Master's Degree in Industrial Engineering

Master's Thesis

Tool Development for Preliminary Technical and Economical Analysis in Subsea Projects

Author
María Esperanza Navarro Torrens

Supervised by
Julio Rafael Portillo García

Madrid
August 2024

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Tool Development for Preliminary Technical and Economical Analysis in Subsea Projects

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el curso académico 2023/2024 es de mi autoría, original e inédito y no ha sido presentado con anterioridad a otros efectos. El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido tomada de otros documentos está debidamente referenciada.

Fdo.: María Esperanza Navarro Torrens Fecha: 26 / 08 / 2024

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

PORTILLO GARCIA JULIO RAFAEL - 51650551A

Digitally signed by PORTILLO GARCIA JULIO RAFAEL - 51650551A
Date: 2024.08.29 11:09:16 +05'30'

Fdo.: Julio Rafael Portillo García Fecha: 26 / 08 / 2024

Master's Degree in Industrial Engineering

Master's Thesis

Tool Development for Preliminary Technical and Economical Analysis in Subsea Projects

Author
María Esperanza Navarro Torrens

Supervised by
Julio Rafael Portillo García

Madrid
August 2024

DESARROLLO DE HERRAMIENTA PARA EL ANÁLISIS TÉCNICO Y ECONÓMICO PRELIMINAR DE PROYECTOS OFFSHORE

Autor: Navarro Torrens, María Esperanza
Director: Portillo García, Julio Rafael
Entidad Colaboradora: ICAI – Universidad Pontificia Comillas

RESUMEN DEL PROYECTO

Este Trabajo de Fin de Máster presenta una herramienta innovadora para facilitar el análisis preliminar de proyectos offshore ante la falta de datos actualizados que enfrenta el sector. Entre sus funcionalidades, incluye el diseño preliminar de las instalaciones, la estimación del CAPEX y el OPEX, y una aproximación de las pérdidas de la instalación y sus costes asociados.

Palabras clave: Submarino, offshore, herramienta, costes, pérdidas, generación eólica offshore.

1. Introducción

El desarrollo de proyectos de infraestructuras de transporte de energía eléctrica offshore se enfrenta actualmente a la falta de datos y herramientas adecuadas para la estimación de resultados. Este problema se debe a la escasez en el mercado de cables submarinos, cuya demanda ha crecido notablemente a causa de la transición energética global, sin que este aumento haya sido acompañado por una expansión equivalente en la capacidad de fabricación. Esta discrepancia ha llevado a que los fabricantes enfrenten dificultades para satisfacer la demanda y sean reticentes a proporcionar costes de referencia, temiendo que esto pueda afectar negativamente a sus intereses comerciales futuros.

La falta de datos fiables y la incertidumbre en los costes complican en gran medida los esfuerzos de los desarrolladores de proyectos, quienes se enfrentan a importantes retos al realizar análisis en las etapas iniciales de proyectos offshore.

2. Definición del proyecto

Con el fin de abordar la cuestión descrita, este Trabajo de Fin de Máster presenta una herramienta innovadora diseñada para facilitar el análisis preliminar de proyectos offshore tipo HVDC-VSC. La herramienta incluye el diseño preliminar de las instalaciones, la estimación del CAPEX y el OPEX, y una aproximación de las pérdidas de la instalación y sus costes asociados.

El proyecto está organizado como se ilustra en la Figura 1. Comienza con una introducción que aborda el contexto y la motivación del proyecto, así como los objetivos y la metodología. A continuación, se presenta un estudio del estado del arte que cubre los principales aspectos técnicos y económicos del tema. Luego, se presenta la nueva herramienta y su aplicación en un caso de estudio propuesto. El proyecto finaliza con las conclusiones.

Figura 1: *Arquitectura del Trabajo de Fin de Máster.*

3. Descripción de la Herramienta

La herramienta está recogida en un archive de Excel que cuenta con cinco pestañas diferentes. Así, mientras la primera pestaña y la última recogen los datos de entrada y los resultados, respectivamente, las tres pestañas intermedias corresponden a las funcionalidades de la herramienta: diseño preliminar, estimación de costes y aproximación de pérdidas.

Cada una de las funcionalidades de la herramienta incluye modelos de aproximación que toman los datos introducidos y otros parámetros incluidos por defecto para dar lugar a los resultados. Estos modelos han sido obtenidos a partir de bibliografía existente y modificados en base a otra información y a la experiencia para ajustarse mejor al tipo de proyecto de interés.

4. Resultados

Teniendo en cuenta los modelos definidos y la información de referencia, se ha obtenido una herramienta Excel que permite el análisis preliminar de proyectos de transporte de energía eléctrica offshore con datos mínimos. Estas estimaciones pueden mejorarse incluyendo datos actualizados de costes en caso de contarse con ellos.

Con el fin de mostrar la validez o vigencia de las aproximaciones realizadas por los modelos calibrados, se ha comparado los resultados obtenidos con algunos datos de proyectos reales conocidos. Así, la Figura 2 muestra el error que se produce en algunos de los casos revisados.

Project	Rated Power (MW)	Voltage (kV)	Real CAPEX (M€)	Estim. CAPEX (M€)	Error (%)
Skagerrak 4	700	500	440	456	3.64%
INELFE	2000	320	700	727	3.86%
Nemo	1000	500	450	481	6.89%
Romulo	400	250	400	334	-16.50%
Ex. P-B	3000	320	1156	1004	-13.15%

Figura 2: Validez de Resultados [1].

Una vez obtenida la versión final de la herramienta, esta se implementa en un caso de estudio de interés para la industria. En este caso, se trata de una interconexión submarina entre la isla de Bornholm, Dinamarca, y el norte de Polonia.

5. Conclusiones

Tras la realización de este proyecto se ha llegado a una serie de conclusiones que quedan listadas a continuación.

- Los modelos disponibles actualmente para el análisis preliminar de proyectos offshore han mostrado carencias y desviaciones en el estudio de los proyectos desarrollados en la actualidad.
- La herramienta desarrollada ha demostrado ser eficaz en esta tarea, facilitando la toma de decisiones por parte de los desarrolladores de proyectos en etapas iniciales de los mismos.
- En caso de ser necesario, la herramienta permite introducir datos actualizados para la obtención de valores más precisos.
- La herramienta permite cambiar al usuario de forma fácil los parámetros iniciales por defecto para la obtención de resultados más precisos. Es destacable que esto lo puede hacer de forma sencilla e intuitiva, sin ser preciso conocer los modelos.

6. Referencias

[1] ENTSO-E AISBL. “Offshore transmission technology”. In: Report, November (2011).

TOOL DEVELOPMENT FOR PRELIMINARY TECHNICAL AND ECONOMICAL ANALYSIS IN SUBSEA PROJECTS

Author: Navarro Torrens, María Esperanza.
Supervisor: Portillo García, Julio Rafael.
Collaborating Entity: ICAI – Universidad Pontificia Comillas.

ABSTRACT

This Master's Thesis presents an innovative tool designed to facilitate the preliminary analysis of offshore projects in light of the lack of updated data within the sector. Among its functionalities, it includes preliminary design of the facilities, estimation of CAPEX and OPEX, and an approximation of the installation losses and associated costs.

Keywords: Subsea, offshore, tool, costs, losses, offshore wind generation.

1. Introduction

The development of offshore electric power transmission infrastructure projects is currently facing a lack of adequate data and tools for outcome estimation. This issue is attributed to a shortage in the subsea cable market, where demand has significantly increased due to the global energy transition, without a corresponding expansion in manufacturing capacity. This discrepancy has led to difficulties for manufacturers in meeting demand and a reluctance to provide reference costs, fearing potential negative impacts on their future commercial interests.

The absence of reliable data and the uncertainty surrounding costs greatly complicate the efforts of project developers, who face significant challenges when conducting analyses in the early stages of offshore projects.

2. Project Definition

To address the described issue, this Master's Thesis presents an innovative tool designed to facilitate the preliminary analysis of offshore projects. The tool includes preliminary design of the facilities, estimation of CAPEX and OPEX, and an approximation of the installation losses and their associated costs.

The project is organized as illustrated in Figure 3. It begins with an introduction that covers the context and motivation of the project, as well as its objectives and methodology. It continues with a review of the literature that covers the main technical and economic aspects of the issue. Next, the new tool is presented and implemented in a proposed case study. The project concludes with the findings and discussion.

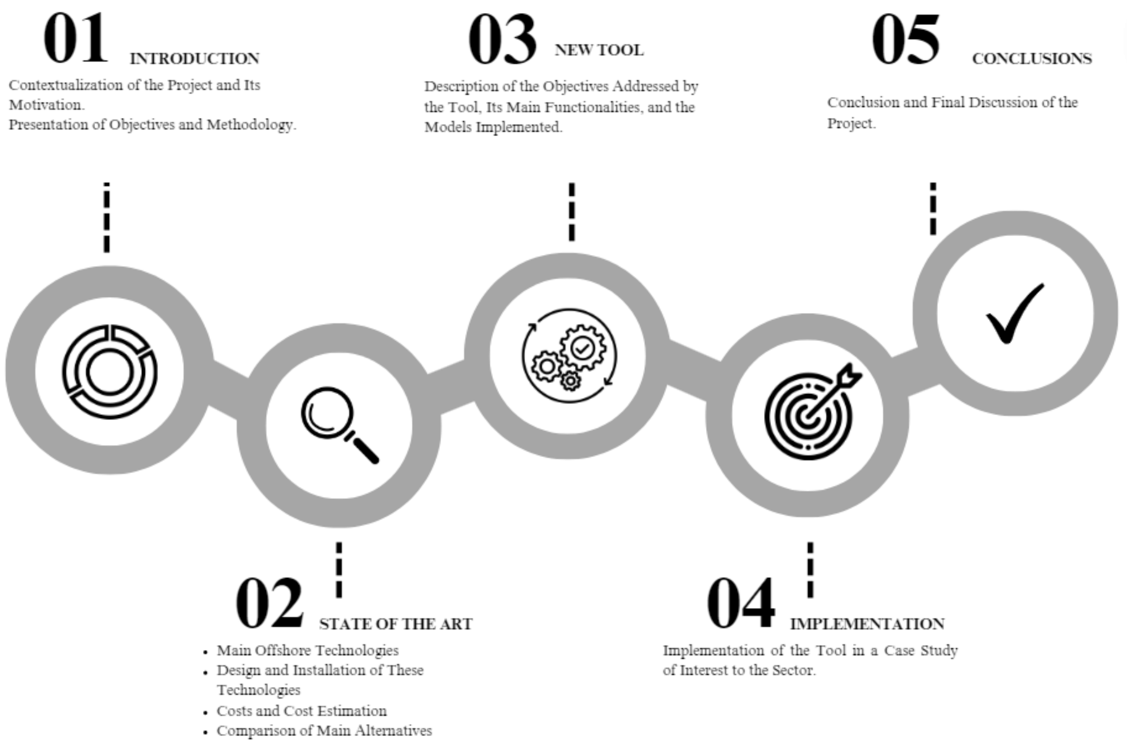

Figure 3: *Master's Thesis Architecture.*

3. Tool Description

The tool is provided in an Excel file that contains five different tabs. The first and last tabs are used for input data and results, respectively, while the three intermediate tabs correspond to the tool's functionalities: preliminary design, cost estimation, and loss approximation.

Each functionality of the tool includes approximation models that take the input data and other default parameters to generate results. These models have been derived from existing literature and modified based on additional information and experience to better fit the specific type of project of interest.

4. Resultados

Taking into account the defined models and reference information, an Excel tool has been developed that allows for the preliminary analysis of offshore electric power transmission projects with minimal data. These estimates can be improved by including updated cost data if available.

To demonstrate the validity or relevance of the approximations made by the calibrated models, the results obtained have been compared with some data from known real projects. Figure 4 shows the error observed in some of the reviewed cases.

Project	Rated Power (MW)	Voltage (kV)	Real CAPEX (M€)	Estim. CAPEX (M€)	Error (%)
Skagerrak 4	700	500	440	456	3.64%
INELFE	2000	320	700	727	3.86%
Nemo	1000	500	450	481	6.89%
Romulo	400	250	400	334	-16.50%
Ex. P-B	3000	320	1156	1004	-13.15%

Figure 4: *Validity of Results [1].*

Once the final version of the tool was obtained, it was implemented in a case study of interest to the industry. In this case, it involves an underwater interconnection between the island of Bornholm, Denmark, and northern Poland.

5. Conclusiones

After completing this project, a series of conclusions have been reached, which are listed below:

- The models currently available for the preliminary analysis of offshore projects have shown deficiencies and deviations in the study of projects developed today.
- The developed tool has proven to be effective in this task, facilitating decision-making by project developers during the early stages of their projects.
- If necessary, the tool allows for the input of updated data to obtain more accurate values.
- The tool enables users to easily modify default initial parameters to achieve more precise results. Notably, this can be done in a simple and intuitive manner, without requiring knowledge of the underlying models.

References

[1] ENTSO-E AISBL. “Offshore transmission technology”. In: Report, November (2011).

Contents

List of Figures

List of Tables

Chapter 1

Introduction

In alignment with the 2030 Agenda and the climate crisis, the increase in wind power as a key element in the shift to sustainable, low-carbon energy sources has become evident in recent years. A substantial growth in total installed wind power capacity began in 2000 and is expected to become even more pronounced in the coming years [1]. As illustrated in Figure 1.1, global projections estimate approximately 323 GW of installed wind power capacity by 2030, with an expected range between 256 GW and 397 GW [2].

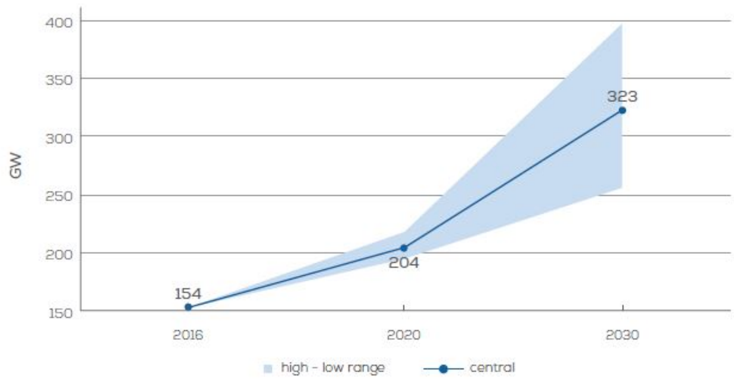

Figure 1.1: *Expected Wind Power Installed Capacity* [2].

In addition to the urgency of the energy transition, other factors must also be considered when identifying the reasons behind the widespread adoption of this technology. As one of the most crucial technologies in the decarbonization process, wind power generation has attracted significant contributions from both public and private investors. Consequently, it has evolved into a renewable energy source that has undergone thorough analysis, leading to the development of highly efficient technologies. This has facilitated key advancements, such as a substantial reduction in costs and an increase in wind turbine capacity.

Regarding the location of wind farms, it should be noted that, while onshore wind generation technology is currently more prevalent in many countries, recent trends have gradually shifted towards offshore generation. Thus, in 2011, offshore wind production accounted for approximately 2.7% of the total installed capacity, while estimates for 2020 are around 6.3% [1] [3]. Environmental concerns and the vast offshore potential are among the major driving forces for investors to explore new offshore locations [4].

Alongside the urgent decarbonization process in the electric power industry, other drivers have contributed to the surge of offshore wind generation. A prominent example in this context is the REPowerEU Plan, elaborated and published by the European Commission [5]. This document outlines the objectives and policies proposed by the European Union to address the energy crisis resulting from the Ukraine-Russia Conflict. The plan approaches the issue from four different perspectives: energy savings, diversification, substitution of fossil fuels, and intelligent investment (proposing an investment of up to 210 billion euros before 2027). Beyond presenting these objectives, the plan introduces specific technologies and areas of interest for the EU, emphasizing the significance of offshore wind generation in this scenario.

