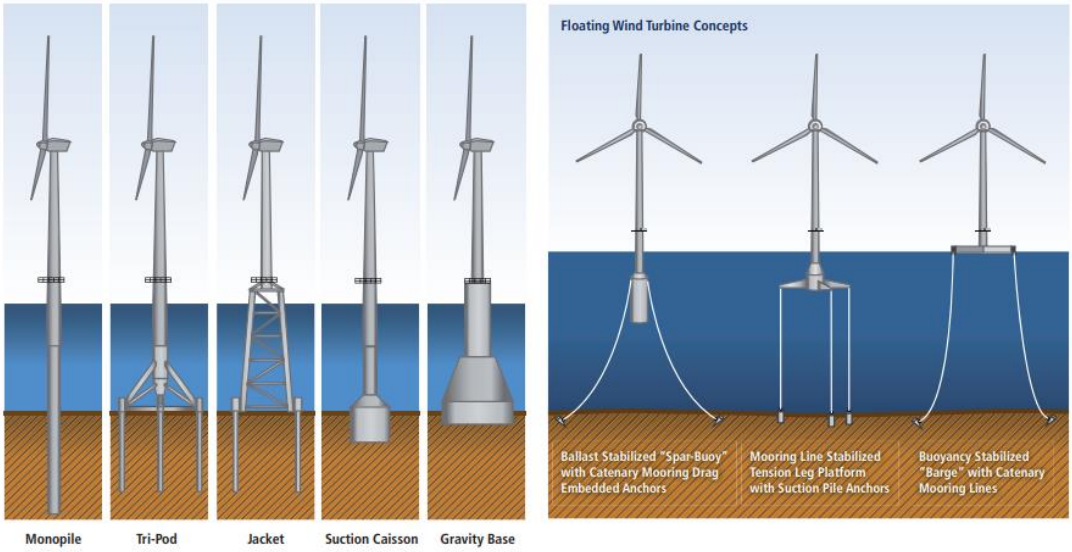

Figure 3: Offshore wind turbine foundation designs. Source: (Working Group III of the IPCC, 2012).

There is a common characteristic shared by all types of fixed installations, which is the need to withstand the constant impact of waves and have sufficient resistance to the corrosion caused by seawater. Furthermore, all of them are designed for locations where the seabed does not exceed 60 meters. The choice of foundation type will vary significantly depending on the project, with the monopile being the most common option.

On the other hand, the floating structures are tethered to the seabed using cables or chains, known as mooring lines. They offer notable advantages, such as the potential for wind farms in depths exceeding 70 meters, increased flexibility in construction and installation processes, the ability to transfer heavy bending loads to the water rather than the rigid ground, and easier dismantling compared to fixed foundations (Canga-Argüelles, 2021).

However, it is essential to note that currently, floating structures represent a costly and less economically viable solution due to the significant number of sensors, computers, and control surfaces required to ensure the structure's stability.

Another technical limitation is the challenge posed by the cables being subjected to environmental movement (waves, wind, etc.). To adapt these cables to the ecosystem, so-called dynamic cables are used. These dynamic cables move in tandem with the floating platform without breaking. Floating elements support the dynamic cable, which has an 'S' shape, allowing it to absorb fluctuations and achieve a longer lifespan.

Despite these challenges, there is already an example of such an installation, like Hywind Tampen by Equinor, which became operational in August 2023. The development of these installations is expected when the market achieves the necessary technology at a competitive price.

2.2 OFFSHORE SUBSTATION

In offshore wind energy production facilities, distances are typically too extensive to transmit electricity directly from the turbines to the shore. As a result, an offshore substation is installed to elevate the voltage, allowing for transmission with reduced losses. The description of the substation components will be provided later in the report. In this section, attention will be given to some contemporary aspects concerning certain elements present in the substation.

Gas-insulated switchgears are the principal component in offshore substations. They are enclosed in a robust metal frame and house various electrical components within shielded compartments containing sulfur hexafluoride gas (SF6). It manages, transforms, and efficiently distributes electrical energy in power systems.

GIS's key attribute is its use of SF_6, an inert gas with excellent insulation properties, chemical stability, and thermal reliability. Compared to air-insulated switchgear, GIS needs only centimeters for effective insulation, offering greater dependability and requiring less space and maintenance. This is the main reason for using GIS technology in offshore wind substations where space and weight is a limitation. Nevertheless, there is a limitation regarding the use of SF_6 since it stands as the most potent greenhouse gas, possessing a Global Warming Potential (GWP) equivalent to 25.200 CO_2 and an extremely lengthy atmospheric lifespan of 3.200 years. Consequently, minimizing SF6 emissions is critical, necessitating special consideration in end-of-life (EoL) management of electrical equipment that uses SF6. Careful procedures for disposal and/or recycling of such equipment parts become crucial.

In recent times, manufacturers have sought alternatives to address this issue. Siemens identified a technology that combines vacuum switching for high performance, easy operation, and optimal gas-handling, along with using clean air for insulation, meeting the highest health, safety, and environmental standards.

Vacuum technology, usually applied in medium voltage with limited high voltage usage, coexists with SF6 technology. For higher voltage applications, the blend of clean air (80% nitrogen and 20% oxygen) with vacuum circuit breakers offers exceptional performance, boasting zero global warming potential (GWP = 0) and zero ozone depletion potential (ODP = 0) (S. Kosse, 2020).

Moreover, clean air, when combined with switchgear materials, maintains material properties over the long term. It remains highly stable compared to proposed F-gas alternatives, which exhibit lower long-term stability and a higher tendency for irreversible decomposition due to electric arcs. Key gas characteristics established in the past decade of research and development are summarized in Figure 4.

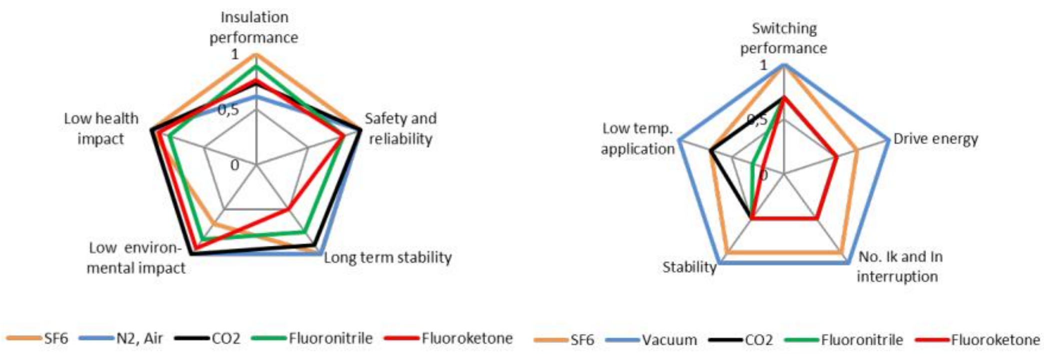

Figure 4: Different gas characteristics regarding technology and safety. Source: (CIGRE, 2008).

Another alternative option is the g[3] gas technology developed by General Electric. This gas mixture is comprised of carbon dioxide, oxygen, and 3M™ Novec™ 4710 Dielectric Fluid from the 3M fluoronitrile family. Through research and development, fluoronitrile was identified as the most suitable additive to CO2 and O2 to achieve the intended environmental benefits as an alternative to SF6, while maintaining the technical performance and physical footprint of the equipment. Consequently, GE's

g^3 gas has a global warming potential (GWP) 99% lower than SF6 when used in the equipment. GE's g^3 gas-insulated products are presently available for live-tank circuit-breakers and gas-insulated substations (GIS) up to 145 kV, along with gas-insulated lines (GIL) up to 420 kV. The g^3 technology enables GE to manufacture electrical equipment with equivalent high performance and compact size as traditional SF6 products (General Electric, 2022).

Pioneering technology companies are actively and successfully seeking solutions to transition from using SF6 gas to other gases or alternatives that are significantly less polluting. Siemens and GE's developments are among the most notable in the market. However, companies like ABB have also developed products such as AirPlus to address this issue.

2.3 TRANSPORT AND CONNECTION TO THE GRID

In designing offshore wind farms, a crucial consideration is how to transport energy from the turbines to the coast. The key factor in this decision is the distance between the installation and the onshore substation. Traditionally, the two options are High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC). The choice between these options depends on two main cost components: terminal cost and route cost.

HVAC technology generally incurs lower terminal costs as it doesn't require converter stations. However, the route cost tends to be higher due to increased losses over longer distances. Conversely, HVDC becomes more cost-effective for longer distances.

Another potential solution, though less commonly used and primarily theoretical, is Low-Frequency Alternating Current (LFAC) technology. This method generates turbine energy at 16.7/20 Hz and transmits it to an onshore substation, where the frequency is increased to match the grid frequency (50 Hz). LFAC has not yet been implemented in real projects but offers compelling characteristics for specific distances. (X. Xiang, 2017).

In Figure 5, Figure 6 and Figure 7, a simplified schematic of each of these technologies is shown.

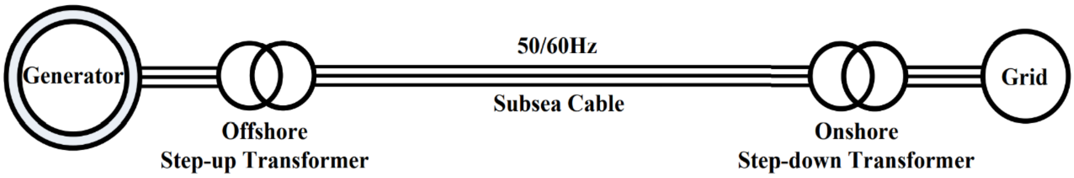

Figure 5: HVAC transmission system. Source: (X. Xiang, 2017).

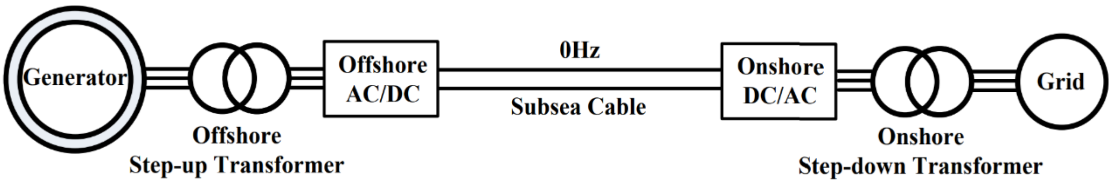

Figure 6: HVDC transmission system. Source: (X. Xiang, 2017).

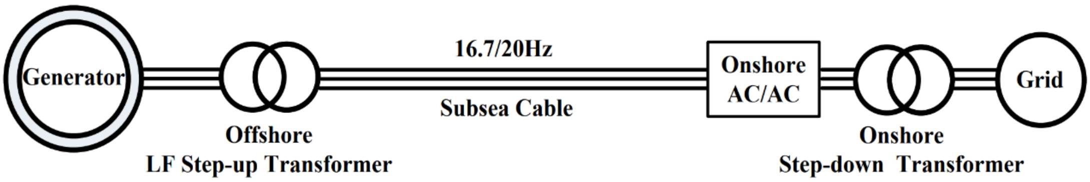

Figure 7: LFAC transmission system. Source: (X. Xiang, 2017).

The primary reason for using DC technology is the reduction in route costs, as previously mentioned. Figure 8 exhibits a break-even point (of around 60-70 km), indicating the distance from which the costs of the two inverter stations are justified by the reduction in cable losses. These losses are primarily attributed to three effects:

- **Joule effect losses**: These are lower in direct current systems due to the uniform distribution of current, compared to alternating current, which experiences periodic fluctuations and greater resistance in cables.

- **Capacitive effect losses**: In alternating current systems, cables act as capacitors, causing an accumulation of electric charge between conductors, leading to energy losses, especially in long-distance transmission lines with high capacity. In direct current (DC), this capacitive effect is significantly reduced or even considered insignificant.

- **Skin and proximity effect losses**: In alternating current systems, currents tend to concentrate on the surface of conductors due to the skin and proximity effects. In direct current, currents distribute more evenly across the entire conductor, thereby reducing losses associated with these surface concentrations.

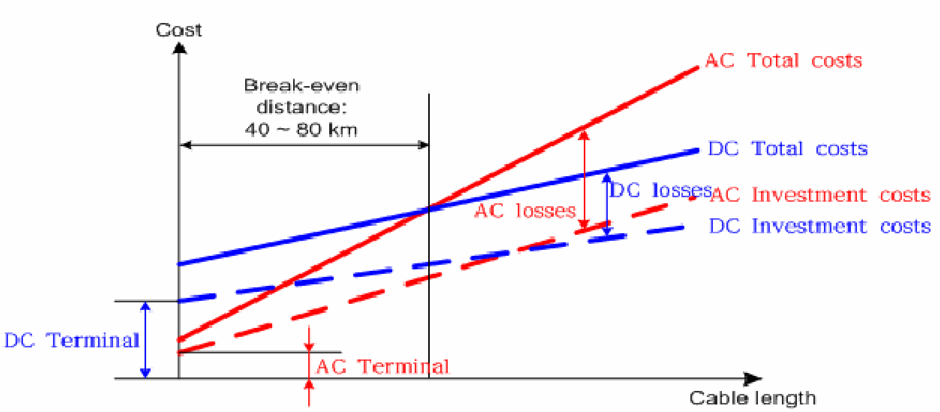

Figure 8: Break-even point of AC vs DC connections. Source: Semantic Scholar.

Furthermore, the range of distances where LFAC technology proves cost-effective is between 30 and 150 kilometers.