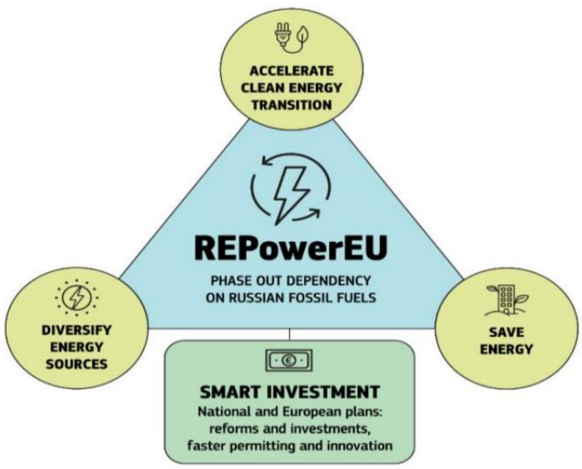

Figure 1.2: *REPowerEU Strategy* [5].

In the described context, concerning the expansion of offshore wind power, connecting facilities across the sea has become a major concern addressed by leading electrical companies worldwide. Therefore, subsea and/or offshore power transmission is required to convey larger amounts of power over greater distances and in the most economically efficient manner. This demand has driven the development of relevant technologies, with a special focus on High Voltage Direct Current (HVDC) as a solution for covering progressively longer distances.

Motivation

Although the development and expansion of offshore technologies have been significant in recent years, the available data and tools for preliminary analysis of offshore projects are quite limited. This situation stems from the scarcity in subsea cable markets that project developers are currently facing. The dramatic increase in subsea cable demand driven by the energy transition has not been matched by a corresponding expansion of manufacturing facilities. Thus, manufacturers are currently unable to satisfy the increasing demand and, as a result, are not even interested in providing reference costs that could compromise their commercial position in the future. Consequently, developers are currently facing multiple complexities in making a priori analyses of subsea projects.

In this context, this master's thesis presents a new tool designed to facilitate the preliminary analysis of offshore projects. By addressing the existing gaps in data availability and providing estimation capabilities, this tool aims to assist the decision-making process for project developers. This solution not only enhances the accuracy of initial project assessments but also contributes to the overall advancement of offshore technology implementation, supporting the broader goals of the energy transition.

Objectives

The project aims to achieve the following objectives:

- Analysis of Existing Technologies. Examining current technologies for subsea power transmission, including the identification of the most relevant technical parameters for estimating costs and losses in subsea transmission projects.

- Evaluation of Costs and Losses Estimation Tools. Assessing available tools for estimating the costs and losses of offshore power transmission projects, including a comparison among some of the most widely used models.

- Development of a New Estimation Tool. Creating a new tool specifically designed for preliminary estimating losses and costs in offshore power transmission projects, including the preliminary design of the facilities.

Methodology

The methodology followed for the completion of this master's thesis and achievement of the stated objectives is as follows:

- **Survey of the State of the Art**: Conduct a comprehensive review of the current state of offshore power links, considering both technical and economic aspects. This involves examining relevant papers, books, and available information.
- **Tool Development**: Create a new tool for losses and cost estimation based on an analysis of existing models.
- **Case Study Selection and Definition**: Choose a suitable case study that facilitates a thorough and detailed exploration of the implementation of the new tool.
- **Implementation of the Tool**: Utilize the developed tool in the selected case study.
- **Results Discussion and Conclusions**: Present final conclusions based on the findings of this master's thesis.

Structure of the Report

This document consists of five chapters, structured as follows:

Chapter 2 presents the current state of the art regarding the topic, covering both technical and economic approaches.

Chapter 3 introduces the developed tool, detailing each of its capabilities and functionalities. Its validity is demonstrated by comparing its results with real data.

Chapter 4 introduces a case study for implementing the tool. The obtained results are included.

Chapter 5 presents the conclusions of this master's thesis.

Chapter 2

State of the Art

This chapter includes a brief overview of available technologies for offshore wind-generated power connection. Thus, HVAC and HVDC technologies have been considered, along with their descriptions, level of development, and main restrictions or limitations. Additionally, other non-commercial technologies have been mentioned.

An overview of the implementation of the previously detailed technologies in subsea transmission projects is presented, highlighting the most relevant aspects of their design and installation, which are critical in determining the costs of these projects.

Additionally, the solutions are analyzed from an economic perspective. A survey of the literature on available methods for estimating interconnection costs is included.

Furthermore, a comparison of the analyzed technologies, including technical and economic considerations, is incorporated.

2.1 Main Technologies in Offshore Facilities

The significant increase in offshore wind generation implies a new need for connection infrastructures that allow the integration of the energy produced into the traditional network. Given the inherent requirement of connecting points across the sea, it introduces complexities that drive the development of technologies tailored to these specifications. Commercialized solutions typically focus on either high-voltage alternating current technology (HVAC) or high-voltage direct current technology (HVDC). However, additional alternative solutions, such as low-frequency alternating current technology (LFAC), have been proposed [6]."

2.1.1 HVAC

High-voltage alternating current technology (HVAC) is the most straightforward approach to the offshore connection problem. Power systems have traditionally been designed for alternating current (AC) use, including AC generators, loads, and transformers. Therefore, AC connections provide a direct means of integrating new elements into the grid. However, its suitability compared to other technologies is not always guaranteed, so its advantages and disadvantages must be analyzed on a case-by-case basis.

One of the main advantages of HVAC technology is the extensive experience of the electric industry in its design, installation, and use. Even in offshore transmission, there is a comprehensive precedent. Among others, numerous interconnections between different power systems have been developed, along with cables for various applications, such as in the oil industry [7].

Additionally, due to the aforementioned characteristics of the traditional design of power systems, AC installations do not require additional converters or other elements to adapt the signal to the system. They can be connected using traditional electrical devices like transformers, simplifying HVAC projects and avoiding significant terminal costs [6]. The traditional HVAC installation structure is outlined in Figure 2.1.

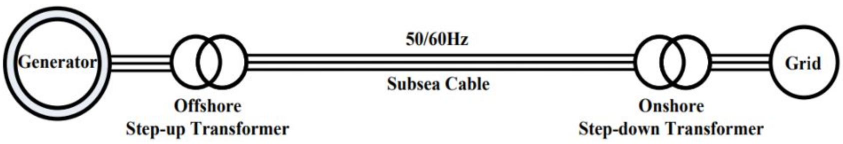

Figure 2.1: *HVAC Subsea Installation Scheme* [6].

The primary limitation in the use of AC in offshore applications is the reactive power consumption of the cable [8]. Water has a different impact on parallel capacitive susceptance than air or soil, leading to a significant increase in its value, which is directly proportional to the associated reactive power consumption [6]. This increase in reactive power has various consequences for the design of the line, including the need for a larger cable cross-section and increased power losses.

To address the resulting impact of the reactive power surge, reactive power compensation is typically recommended [9]. This involves the installation of compensation facilities at both ends of the cable. For long-distance cables, additional mid-route compensation may be necessary, but complexities can arise due to the current state of development of subsea technologies in this area [8]. Additionally, substantial terminal costs should be factored into the budget if compensation is introduced.

While increasing voltage has traditionally been the most effective way to enhance cable capacities, this approach affects the line's reactive power. Reactive power is proportional to the square of the voltage, so excessively high voltages could lead to a decrease in cable capacity. Applications such as subsea connections, where reactive power cannot be ignored, must consider this effect [9].

It's worth noting that reactive power in the line is also proportional to the total length of the cable. Consequently, in cases where the line is relatively short, its adverse effects may be negligible or at least manageable. This differentiation between short and long distances should be considered when selecting the most appropriate technology and becomes particularly relevant when comparing with other solutions [7]. Further details are provided in Section 2.4.

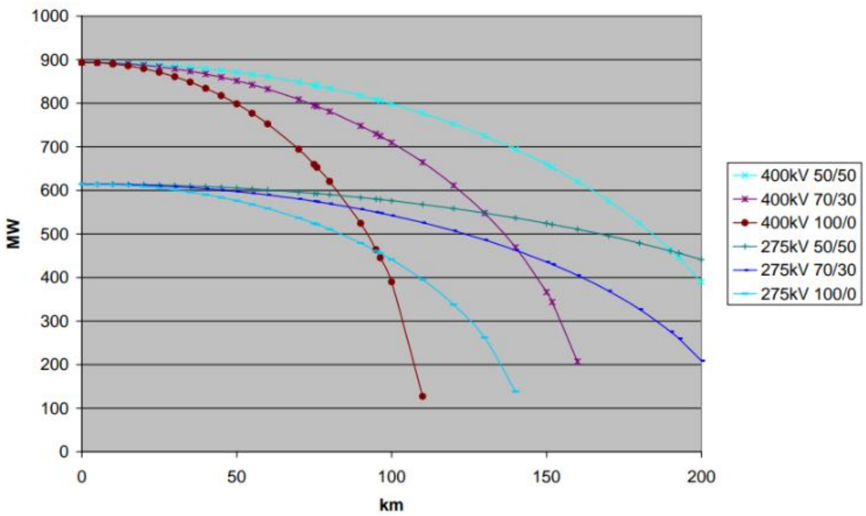

Figure 2.2: *Maximum Real Power Transfer in 275 kV and 400 kV AC cables with 100/0, 50/50 and 70/30 Reactive Power Compensation Split Between Onshore and Offshore (1000 mm^2 copper cross section* [9].

Given that multiple parameters influence the capacity of HVAC lines, several authors have studied the impact of each of them, taking into account distance issues. In this regard, Figure 2.2 provides an overview of the interaction among the considered parameters. Additionally, approximate length limits can be analyzed and compared with the desired applications.

2.1.2 HVDC

The expansion of high-voltage direct current (HVDC) technology in the recent years has been significant. Among others, its main applications include interconnection of asynchronous power systems, the connection of highly distant substations, or the subsea interconnection of isolated systems [9]. In the context of offshore applications, the integration of HVDC technology with the related challenges appears to be a natural fit.

HVDC technology is an alternative solution for offshore applications. This approach proposes the use of direct current in transmission, using converter stations that allows its connection to the AC network. Figure 2.3 illustrates the integration of these elements in the offshore interconnection scheme.

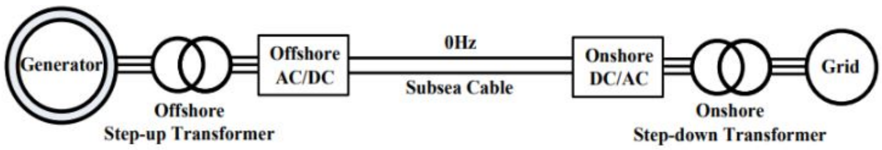

Figure 2.3: *HVDC Subsea Installation Scheme* [6].

HVDC Transmission Technology

The main advantage of direct current, and also the major driver of its development, is the absence of reactive power in the lines. This is a particularly advantageous characteristic for subsea applications.

In general, HVDC enables to reduce cable cross section due to the limitation of current to active power transmission. As mentioned, the presence of water in the surroundings of the line increases dramatically its parallel capacitive susceptance, which is directly proportional to reactive power consumption [6]. This fact may be translated into a particularly significant reduction of cable cross section if using

HVDC technology for subsea applications, along with a decrease in transmission losses, especially for high voltage applications [10].

The absence of reactive power in HVDC also permits the decoupling of active and reactive power problems on both sides of the connection. This, thanks to the electronics, allows a much more exhaustive and simple control of active power transmission [10].

HVDC also has relevant advantages for long distances, which are really common in offshore power transmission. Alternating current, among others, entails stability problems of the signal when long distances are covered. Since the DC waveform is constant, this problem would be avoided and lines, in this concern, could theoretically be infinite without dealing with this issue [6] [9].

Regarding conductors, no significant variations can be found in the typical structure of HVAC and HVDC subsea power transmission cables [9]. Nevertheless, DC cables entail smaller costs due to a less demanding manufacturing process [10].

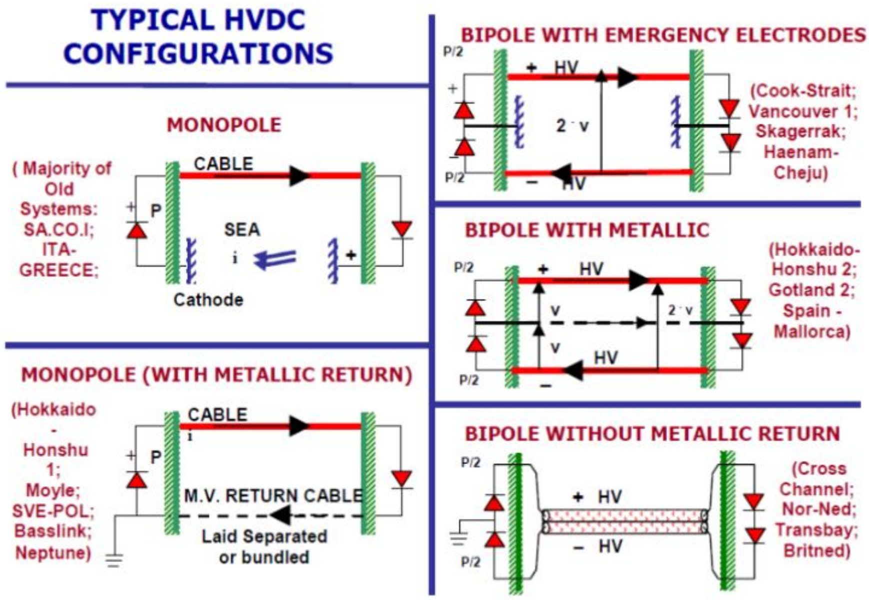

Figure 2.4: *Examples of Typical Layouts of HVDC Connections* [9].

An additional reduction in cable costs arises from the typical HVDC configurations, which require a smaller number of conductors than HVAC connections. There are two different types of HVDC configurations: monopole and bipole.

Monopole uses one single converter device at each end of the line with a cable joining them. On the other hand, bipole requires two converter devices at each end, and an additional conductor is added [7]. Figure 2.4 illustrates the most common HVDC connections layouts, evidencing this reduction.

Despite the numerous advantages of HVDC lines, new complexities inherent to its use and nature are added to its design and installation.

A significant constraint of HVDC technology is the lack of development and consequent costs of DC electrical protections. The focus of the issue is in circuit breakers. Traditionally, due to its high cost, they have been replaced by an AC circuit breaker in the AC side of the connection. However, this strategy has proved to be too slow when protecting sophisticated electronic devices, which are more vulnerable to faults than AC devices, and is not suitable for the development of multi-terminal grids [9] [11].

It is important to emphasize the significance of the development of multi-level systems in the connection of offshore wind generators. These systems have the potential to eliminate the need for converter stations at intermediate points, requiring them only at the locations where this HVDC system would be connected to the AC network. Its level of development remains insufficient for genuine global expansion [9] [11]. However, numerous research groups are working on this area and introducing new approaches such as artificial intelligence algorithms [12] [13] [14].

Converter Station Technology

The primary limitation of HVDC technology is the requirement for converter stations to connect DC links to the AC power grid, which introduces significant complexity and costs to the project. The purpose of these electronic facilities is to modify current and voltage signals to achieve the desired frequency and amplitude at each point in the connection. Two main technologies have been commercialized in this regard: current source converters (CSC) and voltage source converters (VSC) [9] [11].

Current Source Converters (CSC), also called Line Commutated Converters (LCC), was the first developed and commercialized technology in this regard. It is based on thyristors.

Thyristors are semi-conductor electronic devices that permits conduction only when it receives a gate signal and voltage between anode and cathode is positive. Groups of these devices are connected forming electrical valves, which are at the same time connected conforming, in its most modern model, twelve-pulse converters. None of the required conditions to trigger thyristors can be controlled, they depend on the state of the AC grid node where the device is connected. For this reason, this technology does not allow high controllability of the HVDC link [9].

Figure 2.5 shows the main components of a typical CSC HVDC system. As it can be observed, apart from the current source converter itself, the station traditionally includes DC filters, DC smoothing reactors, AC filters and reactive power compensation and control and communication systems [9].

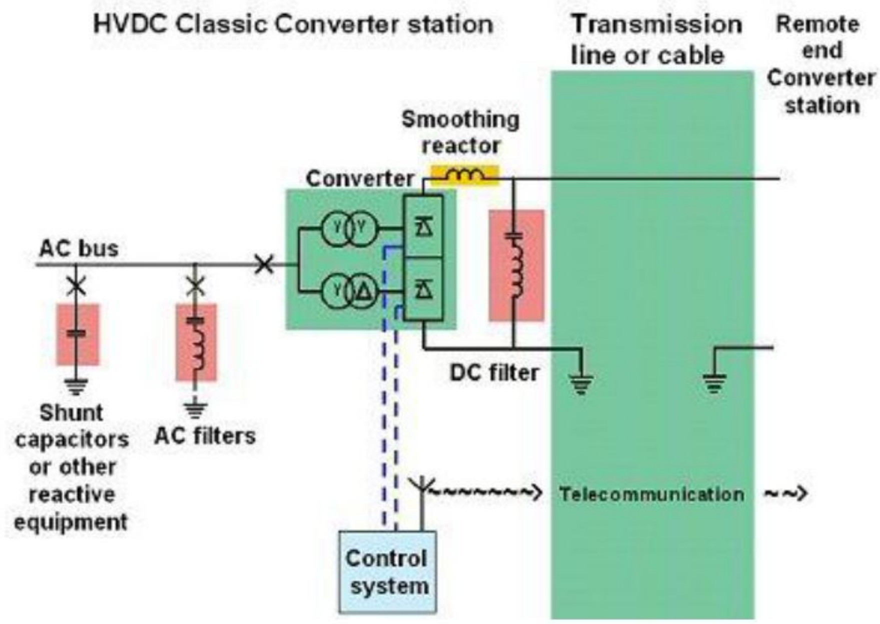

Figure 2.5: *Schematic of a Traditional CSC HVDC System* [9].

One of the main constraints of this technology is that, since thyristors are commutated according to the AC signal, it requires an strong AC grid at both sides of the connection that ensures its correct operation. The parameter that measures the strength of network is its short-circuit ratio (relation between short-circuit power to the rated power of the converter). In cases where it is slightly below the desired values, STATCOMs and other electronic devices can be included [9]. However, considering the objective of this project of connecting offshore generating units, not full grids that may be significantly stronger, this requirement may represent a constraint for using CSC technology. For this reason, other solutions may be preferred.

Voltage Source Converters (VSC) are an alternative to current source converters. Instead of using thyristor-based electronics, they propose the use of insulated-gate bipolar transistors (IGBTs), which are controllable self-commutating semiconductor switches.

IGBTs allows a full wave conversion process for the signal. The most common techniques in this regard are Pulse Width Modulation (PWM), Multi-level Converter technique or a hybrid of both. Hybrid techniques have certain technical disadvantages that must be taken into consideration, especially regarding the required insulation of connected facilities and the electrical components themselves. However, one of the most intriguing solutions for voltage source converters is the use of twelve-pulse diode rectifiers. This technology allows the compensation of 11th and 13th current harmonics, actuating as an active power filter [10]. It is remarkable that these techniques imply higher power losses in converter stations due to a higher switching frequency. Nevertheless, the better approach of these techniques in creating AC signals allows much more flexibility in its operation and, due to the reduction in the need of additional filters, a reduction in the total space that the station may require [11].

Another significant advantage of VSCs is that they allow to control active and reactive power independently. This fact eliminates the need for reactive power compensation in the link and contributes to the stability of the AC network [9].

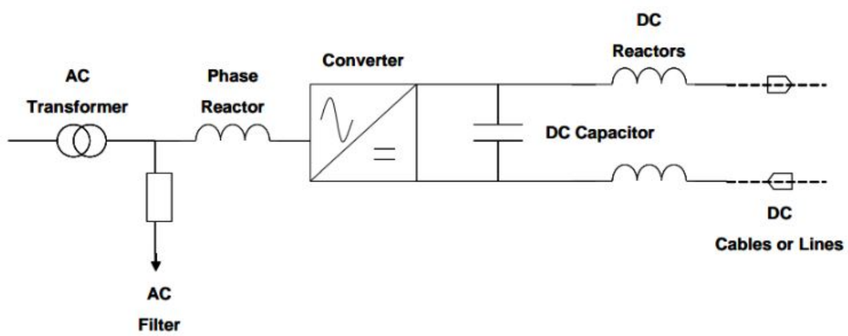

Figure 2.6: *Diagram of VSC HVDC System* [9].

Figure 2.6 shows the main components of VSC converter stations, which consist of the VSC converter itself, AC transformer and filters, phase reactor, DC capacitor and DC reactors. It is remarkable the role of the phase reactor of the station in the control of active and reactive power, as it controls the power flow between AC and DC sides of the station [9].

Voltage source converters introduce an advantageous characteristic in comparison with current source converters. As IGBTs are self-commutating, they do not depend on the AC signal that they receive from the AC side. This enables the station to be connected to any AC grid with independence of the strength in terms of short-circuit ratio, even operating in passive or isolated systems. It is remarkable that this characteristic also provides black start capability and deletes the minimum power limit that affects current source converters [9] [11]. These characteristics are specially relevant when facing the concerning offshore connection problem due to the weakness of the offshore side that, if using this technology, does not represent a constraint anymore. For this reason, voltage source converters are, nowadays, the preferred conversion technology for this application [10].

2.1.3 LFAC

In order to deal with reactive power consumption in HVAC lines and complexity in HVDC installations, the most extended and commercialized solutions, new technologies have been developed. In this context, Low-Frequency Alternating Current (LFAC) technology emerges as an alternative [15].

LFAC proposes an AC line, similar to HVAC, with lower frequency. Typically, it is reduced to one third of its standard value: 16.7 Hz for 50 Hz systems and 20 Hz for 60 Hz systems [6]. This solution is based on the assumption that turbines can adapt the generated signal to the desired frequency, eliminating the need for an AC/DC offshore converter station, and, at the same time, reducing power consumption, which is directly proportional to frequency. Figure 2.7 illustrates the variation in the typical connection infrastructures scheme with this solution.

Because of the difference between the frequency of the line and the frequency of the system to which it is connected, a new onshore AC/AC converter must be included. However, if connecting directly to offshore generators, the offshore facilities, which are the most complex, are simplified due to the flexibility of generation frequency [6] [15].

Despite the interesting approach that this technology proposes, its real applicability has not been conclusively proven. For this reason, it is not a widespread solution for real applications and will not be considered in this project.

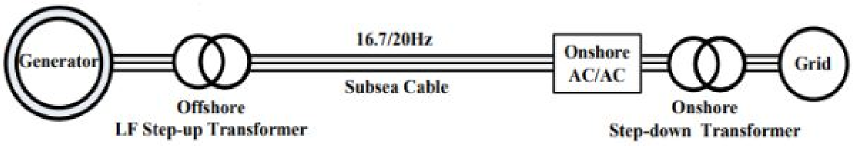

Figure 2.7: *LFAC Subsea Installation Scheme* [6].

2.2 Design and Installation of Offshore Facilities

Offshore projects aim to translate the theoretical approach of offshore transmission technologies (presented in Section 2.1) into real applications. With this objective, they conduct various procedures that shape the stages of design and installation. This section introduces the most relevant processes and properties of subsea projects that characterize these phases.

2.2.1 Design of Offshore Facilities

The design of offshore interconnection facilities comprises multiple phases. The initial stage of the project involves conducting relevant site studies, with particular emphasis on the marine survey. Subsequently, the gathered data is utilized for the design of the involved facilities. This section addresses the main aspects to be considered.

Marine Survey

Subsea projects require a comprehensive study of the entire marine area between landing points, including the seabed. This is essential to determine the best path for the link and design the best solution according to the site. Thus, a marine survey should be conducted as part of the design phase of the project.

Regarding the study of the seafloor conditions and properties, which is essential for choosing the optimal cable route, the following analyses are typically conducted [16]:

- Bathymetry analysis. It is the equivalent to a topographic study in the marine sector, including water depth and slopes in the seabed.
- Sub-bottom profiling. It offers data about the soil layers beneath the seafloor.
- Visual inspection.
- Soil sampling. It is essential for the selection of burial tools if needed, providing data about key soil characteristics, such as hardness.
- Soil and water temperature analysis. Critical for the thermal cable design.

It should be noted that the nature of the site is not the only aspect to be analyzed. Other existing obstacles and activities should be considered.

Cable Design

Numerous cable models have been developed and commercialized by main manufacturers around the world. Thus, the selection of the most adequate cable for the specific considered case is not always straightforward. In this context, there are some fundamental elements in submarine cables that define their main properties. These should be the primary focus during the cable design phase of the project.

Conductor

Conductors are the current-carrying component of the cable. In the case of subsea applications, they are mostly made of copper. Despite being more expensive than other materials, such as aluminium, copper's electrical resistivity is very low (around $0.0176\ \Omega \cdot \mathrm{mm}^2/\mathrm{m}$). This property allows smaller cross sections, entailing costs reductions not only in the conductor itself, but in other related elements of the cable [16].

Different conductors are employed based on their application. Some of the most relevant types can be listed as follows [16]:

- Solid conductor. It consists of a single massive wire. They are mostly used for low voltages and smaller cross-sectional areas.
- Conductors stranded from round wires. They are used for both AC and DC applications.
- Profiled wire conductor. It consists of cake-piece-shaped wire cross sections. They are very common in large HVDC submarine cables.

- Hollow conductors for oil-filled cable. It contains a central duct where a low-viscosity oil flows.
- Miliken conductor. It consists of subconductors which are rolled into a triangular cake-slice shape and, then, laid up into a round conductor. It can include a central duct or a central wire. It is typically used in HVAC applications.

Semiconductor Layers

Semiconductor layers in high-voltage cables control electric fields, prevent stress concentration, and ensure uniform stress distribution. They are essential for reducing the risk of partial discharge, among other functions. Typical structures include an internal semiconductor layer positioned between the conductor and insulation, along with an additional semiconductor layer applied over the insulation.

Insulation System

Insulation serves as an effective barrier within the cable, preventing contact between surfaces with a significant potential difference. Despite numerous insulation materials have been historically developed and implemented in real applications, nowadays the commercialized solutions are confined to a limited list [16].

- Cross-linked polyethylene (XLPE). This material is created by cross-linking the long molecular chains of LDPE (low-density polyethylene). It is one of the preferred insulation solutions due to its ability to withstand high temperatures without damage. Initially, it was only available for AC applications. However, new formulations have been successfully developed, enabling the production of extruded HVDC cables made of XLPE.
- Paper-insulated oil-filled cables. These cables consist of different layers of thick paper impregnated with synthetic oil. It should be noted that pressure in the oil gap needs to be maintained within a given range using feeding units at onshore stations. Thus, this imposes a restriction on the overall cable length based on the performance of that equipment. This type can be used for both AC and DC applications.
- Paper-mass insulation. Similar to the previous type, paper-mass insulation is specifically designed for DC applications where dielectric losses do not occur. Higher-density papers can be used, reducing flow resistance through

the papers. Remarkably, cables with this insulation material do not need to be pressurized; therefore, the limitation of external pressurization equipment does not apply to this type.

Water-Blocking Sheath

Water-blocking sheaths are metallic layers of the cable designed to protect it against water ingress. The most common materials for this component are lead, aluminum, or copper. However, it is common practice to combine one of these metallic sheaths with an additional polymeric sheath that provides protection against corrosion and abrasion. Additionally, it is noteworthy to carefully examine the effect of fatigue phenomena on metallic sheaths. Among causes of that fatigue are vibrations, thermal cycling, or repeating bends [16].

Armoring

Armoring is the part of the cable that establishes its main mechanical properties, providing both tensile stability and mechanical protection. It consists of metal wires wound around the cable. Thus, mechanical characterization may not only depend on the type of wires used but also on the tension and position of those wires around the cable. It is noteworthy that these properties gain significant importance in subsea applications due to the demanding cable laying process required during installation [16].

Several combinations of the mentioned elements can result in different cable models. Thus, cable design in projects may involve selecting an appropriate model considering its main characteristics, which depend directly on the described elements, and doing so in the most economically efficient way. Figure 2.8 depicts some examples of cables in the industry.

					
Cable Type No.	1	2	3	4	5
Rated voltage U_0	33 kV a.c.	150 kV a.c	420 kV a.c.	320 kV d.c.	450 kV d.c.
Insulation	XLPE, EPR	XLPE	Oil/paper or XLPE	Extruded	Mass-impregnated
Typical application	Supply of small islands, connection of offshore WTG	Connection of islands with large population, OWP export cables	Crossing of rivers/straights with large transmission capacity	Long-distance connections of offshore platforms or wind parks	Long-distance connection of autonomous power grids
Max. length	20–30 km	70–150 km	< 50 km	>500 km	>500 km
Typical rating	30 MW	180 MW	700 MW/ three cables	1000 MW/ cable pair	600 MW/ cable

Figure 2.8: *Five Generic Submarine Power Cable Types* [16].

Regarding cable selection, three different criteria should be taken into consideration in order to ensure the suitability of a given cable for the specific project: thermal design, mechanical design and electric design.

Thermal Criteria

The thermal criteria determines the conductor size, which should be able to transmit all the current that flows through the link without exceeding the admissible temperature. These calculations should be carried out under different ambient conditions throughout the year or under overload effects among others. It should also be considered that DC and AC calculations have some particularities each [16].

Mechanical Criteria

While the thermal considerations of subsea cables are quite similar to those of underground cables, mechanical aspects introduce differences due to applied stresses. The challenge begins with transportation and laying processes, which are notably more intricate for submarine cables.

The laying process is not only complicated due to the forces applied to the cable during its installation but also due to the impact of weather conditions on the process. Thus, it should be noted that the mechanical criteria will be highly determined by the laying process and the definition of weather conditions assumed for the mechanical design, which might be a constraint for its later installation.

Although the laying process is typically the most mechanically demanding for the cable, other forces and impacts should also be taken into consideration. These include overbending, object impacts, errors during installation, or vibrations.

Electrical Criteria

The main electrical constraint to be considered in cable design is the electrical strength of its insulation layer. This property refers to its capacity to withstand an applied voltage without a breakdown [16].

Weibull Distribution is the most extended approach to model electrical strength in insulation. This function provides the probability (E) of a breakdown under the application of an electric stress. Apart from the nature of the specific material, this function is highly dependant on temperature and duration of the applied voltage, resulting in different curves according to their values. Figure 2.9 provides an example of Weibull curves variation with duration of applied voltage.

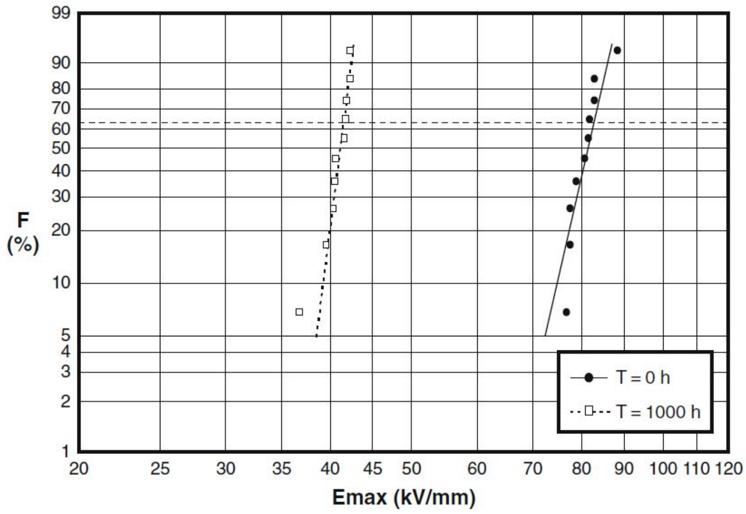

Figure 2.9: *Results of breakdown experiments plotted on Weibull paper* [16].