3 LAYOUT DESIGN

3.1 INTRODUCTION

For a better understanding of offshore technology, its elements, and installation methods, a case study is conducted to analyze an offshore wind farm example with the following characteristics:

- Located in the North Sea.
- Consisting of 50 wind turbines.
- Power supplied per turbine: 15 MW.
- Voltage level at the wind turbine level: 66 kV.
- Voltage level at shore level: 220 kV

3.2 66 KV EVACUATION NETWORK

The 66 kV medium voltage evacuation network comprises all the cables that interconnect the wind turbines. In the study case, the arrangement of the turbines, distances between them and the substation and the distance from the substation to the shore, are known data.

The evacuation network is structured into 12 groups of interconnected turbines arranged in series. Each group consists of 3, 4, or 5 wind turbines connected in series. Consequently, the initial cable section, spanning from the first turbine to the second, will only transport 15 MW, while the subsequent section, from turbine 2 to turbine 3, must handle 30 MW, and so forth. The last section of the cable comprises the distance from the last turbine in the series until the substation. This distribution is graphically shown in Figure 9 for two groups of turbines arranged in series and it can be seen the amount of power that each of these cables will have to withstand:

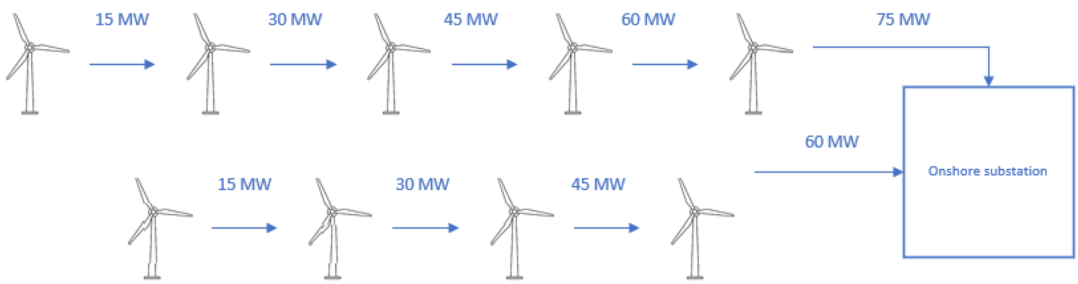

Figure 9: Example of the arrangement of the 66 kV evacuation network. Source: Self-elaboration.

Now that the required power to be transported through each cable section has been determined, the current flowing in each section is computed using equation (2).

$$I = \frac{P}{U * cos(\emptyset)} \tag{2}$$

However, it's important to note that the current obtained from this formula doesn't consider certain external factors that will influence the cable sizing. These factors include the temperature of the seabed terrain, the depth at which the cables will be installed, and the proximity of other circuits among other factors. In the following sections, these factors will be thoroughly examined and considered in determining the current.

For the determination of the first factor, it should be noted that the location of the substation is in the North Sea, where the water temperature at the surface varies between 0 to 8 degrees in the winter and 12 to 20 degrees during the summer. It is assumed that the seabed's temperature will be slightly higher, a temperature of 20 degrees will be considered, which represents the most unfavorable case. With this the temperature correction factor that will be applied is of 1.04 (European Environment Agency , 2002).

Furthermore, to determine the resistivity at the temperature of the terrain, we consider that the seabed of the North Sea is primarily composed of sand, gravel, and silt, with lesser amounts of shales, sandstones, and conglomerates. Therefore, by estimating the percentage of each material and taking into account their respective resistivity, we obtain an approximate resistivity of 760 ohm*m.

With this data, and following (Ruiz, 2020), it was established that the thermal resistivity of the terrain, considering it will be somewhat damp due to the proximity of the sea, as the cables are buried only 1m deep, is 1.03 Km/W. Using this thermal resistivity and for directly buried three-core cables according to (RLAT, 1997), it is determined a resistivity correction factor of 1.18.

Regarding the depth correction factor, consulting the (RLAT, 1997) tables, it is established as 0.96 (allowing for some margin in case any part is slightly more than 1 m deep).

With all this the current is calculated once again using now the corrective factors as follows in equation (3):

$$I = \frac{P}{U * cos(\emptyset) * f_{resist} * f_{temp} * f_{depth}} \tag{3}$$

For the cable section selection, these currents were used, and a cable with a suitable section capable of safely supporting this current, with a 5% safety margin, was chosen for each segment of the evacuation network.

Figure 10 shows an extract of the data sheet of the cables used for the evacuation network. The nominal section and the current that each cable is able to withstand is specified. (ABB, 2021)

10-90 kV XLPE 3-core cables		
Cross section mm²	Copper conductor A	Aluminium conductor A
95	300	235
120	340	265
150	375	300
185	420	335
240	480	385
300	530	430
400	590	485
500	655	540
630	715	600
800	775	660
1000	825	720

Figure 10: Nominal current for different sections in submarine cables. Source: (ABB, 2021).

Figure 11 represents the evacuation network showing the section for each cable used.

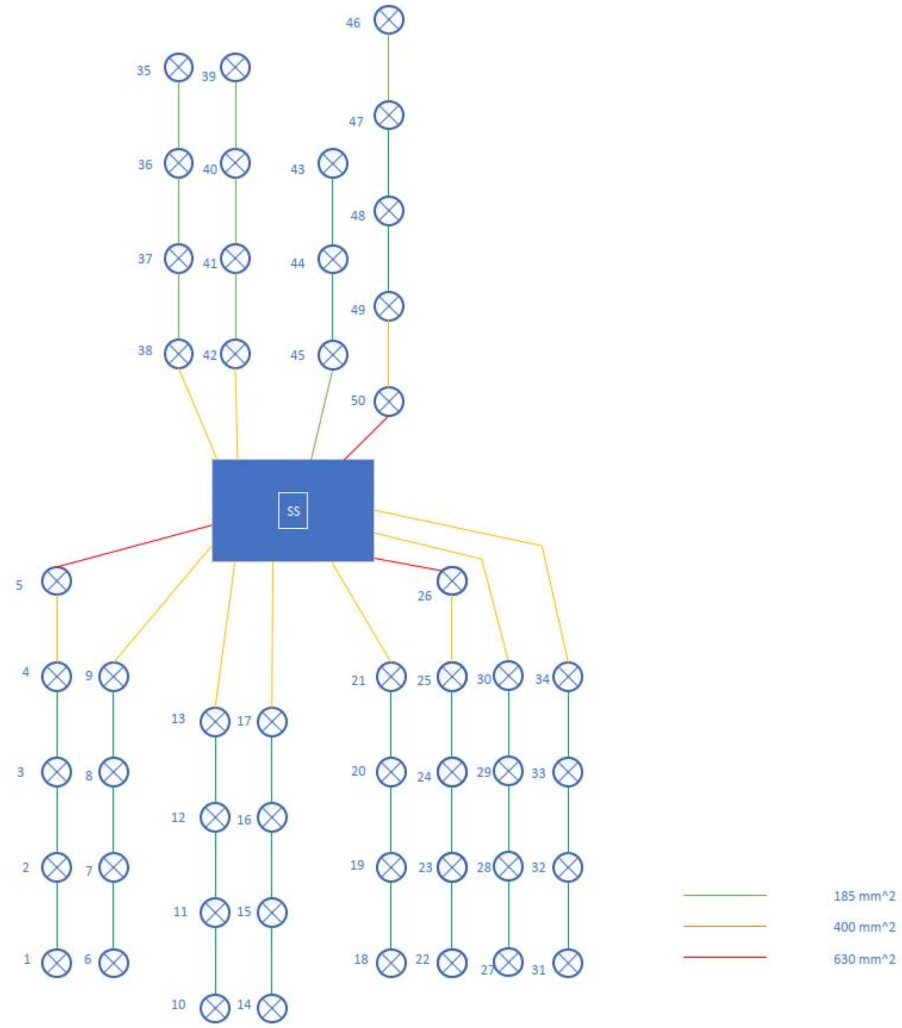

Figure 11: Cable sections for the offshore plant. Source: Self-elaboration.

The calculation of the cable cross sections in the evacuation network are presented on the Cable section in the Annex.

3.3 OFFSHORE SUBSTATION

Following the layout and design of the cables that collect the power generated by the wind turbines at 66 kV, the next step involves the design of the offshore substation. The primary objective of this substation is to increase the transmission voltage from 66 kV to 220 kV, thereby reducing losses due to Joule heating effect during transmission. This substation will consist of various components, including the seabed-anchored structure that serves as the foundation for the rest of the modules, one or more transformers, protective switchgear, and cable entry and coupling systems.

The substation will be divided in the following parts that will be further explained (BVGAssociates, Catapult, The Crown Estate, Crown Estate Scotland, Floating offshore wind center of excellence, 2023):

1) HVAC Electrical system. It integrates the power generated by wind turbines in AC and it increases the voltage to export to the onshore substation. The key components are:

a) Switchgears. High Voltage (HV) switchgear is a collection of electrical components including disconnect switches, fuses, circuit breakers, and other devices. Its primary function is to control, protect, and isolate electrical equipment. HV switchgear comprises different panels, each with common elements but tailored to specific purposes (such as incomer, coupler, motor feeder, transformer feeder, etc.). In this project, the main objective is to safeguard arrays of wind turbines from each other, ensuring that faults in one turbine do not affect others.
The substation will be of the Gas Insulated Switchgear (GIS) type, chosen for its efficient voltage transition management, robust insulation properties suitable for offshore operation in challenging environmental conditions, and its size reduction benefits. GIS is a compact, metal-encapsulated type of switchgear ideal for applications with limited space, such as offshore wind substations. Each voltage level requires its own switchgear, so for this project, there will be two switchgears: one operating at 66 kV and the other at 220 kV. Additionally, the GIS offers benefits including uninterrupted operation at offshore substations, cost savings through its compact design, and extended maintenance intervals.

   GIS main components are:

   i) Circuit breaker: a device designed to interrupt the flow of electricity in a circuit when it detects abnormal conditions such as overcurrent, undervoltage, or overvoltage. Depending on the required level of safety and the types of loads connected, circuit breakers can operate in various modes. Tripping signals, which initiate the opening of the circuit breaker, are generated by a relay. This relay monitors inputs from the circuit breaker's status, as well as current and voltage transformers. Once internal logic processing is complete, the relay sends an output signal to the circuit breaker to trigger its opening mechanism.

   ii) Current and voltage transformers: serve for dual purposes measurement and protection. They convert high-value currents and voltages into lower values that are more manageable for relays and instruments. This transformation is crucial for standardizing instruments and relays to operate effectively within a limited range of currents and voltages.

   iii) Switches: used for manually isolating equipment from the power supply for maintenance or repair purposes.

   iv) Grounding: used for deviating fault currents through a low-resistance path, also for fault detection and localization allowing protective devices such as relays to actuate. Also used for lighting protection reducing with all this the chances of people or devices getting damaged.

   v) Busbars: it is an essential part of the switchgears since they connect the internal elements. From the cables arriving to the switchgear at the low compartment to the grounding or the circuit breaker compartment.

b) Transformers. The power transformers are the main element of the offshore substation due to their intrinsic function of stepping-up the voltage for power transmission under optimal conditions and due to their size, weight and installation requirements that determines to a great extent the arrangement of the platform.

c) <u>Passive and reactive power compensation.</u> To maintain the strict constraints regarding power quality, when integrating electrical power in an existing grid it is necessary to compensate for possible harmonics or stability problems that this equipment can generate. Therefore elements such as large coils and power electronics are used.

2) Topside structure. Physical structure and physical positioning of the different elements in the substation, in Figure 12 it is shown a substation structure, and the different parts will be discussed.

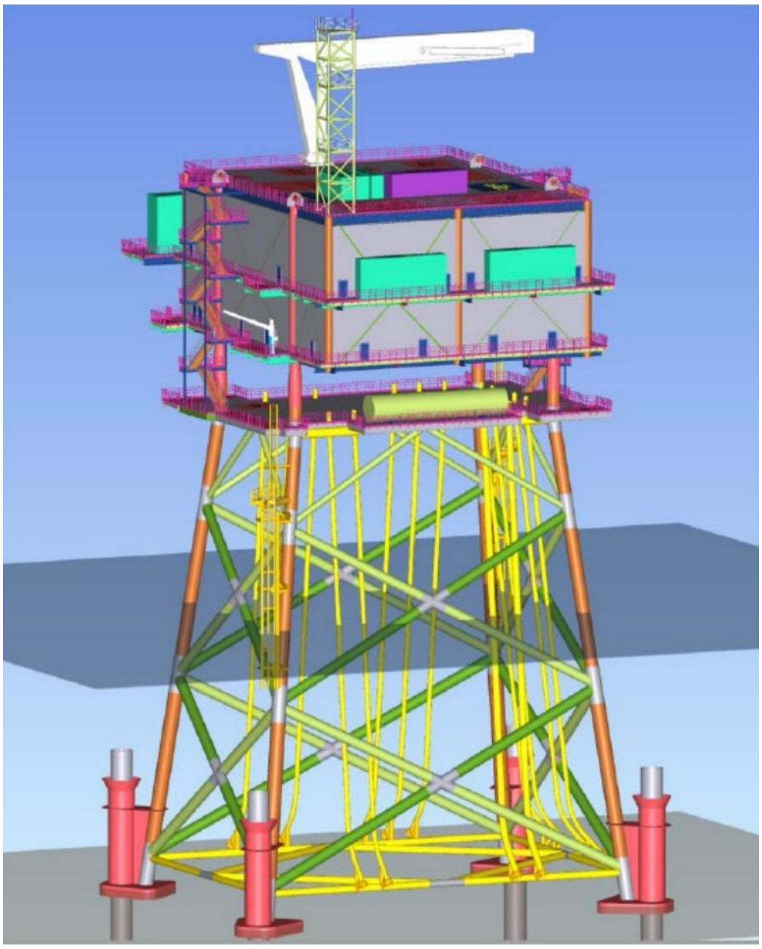

Figure 12: Substation structure. Source: Thesis director.

a) <u>Platform</u>: fixed to the ground by one of the methods previously explained. In this case as it is shown the structure of the substation is a jacket type, this kind of substructure comprises four robust legs, supported by piles that are driven into the seabed, interconnected by cross bracings. All components are constructed using tubular pipe sections and welded together. This substructure is very versatile in terms of seabed conditions.

b) <u>J-tubes</u>: facilitate the interconnection of array cables from the wind turbines to the cable deck. It is important to have a designated management space in the substation, known as the enclosure, to accommodate both the equipment and workers during the installation process.

c) <u>Cable deck</u>: located in the lower part of the substation.

d) Equipment deck.

e) Helicopter deck.