Taking into consideration the specific electrical strength of the insulation material, the electrical design of the cable should be focused on establishing the thickness of the insulation layer. Different approaches should be considered when dealing with AC or DC installations [16].

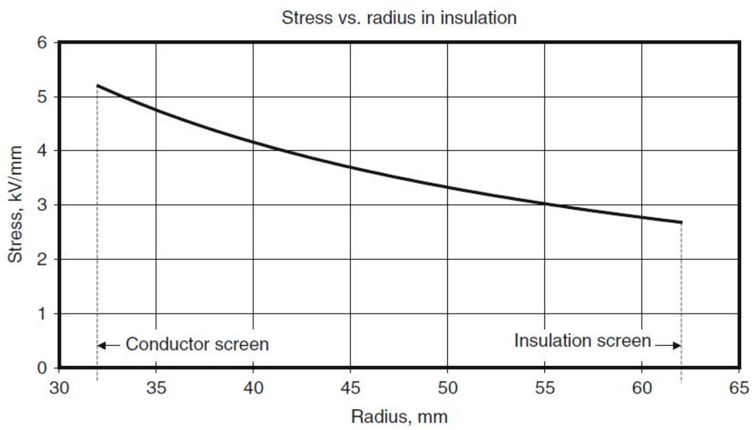

Figure 2.10: *Electric stress in a 110 kV a.c. XLPE cable* [16].

For HVAC cables, calculations must focus on determining the stress at every point of the insulation layer under all possible operating voltages and ensuring that the resulting values are valid according to the Weibull Distribution obtained for that material. The results are presented in stress curves. Figure 2.10 provides an example.

HVDC technology implies a much more complex calculation in this regard. The approach is similar: draw the curve of electric stresses in the insulation layer and compare it with the electric strength of the material. However, in DC cables, the applied voltage creates a field distribution that significantly depends on the specific conductivity of the material, and, consequently, on its operating temperature. This property has multiple consequences that shape the stress curve. Two of the main effects are as follows:

- Relaxation is a process that takes place the first time the cable operates. It modifies the non-load stress curve of the insulation layer, reducing stress in the critical area (next to the conductor).
- The load effect is much more significant due to the high dependence of conductivity on temperature. Thus, the area next to the conductor, which achieves higher temperatures, significantly increases its conductivity and becomes the less stressed area in the insulator layer.

Both effects on the stress curve can be observed in the example depicted in Figure 2.11.

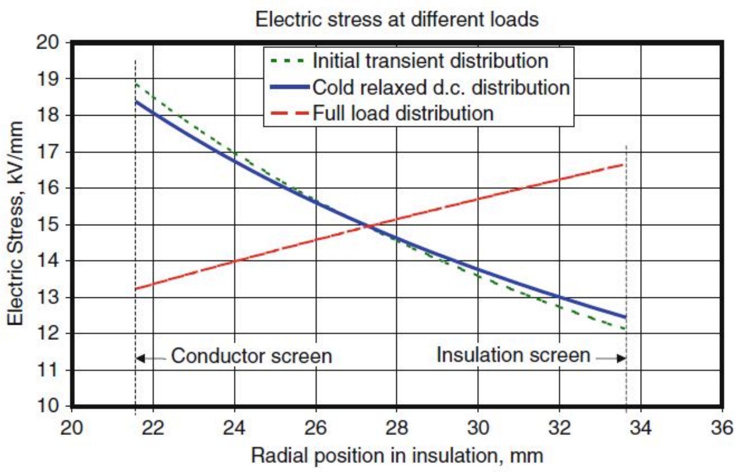

Figure 2.11: *Electric stress in d.c. cable insulation under different load conditions* [16].

Considering that the Weibull Distribution, which models the behavior of the insulation material, is a probability function, it is readily apparent that the design of the insulation layer is, in any case, a risk management issue. Thus, the determination of the layer's thickness is based on the assumed breakdown risk.

The previous considerations gather the primary criteria for designing conductors for subsea facilities. Nevertheless, it should be noted that it is common practice to simplify the application of this methodology through the use of catalogues that provide the main features of different models. Comparing these features with the requirements of the cable's use leads to the choice of the appropriate conductor.

Converter Station Design

Converter stations comprise electronic elements that convert alternating current into direct current and vice versa. Consequently, they are exclusively used in HVDC connections. Notably, in the case of offshore transmission, they are located on offshore platforms, as illustrated in Figure 2.12.

Figure 2.12: *BORWIN ALPHA Offshore Converter Station* [17].

The design of converter stations depends on the lines that they connect, considering the transmitted power, voltage, configuration, application and location, among others. However, as described in Section 2.1, the following elements are included in most of them [18]:

- AC switchgear.
- Transformers.
- AC filters and reactive power compensation (if applicable).
- Conversion equipment.
- DC reactors and filters.
- DC switchgear.

The design of AC elements is quite similar to that of AC substations, as well as the main requirements of the building that houses them. Thus, the primary differences emerge in the conversion and DC equipment.

The initial step in designing conversion equipment involves selecting the appropriate technology: Line Commutated Converter (LCC) or Voltage Source Converter (VSC). As explained in previous sections, VSC is the most suitable solution for the type of interconnections addressed in this project. Following this, the specific conversion technique should be specified. Considering these choices, a detailed electronic design tailored to the characteristics of the link should be developed. It is remarkable the incorporation of converter transformers to manage the difference between DC and AC insulation stresses.

DC reactors and filters are included in series and parallel to the connection, respectively. Their function is to smooth the signal on the DC side of the link, eliminating harmonics, reducing DC current ripple, and protecting conversion valves. Their design should focus on the proper fulfillment of these tasks.

Concerning DC switchgear, it is typically limited to disconnectors and earth switches. As mentioned in previous sections, the complexities and low level of development of DC switchgear lead to transferring most functions to the AC side of the station, where their design bear little difference from typical HVAC electrical substations [13].

Earthing System

As mentioned in previous sections, subsea cables include metallic layers surrounding the conductor. Due to the coupling between magnetic and electric fields, the presence of these metallic layers around an operating conductor gives rise to an additional current that flows through these layers. To mitigate the electrical danger resulting from this current flow, it is necessary to connect them to an earthing system.

In this context, the approach for subsea facilities involves connecting the armoring and sheaths of the cables to the grounding systems of conversion stations.

2.2.2 Installation of Subsea Power Cables

Although the installation of onshore facilities of subsea links, such as substations, has no distinguishing characteristics when compared to completely onshore transmission links, cable installation is an entirely different process. This section aims to describe the most significant aspects of the procedure.

Cable Laying Vessels

Cable laying is carried out by a vessel specifically modified for this purpose, known as cable laying vessels. These boats are equipped with turntables to transport large amounts of cable and place it in trenches on the seabed. Two techniques are commonly used to create these trenches: plowing or cutting the seabed with specific tools and introducing the cable into the resulting trench, or using 'water jetting' techniques that involve introducing water into the compact terrain, fluidizing it, and allowing the cable to sink. The preferred option for most cable laying vessels is plowing [9]. Figure 2.13 depicts a conceptual sketch of this technique.

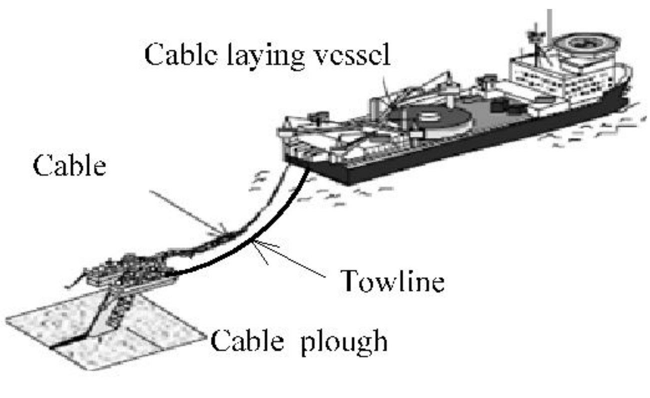

Figure 2.13: *Sketch map of submarine cable laying and buring* [19].

Landing of Subsea Cables

The landing of subsea cables is typically a critical task of subsea transmission projects. Various techniques have been developed for this purpose, and their suitability may depend on the specific project's characteristics. Nevertheless, one of the most extended methods consists of an Horizontal Directional Drilling (HDD) that crosses the surrounding cost areas to reach the onshore point where the land cable and the subsea cable concur.

The execution of the HDD is conducted by a drilling station that methodically drills a hole under the beach's soil, ultimately ending in open water. Following the completion of the drilling process, the resultant hole is equipped with steel or plastic pipes, which may protect the subsea cable that will later be installed inside. It is remarkable that the total length of the HDD is constrained not only by the capabilities of the execution equipment, but also by the properties of the materials used, including the cable itself [16].

Concerning the cable installation inside the pipes of the HDD, it is worth noting that it is a complex process where factors such as the cable's weight and the friction coefficient of the pipes are critical. Lubricating materials may even be necessary to facilitate the cable's passage through the pipes without causing damage [16].

In case of incorporating offshore substations, this process would be absolutely different. Its characteristics may differ according to the design of the offshore platform.

Joints

Despite cables with a highly significant length can be manufactured and transported in cable laying vessels, sometimes it is unavoidable to use more than one single piece of cable. In this context, joining cables in open sea arises as a complicated task to be accomplished.

The most challenging aspect of a subsea joint execution is that the two cables to be joined need to be handled simultaneously while controlling their relative position to avoid overbending or overtensioning. Additionally, the joint itself must be carried out within a controlled environment area onboard the vessel [16].

Two types of joints are mainly considered: factory joints and offshore installation joints. Regarding factory joints, they are semi-finished pieces at whom cable's ends are welded. In order to detect defects, such as discontinuities or porosities, the weld is usually checked by X-rays. On the other hand, offshore installation joints imply the joint of every layer of the implicated conductors. This method is more time-consuming, and, consequently, needs a wider window of suitable weather conditions [16].

Meteorological considerations

As previously mentioned, weather plays a significant role in subsea cable installation. The primary reason is that strong winds and waves can cause cable laying vessels to become uncontrollable. Thus, the constraints imposed by weather for a safe cable installation are innumerable. In this context, the risk of delays in the operation involved becomes enormous. This fact, coupled with the scarcity and high cost of cable laying vessels, results in cable laying accounting for a significant percentage of the total budget in subsea applications [16] [20].

2.3 Costs Estimation of Offshore Facilities

Several costs analysis have been conducted by numerous research groups, leading to different approaches in terms of costs classification. However, most of them coincide in dividing costs according to two different criteria.

The first classification distinguishes between capital costs (CC) and capitalized costs of power losses (LC). Some authors in the literature also refer to expenses such as environmental assessments or project management as separate costs [20] [21]. However, due to its negligible impact on the total budget, in this project they will be considered to be already included in other expenditure items.

Another way of classifying costs is to divide them into terminal costs (TC) and route costs (RC). Terminal costs encompass such expenses that do not depend on the length of the line. Typical terminal cost elements include converters or transformers. On the other hand, route costs are directly proportional to the length of the line. Cables would be included in this category [6]. Some authors also include a third group in this classification, referring to expenses that depend not only on the length of the line, but also on the capacity that it transmits. Power losses would be included in this class [20]. However, many studies assume that the lines operate at its nominal capacity, integrating this expenses in route costs. This project follows this assumption.

The following sections analyze the major expenses associated with offshore projects when utilizing the proposed technologies, HVAC and HVDC, and classify them according to the described groups. A summary of the resulting categories can be found in Table 2.1.

Costs (C)	**Capital Costs (CC)**	**Losses Costs (LC)**
Terminal Costs (TC)	Terminal Capital Costs (TCC)	Terminal Losses Costs (TLC)
Route Costs (RC)	Route Capital Costs (RCC)	Route Losses Costs (RLC)

Table 2.1: Costs Classification [6].

It should be noted that, during the development of this project, consistent sources such as [9], [20], [21], and [22] might be considered to obtain variations of theoretical and experimental models. These sources will be analyzed for their accuracy and potential improvements. However, this section presents significant models that illustrate the most widely used approaches for cost estimation.

2.3.1 Terminal Capital Costs

Terminal capital costs in offshore interconnections mainly consists of all the elements related to the stations located at both ends of the conductors, which enable the line to connect to other parts of the power grid. It should be taken into consideration that many offshore connections include an additional complexity: one of its ends is placed in the sea. This is the case for the connection of wind turbines to the power grid. In such applications, as mentioned, the offshore station is installed on a platform, incurring additional expenses.

While certain elements, such as step-up transformers, are normally included in most stations, others may vary according to the technology of the line. Consequently, terminal capital costs and their impact on the total budget may differ significantly depending on the proposed solution.

HVAC Terminal Capital Costs

HVAC technology is much simpler in this regard. In this case, stations basically consist of the traditional elements of power substations: transformers, protection cells and other line switchgear. In addition to its lack of complex electronic devices, HVAC components have been widely commercialized, and the sector has extensive experience in its manufacturing. These factors have lead to relatively low costs of stations. Thus, terminal capital costs represent a relatively small part of the total HVAC typical budget. Figures may depend on the transmission power rating [6] [20].

Within the literature, many costs models for HVAC terminal capital costs can be found. For instance, in [6], theoretical and experimental equations based on the indicative costs information given in [22] are proposed for both offshore, Equation 2.1, and onshore stations, Equation 2.2. Appendix II includes variable descriptions.

$$TCC_{Offsh} = FC_{AC} + [1 + dc(n_T - 2)] \cdot (fc_T + pc_T) \cdot n_T \cdot S_{ST} = 5 + 0.0415 \cdot S_T; \quad (2.1)$$

$$TCC_{Onsh} = \mathit{0.02621} \cdot S_T^{0.7513}. \quad (2.2)$$

Gathering the information provided by these equations, [6], [20], and [21], it can be inferred that most studies pursue the simplification of costs models, limiting cost estimation to a single parameter which is the transmission power rating of the line. This simplification may lead to the necessity of studying the validity range of each model and its suitability for specific cases.

HVDC Terminal Capital Costs

Concerning HVDC solutions, they necessary include additional electronics that conform AC/DC converters. It must be highlighted that capital costs associated to converter stations are the main limitation of HVDC technology implementation. Thus, it is estimated that TCC represent more than 50% of the total budget for HVDC projects of up to 200 km [6] [20]. This percentage decreases with the length of the line. Despite the high figures, it should be considered that the development of the technologies is gradually reducing these fixed costs and, due to improvements in the overall efficiency of the stations, also those associated to power losses in the conversion process (TLC) [10].

Similar to HVAC technology, HVDC costs have been extensively analyzed. [6] also proposes a model based on data provided by [22] for both offshore, Equation 2.3, and onshore stations, Equation 2.4. As it can be observed, the equations are also simplified to consider the transmission power rating as an input.

$$TCC_{Offsh} = FC_{DC} + [1 + dc(n_c - 2)] \cdot c_c \cdot n_c \cdot S_{SC} = 25 + 0.11 \cdot S_T; \qquad (2.3)$$

$$TCC_{Onsh} = 0.08148 \cdot S_T. \qquad (2.4)$$

It should be considered that these models assume the use of VSC technology. In the case of LCC applications, fixed costs would be higher, implying the need of reviewing related parameters [20].

A different approach to terminal capital costs estimation can be found in [21]. It proposes an experimental equation, Equation 2.5, which is a function of different multipliers. The value for these multipliers should be looked up in auxiliary tables, such as the one shown in Figure 2.14, which are based on experience. It should be noted that [21] is focused on onshore interconnections. However, the approach is valid and can be corrected for offshore applications.

EQUIPMENT	230 KV SUBSTATION	345 KV SUBSTATION	500 KV SUBSTATION
Base Cost (New Substation)	$1,706,174	$2,132,718	$2,559,262
Cost Per Line/XFMR Position	$1,492,903	$2,239,354	$2,985,805
Ring Bus Multiplier	1	1	1
Breaker and a Half Multiplier	1.5	1.5	1.5
500 kV HVDC Converter Station			$460,708,500
600 kV HVDC Converter Station			$506,779,350
Shunt Reactor ($/MVAR)	$20,706	$20,706	$20,706
Series Capacitor ($/MVAR)	$31,059	$10,353	$10,353
SVC Cost ($/MVAR)	$88,001	$88,001	$88,001

Figure 2.14: *Substation Capital Cost Summary* [21].

$$TCC = [(SubstationBaseCost) \cdot (Line/XFMRPositionBaseCost) \cdot (\#Lines/ XFMRPositions) \cdot (RBorBAAHMultiplier) \cdot (XFMRCost/MVA) \cdot (XFMRMVARating) + (SVCCost/MVAR) \cdot (\#MVARs) + (Series Cap.Cost/MVAR) \cdot (\#MVARs) + (ShuntReactorCost/MVARs) + (HVDCConverterStationCost) \tag{2.5}$$

2.3.2 Terminal Losses Costs

Terminal losses costs are those related to power losses in terminal station elements. Thus, HVAC terminal losses costs are mainly focus on transformer losses, while HVDC also considers AC/DC converter devices losses. In [6] a calculation model for each technology has been proposed: Equation 2.6 and Equation 2.7, respectively.

$$TLC_{HVAC} = S_T \cdot pf \cdot (1 - \eta_t) \cdot T_{op} \cdot \delta \cdot E_{op}; \tag{2.6}$$

$$TLC_{HVDC} = S_T \cdot (1 - \eta_t) \cdot T_{op} \cdot \delta \cdot E_{op}. \tag{2.7}$$

It should be noted that the efficiency of the station may change according to the selected solution, leading to specific equations for HVAC, Equation 2.8, and HVDC, Equation 2.9, when considering the data provided by [22]. These models consider onshore stations.

$$TLC_{HVAC} = 0.00906 \cdot S_T; \tag{2.8}$$

$$TLC_{HVDC} = 0.02610 \cdot S_T. \tag{2.9}$$

Additionally, [6] proposes different models for offshore stations, Equations 2.10 and 2.11. As it can be observed, the difference between onshore and offshore costs is not significant in this regard.

$$TLC_{HVAC} = 0.00911 \cdot S_T; \tag{2.10}$$

$$TLC_{HVDC} = 0.02610 \cdot S_T. \tag{2.11}$$

2.3.3 Route Capital Costs

Route capital costs depend mainly on the length of the line. This group includes cables costs, cable installation and the station equipment that depends on the length of the line.

Cable materials and installation represent a significant percentage of the total budget of the project [20]. The first group includes not only conductors themselves, but also joints. Regarding the second, it includes the installation of cable between terminal stations, which is a challenging activity that implies most of the budget dedicated to transmission components.

A route capital costs estimation model is proposed in [6] for both HVAC and HVDC technologies (Equation 2.12).

$$RCC = t_c \cdot l_c \cdot nc_c. \tag{2.12}$$

Apart from cables costs, this group includes the costs for every equipment in the final stations that depend on the length of the line. The most significant item in this regard is HVAC compensation cost. As it was mentioned, parallel capacitive susceptance can not be dismissed in subsea applications, and, in order to avoid its effect and increase the capacity of the line, compensation power is commonly installed at both ends of the cable. Costs can be calculated and must be added to cable costs in HVAC installations (Equation 2.13).

$$Qc = V_n^2 \cdot 2\pi \cdot f_n \cdot C \cdot l_c. \tag{2.13}$$

[21] approaches route capital costs estimation in a similar way of terminal capital costs. Thus, an equation based on different multipliers, Equation 2.14, and its respective auxiliary table, Figure 2.15, are proposed.

$$\begin{aligned} RCC = {} & [(BaseTransmissionCost) \cdot (ConductorMultiplier) \cdot (StructureMultiplier) \\ & \cdot (Re-conductorMultiplier) \cdot (TerrainMultiplier) \cdot (ROWArea/Length) \\ & \cdot (LandCost/Area)] \cdot (Length); \end{aligned} \tag{2.14}$$

	230 KV SINGLE CIRCUIT	230 KV DOUBLE CIRCUIT	345 KV SINGLE CIRCUIT	345 KV DOUBLE CIRCUIT	500 KV SINGLE CIRCUIT	500 KV DOUBLE CIRCUIT	500 KV HVDC BI-POLE	600 KV HVDC BI-POLE
Base Cost ($/mi)	$959,723	$1,536,385	$1,343,819	$2,150,318	$1,919,446	$3,071,735	$1,536,385	$1,613,204
Multipliers								
Conductor								
ACSR	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ACSS	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08
HTLS	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60
Structure								
Lattice	0.90	0.90	1.00	1.00	1.00	1.00	1.00	1.00
Tubular Steel	1.00	1.00	1.30	1.30	1.50	1.50	1.50	1.50
Length								
> 10 miles	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
3-10 miles	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
< 3 miles	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Age								
New	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Re-conductor	0.35	0.45	0.45	0.55	0.55	0.65	0.55	0.55
Terrain								
Desert	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Scrub / Flat	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Farmland	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Forested	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
Rolling Hill (2-8% slope)	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40
Mountain (>8% slope)	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Wetland	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Suburban	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27
Urban	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59

Figure 2.15: *Transmission Capital Cost Summary* [21].

2.3.4 Route Losses Costs

Route losses costs are mainly related to cable losses. As a consequence, they depend directly on the characteristics of the cable, current that goes through it, operation time and energy price. Theoretical and experimental equations can be found in [6] for both HVAC, Equations 2.15 and 2.16, and HVDC, Equations 2.17 and 2.18, technologies.

$$RLC_{HVAC} = 3 \cdot (S_T \cdot pf \cdot \eta_{offt})/(nc_c \cdot \sqrt{3} \cdot V_n)^2 \cdot r_c \cdot l_c \cdot nc_c \cdot T_{op} \cdot \delta \cdot E_{op}; \quad (2.15)$$

$$RLC_{HVAC} = 1.51767 \cdot (0.994 S_T/nc_c \cdot V_n)^2 \cdot r_c \cdot l_c \cdot nc_c; \quad (2.16)$$

$$RLC_{HVDC} = (P_T \cdot \eta_{offt})/(nc_c \cdot V_n)^2 \cdot r_c \cdot l_c \cdot nc_c \cdot T_{op} \cdot \delta \cdot E_{op}; \quad (2.17)$$

$$RLC_{HVDC} = 3.03534 \cdot (0.9828 S_T/nc_c \cdot V_n)^2 \cdot r_c \cdot l_c \cdot nc_c. \quad (2.18)$$

It is remarkable that Equations 2.15 and 2.17 concur with the approaches of [21] for route losses cost estimation.

2.3.5 Total Costs

Total costs of subsea transmission links can be estimated taking into consideration all the aforementioned items (TCC, TLC, RCC, and RLC). Thus, [6] proposes a model for both HVAC, Equation 2.19, and HVDC, Equation 2.20, that gathers the previous, simplifying the total costs estimation process to a function that only depends on basic characteristics of the link that can be determined at the very beginning of the project.

$$\begin{aligned} C_{HVAC} = 2 \cdot 0.02621 S_T^{0.7513} + t_c \cdot l_c \cdot nc_c + 0.02 \cdot V_n^2 \cdot f_n \cdot C \cdot l_c + 2 \\ \cdot 0.00906 S_T + 1.51767 \cdot (0.994 S_T/nc_c \cdot V_n)^2 \cdot r_c \cdot l_c \cdot nc_c; \end{aligned} \quad (2.19)$$

$$\begin{aligned} C_{HVDC} = 2 \cdot 0.08148 S_T + t_c \cdot l_c \cdot nc_c + 2 \cdot 0.02610 S_T + 3.03534 \cdot \\ (0.9828 S_T/nc_c \cdot V_n)^2 \cdot r_c \cdot l_c \cdot nc_c. \end{aligned} \quad (2.20)$$

	INDEPENDENT DEVELOPER	INVESTOR-OWNED UTILITY	PUBLIC UTILITY
Source	B&V Estimate	NV Energy/PacifiCorp	BPA
AFUDC Cost	10.0%	8.6%	4.1%
Overhead Cost	10.0%	6.2%	23.0%
Recommended Values	7.5% (AFUDC) + 10.0% (Overhead) = 17.5%		

Figure 2.16: *AFUDC and Overhead Costs and Recommended Values* [21].

Regarding the approach proposed in [21], it can be observed the use of three specific tools that compute TCC, RCC and RLC, respectively, whom results are added in order to obtain the total cost of the line. It should be highlighted that it does not take into consideration terminal losses costs. However, it includes an additional percentage related to allowances for funds used during construction and overhead costs which leads to a more realistic total project cost estimation. Figure 2.16 shows recommended percentage values for this purpose.

Other studies simply gather the information of various real cases and make comparisons among them. For instance, in [20], five typical basic cases of different technologies are compared, obtaining costs per length figures. It does not provide an exhaustive estimation model. However, it gives an outlook of the expected range of costs in projects of similar capacity and length.

In conclusion, the literature offers several models to estimate total costs. However, in aiming to simplify these models to require minimal inputs, they make some assumptions that may not accurately reflect the characteristics of each specific case. Therefore, despite their validity within a specific range, it should be considered that there is an implicit error in their use.

2.4 HVAC vs HVDC in Offshore Applications

2.4.1 Technical and Economical Comparison

HVAC and HVDC technologies have proved their adequacy and suitability in real applications in several occasions. However, they have different characteristics and costs that make each of them more appropriate for certain projects.

When considering substation equipment, it is worth noting the requirement of expensive AC/DC converters in HVDC technology, which significantly impacts the total transmission budget. In contrast, HVAC not only avoids this cost but also entails the use of simpler and more mature devices in its substations. Consequently, as evidenced in Figure 2.17 (Platform & Plant Cost), terminal capital costs tend to play a much more significant role in HVDC projects than in HVAC projects, regardless of most of the electrical characteristics of the line [6] [22].

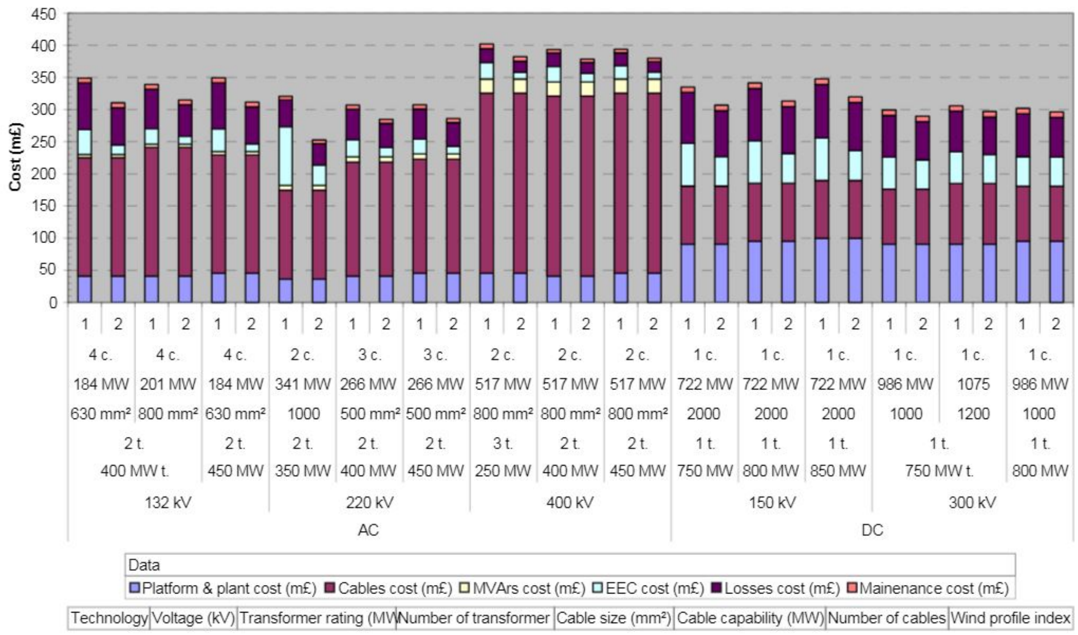

Figure 2.17: *Total costs for various solutions for offshore network* [22].

Additionally, the lack of suitable DC protection devices still represents a barrier to the construction of multi-level systems. This system configuration would avoid several terminal costs, boosting the advantages of HVDC technologies in subsea applications.

When comparing the exposed models proposed in [6] and [21], it can be observed that for both onshore and offshore substations terminal capital costs may result higher if using HVDC technologies. This observation is supported by other sources as well.

Apart from terminal capital costs comparison, Figure 2.17 also provides information of route capital costs. Thus, it evidences a higher percentage of cable costs, and, accordingly, route capital costs, in all the considered cases of AC projects. Due to the lack of reactive power in DC and the absence of skin effect, DC lines can transmit a given capacity using smaller cable sections than AC. Additionally, as it was shown in Figure 2.4, HVDC links use less poles than HVAC, and consequently, reduces significantly the total need of conductor. These facts lead to the evidenced cable costs reduction.

It should also be noted that HVAC projects include an additional cost item related to reactive power compensation. It increases route capital costs, which are significantly higher than HVDC RCC in all cases. Experimental models shown in Section 2.3 are in accordance with this conclusion.

It can be found within the literature studies that analyze power losses, both route and terminal, in subsea transmission links with HVAC and HVDC technologies. In [23], a comprehensive analysis of power losses in links between offshore wind generation facilities and onshore electrical substations is included.

Figure 2.18 shows the obtained participation of each transmission losses for a 500 MW wind farm at 100 km distance in [23]. It can be observed that the considered items coincide with the ones presented in Section 2.3: substation transformers (TLC) and cables and compensation (RLC) for HVAC links and converter stations (TLC) and cables (RLC) for HVDC links. From this figures it can be inferred that in HVAC route power losses are much more significant than terminal losses. The opposite effect can be observed in the HVDC breakdown.

Despite the exact percentages of losses may depend on the specific project and, of course, the length of the link, the predominant loss in HVAC tends to be those related to route, while in HVDC the most significant are the ones related to terminal devices. It is remarkable that [23] establishes that total losses of HVAC links surpasses HVDC losses when the transmission distance is between 55 and 70 km. This fact can also be derived from the equations in Section 2.3.

2.4.2 Break-Even Point

Based on the information presented in the previous section, it can be concluded that HVAC costs and losses are primarily influenced by their route component, while terminal elements pose a more significant challenge for HVDC transmission

Figure 2.18: *Participation of each transmission losses for 500 MW wind farm at 100 km transmission distance in HVAC (left) and HVDC (right).* [23].

projects. This observation turns the HVAC-HVDC comparison into a matter of distance: HVAC may generally be the most cost-effective technology for shorter distances, while HVDC may be better suited for longer distances. Much research is focused on establishing the break-even point that defines the distance at which each technology becomes more advantageous.

In [6], costs analysis is carried out based on two scenarios. They represent typical links which connect offshore and onshore points with power transmission capacities of 0.6 GW and 1.4 GW, respectively. The results are presented in Figure 2.19. As it can be observed, [6] establishes the break-even point at 87 km and 73 km for 0.6 GW and 1.4 GW, respectively.