3) Auxiliary systems. These elements are diesel generators, inert gas systems, SF6 gas detection systems, electrical design for lighting and small power, lightning protection, earthing and bonding systems, ventilation and HVAC systems, water handling for sea and fresh water, drainage for grey and black water, auxiliary system control and monitoring, and public address, navigation, aviation aids, SCADA, UPS, and fire detection and alarm systems and they are located in the substation also in containers.
As mentioned, all these elements are located inside containers which help the equipment to be protected against corrosion or other hazardous situations. (CIGRE, 2011)

After this description of the typical elements who take part in the substation of a wind power generation plant, the selection of this elements for the particular offshore wind power generation plant is now presented.

The first element to be explained is the 66 kV switchgear, which will be part of a GIS substation. To ensure proper sizing, the initial step is to calculate the current generated ((4) &(5)) by the wind turbines that will reach the substation:

$$P_{total} = 15MW * 50 = 750\ MW \quad (4)$$

$$I_{n_{\text{total}}} = \frac{P_{total}}{\sqrt{3} \times 66\,\text{kV}} = 6560{,}8\,\text{A} \quad (5)$$

Due to the high amount of current and considering that 2500 A is a typical rated current for this type of switchgear, the following number of GIS units will be necessary at this voltage level:

$$n^{\circ}{}_{66kV\_switchgears} = \frac{I_n(total)}{I_n(switchgear)} = \frac{6560{,}5}{2500} = 2{,}62 \ \approx\ 3\ switchgears \quad (6)$$

From the configuration of the 66 kV evacuation network, there are 12 circuits that need to be distributed among the three 66 kV-level switchgears, therefore 4 circuits will enter each switchgear.

The configuration will be as shown in Figure 13, where each color represents a different 66 kV switchgear:

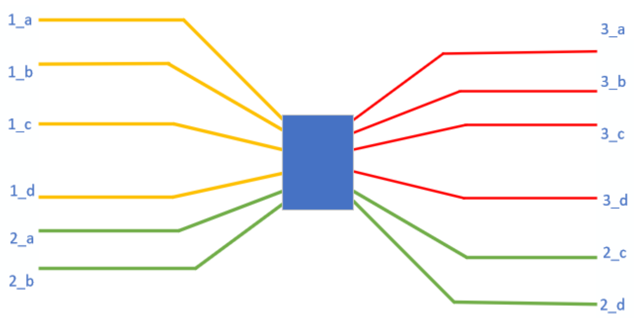

Figure 13: Incoming circuits of the offshore substation. Source: Self-elaboration.

Each one of these 66 kV switchgears will have 4 incomers and 1 feeder which will be connected to a transformer that will rise the voltage to 220 kV.

The rated current of the transformers is calculated as follows (rounded to the closest decimal):

$$\frac{P_{total}}{n°_{66kV\_switchgears} * cos(\emptyset)} = 270\ MVA \tag{7}$$

The chosen transformer is detailed in (Hitachi Energy, 2023) and is shown in the central part of Figure 14.

Figure 14: 270 MVA transformer. Source : (Hitachi Energy, 2023).

These 3 transformers will be then the incomers for the 220 kV switchgear which will have to be able to withstand the following nominal current:

$$I_{n_{\text{total}}} = \frac{750000\,\text{kW}}{\sqrt{3} \times 220\,\text{kV}} = 1968{,}2\,\text{A} \tag{8}$$

Since this is a typical nominal current value for switchgears, one switchgear will be sufficient. The simplified single-line diagram is shown in Figure 15:

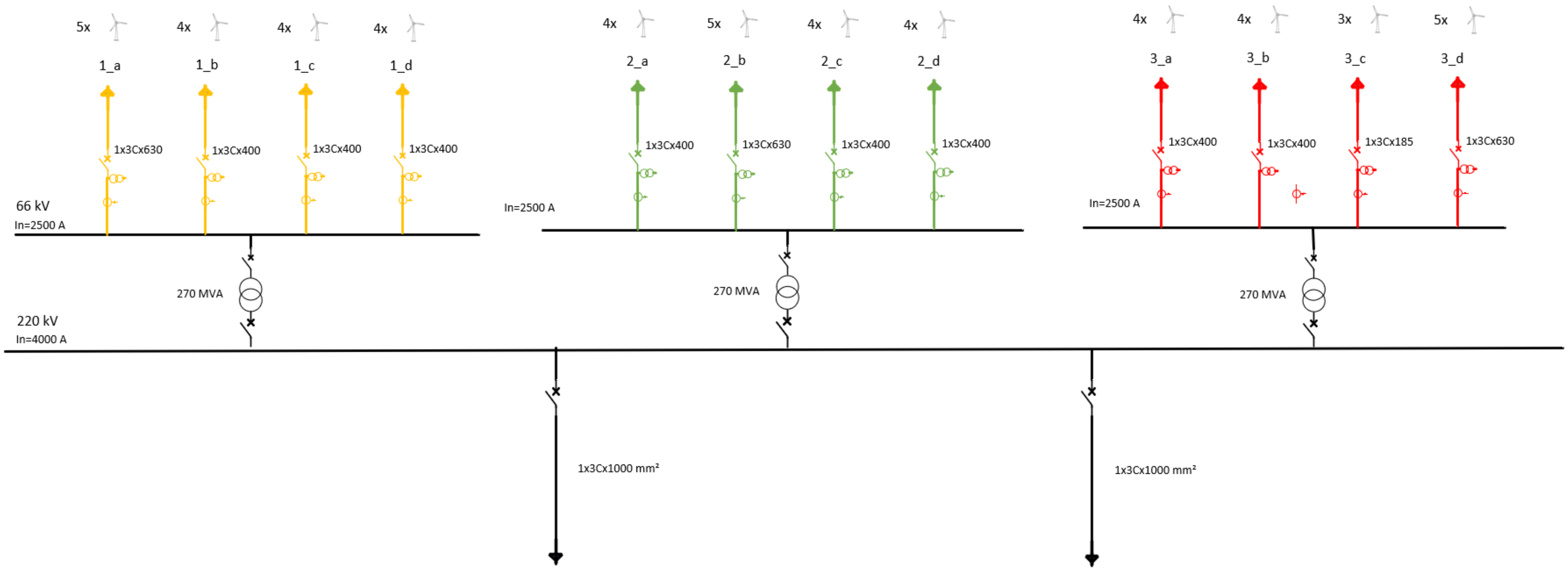

Figure 15: Simplified SLD. Source: Self-elaboration.

In Table 1 the chosen switchgear's parameters are described.

Parameters	Units	66 kV Switchgear	220 kV Switchgear
Rated voltage	kV	≤ 72.5 kV	≤245 kV
Rated frequency	Hz	50/60	50/60
Rated continuous current	A	2500	≤4000
Rated short circuit-breaking current	kA	40	40
Rated peak withstand current (2,5*Icc)	kA	100	100
Type of installation	-	indoor	indoor/outdoor
Bay width	mm	800	1680

Table 1: Technical specifications of the switchgear. Source: (Hitachy Energy, 2024) (Hitachy Energy, 2022).

Figure 16: Switchgear model ELK-14 C. Source: Hitachi Energy.

Offshore substations have unique features that complicate their design. Harsh weather conditions, corrosive elements, and transportation and weight constraints are key factors considered in such projects. However, to focus on the core aspects of the design, these constraints will not be considered in this study.

3.4 220 kV Evacuation Network

As explained, after elevating the voltage to 220 kV, there are two feeders from the 220 kV switchgear. These will be two 1000 mm² cables that connect the offshore substation to the shore, where the landfall will take place.

The cross section was calculated following the same method as for the medium voltage evacuation network of 66 kV and it is shown in Table 26 of Cable calculation presented in the annex. The grouping factor could have been considered; nevertheless, in this scenario, the cables will be laid out with a 150 m distance between them.

This is done to mitigate the following risks, ensuring that potential issues do not affect both cables simultaneously:

- The amount of current that needs to be transferred needs a big section cable, if only one cable had to transport all this current, the cable section would need to be of 2000 mm^2 or higher. The impact is a big increase of the cost since these cables are not that common in the current market.

- On the other hand, another justified reason for using two cables is reliability. There is a risk that a cable may cease to provide service if a ship becomes entangled with-it during anchoring/unanchoring processes. Additionally, there is the possibility of seismic activity causing changes in the terrain or activities such as trawling fishing that could damage or displace the cable.

If one of the two cables results damaged during the operation of the plant, the energy supply would be reduced by half instead of completely nullified.

The total distance of the cable is around 28 km, and the cable characteristics are shown in Table 2:

Table 2 Three-core Optical Fiber Composite Submarine Cable 127/220kV

Size	Max. Conductor resistance		Amps			Approx. O. D.	Approx. O. D. weight	Inductance	Capacitance
mm2	20℃ DC Ω/km	90℃ AC Ω/km	Seabed	Land	Intertidal	mm	kg/km	mH/km	uF/km
3×400	0.047	0.062	675	504	610	259.6	150104	0.485	0.117
3×500	0.0366	0.049	753	559	677	266.2	157961	0.467	0.124
3×630	0.0283	0.039	835	617	749	270.7	165364	0.444	0.137
3×800	0.0221	0.032	915	671	817	275.7	173948	0.42	0.152
3×1000	0.0176	0.027	986	720	878	280.5	183206	0.402	0.168
3×1200	0.0151	0.024	1076	789	961	290.1	198029	0.387	0.181

Table 2: Submarine cable 220 kV. Source: (Qifan, 2022).

3.5 LANDFALL

The landfall refers to the arrival of the two 220 kV cables to the shoreline and their subsequent connection to the transition joint bay where the necessary conversion from three-phase to single-phase of the cables is done. Afterwards, the final connection to the onshore substation is performed.

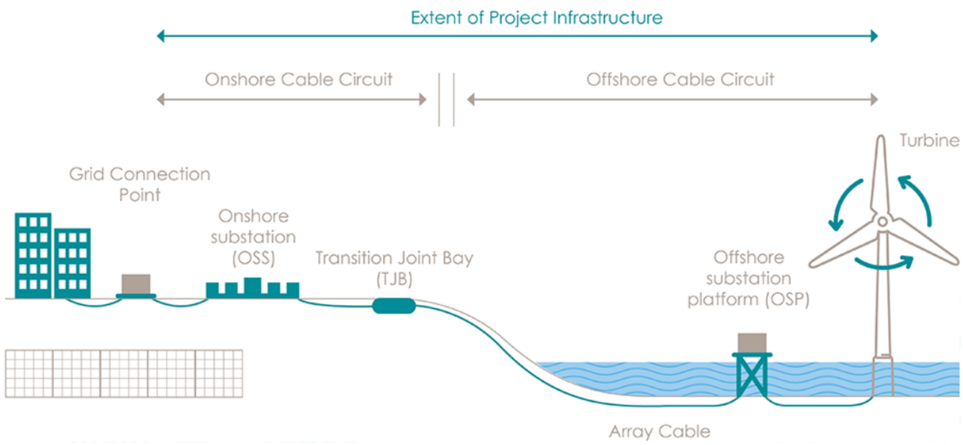

Figure 17: Visual scheme of the landfall. Source: (Orsted, 2022).

The first stage involves transitioning the cables from being buried in the seabed to the transition joint bay where the conversion from three-phase to single-phase will occur. In this case the procedure is done by a technique called horizontal directional drilling.

The procedure to perform HDD (horizontal directional drilling) is as follows:

1. Establish an offshore worksite (typically on a barge) and another worksite on land that will be used to position drilling equipment.

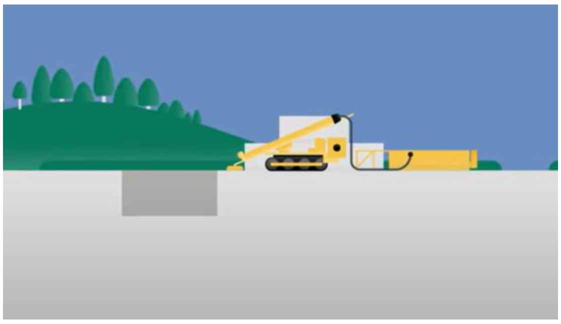

Figure 18: Onshore worksite. Source: (Orsted, 2022).

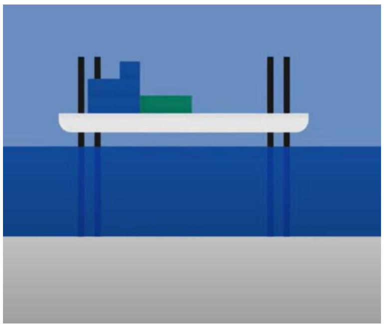

Figure 19: Offshore worksite. Source: (Orsted, 2022).

2. To install the cable, first a borehole is drilled under the cost line or beach. The drilling is controlled by keeping enough distance from the seabed.

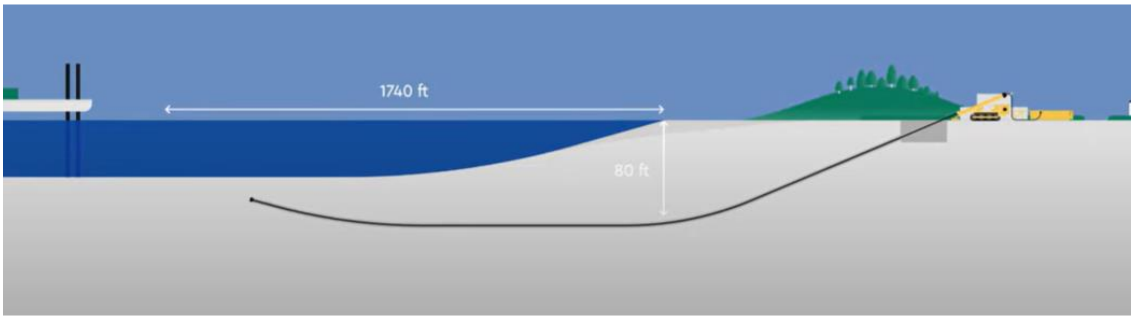

Figure 20: Drilled borehole. Source: (Orsted, 2022).

3. When the distance from the coast line or the beach is sufficient, the drill head emerges from the seabed.

4. Then the drilling rig installed in the land pulls back a conduit pipe through the borehole connecting the onshore and offshore workspaces.

Figure 21: Installation of the conduit pipe. Source: (Orsted, 2022).

5. Pull equipment is installed in the land side and it pulls back the cable from the cable lay bezel through the conduit pipe to the shore.

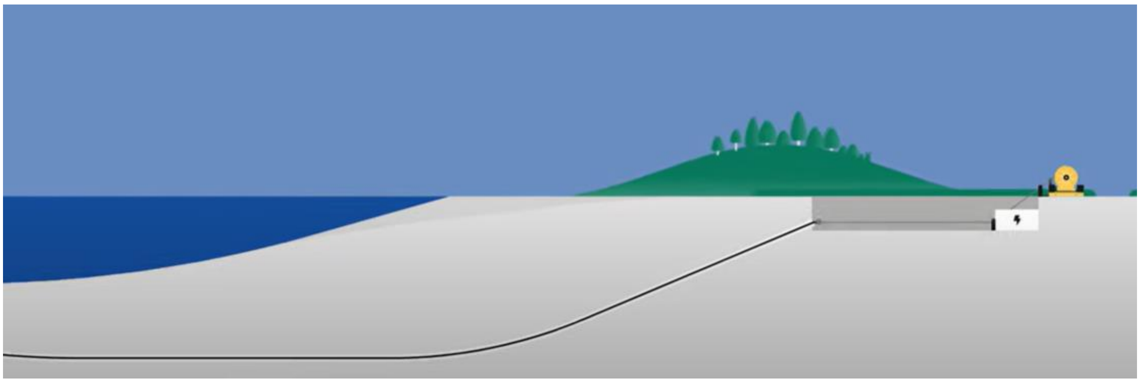

Figure 22: Pull equipment installing the cable. Source: (Orsted, 2022).

6. Finally, the end of the cable in the shore arrives to the transition joint bay (TJB).

In this case there will be two landfalls, one for each 220 kV cable.

The transition joint bay is an underground concrete housing that joins the cable coming from the shore with a cable that will arrive to the onshore substation. The installation of the cables by HDD is a very complex method that also requires high economic investments therefore it is preferred to use a three-phase cable, to streamline operations and minimize investment requirements. As previously discussed, the cables required for the 220 kV evacuation network involve substantial costs, needing a strategic approach to minimize installation length. Given the prevalent use of underground onshore cables with lower economic implications, particularly those utilizing single core configurations, they are preferred for connecting the landfall endpoint to the onshore substation in this case.

Consequently, the TJB is used to perform this splice and transition from triphasic cables to monophasic as well as to install the earthing of the shields and to connect the fiber optic cables. Triphasic and monophasic cables may have different sizes, insulation materials, or other characteristics. The TJB is designed to adapt to these differences, providing a seamless connection between the two types of cables. These joints are highly protected with insulating materials to prevent electrical faults and that some environmental factors affect the power transmission. The connections in the TJB are shown in Figure 23.

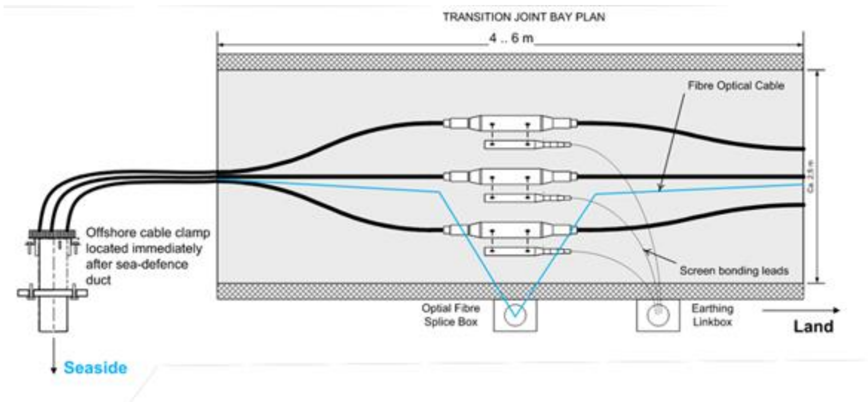

Figure 23: TJB connection scheme. Source: Thesis Director.

The TJB is built as a concrete enclosure with pre-drilled holes to accommodate cable passage. This design guarantees the cables are adequately shielded and arranged, as shown in Figure 24.

Figure 24: TJB concrete enclosure. Source: Thesis Director.

3.6 FINAL CONNECTION TO THE ONSHORE SUBSTATION

From the TJB to the connection point in the onshore substation the cables will be installed under conduit buried in a trench.

The procedure followed to do this type of installation is as follows:

1. Excavation of the trench.
2. Installation of tubes.
3. Cable laying using a pulling machine and a coil lifting jack with a braking device.
4. Backfill with soil.
5. Soil compaction.

On many occasions a warning tape is located on the top layers of the soil with the purpose of alerting people of the presence of high voltage underground cables underground.

In Figure 25 the cables layout can be appreciated, with a length of approximately 22 km.

Figure 25: Cable layout from TJB to Onshore substation. Source: Thesis Director.

The cable is chosen to comply with the needed rated current. The cable selected characteristics are the following (Nexans , 2021):

- Single core copper cables, 220kV.
- Cross section: 1000 mm^2.
- I max. @ 90°C-buried in flat formation spaced: 1205 A.
- Stranded round copper conductor.
- Insulation material cross-linked polyethylene (XLPE).
- Radial sealing (copper or aluminum tape).

3.7 ONSHORE SUBSTATION

For the transmission of electric power generated at the offshore wind farm to the electrical grid, the buried cables carrying the power are connected to an existing substation. To adapt it to this new energy input, an expansion of two-line bays with the same technology, standards, and arrangement as the current ones is carried out. In Figure 26 an ampliation of a substation is shown.

Figure 26: Onshore substation. Source : (Ingenieria de Subestaciones, 2020).

4 ECONOMIC TOOL

This section presents an economic tool designed for the preliminary estimation of Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) costs of an offshore wind power generation plant. Intended for use in the initial stages of project development, the tool requires basic inputs such as the general characteristics of the plant, essential equipment criteria (available in data sheets or recommended by the tool), and fundamental technical design decisions. Additionally, it incorporates price estimations per kilometer for cables, per bay for switchgear, and per MVA for transformers. The tool also provides a basic layout design, detailing the number of circuits, switchgears, and the necessary transformers, ensuring a comprehensive overview even in the project's early phases.

4.1 DESIGN CALCULATION

In this section the design calculation and way of using the first sheets of this Excel tool is explained.

1. The “Initial Guideline” sheet explains the color guidelines for the filling of the cells and then there is an instruction to move to the next sheet.

   As shown in the Table 3:

Color legend for the Cost Calculation Tool
All cells in this color have to be filled with the input data from the project
All cells in this color have to be filled with the input data from the equipment to be used. In case of lack of information, in the comments of each of this cells there are typical values
All cells in this color imply design decisions. Also some recomendations will be displayed in the comments
All cells in this color are related to the cost of the equipment used for the electrical installation
Move to next Excel sheet: Basic initial data

Table 3: Color legend. Source: Self-elaboration.

2. The "Basic Initial Data" sheet is designed for users to input fundamental project data. This data is typically available during the initial stages of any project and includes essential information required for the subsea cable design. To determine these parameters, users can refer to standard tables and must also know the plant's location.

   - Depth Factor: To obtain this value, the installation characteristics of the plant must be known. Typically, subsea cables are installed at a depth of approximately 1 meter below the seabed. The (RLAT, 1997) standard should be used to determine the precise depth factor based on these installation details.

   - Thermal resistivity factor: obtained by knowing the material of the seabed where the cables will be laid out and making use of (RLAT, 1997).

   - Temperature factor: depending on the location of the plant and the temperature of the terrain composing the seabed where the cables will be laid. This factor to be obtained from the (RLAT, 1997).

- Grouping factor: this parameter is highlighted in green because it depends on the plant design. As explained in the Excel cell comments, the initial value should be set to 1. After calculating the number of outgoing circuits in the CAPEX sheet, cell D17, this value can be adjusted if there are more than 2 outgoing circuits. If there are more than 2 outgoing circuits on the high voltage side, this indicates that there will be more than one cable per circuit, requiring the application of a grouping factor. This grouping factor can be found in the (RLAT, 1997) standard. For the case study that is being analyzed, the data is as shown in the Table 4.

1. Fill all requiered data

Initial data		
Parameter	**Units**	**Value**
Number of wind turbines	(ud)	50
Nominal power of the turbines	(MW)	15
Voltage level at primary of the transformer	(kV)	66
Voltage level at secondary of the transformer	(kV)	220
Cos phi	-	0.95

For subsea cables:		
Parameter	**Units**	**Value**
Depth factor	-	0.96
Thermal resistivity factor	-	1.18
Temperature factor	-	1.04
Grouping factor at 220 kV	-	1

2. Move to next Excel sheet

Table 4: Initial data Source: Self-elaboration.

3. The "design calculation" sheet includes most of the plant design.

3.1. First with the given data, some basic calculations are performed which are necessary for further design and price calculations.

- Total power:

$$P(MW) = n°_{turbines} * P_{turbine}(MW) \tag{9}$$

- Current produced by 1 turbine:

$$I_{turbine}(A) = \frac{P_{turbine}(W)}{\sqrt{3} * V_{primary} * \cos(\emptyset)} \tag{10}$$

- Current produced by 1 turbine with the correction factors:

$$I_{turbine_{corrected}}(A) = \frac{I_{turbine}(A)}{Depth_{cf} * Thermal\ resistivity_{cf} * Thermal_{cf}} \quad (11)$$

$$I_{turbine_{corrected}}(A) = \frac{I_{turbine}(A)}{Depth_{cf} * Thermal\ resistivity_{cf} * Thermal_{cf}} \quad (12)$$

- Total current with correction factors at 220 kV level

$$I_{total_{220kV}}(A) = \frac{Plant_{power}(W)}{\sqrt{3} * V_{sec}(V) * \cos(\emptyset) * Depth_{cf} * Thermal\ resistivity_{cf} * Thermal_{cf} * Grouping_{cf}} \quad (13)$$

With all these, the results for the study case taking place are as shown in Table 5.

1. Some basic calculations are performed for further use		
Basic calculations		
Parameter	**Units**	**Result**
Total power	(MW)	750.0
Current produced by 1 turbine	(A)	138.1
Corrected by factors current produced by 1 turbine	(A)	117.2
Total current produced at 220 kV	(A)	1758.6

Table 5: Basic calculations results Source: Self-elaboration.

In this step, the user inputs the section and nominal current (available in catalogs) of the selected cables for the installation. The last column in this section calculates the number of turbines that each cable section can support at the 66 kV level. Specifically, based on the current produced by each turbine and the nominal current of the cables, the tool determines how many turbines can be grouped under each cable section, incorporating a 5% safety factor. The calculation follows formula (14):

$$n°turbines_{cable\ type} = \frac{I_{n\ cable\ type}}{I_{turbine_{corrected}} * 1.05} \quad (14)$$

The result is rounded down to the closest unit.

For the 220 kV voltage level, the calculated value is the number of necessary cables to transport the total current at 220 kV voltage level. A security factor of 5% is used to cover any unexpected variations. This calculation is performed using equation (15):

$$n°_{220\ kV\ cables} = \frac{I_{total\ at\ 220\ kV_{corrected}} * 1.05}{I_{n\ cable\ type}} \quad (15)$$

The number of cables is rounded up.

Table 6 shows the results for the study case:

. Fill in the required data for the cables and some design calculations will be performe			
Cable data at 66 kV			
Type	Section (mm2)	I_n (A)	n°turbines/cable w/security factor
Type 1	185	420	3
Type 2	400	590	4
Type 3	630	715	5
Cable data at 220 kV			
Type	Section (mm2)	I_n (A)	n°outgoing cables w/security factor
Type 1	1000	1070	2

Table 6: Number of turbines per-cable and number of necessary outgoing cables Source: Self-elaboration.