A similar graphic can be found in [7]. This analysis considers a similar connection, but the proposed transmitted powers are 0.25 GW, 0.5 GW and 1 GW. Figure 2.20 has been extracted from the presented results. As it can be observed, in the smaller transmitted power scenario, 0.25 GW, HVAC costs are estimated to be lower for any distance. However, HVDC costs become more cost-effective at distances of 160 km and 200 km for the 0.5 GW and 1 GW scenarios, respectively.

It is remarkable that in both cases, [6] and [7], an increase in transmitted power decreases the critical distance significantly.

Another aspect in this regard is analyzed in [24]. This paper studies the break-even point considering short-distance and medium-distance models. It shall be

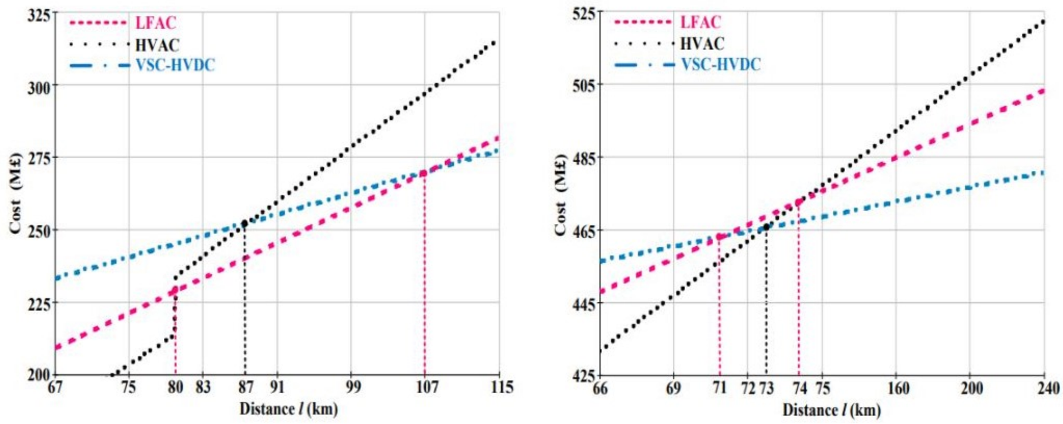

Figure 2.19: *Costs comparison HVAC vs HVDC 0.6 GW (left) and 1.4 GW (right)* [6].

noted that the difference between them is that medium-distance models consider the susceptance of the lines, while short-distance models neglect this parameter. Thus, the break-even point for short-distance models is established in 236 km, while considering medium-distance it is reduced to around 50 km. This fact evidences the huge impact of capacitance in HVAC subsea transmission.

Section 2.1 includes a brief analysis on low frequency alternating current (LFAC) technology. Due to the lack of experience in its use, it has been excluded in this project. However, it should be mentioned that there are studies focused on analyzing its feasibility. Figure 2.19 includes its costs comparison with HVAC and HVDC technologies. It shows that, for the scenario with 0.6 GW of transmitted power, LFAC is the most cost-effective option for distances ranging from 80 to 87 km. However, in the case of 1.4 GW, LFAC is not suitable for any distance. Additionally, in [15], it has been concluded that LFAC is suitable for lines between 80 and 180 km, but the considered transmitted powers are also relatively low.

Taking into consideration all the provided information, it can be inferred that the best technology for offshore applications may depend on the characteristics of the line. The most relevant parameters in this concern are transmitted power and distance to be covered. However, in order to select the best solution, every specific case should be carefully analyzed, considering also the fast development of new technologies.

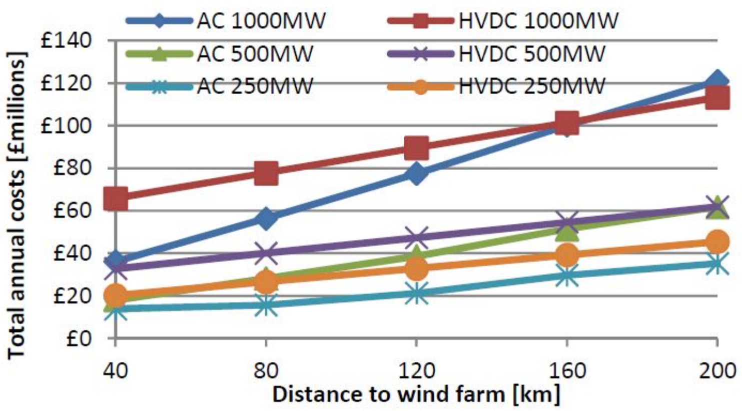

Figure 2.20: *Costs comparison HVAC vs HVDC* [7].

Chapter 3

The Development of a New Tool

Although the development and expansion of offshore technologies have been significant in recent years, the available data and tools for preliminary analysis of offshore projects are quite limited. This situation is a consequence of the scarcity in subsea cable markets that project developers are currently facing. The dramatic increase in subsea cable demand driven by the energy transition has not been matched by a corresponding expansion of manufacturing facilities. Thus, manufacturers are currently unable to satisfy the increasing demand and, as a result, are not even interested in providing reference costs that could compromise their commercial position in the future. Consequently, developers are currently facing multiple complexities in making a priori analyses of offshore transmission projects. This master's thesis presents a new tool for facilitating this process.

It should be noted that the developed tool is limited to HVDC-VSC projects, as they are the most prevalent type nowadays. Additionally, HVAC overhead and underground lines, typically built at the ends of HVDC links for connecting to the power grid, are considered.

3.1 Objectives

This project presents a tool designed to fulfill the following objectives:

- Conduct a preliminary design of the offshore interconnection under study.
- Provide a cost estimation that serves as a guide for project developers, including both CAPEX and OPEX of the facilities.
- Estimate the losses caused by the main facilities of the link, along with their associated costs.

Following sections present the main features and capabilities of the tool.

3.2 Inputs

The tool has been designed to require only the main parameters of the interconnection to provide consistent approximations. This information must be incorporated into the first worksheet of the Excel file, named *Inputs*. Figure 3.1 provides an overview of this worksheet.

The first area includes the **general features** of the interconnection. They are listed as follows:

- Transmission Power Rating: Enter the power rating in MW.
- Origin Converter Station: Specify if the station is onshore or offshore.
- Final Converter Station: Specify if the station is onshore or offshore.
- Utilization Factor: Enter the utilization factor.
- Commissioning Date (Year): Enter the year of commissioning.

It should be noted that the tool allows the user to choose whether each converter station is planned to be onshore or offshore. This capability has been included for analyzing offshore wind production projects, where the origin converter station is normally located offshore.

The next sections allow the user to include the most relevant information about the HVDC subsea line and, if applicable, the HVAC overhead or underground lines that are to be included as part of the link. These sections are **HVDC - Subsea**, **HVAC - Overhead**, and **HVAC - Underground**. The characteristics to be included are:

- Nominal Voltage (HVDC - Subsea): Enter the nominal voltage in kV.
- Cable Length (HVDC - Subsea): Enter the cable length in km.
- Terrain Resistivity (HVDC - Subsea): Enter the terrain resistivity in kΩ·m/W.
- Terrain Temperature (HVDC - Subsea): Enter the terrain temperature in ºC.

- Nominal Voltage (HVAC - Overhead): Enter the nominal voltage in kV.
- Cable Length (HVAC - Overhead): Enter the cable length in km.
- Nominal Voltage (HVAC - Underground): Enter the nominal voltage in kV.
- Cable Length (HVAC - Underground): Enter the cable length in km.
- Terrain Resistivity (HVAC - Underground): Enter the terrain resistivity in kΩ·m/W.
- Terrain Temperature (HVAC - Underground): Enter the terrain temperature in ºC.

As observed, for the offshore link and the HVAC underground cable, the terrain resistivity and temperature should be included.

The next sections pertain to prices, which are **Prices - CAPEX**, **Prices - OPEX**, and **Prices - Losses**. These sections are optional. The user can decide to use the *Default* values or select *Other* in the dropdown menu. If the latter is chosen, a new value should be specified in the following cells (colored in grey). The considered characteristics are listed as follows:

- Converter Station (Onshore) CAPEX (M€/MVA and/or M€)
- Cable (HVDC) CAPEX (M€/km)
- Converter Station (Offshore) CAPEX (M€/MVA and/or M€)
- Cable (HVAC - Overhead) CAPEX (M€/km)
- Cable (HVAC - Underground) CAPEX (M€/km)
- Converter Station (Onshore) OPEX (M€/MVA/year)
- Cable (HVDC) OPEX (M€/km/year)
- Converter Station (Offshore) OPEX (M€/MVA/year)
- Cable (HVAC - Overhead) OPEX (M€/km/year)
- Cable (HVAC - Underground) OPEX (M€/km/year)
- Energy Prices for Losses (€/MWh)

The default values considered for these characteristics are listed in Table 3.1. These values are used if the user selects *Default* in the dropdown menu for any of the pricing sections. If the user chooses this option, there is no need to enter a new value in the grey cells, as the tool will automatically apply the default values provided.

Prices - CAPEX	
Converter Station (Onshore)	0.0994 M€/MVA
Converter Station (Offshore)	0.1342 M€/MVA
	30.5072 M€
Cable (HVDC)	0.0017 M€/km
Cable (HVAC - Overhead)	0.0005 M€/km
	0.15 M€
Cable (HVAC - Underground)	0.0031 M€/km
	0.383 M€
Cable (HVAC - Underground, further)	0.0057 M€/km
	-2.059 M€
Prices - OPEX	
Converter Station (Onshore)	0.3735 M€/MVA/year
Converter Station (Offshore)	0.1 M€/MVA/year
Cable (HVDC)	0.00015 M€/km/year
Cable (HVAC - Overhead)	0.0037 M€/km/year
Cable (HVAC - Underground)	0.0014 M€/km/year
Prices - Losses	
Energy	60 €/MWh

Table 3.1: Default Values for CAPEX, OPEX and Losses Costs.

These values are detailed and explained in the following sections. Most of them are derived from experimental models and real data.

INPUTS
OPTIONAL INPUT

General Features		
Transmission Power Rating	700	MW
Origin Converter Station	Onshore	-
Final Converter Station	Onshore	-
Utilization Factor	0.55	-
Commisioning Date (Year)	2014	-
HVDC - Subsea		
Nominal Voltage	500	kV
Cable Length	140	km
Terrain Resistivity	0.8	k.m/W
Terrain Temperature	18	ºC
HVAC - Overhead		
Nominal Voltage	400	kV
Cable Length	18	km
HVAC - Underground		
Nominal Voltage	400	kV
Cable Length	0.56	km
Terrain Resistivity	1.5	k.m/W
Terrain Temperature	18	ºC
Prices - CAPEX		
Converter Station (Onshore)	Default	M€/MVA
New Value (if applicable)		*M€/MVA*
New Value (if applicable)		*M€*
Cable (HVDC)	Default	M€/km
New Value (if applicable)		*M€/km*
Converter Station (Offshore)	Default	M€/MVA
New Value (if applicable)		*M€/MVA*
New Value (if applicable)		*M€*
Cable (HVAC - Overhead)	Default	M€/km
New Value (if applicable)		*M€/km*
Cable (HVAC - Underground)	Default	M€/km
New Value (if applicable)		*M€/km*
Prices - OPEX		
Converter Station (Onshore)	Default	M€/MVA/year
New Value (if applicable)		*M€/MVA/year*
Cable (HVDC)	Default	M€/km/year
New Value (if applicable)		*M€/km/year*
Converter Station (Offshore)	Default	M€/MVA/year
New Value (if applicable)		*M€/MVA/year*
Cable (HVAC - Overhead)	Default	M€/km/year
New Value (if applicable)		*M€/km/year*
Cable (HVAC - Underground)	Default	M€/km/year
New Value (if applicable)		*M€/km/year*
Prices - Losses		
Energy	Default	€/MWh
New Value (if applicable)		*€/MWh*

Figure 3.1: *Inputs to the Developed Tool. Own Elaboration.*

3.3 Cable Design

Once all parameters have been defined, the tool proceeds with a preliminary cable design. This task is carried out in a separate worksheet named *A-Cable Design*. As previously mentioned, this section not only approximates the required cables for the subsea line but also offers the option to conduct a preliminary design for HVAC overhead and underground lines. The results, which include the required cross-sectional areas and the number of cables per pole or phase for each line, are summarized in the final section of the worksheet named *Results*.

3.3.1 HVDC - Subsea

The tool has been designed under the assumption of utilizing HVDC-VSC technology in its bipole configuration. Nevertheless, it should be highlighted that its modification for the analysis of other technologies would be perfectly feasible.

Focusing on the targeted technology, subsea cables for high-power uses are quite limited and the level of standardization in this regard is significant. For this reason, this preliminary design only considers the three most commercialized sections for subsea applications, which are 1000 mm^2, 1500 mm^2, and 2000 mm^2. Its selection is simplified to the thermal criteria in steady-state conditions.

HVDC - Subsea		
Transmission Power Rating	MW	700
Nominal Voltage	kV	500
Current	A	1400.00
Power factor	-	1
Poles	#	2
Number of Cables per Pole	*#*	*1*
Correction Factor - # Circuits	*-*	*1*
Correction Factor - Temperature	-	1.052
Correction Factor - Resistivity	-	1.3
Number of Cables per Pole	#	1
Correction Factor - # Circuits	-	1
Cable Cross Section	mm2	1000
Ampacity	A	3288
Sec. Coefficient	-	2.35

Figure 3.2: *Preliminary Design of the HVDC Offshore Line. Own Elaboration.*

It should be noted that correction factors associated to temperature and resistivity of the terrain and cable aggregation have been considered. These values have been approximated using the estimations for underground lines of the *Reglamento de Líneas de Alta Tensión (RLAT)*.

Figure 3.2 illustrates the input data and the results provided by the tool for a given scenario.

3.3.2 HVAC - Overhead

The tool follows a similar procedure for the preliminary design of HVAC overhead lines, which are typically installed at the ends of the subsea link. In this case, no correction factors are required, and the library of available cables and cross-sections includes up to 64 models with maximum ampacities ranging from 100 A to 1400 A.

Figure 3.3 provides an example of the results for a given scenario.

HVAC - Overhead		
Transmission Power Rating	MW	700
Nominal Voltage	kV	400
Current	A	1063.54
Power factor	-	0.95
Number of Circuits	#	1
Cable Cross Section	mm2	564
Cable Maximum Ampacity	A	1100
Sec. Coefficient	-	1.09

Figure 3.3: *Preliminary Design of the HVAC Overhead Line. Own Elaboration.*

3.3.3 HVAC - Underground

Lastly, the tool carries out a preliminary sizing for HVAC underground cables, employing a methodology similar to that used for subsea cables. The preliminary design incorporates correction factors for temperature, terrain resistivity, and cable aggregation, consistent with those used in subsea cable design. Furthermore, the tool includes a range of cable cross-sections from 300 mm^2 to 2000 mm^2, ensuring that the design is well-suited to the specific conditions and requirements of underground installations.

Figure 3.4 provides an example of the results for a given scenario.

HVAC - Underground		
Transmission Power Rating	MW	700
Nominal Voltage	kV	400
Ampacity	A	1063.54
Power factor	-	0.95
Number of Circuits	*#*	*2*
Correction Factor - # Circuits	*-*	*0.76*
Correction Factor - Temperature	-	1.052
Correction Factor - Resistivity	-	1
Number of Circuits	#	2
Correction Factor - # Circuits	-	0.76
Cable Cross Section	mm2	630
Cable Maximum Ampacity	A	1127.3232
Sec. Coefficient	-	1.12

Figure 3.4: *Preliminary Design of the HVAC Underground Line. Own Elaboration.*

3.4 Costs Estimation

Cost estimation is one of the main objectives addressed by the developed tool. Taking into consideration the provided inputs, the tool applies different models to estimate the CAPEX and OPEX of the analyzed project. This task is carried out in the worksheet *B-Costs*.