It can be noted that since the number of outgoing cables is 2 and as explained before they will be laid under different circuits, no grouping factor will need to be applied.

3.2. The next step is to calculate the number of circuits needed to group all the turbines. First, the ideal number of circuits at the low voltage level is calculated by determining how many circuits can accommodate the maximum number of turbines. The objective is to maximize the number of circuits where the final section uses the cable with the largest section. The formula used for this calculation is equation (16):

$$n°circuits_{last\ section\ cable_{type3}} = \frac{Total\ n°_{turbines}}{N°\ turbines_{cable\ type\ 3}} \tag{16}$$

The number is rounded up. In the analyzed case study, the result is 10.
The next step is to align this number of circuits with the number of switchgears. Further explanation will be provided once the number of switchgears is determined in 3.3.2.
Table 7 shows the results for the study case:

3. Turbines grouped in circuits		
Grouping calculation		
Parameter	Units	Result
Ideal n° circuits at 66 kV	(ud)	10
N° circuits according to n° of swrg at 66 kV	(ud)	12

Table 7: Turbines grouped in circuits Source: Self-elaboration.

3.3. Switchgear and transformer design calculations are now performed:

3.3.1. First, the technical data for the switchgear is requested and highlighted in yellow. This includes the nominal current of the switchgears at both voltage levels. If the switchgear model has not been chosen yet, recommendations are provided in the cell comments.

3.3.2. Then the electrical design of the switchgear at low voltage level is performed. The calculations and formulas used are the following:
- The total current produced by the turbines at LV level:

$$I_{total\ at\ LV\ level} = I_{turbine_{corrected}}(A) * n°_{turbines} \tag{17}$$

- The required number of switchgears to support this current is determined by considering their nominal current:

$$N°_{switchgear_{LV}} = \frac{I_{total\ at\ LV\ level}}{In_{switchgear\ at\ LV}} \quad (18)$$

This number is then rounded up.

Having established the required number of switchgears, the next step is to determine the associated circuits. Each circuit corresponds to one bay within the switchgear system. The objective is to find the number of switchgears that comes closest to the previously determined ideal count (always rounding up to the next whole number). This ensures practical alignment while minimizing excess capacity.

- Next, it is calculated the number of entering circuits for each low-voltage switchgear, where an "entering circuit" occupies one bay within the switchgear, as follows in equation (19):

$$N°_{entering\ circuits_{LV}} = \frac{N°\ of\ circuits_{according\ to\ the\ n°\ of\ switchgears\ at\ LV\ level}}{N°_{switchgear_{LV}}} \quad (19)$$

- Number of outgoing circuits to the transformer:
This number matches the number of transformers per switchgear, this parameter will be explained in section 3.3.3.
- Finally, the number of bays at low voltage level involves a simple calculation:

$$N°\ of\ bays_{LV} = N°_{entering\ circuits_{LV}} + N°_{outgoing\ circuits\ to\ transformer} \quad (20)$$

3.3.3. Similarly, the design of the high voltage switchgear is now explained:

- The first parameter is the total current produced by the plant at high voltage level which was previously calculated in the basic calculations section.

- The number of necessary switchgears at high voltage level is calculated similarly as before:

$$N°_{switchgear_{HV}} = \frac{I_{total\ at\ HV\ level}}{In_{switchgear\ at\ HV}} \quad (21)$$

- The number of incoming circuits in the switchgears (which is one bay per incoming circuit):

$$N°_{entering\ circuits_{HV}} = N°_{switchgear_{LV}} * N°transformer_{LV\ switchgear} \quad (22)$$

- The number of outgoing circuits to the onshore substation is a critical parameter, previously calculated in section 3.2. If this count falls below 2, a decision must be made regarding reliability. When reliability is prioritized, it becomes a design parameter. In such cases, the number of cables laid in separate circuits must always be 2 or more (as indicated in a comment within the cell). If the value changes, it is essential to adjust the corresponding parameter, labeled “n° outgoing cables w/security factor,” in section 2 of the Excel document.

- Number of bays at high voltage:

$$N°_{bay_{HV}} = N°_{entering\ circuits_{HV}} + N°_{outgoing\ circuits_{HV}} \quad (23)$$

3.3.4. Lastly the transformer calculations are performed:

- The number of transformers connecting the low-voltage and high-voltage switchgears is determined through iterative calculation (considered a design parameter). Initially, a value of 1 is tested. However, if the rated power of the transformers exceeds 650 MVA, the value should be adjusted to 2.

- The rated power of the transformers:_this calculation is performed as equation (24) shows:

$$Transformer\ Rating = \frac{Plant_{total\ power}}{\cos(\emptyset) * N°_{switchgear_{LV}}} \quad (24)$$

This value is rounded up to the closest decimal.

The results for the study case are shown in Table 8:

4. Switchgear and transformer design calculations are performed once the indicated cells are filled		
Switchgear data		
Parameter	**Units**	**Result**
Switchgear nominal current at 66 kV	(A)	2500
Switchgear nominal current at 220 kV	(A)	4000

Switchgear calculation		
Parameter	**Units**	**Result**
I_n total entering the 66 kV switchgear	(A)	5862.01
N° of switchgear at 66 kV	(ud)	3
N° of entering circuits at 66 kV	(ud)	4
Number of outgoing to tfr	(ud)	1
N° of bay at 66 kV	(ud)	5
I_n total entering the 220 kV switchgear	(A)	1758.60
N° of switchgear at 220 kV	(ud)	1
N° of entering circuits at 220 kV	(ud)	3
Number of outgoing circuits to onshore substation	(ud)	2
N° of bay at 220 kV	(ud)	5

Transformer calculation		
Parameter	**Units**	**Result**
Number of transformers/ switchgear at 66 / 220 kV	(ud)	1
Rated power of transformers 66 / 220 kV	(MVA)	270

Table 8: Switchgear and transformer design calculations. Source: Self-elaboration.

3.4. Plant dimensions data and geometrical calculations:

3.4.1. The dimensions of the surface occupied by the turbines and the substation is input from the project and should be filled in the indicated cells in km as unit.

3.4.2. For the geometric calculations:

- The number of rows on side 1: the calculation is done as equation (25):

$$N° \; of rows_{side1} = \frac{N° \; of \; circuits_{according \; to \; the \; n° \; of \; switchgears \; at \; LV \; level}}{2} \tag{25}$$

If it results on a number that is not integer, then it is rounded to closest smallest integer number.

- The number of rows on side 2: the calculation is done as follows:

$$N° \; of rows_{side2} = \frac{N° \; of \; circuits_{according \; to \; the \; n° \; of \; switchgears \; at \; LV \; level}}{2} \tag{26}$$

If it results on a number that is not integer, then it is rounded to closest biggest integer number.

- The total distance per row in vertical direction (it will be the same for all rows):

$$Vertical \; distance_{row}(km) = \frac{plant_{lenght}(km)}{2} - \frac{offshore \; subestation_{lenght}(km)}{2} \tag{27}$$

- The distance between rows on side 1, it is a simple calculation:

$$Distance \; between \; rows_{side1}(km) = \frac{Plant_{width}(km)}{N° \; of rows_{side1}} \tag{28}$$

- Similarly for the distance between rows on side 2:

$$Distance \; between \; rows_{side2}(km) = \frac{Plant_{width}(km)}{N° \; of rows_{side2}} \tag{29}$$

The results for the study case are shown in Table 9:

5. Insert the plant dimentions and some geometrical calculations are performed		
Dimentions of the plant data		
Parameter	**Units**	**Result**
width	(km)	10.00
lengt	(km)	14.00
dimentions of the off-substation data		
width	(km)	0.50
lengt	(km)	1.00

Geometric calculations		
Parameter	**Units**	**Result**
number of rows side 1	(ud)	6
number of rows side 2	(ud)	6
total distance per row in vertical	(km)	6.50
distance between rows side 1	(km)	1.67
distance between rows side 2	(km)	1.67

Table 9: Geometrical calculations. Source: Self-elaboration.

3.5. In the final step of plant design, the number of circuits per cable type is determined. This calculation varies based on whether the distribution is known or remains unknown, as further elaborated.

3.5.1. The first step is to indicate if the distribution known or unknown, and the Excel tool will indicate which will be the next step to be followed.

3.5.2. If the distribution is unknown, follow step 6a. The tool will suggest an initial distribution based on the number circuits and turbines, prioritizing the maximum number of circuits with the final cable section being the largest (type 3). Following this approach, the number of turbines that have not been grouped into Type 3 circuits (with the largest final section) is calculated. These turbines are then attempted to be grouped into circuits with the second largest final section. Finally, the number of circuits with the smallest final section is calculated by subtracting the total number of circuits from the number of circuits with the other two final sections. As a final step and as a verification that the grouping has been correct, the number of turbines involved in this distribution is calculated, as shown in equation (30):

$$\text{Total turbines covered} = \sum_{i=1}^{3} \left(\text{n° circuits}_{\text{cable type i}} \cdot \text{n° turbines}_{\text{cable type i}}\right) \tag{30}$$

If this number differs from the total number of turbines (initial project data), the process moves on to the next step. If it matches the number of turbines, the next column has to be equally filled.

The "Adjustment" column must be filled out separately. The only parameter that is determined by the design, indicated by the green color in the cell, is the number of circuits with cable type 3. If the total number of turbines covered in the previous step matches the project's total number of turbines, the number of circuits with cable type 3 in the "Adjustment" column should match the number of circuits with cable type 3 in the initial distribution column. Otherwise, this number needs to be adjusted until the total number of turbines covered in the "Adjustment" column matches the project's total number of turbines.

3.5.3. If the distribution is known, follow step 6b. In this case, the number of turbines per circuit is known and should be filled in. Then the tool will automatically calculate the number of turbines per type of circuit (depending on the section) and on the last row the total number of sections per type of circuit is indicated.

The study case results are presented in Table 10 and Table 11. Notably, the adjustment column does not align with the initial distribution column. The discrepancy arises because the initial distribution accounts for a total of covered turbines that differs from the project's overall turbine count. In this known distribution scenario, Case 6b would be applicable.

6. Select if the distribution is known or unknown and after move on to step indicated		
The distribution is :	Known	
Please follow :	6b	

6.a In case the distribution is unknown: The initial distribution is automatically filled, there are two possibilities: - B70 = total turbines of the plant, fill the same number of cell B67 in C67 - B70 ≠ total turbines of the plant, adjust C67 until C70 = total turbines of the plant

n°_circuits per type of cable		
	initial distribution	adjustment
n°_circuits type 3	10	2
n°_circuits type 2	0	10
n°_circuits type 1	2	0
total turbines covered	56	50

Table 10: Number of circuits/ cable type. Unknown distribution. Source: Self-elaboration.

6.b In case the distribution is known: Fill in the number of turbines in each circuit The total number of sections per type of cable is calculated				
	Total	n°_type1_sections	n°_type2_sections	n°_type3_sections
n° turbines circuit 1	5	3	1	1
n° turbines circuit 2	4	3	1	0
n° turbines circuit 3	4	3	1	0
n° turbines circuit 4	4	3	1	0
n° turbines circuit 5	4	3	1	0
n° turbines circuit 6	5	3	1	1
n° turbines circuit 7	4	3	1	0
n° turbines circuit 8	4	3	1	0
n° turbines circuit 9	4	3	1	0
n° turbines circuit 10	4	3	1	0
n° turbines circuit 11	3	3	0	0
n° turbines circuit 12	5	3	1	1
Total sections/type of circuit		12	11	3

7. Move to next Excel sheet

Table 11: Number of circuits/ cable type. Known distribution. Source: Self-elaboration.

4.2 CAPEX CALCULATION

CAPEX (Capital Expenditure) represents the initial investment required to develop and construct an offshore wind farm. It encompasses costs related to project planning, feasibility studies, site assessment, obtaining permits, building wind turbines, foundations, substations, electrical infrastructure, and inter-array cables. In this case the CAPEX calculations will only involve the basic electrical equipment mentioned in the previous Excel sheet: "Basic initial data".

4. Following the last step in the previous section, the next sheet is called CAPEX and now the different steps to follow in it will be explained similarly as before:

    4.1. First the cable price calculation is performed. For that the necessary input data is the cost in k€/km of the 4 different types of cable section. The cable costs have been estimated.

Appendix Table I Electrical parameters of some common cables in HVAC

Voltage V_n (kV)	Size (mm^2)	Resistance r_c (mΩ/km)	Capacitance C (nF/km)	Steady state current I_{ssn} (A)	Cable cost per set t_c (k£/km)
132	630	39.5	209	818	685
	800	32.4	217	888	795
	1000	27.5	238	949	860
220	500	48.9	136	732	815
	630	39.1	151	808	850
	800	31.9	163	879	975
	1000	27.0	177	942	1000
400	800	31.4	130	870	1400
	1000	26.5	140	932	1550
	1200	22.1	170	986	1700
	1400	18.9	180	1015	1850
	1600	16.6	190	1036	2000
	2000	13.2	200	1078	2150

Table 12: Cable costs. Source: (X. Xiang, 2017).

Using Table 12. It can be extracted the price of 860£/km for the 1000m^2 cable at 132 kV voltage level. From an input from the director of the thesis, the price of a 1000m^2 cable at 66 kV voltage level is 686.2 k€/km.
With this and using proportions, the cable costs in k€/km that will be used as input for the study case (the light orange color indicating that the input data is related to cost of the equipment) in the Excel tool are as shown in Table 13:

1. Cable CAPEX calculation: fill in the price/ section and the next step is indicated below depending if the distributions is know or not		
Cable type	**Section (mm2)**	**Price (keuro/km)**
Type 1	**185**	447.14
Type 2	**400**	491.91
Type 3	**630**	547.78
Type 4	**1000**	1174.50

Please follow :	**1b**

Table 13: Cable cost (keuro/km). Source: Self-elaboration.

Depending on the type of distribution (known or unknown) the following step will be indicated.

4.1.1. If the distribution is unknown, the next step (1.a) involves calculating cable lengths. The critical input required for this calculation is the distance between the offshore substation and the shore connection point (highlighted in blue as a project parameter). The calculations proceed as follows.

4.1.1.1. Number of sections between cables of each cable type: as an example, the number of sections of cable type 1 (the one with smaller cross section) is explained. Since all aggrupation of turbines (circuits) include cable of this cross section, they are all added and multiplied by the number of turbines that this cross section can hold; then the number of circuits whose last cross section is the of type 3 are subtracted, the excel formula is as equation (31) shows:

$$\begin{aligned}\text{n° of cable section between cables}_{\text{cable type 1}} &= \text{n°\_turbines}_{\text{type1}} \\ &\cdot \left(\text{n°\_circuit}_{\text{type3\_2}} + \text{n°\_circuit}_{\text{type2\_2}} + \text{n°\_circuit}_{\text{type1\_2}}\right) \\ &- \text{IF}\left(\left(\text{n°\_circuit}_{\text{type1\_2}} = 0\right); 0; \text{n°\_circuit}_{\text{type1\_2}}\right)\end{aligned} \tag{31}$$

For cable type 2:

$$\begin{aligned}\text{n° of cable section between cables}_{\text{cable type 2}} &= \left(\text{n°\_turbines}_{\text{type2}} - \text{n°\_turbines}_{\text{type1}}\right) \\ &\cdot \left(\text{n°\_circuit}_{\text{type3\_2}} + \text{n°\_circuit}_{\text{type2\_2}}\right) \\ &- \text{IF}\left(\left(\text{n°\_circuit}_{\text{type2\_2}} = 0\right); 0; \text{n°\_circuit}_{\text{type2\_2}}\right)\end{aligned} \tag{32}$$

For cable type 3:

$$\text{n° of cable section between cables}_{\text{cable type 3}} = \left(\text{n°\_turbines}_{\text{type3}} - \left(\text{n°\_turbines}_{\text{type2}} + \text{n°\_turbines}_{\text{type1}}\right)\right) \cdot \left(\text{n°\_circuit}_{\text{type3\_2}} - \text{IF}\left(\left(\text{n°\_circuit}_{\text{type3\_2}} = 0\right); 0; \text{n°\_circuit}_{\text{type3\_2}}\right)\right) \quad (33)$$

For cable type 4: it is simply the number of outgoing circuits.

4.1.1.2. The number of cable sections between the cable and the offshore substation is determined by examining circuits that end with each specific cross section. If such circuits exist, the count of circuits with that cross section aligns with the number of cable sections connecting from the last turbine of the row to the offshore substation.

4.1.1.3. Next, the distance between turbines is calculated for each type of circuit as:

$$Vertical\ distance\ between\ turbines_{cable\ type} \frac{Vertical\ distance_{row}(km)}{n°turbines_{cable\ type}} \quad (34)$$

4.1.1.4. The average distance between rows for each cable type, which remains consistent across all low-voltage level cable types, is calculated. This approach is considered sufficiently accurate for practical purposes. The calculation is as follows:

$$Average\ distance\ between\ rows_{cable\ type} = \frac{Distance\ between\ rows\_side1\ (km) + Distance\ between\ rows\_side2\ (km)}{2} \quad (35)$$

4.1.1.5. The subsequent step involves estimating the distance from each turbine to the offshore substation for each cable type. This estimation relies on the Euclidean distance calculation, considering both the vertical distance between turbines and the distance between rows specific to each cable type. The calculation is as follows:

$$Distance\ from\ turbine\ to\ offshore\ substation_{cable\ type} = \sqrt{Av.dist.bet.rows_{cable\ type}{}^2 + Vert.dist.bet.turbines_{cable\ type}{}^2} \quad (36)$$

4.1.1.6. The total distance for each type of cable is calculated now:

$$Total\ distance_{cable\ type} = n°\ of\ cable\ section\ betweeen\ cables_{cable\ type} * Vertical\ distance\ between\ turbines_{cable\ type} + n°cable\ sections\ betweeen\ cable\ and\ substation_{cable\ type} * Distance\ from\ turbine\ to\ offshore\ substation_{cable\ type} \quad (37)$$

4.1.1.7. Finally, the cost is calculated as a multiplication of the total distance per cable type and the cost in k€/km of each cable type. The results for the case study are shown in Table 14.

1.a In case the distribution is unknown: only the distance from the off-subst to the coast is a necessary input				
	Cable type 1	Cable type 2	Cable type 3	Cable type 4
n°cable sections between cables	36	2	0	2
n°cable sections between cable and off-substation	0	10	2	-
Distance between turbines (km)	2.17	1.63	1.30	-
Distance between rows (km)	1.67	1.67	1.67	-
Distance from turbine to offsubss (km)	2.73	2.33	2.11	-
Total cable distance (km)	78.00	26.53	4.23	27.70
Total cost (k€)	34'877.15	13'049.03	2'315.70	32'533.65

Table 14: CAPEX Cable total cost/cable type. Unknown distribution. Source: Self-elaboration.

4.1.2. On the other hand, if the distribution is known the following step stated by the tool after introducing the pricing information for the cables will be 1.b.

4.1.2.1. The input needed to perform the calculation is simply the cable distance in km of each cable type.

4.1.2.2. The calculation performed is simple, total distance per cable multiplied by the cost per cable type indicated in the first part of the CAPEX sheet. In Table 15 the results for the study case are shown:

1.b In case the distribution is known: fill in the total distance per type of cable				
	Cable type 1	Cable type 2	Cable type 3	Cable type 4
Total cable distance (km)	71.10	24.00	60.10	27.70
Total cost (k€)	31'791.86	11'805.75	32'921.58	32'533.65

Table 15: CAPEX Cable total cost/cable type. Known distribution. Source: Self-elaboration.

4.2. The following CAPEX calculation focuses on the switchgear. For an initial and general estimation, the switchgear price is determined based on the number of bays and the voltage level of the switchgear. The cells highlighted in light orange indicate the input data related to the equipment pricing.

4.2.1. After entering the price per bay (in k€/bay) for both voltage levels, the rest of the calculations are performed automatically. This is because the number of switchgears and bays has already been determined in the "Design calculation" Excel sheet.

The price (k€/bay) was provided by the thesis director.

In Table 16 the total CAPEX cost of the two switchgears implemented in the project study case are calculated:

2. Switchgear CAPEX calculation: fill in the cost/bay and the cost per type of swgr will be calculated				
Switchgear type	Cost (k€/bay)	N° of swgr	N° of bays	Total price (k€)
Switchgear at 66 kV	900.00	3	5	13'500.00
Switchgear at 220 kV	2500.00	1	5	12'500.00

Table 16: CAPEX switchgear total cost/voltage level. Source: Self-elaboration.

4.3. As a final step in the CAPEX Excel sheet, the CAPEX calculation for the transformers is performed. Similar to the switchgear estimation, the transformer CAPEX is initially approximated based on the price per MVA.

4.3.1. Since there is only one transformer type, the calculation is performed by the only input of the (k€/MVA) of the transformer to be used. After this input indicated in light orange as it is an input based on the price of the equipment, the total price in k€ is calculated since the number of transformers and the rating of the chosen transformer was determined in the design calculation sheet.

The price (k€/MVA) was data provided by the thesis director.
In Table 17 the total CAPEX cost of the transformer implemented in the project study case is calculated:

3. Transformer CAPEX calculation: fill in the cost/ MVA and the transformer cost is calculated				
Transformer	**Cost (k€/MVA)**	**N° of transformers**	**MVA**	**Total price (k€)**
Type 1	14.00	3	270	11'340.00

Table 17: CAPEX transformer total cost/transformer rating Source: Self-elaboration.

4.3 OPEX CALCULATION

Now that the CAPEX calculation is complete, the next and final sheet in this tool will calculate the OPEX of the installation. Since the structure and calculations for the OPEX are similar to those used for the CAPEX, this sheet will primarily focus on explaining the sources of the price data for each piece of equipment.

5. The steps presented in the sheet: "OPEX" should be followed, similarly as before:

Given the input from the thesis director that a 220 kV cable can be considered to cost around 150 k€/km, we can use similar proportions as in the CAPEX calculation to determine the cable costs in k€/km/year. These costs are entered as inputs for the case study in the light orange cells. The results for the case study are shown in Table 18.

1. Cable cost calculation: fill in the cost/ section and the next step is indicated below depending if the distributions is know or not		
Cable type	**Section (mm2)**	**Cost (keuro/km/year)**
Type 1	**185**	57.06
Type 2	**400**	62.78
Type 3	**630**	69.91
Type 4	**1000**	150.00

Please follow :	**1b**

Table 18: Cable cost (keuro/km/year). Source: Self-elaboration.

Depending on the type of distribution (known or unknown) the following step will be indicated.

5.1.1. If the distribution is unknown, insert in the blue cell the distance between the offshore substation and the point of connection in the shore. The calculations will be performed as in the previous sheet: "CAPEX".

5.1.1.1. The cost is calculated as a multiplication of the total distance per cable type and the price regarding OPEX in k€/km of each cable type and the results for the study case that are presented in Table 19.

1.a In case the distribution is unknown: only the distance from the off-subst to the coast is a necessary input				
	Cable type 1	Cable type 2	Cable type 3	Cable type 4
n°cable sections between cables	36	2	0	2
n°cable sections between cable and off-substation	0	10	2	-
Distance between turbines (km)	2.17	1.63	1.30	-
Distance between rows (km)	1.67	1.67	1.67	-
Distance from turbine to offsubss (km)	2.73	2.33	2.11	-
Total cable distance (km)	78.00	26.53	4.23	27.70
Total cost (k€/year)	4'450.94	1'665.28	295.52	4'155.00

Table 19: OPEX Cable total cost /cable type. Unknown distribution. Source: Self-elaboration.

5.1.2. On the other hand, if the distribution is known the following step stated by the tool after introducing the costing information for the cables will be 1.b.

5.1.2.1. The input needed to perform the calculation is simply the cable distance in km of each cable type.

5.1.2.2. The calculation performed as before has now as an output the total OPEX cost per cable type. The results for the study case are shown in Table 20:

1.b In case the distribution is known: fill in the total distance per type of cable				
	Cable type 1	Cable type 2	Cable type 3	Cable type 4
Total cable distance (km)	71.10	24.00	60.10	27.70
Total cost (k€/year)	4'057.20	1'369.52	3'429.50	1'580.65

Table 20: OPEX Cable total cost/cable type. Known distribution. Source: Self-elaboration.

5.2. The next OPEX calculation is focused on the switchgear.

5.2.1. Following the same dynamic as for the CAPEX calculation, the cost has to be entered in the indicated cells and the rest of the calculations are performed automatically.

The costs (k€/bay/year) were extracted from (BOE, 2011).
On Table 21 the total OPEX cost of the two switchgears implemented in the project study case are calculated:

2. Switchgear OPEX calculation: fill in the cost/bay and the price per type of swgr will be calculated				
Switchgear type	Price (keuro/bay/year)	N° of swgr	N° of bays	Total cost (keuros)
Switchgear at 66 kV	17.00	3.00	5.00	255.00
Switchgear at 220 kV	43.00	1.00	5.00	215.00

Table 21: OPEX switchgear total cost/voltage level. Source: Self-elaboration.

5.3. As a final step in the OPEX excel sheet, the OPEX calculation of the transformers is performed.

5.3.1. Since there is only one transformer type, the calculation is performed using the only input of the (k€/MVA/year) OPEX cost of the transformer to be used. After this input indicated the total price in k€/year is calculated.

The price (k€/MVA) was derived from (BOE, 2011).

In Table 22 the total CAPEX cost of the transformer implemented in the project study case is calculated.

3. Transformer price calculation: fill in the price/ MVA and the transformer price is calculated				
Transformer	**Price (keuro/MVA/year)**	**N° of transform**	**MVA**	**Total price (keuros)**
Type 1	0.25	3.00	270.00	199.26

Table 22: OPEX transformer total cost/transformer rating Source: Self-elaboration.

4.4 FINAL RESULTS

To have a better overview of the total CAPEX and OPEX costs of the installation, Table 23 shows a summary. Capex cost account for around 146 M€ in total and OPEX cost account for approximately 11 M€ per year. These values include the cost of electrical components in the plant (cables, switchgears and transformers); the cost of the wind turbines or the structural cost and foundations present in the offshore substation are not taken into account.

FINAL COSTS		
	CAPEX (k€)	OPEX (k€/year)
Cables	109’052.85	10’566.74
Switchgear	26’000.00	470.00
Transformer	11’340.00	199.26
TOTAL	**146’392.85**	**11’236.00**
TOTAL CAPEX+OPEX (M€)	**157.63**	

Table 23: Final CAPEX and OPEX costs. Source: Self-elaboration.

5 POWER LOSSES CALCULATION

In this section, a calculation of power losses in cables is presented, highlighting a crucial factor in determining the energy costs of offshore wind turbine power plants. The power loss in cables significantly impacts the overall efficiency and economic feasibility of these energy systems.

In real life projects the power loss percentage over the total power generated is used to perform a more accurate Leverage Cost of Energy Analysis, however in this project this value is calculated to ensure it is constrained to reasonable percentages in these types of projects.