As previously explained, one of the most challenging aspects of developing subsea projects today is the lack of information regarding prices. Thus, one of the key advantages of this tool is that, in cases of uncertainty, default values are applied. These default values are updated by an inflation coefficient. However, it should be noted that this simplification may introduce a significant implicit error. Consequently, this tool should only be used for preliminary estimations rather than definitive calculations. The accuracy of the results can be enhanced with the introduction of updated data in the optional inputs of the worksheet *Inputs*.

3.4.1 HVDC - Offshore

This section includes the CAPEX and OPEX calculations for the origin and final converter stations and the HVDC facilities. Different estimation models have been applied in each case. Figure 3.5 illustrates how they are reflected in the tool.

HVDC - Subsea		
Transmission Power Rating	GW	0.7
Nominal Voltage	kV	500
Total Length	km	140

CAPEX		
Origin Converter Station	M€	57.10
Final Converter Station	M€	57.10
HVDC Cable	M€	297.10

OPEX		
Origin Converter Station	M€/year	0.21
	% over CAPEX	0.38
Final Converter Station	M€/year	0.21
	% over CAPEX	0.38
HVDC Cable	M€/year	0.03
	% over CAPEX	0.01

Figure 3.5: *Costs Estimation - HVDC Offshore Line. Own Elaboration.*

Converter Stations

CAPEX estimation of the converter stations varies depending on whether the selected option in the *Inputs* worksheet is onshore or offshore. Nevertheless, the models proposed by [6] for both cases have been deemed adequate. It should be noted that these correspond to terminal capital costs for onshore and offshore configurations, respectively. As a consequence, Equations 3.1 and 3.2 have been incorporated into the tool for this purpose.

$$Conv.\ Station\ Cost_{\ Onsh} = 0.0994 \cdot S_T; \tag{3.1}$$

$$Conv.\ Station\ Cost_{\ Offsh} = 30.51 + 0.134 \cdot S_T. \tag{3.2}$$

Regarding the OPEX figures, the incorporated values are those included in [25].

HVDC Cable

On the other hand, HVDC cable CAPEX and OPEX estimations are conducted using the model proposed by [25]. Thus, Equation 3.3 has been implemented.

$$HVDC\ Cable\ Cost = 2 \cdot 1.742 \cdot S_T \cdot (l_c + 8.5). \tag{3.3}$$

3.4.2 HVAC - Overhead

The estimation of HVAC overhead lines has been thoroughly analyzed, and approximating their costs is no longer a challenge for the industry. In this case, the information provided by [25] has been incorporated, leading to Equation 3.4. Figure 3.6 illustrates how it is reflected in the tool.

$$HVDC\ Cable\ Cost = 0.15 + 0.000534 \cdot S_T. \tag{3.4}$$

HVAC - Overhead		
Total power	GW	0.7
Power factor	-	0.9
Total power	GVA	0.78
Distance	km	18

CAPEX		
HVAC - Overhead	M€	8.35

OPEX		
HVAC - Overhead	M€/year	0.05
	% over CAPEX	0.65

Figure 3.6: *Costs Estimation - HVAC Overhead Line. Own Elaboration.*

Regarding the OPEX figures, the incorporated values are those included in [25].

3.4.3 HVAC - Underground

The estimation of HVAC underground cables has been similarly addressed, and their cost approximation is also well-established in the industry. For this purpose, the same source, [25], has been utilized, leading to Equation 3.5. Figure 3.7 illustrates how this information is reflected in the tool.

$$HVDC\ Cable\ Cost = max\ (0.0031 \cdot S_T + 0.383); (0.0057 \cdot S_T - 2.059). \tag{3.5}$$

Regarding the OPEX figures, the incorporated values are those included in [25].

HVAC - Underground		
Total power	GW	0.7
Power factor	-	0.9
Total power	GVA	0.78
Distance	km	0.56

CAPEX		
HVAC - Underground	M€	1.29

OPEX		
HVAC - Underground	M€/year	0.000643
	% over CAPEX	0.05

Figure 3.7: *Costs Estimation - HVAC Underground Line. Own Elaboration.*

3.5 Losses Estimation

The last task that this tool tackles is associated to the estimation of losses of the most significant parts of the infrastructures in a typical year. These calculations are included in worksheet *C-Losses*.

One of the most relevant parameters in this regard is the *Utilization Factor* that the user is required to enter in the first worksheet *Inputs*. This parameter sets the percentage of equivalent hours of the year (T_{op}) that the installation might be working. As a consequence, it is highly dependant on the application of the link. For instance, it is estimated that lines for offshore wind production evacuation account with an Utilization Factor around 0.55.

Another critical parameter for losses estimation is the *Loss Adjustment Factor*. It varies significantly within the literature and, consequently, its definition is not clear and could lead to significant errors in this approximation. This tool implements the values proposed by [21], which can be observed in Figure 3.8.

	30 PERCENT UTILIZATION	50 PERCENT UTILIZATION	70 PERCENT UTILIZATION	90 PERCENT UTILIZATION
Load Adjustment Factor	0.195	0.375	0.595	0.855

Figure 3.8: *Loss Adjustment Factor* [21].

3.5.1 HVDC - Offshore

Once again, the most critical aspect of analyzing these types of projects relates to the offshore components. This section estimates power losses for the origin and final converter stations as well as the HVDC cable. Figure 3.9 illustrates how they are reflected in the tool.

HVDC - Subsea		
Transmission Power Rating	GW	0.7
Nominal Voltage	kV	500
Current	A	1400
Cable Cross Section	mm2	1000
Number of Cables per Pole	#	1
Ampacity	A	3288
Cable resistance	mOhm/km	22.4
Efficiency of VSC-HVDC offshore	-	0.9828
Efficiency of VSC-HVDC onshore i	-	0.9819
Total Operation Hours/Year	h	4818
Loss Load Factor	-	0.415
Total Length	km	140

Power losses - Origin Converter Station		
Power losses	GWh/year	25.33
Total transmission	GWh/year	3372.60
Losses	%	0.75

Power losses - HVDC Cable		
Power losses	GWh/year	2.96
Total transmission	GWh/year	3372.60
Losses	%	0.09

Power losses - Final Converter Station		
Power losses	GWh/year	25.33
Total transmission	GWh/year	3372.60
Losses	%	0.75

LOSSES COSTS		
Power Losses - Origin Converter St	M€/year	1.55
Power Losses - HVDC Cable	M€/year	0.18
Power Losses - Final Converter Stat	M€/year	1.55

Figure 3.9: *Losses Estimation - HVDC Offshore Line. Own Elaboration.*

Converter Stations

The model used for estimating losses in converter stations provides an alternative to the one proposed by [6]. The primary variation involves replacing the Loss Load Factor with the Loss Adjustment Factor previously introduced. Therefore, the tool uses Equation 3.6 to estimate these losses.

$$\textit{Converter Losses} = ST \cdot (1 - \eta t) \cdot T_{op} \cdot \textit{Loss Adjtm. Factor.} \tag{3.6}$$

It is important to note that η_t may vary depending on whether the analyzed converter station is onshore or offshore (a feature defined by the user in the worksheet *Inputs*). The incorporated values are 0.9819 for onshore and 0.9828 for offshore stations.

HVDC Cable

The model used for calculating the losses in the HVDC cable is the one proposed by [6]. The only modification is once again the introduction of the Loss Adjustment Factor presented at the beginning of this section. Thus, Equation 3.7 has been implemented in the tool.

$$\textit{HVDC Cable Losses} = (P_T \cdot \eta_t)/(nc_c \cdot V_n)^2 \cdot r_c \cdot l_c \cdot nc_c \cdot T_{op} \cdot \textit{Loss Adjtm. Factor.} \tag{3.7}$$

3.5.2 HVAC - Overhead

Losses have also been estimated for the overhead line at the ends of the interconnection (if applicable). Therefore, Equation 3.8 has been incorporated into the model, applying the formula proposed by [6] along with the Loss Adjustment Factor from [21]. Figure 3.10 illustrates how this is implemented in the tool.

$$\textit{HVAC-OHL Losses} = 3 \cdot (S_T \cdot pf \cdot \eta_t)/(nc_c \cdot \sqrt{3} \cdot V_n)^2 \cdot r_c \cdot l_c \cdot nc_c \cdot T_{op} \cdot \textit{Loss Adjtm. Factor.} \tag{3.8}$$

HVAC - Overhead		
Total power	GW	0.7
Power factor	-	0.9
Total power	GVA	0.78
Voltage	kV	400
Current	A	1123
Cable cross section	mm2	564
Cable resistance	mOhm/km	51.4
Ampacity	A	1100.00
Number of circuits	-	1
Total Operation Hours	h	4818
Loss Load Factor	-	0.415
Distance	km	18

Power losses		
Power losses (GWh/year):	GWh/year	7.0
Total transmission (GWh/year):	GWh/year	3372.6
Losses (%):	%	0.2

LOSSES COSTS		
HVAC - Overhead	M€/year	0.43

Figure 3.10: *Losses Estimation - HVAC Overhead Line. Own Elaboration.*

3.5.3 HVAC - Underground

Losses have also been estimated for the HVAC underground cables at the ends of the interconnection (if applicable). Similarly, Equation 3.8 has been incorporated into the model once again, using the formula proposed by [6] along with the Loss Adjustment Factor from [21]. Figure 3.11 illustrates how this is implemented in the tool.

HVAC - Underground		
Total power	GW	0.7
Power factor	-	0.9
Total power	GVA	0.78
Voltage	kV	400
Current	A	1123
Cable cross section	mm2	630
Cable resistance	mOhm/km	28.3
Ampacity	A	1127.32
Number of circuits	-	2
Total Operation Hours	h	4818
Loss Load Factor	-	0.415
Distance	km	0.56

Power losses		
Power losses (GWh/year):	GWh/year	0.0
Total transmission (GWh/year):	GWh/year	3372.6
Losses (%):	%	0.0

LOSSES COSTS		
HVAC - Underground	M€/year	0.00

Figure 3.11: *Losses Estimation - HVAC Underground Line. Own Elaboration.*

3.6 Results

The final worksheet, named *Results*, summarizes the outcomes of the calculations performed by the tool. Figure 3.12 provides an example of the results for a given scenario.

CABLE DESIGN		
HVDC Submarine		
Number of Cables per Pole	#	1.00
Cable Cross Section	mm2	1000.00
HVAC Overhead		
Number of Circuits	#	1.00
Cable Cross Section	mm2	564.00
HVAC Underground		
Number of Circuits	#	2.00
Cable Cross Section	mm2	630.00

COSTS		
CAPEX	M€	420.93
OPEX	M€/year	0.52

LOSSES		
Total Losses	GWh/year	60.65
Losses Costs	M€/year	3.70

Figure 3.12: *Results. Own Elaboration.*

3.7 Validation and Comparison with Real-World Data

In order to validate the estimations provided by the tool, it has been applied to analyze real projects with known outcomes.

The first source consulted is [9]. This document, published by ENTSO-E, shows the CAPEX of various projects, which have been recalculated using the presented tool. The same procedure has been followed for the estimations of an exemplary project presented in [20]. Table 3.2 presents the real data and the results obtained by implementing the tool.

Project	Rated Power (MW)	Voltage (kV)	Real CAPEX (M€)	Estim. CAPEX (M€)	Error (%)
Skagerrak 4	700	500	440	456	3.64%
INELFE	2000	320	700	727	3.86%
Nemo	1000	500	450	481	6.89%
Romulo	400	250	400	334	-16.50%
Ex. P-B	3000	320	1156	1004	-13.15%

Table 3.2: CAPEX Comparison with Real Projects [9].

The data provided in [26] and [21] has also been reviewed to check the defined parameters for CAPEX and OPEX.

Different sources have been reviewed to verify the validity of loss calculations. Information provided in [6], [21], and [26] has been used to fine-tune existing models and adapt them to the current situation.

Chapter 4

Implementation in a Case Study

In order to illustrate the implementation of the developed tool in a new project, a specific case study has been included. Thus, this master's thesis incorporate the analysis of the electrical interconnection of Bornholm, a Danish island located in the Baltic Sea, with the northern area of Poland. The selection of this interconnection is based on the interest of the sector in the area.

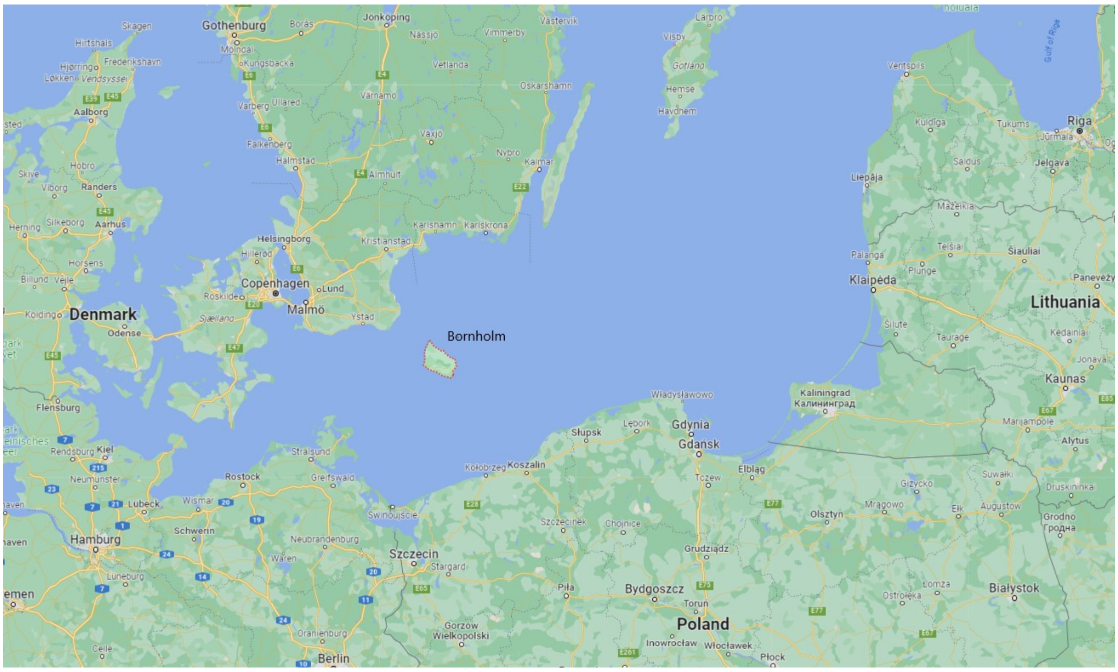

Figure 4.1: *Bornholm Location in Europe* [27].

Bornholm is one of the largest islands in the Baltic Sea, with an area of approximately 590 km^2 and a total population of around 40,000 inhabitants [28]. It constitutes a strategic terrain placed between Denmark, Germany, Poland, Lithuania, and Sweden, all of which are significant European countries. Its location can be observed in Figure 4.1.

Concerning electrical generation, numerous studies evidence that the Baltic Sea constitutes one of the areas with the greatest offshore wind generation potential in Europe [29] [30]. Currently, it concentrates up to 93 GW of offshore wind generation. Nevertheless, several new projects have been proposed and approved, and it is expected that the total installed capacity in Europe increases dramatically in the following years [31]. In this context, the preferential location of Bornholm is undeniable and interconnections of this island with the main nearby countries becomes essential for the development of the wind energy area and the whole European network.