This calculation offers a reasonably accurate estimate as it is based on the Weibull distribution curve, which represents the percentage of time that various wind speeds occur throughout the year. Additionally, the calculations incorporate a power curve graph that indicates the output power of the turbines at different wind speeds. Following this, the initial data used for these calculations and the methodology applied to determine the power losses is outlined.

This tool is closely linked to the previously presented section 66 kV Evacuation Network and utilizes the data obtained from it. First, the cable electrical and mechanical properties obtained in section 9.1 are retrieved.

For each section, the accumulated number of turbines is indicated according to the following formula:

$$N° \, accumulated \, turbines = \frac{Total \, power \, transported \, by \, section}{Power \, supplied \, by \, 1 \, turbine} \tag{38}$$

Additionally, the total transmission distance and the cable radius is calculated using the following formula:

$$R_{cable} = \sqrt{D(mm^2)/\pi} \tag{39}$$

The formula for calculating the losses is based on the study (X. Xiang, 2017) conducted to differentiate the methods of transmitting the generated electrical energy (HVAC, HVDC, LFAC). The formula, adapted from this study, is as follows:

$$\begin{aligned} Power_{losses}(W) \\ = 3 * \left(\frac{n°_{turnines} * Power_{displayed}(W) * \text{ƅ}offt}{n°_{cables} * \sqrt{3} * Vn\,(V)}\right) * R_{cable} \\ * Transmission \, distance * n°_{cables} * Delta \end{aligned} \tag{40}$$

The fixed parameters and their explanation are the following:

-V_n: Nominal voltage at which the cable is installed, 66 kV for the study case proposed.

- ƅofft: efficiency of HVAC offshore transformers, it is fixed to 0.994 according to the study followed.

-Delta: loss load factor, it is fixed to 0.5. This is an experimental factor.

The only missing parameter to perform the loss calculation for each cable section is the power displayed. As mentioned before, this power depends on the wind speed. The wind speed is given by a Weibull distribution. On the x-axis the different wind speeds (from 0 to 30 km/h), and on the y-axis the percentage of time that these wind speeds are present on the geographical area analyzed (in this case in the North Sea). This is shown in Figure 27:

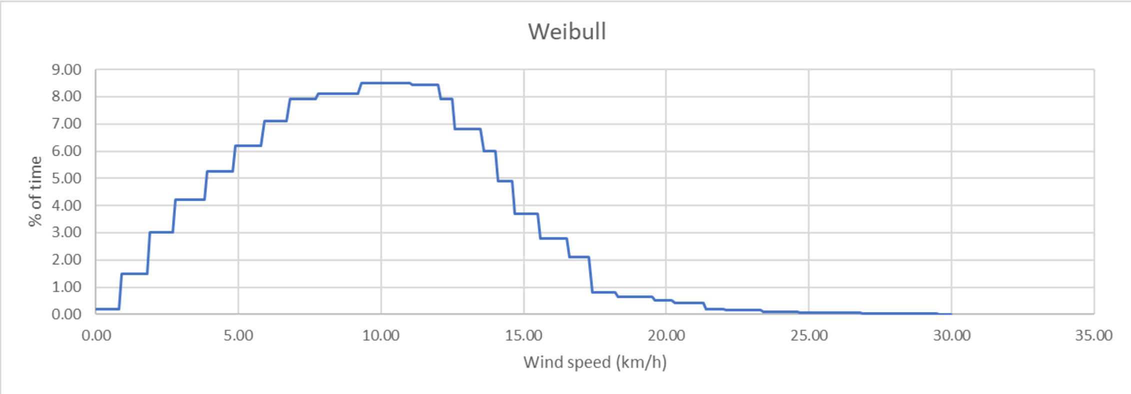

Figure 27: Weibull's distribution for different wind speeds. Source: Self-Elaboration.

The power displayed by the wind turbines depending on the wind speed is shown in Figure 28.

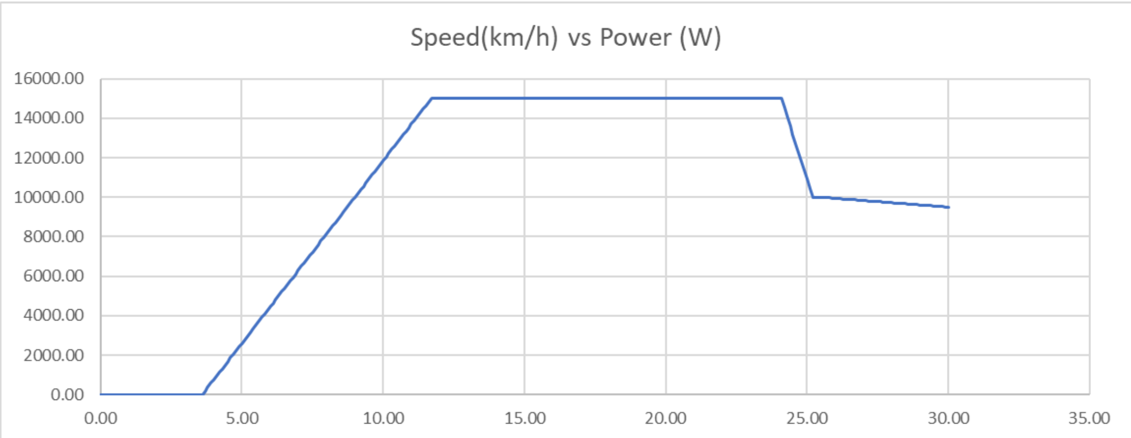

Figure 28: Power displayed by wind turbines. Source: Self-Elaboration.

To perform the power loss calculation with the highest possible accuracy, wind speeds are indicated from 0 to 30 km/h in increments of 0.1 km/h. Each of these wind speeds is assigned the probability of occurring in a year according to the previously presented Weibull distribution as shown in the "% time in a year" column of Table 24.

To refine the calculation, an adjustment is made to the percentage of time each wind speed occurs ("density corrected %" column). Since the data was extracted from a continuous instead of discrete graph, the sum of the percentages was not exactly 100%. Therefore, the necessary adjustment is made as follows:

$$\%time_{wind\ speed}corrected = \frac{\%time_{wind\ speed}}{\sum \%time_{wind\ speed}} \tag{41}$$

Then, the power that the turbine can supply at each wind speed is assigned ("Power displayed (W)" column). Using this information and following equation (40), the losses in each cable section for each wind speed are calculated.

Additionally, since the percentages are stepwise as shown in Table 24, the cable losses for wind speeds sharing the same percentage of occurrence are averaged ("power loss" column). The goal is to obtain the total losses across the entire cable system of the 66 kV evacuation network for each wind speed (grouped by the percentage of occurrence of that wind speed throughout the year). All these losses are added and compared with the total power generated by the entire wind farm for each wind speed (grouped by the percentage of occurrence of that wind speed throughout the year).

Wind speed (km/h)	% time in a year	% density corrected	Power displayed (W)	losses of cable 1-2 (W)	losses of cable 2-3	…	losses of cable 48-49 (W)	losses of cable 49-50 (W)	losses of cable 50-SS (W)	TOTAL LOSS PER WIND SPEED (W)	POWER_LOSS / % density	TOTAL POWER (W)
0.00	0.20	0.00	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
0.10	0.20	0.00	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
0.20	0.20	0.00	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
0.30	0.20	0.00	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
0.40	0.20	0.00	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00	0.00	0.00
0.50	0.20	0.00	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
0.60	0.20	0.00	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
0.70	0.20	0.00	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
0.80	0.20	0.00	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
0.90	1.50	0.02	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
1.00	1.50	0.02	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
1.10	1.50	0.02	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
1.20	1.50	0.02	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
1.30	1.50	0.02	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00	0.00	0.00
1.40	1.50	0.02	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
1.50	1.50	0.02	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
1.60	1.50	0.02	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
1.70	1.50	0.02	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
1.80	1.50	0.02	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
1.90	3.00	0.03	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
2.00	3.00	0.03	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
2.10	3.00	0.03	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
2.20	3.00	0.03	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
2.30	3.00	0.03	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00	0.00	0.00
2.40	3.00	0.03	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
2.50	3.00	0.03	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
2.60	3.00	0.03	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
2.70	3.00	0.03	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
2.80	4.20	0.04	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
2.90	4.20	0.04	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
3.00	4.20	0.04	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
3.10	4.20	0.04	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
3.20	4.20	0.04	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
3.30	4.20	0.04	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00	0.08	2.39
3.40	4.20	0.04	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
3.50	4.20	0.04	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
3.60	4.20	0.04	0.00	0.00	0.00	…	0.00	0.00	0.00	0.00		
3.70	4.20	0.04	185.23	0.04	0.07	…	0.14	0.24	0.14	6.33		
3.80	4.20	0.04	370.42	0.08	0.13	…	0.28	0.47	0.28	12.66		
3.90	5.25	0.05	555.61	0.12	0.20	…	0.41	0.71	0.42	19.00		
4.00	5.25	0.05	740.80	0.16	0.26	…	0.55	0.94	0.56	25.33		
4.10	5.25	0.05	925.99	0.20	0.33	…	0.69	1.18	0.70	31.66		
4.20	5.25	0.05	1111.18	0.24	0.39	…	0.83	1.41	0.83	37.99		
4.30	5.25	0.05	1296.37	0.28	0.46	…	0.96	1.65	0.97	44.32	2.84	83.06
4.40	5.25	0.05	1481.56	0.32	0.52	…	1.10	1.88	1.11	50.65		
4.50	5.25	0.05	1666.75	0.36	0.59	…	1.24	2.12	1.25	56.99		
4.60	5.25	0.05	1851.94	0.40	0.65	…	1.38	2.36	1.39	63.32		
4.70	5.25	0.05	2037.13	0.44	0.72	…	1.52	2.59	1.53	69.65		
4.80	5.25	0.05	2222.32	0.48	0.78	…	1.65	2.83	1.67	75.98		
…	…	…	…	…	…	…	…	…	…	…	…	…

24.70	0.06	0.00	12273.15	2.63	4.32	...	9.14	15.61	9.21	419.61	0.23	6.61
24.80	0.06	0.00	11818.60	2.53	4.16	...	8.80	15.04	8.87	404.07		
24.90	0.06	0.00	11364.05	2.44	4.00	...	8.46	14.46	8.53	388.53		
25.00	0.06	0.00	10909.50	2.34	3.84	...	8.12	13.88	8.19	372.99		
25.10	0.06	0.00	10454.95	2.24	3.68	...	7.78	13.30	7.85	357.45		
25.20	0.06	0.00	10000.40	2.14	3.52	...	7.44	12.72	7.51	341.91		
25.30	0.06	0.00	10000.00	2.14	3.52	...	7.44	12.72	7.51	341.89		
25.40	0.06	0.00	10000.00	2.14	3.52	...	7.44	12.72	7.51	341.89		
25.50	0.06	0.00	10000.00	2.14	3.52	...	7.44	12.72	7.51	341.89		
25.60	0.06	0.00	9988.58	2.14	3.51	...	7.43	12.71	7.50	341.50		
25.70	0.06	0.00	9977.47	2.14	3.51	...	7.43	12.69	7.49	341.12		
25.80	0.06	0.00	9966.36	2.14	3.51	...	7.42	12.68	7.48	340.74		
25.90	0.06	0.00	9955.25	2.14	3.50	...	7.41	12.67	7.47	340.36		
26.00	0.06	0.00	9944.14	2.13	3.50	...	7.40	12.65	7.47	339.98		
26.10	0.06	0.00	9933.03	2.13	3.50	...	7.39	12.64	7.46	339.60		
26.20	0.06	0.00	9921.92	2.13	3.49	...	7.39	12.62	7.45	339.22		
26.30	0.06	0.00	9910.81	2.13	3.49	...	7.38	12.61	7.44	338.84		
26.40	0.06	0.00	9899.70	2.12	3.48	...	7.37	12.59	7.43	338.46		
26.50	0.06	0.00	9888.59	2.12	3.48	...	7.36	12.58	7.42	338.08		
26.60	0.06	0.00	9877.47	2.12	3.48	...	7.35	12.57	7.42	337.70		
26.70	0.06	0.00	9866.36	2.12	3.47	...	7.34	12.55	7.41	337.32		
26.80	0.06	0.00	9855.25	2.11	3.47	...	7.34	12.54	7.40	336.94		
26.90	0.04	0.00	9844.14	2.11	3.46	...	7.33	12.52	7.39	336.57	0.14	4.23
27.00	0.04	0.00	9833.03	2.11	3.46	...	7.32	12.51	7.38	336.19		
27.10	0.04	0.00	9821.92	2.11	3.46	...	7.31	12.50	7.37	335.81		
27.20	0.04	0.00	9810.81	2.10	3.45	...	7.30	12.48	7.37	335.43		
27.30	0.04	0.00	9799.70	2.10	3.45	...	7.29	12.47	7.36	335.05		
27.40	0.04	0.00	9788.59	2.10	3.44	...	7.29	12.45	7.35	334.67		
27.50	0.04	0.00	9777.48	2.10	3.44	...	7.28	12.44	7.34	334.29		
27.60	0.04	0.00	9766.36	2.09	3.44	...	7.27	12.42	7.33	333.91		
27.70	0.04	0.00	9755.25	2.09	3.43	...	7.26	12.41	7.32	333.53		
27.80	0.04	0.00	9744.14	2.09	3.43	...	7.25	12.40	7.32	333.15		
27.90	0.04	0.00	9733.03	2.09	3.42	...	7.24	12.38	7.31	332.77		
28.00	0.04	0.00	9721.92	2.09	3.42	...	7.24	12.37	7.30	332.39		
28.10	0.04	0.00	9710.81	2.08	3.42	...	7.23	12.35	7.29	332.01		
28.20	0.04	0.00	9699.70	2.08	3.41	...	7.22	12.34	7.28	331.63		
28.30	0.04	0.00	9688.59	2.08	3.41	...	7.21	12.33	7.27	331.25		
28.40	0.04	0.00	9677.48	2.08	3.41	...	7.20	12.31	7.27	330.87		
28.50	0.04	0.00	9666.37	2.07	3.40	...	7.20	12.30	7.26	330.49		
28.60	0.04	0.00	9655.25	2.07	3.40	...	7.19	12.28	7.25	330.11		
28.70	0.02	0.00	9644.14	2.07	3.39	...	7.18	12.27	7.24	329.73	0.09	2.53
28.80	0.02	0.00	9633.03	2.07	3.39	...	7.17	12.26	7.23	329.35		
28.90	0.02	0.00	9621.92	2.06	3.39	...	7.16	12.24	7.22	328.97		
29.00	0.02	0.00	9610.81	2.06	3.38	...	7.15	12.23	7.22	328.59		
29.10	0.02	0.00	9599.70	2.06	3.38	...	7.15	12.21	7.21	328.21		
29.20	0.02	0.00	9588.59	2.06	3.37	...	7.14	12.20	7.20	327.83		
29.30	0.02	0.00	9577.48	2.05	3.37	...	7.13	12.18	7.19	327.45		
29.40	0.02	0.00	9566.37	2.05	3.37	...	7.12	12.17	7.18	327.07		
29.50	0.02	0.00	9555.26	2.05	3.36	...	7.11	12.16	7.17	326.69		
29.60	0.01	0.00	9544.14	2.05	3.36	...	7.10	12.14	7.17	326.31	0.04	1.22
29.70	0.01	0.00	9533.03	2.04	3.35	...	7.10	12.13	7.16	325.93		
29.80	0.01	0.00	9521.92	2.04	3.35	...	7.09	12.11	7.15	325.55		
29.90	0.01	0.00	9510.81	2.04	3.35	...	7.08	12.10	7.14	325.17		
30.00	0.01	0.00	9499.70	2.04	3.34	...	7.07	12.09	7.13	324.79		
TOTAL (W)											390.24	10360.82
%Power losses over Total losses											3.77	

*Table 24: Loss calculation tool. *The dashed rows and columns refer to the omitted datapoints. Source: Self-Elaboration.*

With this approach, the result of the comparison shows that losses account for 3.76% of the generated power in this study.

6 CONCLUSIONS

This project has as the main objective the design, sizing, and economic impact calculation of an offshore wind power plant with specific characteristics: located in the northern sea, consisting of 50 wind turbines, each supplying 15 MW of power. The voltage levels were set at 66 kV at the wind turbine level and 220 kV at the shore level.

1. A calculation of the main electrical components of an offshore wind power plant, including substations, cables (developed using an Excel tool), transformers, and a detailed description of the installation method.

2. An Excel calculation tool with two main functions:

    - Electrical Design: This part of the tool is capable of designing the electrical elements such as substations, cables, transformers, and switchgears, as well as the distribution and grouping of turbines with minimal input information. The tool meets this objective by considering inputs such as:

        - Voltages at the wind turbine level and secondary transformer level.
        - Power factor.
        - Number of turbines and their power output.
        - Cable cross-sections and rated current according to catalog.
        - Nominal currents of the switchgears.
        - Basic dimensions of the plant (width and length, and the offshore substation).
        - Temperature factors, resistivity, and cable depth.

    - Cost Calculation: This part of the tool aims to determine the CAPEX and OPEX of the electrical components of the offshore project. This goal has been achieved by inputting costs (CAPEX or OPEX) per kilometer for cables, per MVA for transformers, and per bay for switchgears, resulting in the total CAPEX and OPEX. It can be observed that by easily and intuitively changing these cost inputs, new values can be obtained, which is a significant advantage as they can be kept updated with current market prices.

3. This tool provides a straightforward and intuitive, step-by-step method to obtain crucial data at the main stages of a project. Additionally, the tool was requested to be developed in English to ensure its usability in future real-world projects by the thesis supervisor. Consequently, both the tool and the report were produced in English.

4. An additional calculation includes a detailed estimation of cable losses, which helps understand their impact on the LCOE (Levelized Cost of Energy). Using the Weibull distribution and wind power curve, the losses are estimated to be 3.7% in the 66 kV evacuation network, a realistic figure based on measurements from actual projects.

Additionally, this project demonstrates that conducting such a pre-calculation is crucial for identifying potential challenges and optimizing the design and financial planning of offshore wind projects. It ensures that projects are both technically feasible and economically viable, contributing to the advancement of sustainable energy solutions.

For me, this project has significantly expanded my knowledge of this type of energy production and introduced me to the design and sizing of electrical components applicable to all types of installations. Moreover, it provides an understanding of the investment and operation and maintenance costs of these plants, which are substantial. I believe this experience has been highly beneficial and will be of great use for future real-world projects, as well as enhancing my knowledge of electrical components for my professional career.

Note: (Open AI, 2024) was used to improve the writing and the language use in this thesis.

7 ALIGNMENT WITH SUSTAINABLE DEVELOPMENT GOALS

Below is a description of which sustainable development goals this project aligns with, along with a brief explanation of the reasons (United Nations, 2022):

1. End of Poverty: The energy poverty is one form in which poverty can be experienced. The installation of wind parks (in this case, offshore) can help generate electricity at lower costs, thus reducing the financial burden. Additionally, it entails significant job growth in coastal areas, providing additional income to economically challenged communities. Moreover, it signifies regional economic development as these installations may necessitate the use of previously nonexistent infrastructures and services. Finally, such projects can contribute to ending poverty through lease agreements or royalties for the use of land and coastal waters.

2. Affordable and Clean Energy: This objective is clearly achieved. Energy produced in offshore wind parks comes from the kinetic energy of the wind, reducing dependence on fossil fuels. Furthermore, by using renewable sources, greenhouse gas emissions are reduced, and air quality is improved. It also promotes affordable energy by ensuring communities have access to energy without incurring excessive costs.

3. Industry, Innovation, and Infrastructure: As a large-scale engineering project and a form of energy production still in development, this project significantly contributes to innovation. For instance, the design of wind turbines, underwater energy transmission, and anchoring systems still present technological challenges. Additionally, it undoubtedly creates numerous jobs at the installation site and provides economic stimulus to the area. Lastly, in line with this objective, technical and engineering capabilities are developed, promoting the training of professionals in the field of infrastructure.

4. Sustainable Cities and Communities: Offshore wind parks generate electricity without burning fossil fuels, reducing local pollutant emissions and improving air quality in nearby urban areas, thereby decreasing health risks associated with air pollution. Moreover, it reduces the carbon footprint in urban areas and mitigates climate change, which currently poses a significant risk to urban areas due to increasing occurrences of floods and extreme weather events.

5. Climate Action: Generating energy from renewable sources such as offshore wind contributes to mitigating climate change by reducing greenhouse gas emissions. This is crucial to limit the rise in global temperature and its adverse effects on climate and the environment. Additionally, promoting renewable energy like offshore wind increases public awareness of the importance of taking action against climate change and encourages the adoption of more sustainable practices in society.

6. Life on Land and Below Water: Despite the construction of infrastructure in the sea and laying cables, offshore wind parks undergo environmental assessments and implement measures to minimize impact on marine life during the planning and construction phases. These efforts help protect marine and terrestrial ecosystems. Furthermore, energy generation in this way prevents the expansion of other forms of generation that can have a significant impact on terrestrial habitats and biodiversity in the area.

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9 ANNEX

9.1 CABLE CALCULATION

The cable sizing calculation shown in Figure 15 is performed using an Excel tool.

As shown in Table 25 the first column lists all the generators present in the plant. The column “cable section” shows the different cables connecting the turbines or linking the last turbine in the circuit to the substation (highlighted in light orange). Using the plant’s geometric layout data and the characteristics of the terrain, the vertical distance from the bottom of the turbine to the seabed (water depth) and the horizontal distance between turbines (horizontal distance) are specified. These inputs are used to calculate the total length of each cable section (column “total cable distance (km)”).

Next, the power transmitted by each cable is calculated as the multiplication of power generated by one turbine by the number of turbines that feed into that cable section (for each circuit). Finally, the current carried by each cable section is calculated using equation (2) and is corrected using equation (3) by the correction factors explained in section 3.2.

Finally, the calculated current for each cable segment is compared with the catalogue’s (ABB, 2021) rated current (Figure 10) from the three cable sections chosen for the project (185, 400 & 630 mm^2). For each cable segment one of the three cables sections is selected, taking into account a security factor of 1.05. Although the catalog offers 11 different cable sections, only 3 of them are used to minimize project costs.

Next, the cable sections of the evacuation network at 220 kV are calculated using the same procedure. This is shown in Table 26. With the use of (Qifan, 2022) catalogue, and the decision to opt for 2 cables instead of 1 for the 220 kV evacuation network, the 1000 mm^2 is chosen.

Generator	Water depth	Cable Section	Vertical distance (km)	Horizontal distance (km)	Total cable distance (km)	Power (MW)	Current (A)	Current after factors (A)	Nominal Section (mm^2)
1	39	1-2	70	2’071	2’143	15	138.12	117.2401894	185
2	31	2-3	62	1’694	1’758	30	276.24	234.4803787	185
3	31	3-4	62	1’691	1’755	45	414.37	351.7205681	185
4	31	4-5	63	1’797	1’862	60	552.49	468.9607574	400
5	32	5-SS	66	2’449	2’517	75	690.61	586.2009468	630
6	33	6-7	65	2’647	2’714	15	138.12	117.2401894	185
7	32	7-8	64	1’695	1’761	30	276.24	234.4803787	185
8	32	8-9	65	2’379	2’446	45	414.37	351.7205681	185
9	33	9-SS	67	711	780	60	552.49	468.9607574	400
10	34	10-11	68	1’695	1’765	15	138.12	117.2401894	185
11	34	11-12	67	2’033	2’102	30	276.24	234.4803787	185
12	33	12-13	66	1’691	1’759	45	414.37	351.7205681	185
13	33	13-SS	67	2’214	2’283	60	552.49	468.9607574	400
14	35	14-15	70	1’692	1’764	15	138.12	117.2401894	185
15	35	15-16	69	2’999	3’070	30	276.24	234.4803787	185
16	34	16-17	68	1’691	1’761	45	414.37	351.7205681	185
17	34	17-SS	68	1’451	1’521	60	552.49	468.9607574	400
18	37	18-19	74	1’694	1’770	15	138.12	117.2401894	185
19	37	19-20	72	2’750	2’824	30	276.24	234.4803787	185
20	35	20-21	70	1’690	1’762	45	414.37	351.7205681	185
21	35	21-SS	69	3’336	3’407	60	552.49	468.9607574	400
22	42	22-23	85	1’500	1’587	15	138.12	117.2401894	185
23	43	23-24	86	1’691	1’779	30	276.24	234.4803787	185
24	43	24-25	86	1’692	1’780	45	414.37	351.7205681	185
25	43	25-26	84	2’259	2’345	60	552.49	468.9607574	400
26	41	26-SS	75	2’679	2’756	75	690.61	586.2009468	630
27	31	27-28	62	1’691	1’755	15	138.12	117.2401894	185
28	31	28-29	62	1’690	1’754	30	276.24	234.4803787	185
29	31	29-30	62	1’691	1’755	45	414.37	351.7205681	185
30	31	30-SS	65	4’264	4’331	60	552.49	468.9607574	400
31	32	31-32	64	1’690	1’756	15	138.12	117.2401894	185
32	32	32-33	64	1’690	1’756	30	276.24	234.4803787	185
33	32	33-34	64	1’690	1’756	45	414.37	351.7205681	185
34	32	34-SS	66	2’542	2’610	60	552.49	468.9607574	400
35	38	35-36	71	2’080	2’153	15	138.12	117.2401894	185
36	33	36-37	66	1’691	1’759	30	276.24	234.4803787	185
37	33	37-38	66	1’691	1’759	45	414.37	351.7205681	185
38	33	38-SS	67	761	830	60	552.49	468.9607574	400
39	44	39-40	78	1’482	1’562	15	138.12	117.2401894	185
40	34	40-41	68	1’691	1’761	30	276.24	234.4803787	185
41	34	41-42	68	1’691	1’761	45	414.37	351.7205681	185
42	34	42-SS	68	1’791	1’861	60	552.49	468.9607574	400
43	40	43-44	80	1’690	1’772	15	138.12	117.2401894	185
44	40	44-45	80	1’690	1’772	30	276.24	234.4803787	185
45	40	45-SS	74	3’834	3’910	45	414.37	351.7205681	185
46	43	46-47	86	1’691	1’779	15	138.12	117.2401894	185
47	43	47-48	86	1’691	1’779	30	276.24	234.4803787	185
48	43	48-49	83	2’394	2’479	45	414.37	351.7205681	185
49	40	49-50	74	2’085	2’161	60	552.49	468.9607574	400
50	34	50-SS	68	743	813	75	690.61	586.2009468	630

Table 25: 66 kV evacuation network cable sizing tool. Source: Self-Elaboration.

Source	Water depth	Cable Section	Vertical distance (km)	Horizontal distance (km)	Total cable distance (km)	Power (MW)	Current (A)	Current after factors (A)	Nominal Section (mm^2)
SS	34	SS-GROUND	54	27’634	27’690	750	2071.83	1954.003156	2x1000

Table 26: 220 kV evacuation network cable sizing tool. Self-Elaboration.