Many European policies involve the expansion of renewable energies in this area, as well as their interconnection with the power grid. In recent years, however, their development has become even more important as a result of the Russian-Ukrainian conflict. In order to promote Europe's independence from Russian gas and to avoid the high costs of purchasing liquefied gas from the United States, the need of expanding renewable energy generation and eliminating gas-based generation from the European energy mix has become absolutely urgent. Thus, the Baltic region, as one of the areas with the greatest wind potential in Europe, plays an important role in the plan that the European Commission has drawn up for this purpose: REPowerEU. It should be noted that, in addition to the renewable generation aspect, this area is also essential for the diversification of gas sources that this plan aims to achieve. To this end, REPowerEU proposes new interconnections, such as the Poland-Lithuania Gas Interconnector, whose objective is to connect each area of Europe with at least three different sources of gas or liquefied gas [5] [32].

4.1 Case Study Presentation

For this case study, it has been determined that the Denmark-Poland desired connection may have a total capacity of 1.4 GW. The ends of the line are the existing electrical substation GPZ Dunowo (Poland) and a future substation in the south of Bornholm (Denmark), which are out of the scope of this project.

4.1.1 Layout

The concerning transmission line will connect Bornholm (Denmark) with the northern area of Poland. Due to the geographical characteristics of the zone, the interconnection needs to include three different lines: two onshore lines (overhead or underground), one at each end, which arrives to the initial and final substations, respectively, and the main subsea line, which is the focus of this project. From this point on, they will be referred to as Danish Line, Subsea Line, and Polish Line.

With respect to the Danish facilities, it should be noted that Bornholm is not an intensively populated area. Most of the island consists of rural terrain, besides one city in its western part. In this context, the future substation in the south of the territory has been assumed to be in the southwest area, where a less vegetated zone can be found, facilitating its permitting and construction.

Figure 4.2: *Future Substation Location in Bornholm* [27].

Assuming that the substation is placed in that location, this project proposes an underground line that starts in the substation and connects it to the Subsea Line through an horizontal directional drilling (HDD). The coast has been analyzed in order to find the best corridor for the line. The most straightforward and cost-effective approach would be that the line finishes as close as possible to Poland, minimizing the length of the Subsea Line, which is the most expensive part of the link. However, as can be observed in Figure 4.2, the south coast of Bornholm is densely vegetated. Thus, in order to avoid the environmental impact of building and operating a transmission line there, the suitable zone for the line has been restricted to a less forested area in the southwestern of the island (highlighted in red in Figure 4.2).

The context of the targeted Polish area is completely different in this regard. Three relatively large cities can be found within the north cost area: Kolobrzeg, Koszalin and Slupsk. Therefore, the zone is filled with urban terrains, buildings, and infrastructures, including various electrical substations. In this context, connecting the Overhead Polish Line to an existing substation is the most suitable option.

In order to determine the most convenient point for connecting the line, the information provided by the ENTSO-E Transmission System Map has been taken into consideration [33]. According to this source, there are two existing substations in the targeted area, both able to connect 400 kV facilities: GPZ Dunowo and GPZ Slupsk (Figure 4.3).

Figure 4.3: *Substations in the Target Area of Poland* [27].

Due to its proximity to the sea and a shorter distance to Bornholm substation, GPZ Dunowo will be the selected substation in Poland. It should be noted that it has been assumed that the chosen substation has enough capacity for the new link and, same as in Bornholm area, that the terrain has no regulatory limitations to be considered.

The proposed strategy for connecting this substation to the Subsea Line involves an overhead line (Polish Overhead Line) starting at GPZ Dunowo. This line will cross the northern area to reach the coast, where horizontal directional drilling may be executed for the connection with the Subsea Line.

Regarding the seabed where the Subsea Line may be installed, no relevant constraints have been observed for the purpose of this project. The bathymetry of the zone has been preliminary studied, and the area results with no abrupt changes in this regard [34]. However, for a non-academic case, a detailed study should be conducted.

Taking into consideration the aforementioned specifications and particularities of the terrain, the layout shown in Figure 4.4 is proposed for the interconnection. Table 4.1 gathers the total length of the resulting lines.

Figure 4.4: *Layout* [27].

4.1.2 Technology Selection

According to the information presented in Chapter 2, the most relevant parameters in technology selection based on technical and economical constraints are the total

Line	Length (km)
Danish Underground Line	0.56
Subsea Line	103
Polish Overhead Line	18

Table 4.1: Total Length of the Lines.

length of the line and the power to be transmitted. As described in the previous section, the subsea line of the case study is 103 km long, and it should transmit a total power of 1.4 GW.

Taking into consideration the characteristics of the line and the information provided by [6] in Figure 4.5, the most suitable technology for the power and length of the link to be designed is HVDC-VSC. Specifically, a bipole configuration might be chosen.

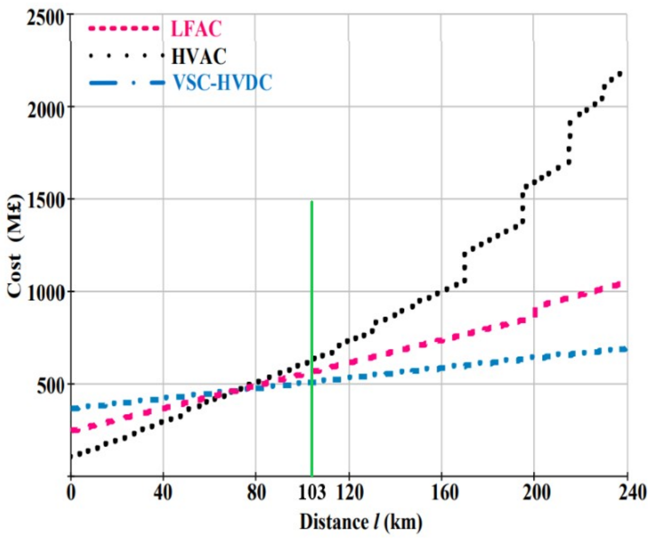

Figure 4.5: *Cost comparison HVAC vs HVDC 1.4 GW. Various lengths.* [6].

No additional concerns regarding technical or economical aspects may cause a variation in the chosen solution. In fact, this technology have other advantages such as active-reactive power decoupled control that supports the selected option. Consequently, the case study is focused on the use of HVDC technology VSC based.

4.1.3 Main Electrical Characteristics

The main electrical characteristics of the project must be defined for establishing the inputs to the the tool. They are listed as follows:

- Technology choice: According to previous sections, the selected technology is HVDC (bi-pole) with VSC converter stations.
- Converter stations locations: According to the characteristics of the projects, both converter stations are onshore.
- Capacity of the link: The interconnection planned capacity is 1,400 MW.
- AC Voltage: The HVDC line might be connected to 400 kV AC electrical substations through AC lines at the same voltage level.
- DC Voltage: The voltage level in the HVDC link is ±500 kV.

4.2 Tool Implementation

4.2.1 Inputs

Once the main characteristics of the project have been set, the inputs can be provided to the tool, as illustrated in Figure 4.6.

General Features		
Transmission Power Rating	1400	MW
Origin Converter Station	Onshore	-
Final Converter Station	Onshore	-
Utilization Factor	0.55	-
Commisioning Date (Year)	2024	-
HVDC - Subsea		
Nominal Voltage	500	kV
Cable Length	103	km
Terrain Resistivity	0.8	k.m/W
Terrain Temperature	15	ºC
HVAC - Overhead		
Nominal Voltage	400	kV
Cable Length	18	km
HVAC - Underground		
Nominal Voltage	400	kV
Cable Length	0.56	km
Terrain Resistivity	1.5	k.m/W
Terrain Temperature	20	ºC

Figure 4.6: *Case Study - Inputs.*

It should be noted that all optional inputs have been set to *Default* values to verify the functionality of the tool. However, different values could be introduced if desired.

4.2.2 Results

The results provided by the tool, based on the defined inputs, are shown in Figure 4.7. These results offer a preliminary overview of the project, including CAPEX, OPEX, and power loss estimations.

CABLE DESIGN		
HVDC Submarine		
Number of Cables per Pole	#	1.00
Cable Cross Section	mm2	1000.00
HVAC Overhead		
Number of Circuits	#	2.00
Cable Cross Section	mm2	564.00
HVAC Underground		
Number of Circuits	#	4.00
Cable Cross Section	mm2	1000.00

COSTS		
CAPEX	M€	843.74
OPEX	M€/year	1.14

LOSSES		
Total Losses	GWh/year	117.08
Losses Costs	M€/year	7.14

Figure 4.7: *Case Study - Results.*

Chapter 5

Conclusions

This master's thesis presents a new tool designed to provide preliminary analysis for offshore projects. As discussed earlier, this task has become increasingly complex in recent years due to the lack of available cost data for key infrastructure elements. Consequently, while the tool offers approximations rather than exact results, it remains a valuable resource for project developers during the initial phases of offshore projects.

Although the default values entered into the tool are sufficient for a valid preliminary analysis, the option to include updated inputs can significantly enhance the accuracy of the results. This is particularly important given the current volatility in the subsea elements market. A notable advantage of the tool is that these improvements can be made without needing to delve into the underlying equations and models. User-friendly and intuitive fields have been provided for this purpose.

One of the most significant contributions of this project has been the analysis and selection of equations and models for the tool. Various approximations are available in the literature, but the challenge was that none consistently aligned with real-world projects across all studied variables. For instance, the results from [6] show that while CAPEX values appear reasonable, the loss results are lower than expected. The main contribution of this project is identifying such discrepancies and suggesting alternatives based on other sources to achieve more accurate results.

While there is potential to expand the tool to include other technologies, this has not been pursued, as HVDC-VSC technology remains the preferred choice for the offshore applications considered in this project.

In summary, the tool offers valuable preliminary analysis in the absence of comprehensive data, addressing uncertainties and price fluctuations in the subsea cable market. Its results should be viewed as approximations, with accuracy heavily dependent on the input of updated data. While designed to provide insights based on available information, the tool allows users to incorporate more detailed data as it becomes available, further enhancing its effectiveness.

Appendix A

List of Acronyms

AC Alternating Current. El tipo de corriente eléctrica que cambia de dirección periódicamente.

CAPEX Capital Expenditure. Gasto en la adquisición o mejora de activos físicos.

CC Capital Costs. Costos iniciales asociados a la construcción o adquisición de activos físicos.

CSC Current Source Converter. Un tipo de convertidor que convierte corriente continua en corriente alterna.

DC Direct Current. Corriente eléctrica que fluye en una sola dirección.

EU European Union. La Unión Europea, una unión política y económica de estados europeos.

HVAC High Voltage Alternating Current. Transmisión de energía eléctrica a alta tensión usando corriente alterna.

HVDC High Voltage Direct Current. Transmisión de energía eléctrica a alta tensión usando corriente continua.

HDD Horizontal Directional Drilling. Técnica de perforación para instalar tuberías o cables sin necesidad de excavación extensa.

IGBT Insulated Gate Bipolar Transistor. Transistor de potencia que combina características de un transistor bipolar y un transistor de efecto de campo.

LFAC Low Frequency Alternating Current. Corriente alterna de baja frecuencia, usada en aplicaciones especiales.

LCC Line Commutated Converter. Convertidor que utiliza tiristores para la conversión de AC a DC en sistemas HVDC.

LDPE Low-Density Polyethylene. Polietileno de baja densidad, usado en aislamiento de cables y otros productos.

LC Losses Costs. Costos asociados a las pérdidas de energía en el sistema.

OHL Overhead Line. Línea eléctrica que se encuentra sobre el suelo, montada en torres o postes.

OPEX Operational Expenditure. Gastos operativos asociados al funcionamiento diario de un activo o sistema.

PWM Pulse Width Modulation. Técnica para controlar la potencia enviada a una carga variando el ancho de los pulsos.

RC Route Costs. Costos relacionados con el trazado físico de las líneas de transmisión.

RCC Route Capital Costs. Costos de capital asociados con la construcción y establecimiento del trazado de líneas.

RLC Route Losses Costs. Costos relacionados con las pérdidas de energía a lo largo de la ruta de transmisión.

STATCOM Static Synchronous Compensator. Dispositivo de compensación de voltaje usado para estabilizar redes eléctricas.

TCC Terminal Capital Costs. Costos de capital específicos asociados a la construcción o mejora de terminales o subestaciones.

TLC Terminal Losses Costs. Costos asociados a las pérdidas de energía en los terminales o subestaciones.

VSC Voltage Source Converter. Convertidor que convierte corriente continua en corriente alterna, utilizado en sistemas HVDC.

XLPE Cross-Linked Polyethylene. Polietileno reticulado, usado en aislamiento de cables eléctricos por su alta resistencia y durabilidad.

Appendix B

List of Variables

Variable	Description	Assumption Value
c	Cable capacitance per unit length	
d_c	Cost factor for a different number (≥2) of transformers, converters	0.2
E_{op}	Energy price per unit	50 £/MWh
FC_{DC}	VSC-HVDC offshore converter station platform fixed cost	25 M£
FC_{AC}	HVAC offshore transformer platform fixed cost	5 M£
f_n	Transmission frequency	50 Hz
l_c	Cable, OHL transmission distance	100 km
n_T, n_c	Number of transformers, converters per offshore platform	2
n_{c_c}, n_{o_c}	Number of cable, OHL parallel circuits	3
pC_T	HVAC offshore transformer plant variable cost	0.025 M£/MVA
pf	Power factor	1
η_{off}	Efficiency of VSC-HVDC offshore rectifier station	98.28%
η_{on}	Efficiency of VSC-HVDC onshore inverter station	98.19%
r_c	Cable resistance per unit length	
S_{SC}	VSC-HVDC single converter power rating	1000 MVA
S_{ST}	HVAC single transformer power rating	800 MVA
S_T	Transmission power rating	2000 MVA
t_c	Cable cost	

Variable	Description	Assumption Value
T_{op}	Total operation hours	
δ	Loss load factor	
V_n	Nominal voltage level	

Table B.1: Assumption Values for Different Variables

Appendix C

Alignment with the Sustainable Development Goals

This master's thesis concentrates on various aspects of connecting offshore wind power generation. As a result, its alignment with the Sustainable Development Goals (SDGs) is attributed not only to its contribution to transmission infrastructure but also to the impact of these infrastructures on the integration of offshore generation into the grid.

Figure C.1: *Sustainable Development Goals* [35].

While the project relates to several Sustainable Development Goals (SDGs), there are specific goals that are particularly interconnected with it. These include the following [36].

- **Affordable and Clean Energy (SDG 7)**.Wind power is a renewable energy source specifically designed to be economically efficient and produce zero emissions.
- **Industry, Innovation and Infrastructure (SDG 9)**.Subsea links not only facilitate the connection of offshore wind production but also enable energy transmission, enhancing the reliability of electrical systems.
- **Climate Action (SDG 13)**. Wind power production avoids significant emissions, and its expansion represents a crucial step forward in the pursuit of combating climate change.
- **Partnerships for the Goals (SDG 17)**. This goal has already been fulfilled to some extent. The elaboration of common international plans, such as the already mentioned REPowerEU, evidences that cooperation among nations in the pursuit of SDGs is possible.

It's noteworthy that some researchers propose an alternative perspective on this matter, claiming that, despite the positive influence of subsea lines on the mentioned SDGs, they have a detrimental impact on 'life below water' (SDG 14). Studies have demonstrated that operational submarine power cables can affect the environment by generating electromagnetic fields, creating artificial reefs, and imposing restrictions on human activities. Furthermore, they alter habitats, particularly sensitive ones, and can result in the resuspension of particles in coastal areas. Nevertheless, mitigation measures have been developed and can be implemented to minimize these impacts and align with environmentally friendly principles [37].

Bibliography

[1] International Renewable Energy Agency. https://www.irena.org/. 2023.

[2] Wind Europe. “Wind energy in Europe: Scenarios for 2030”. In: *Wind Europe: Brussels, Belgium* (2017).

[3] Climate Policy Initiative et al. “Global Landscape of Renewable Energy Finance 2023”. In: (2023).

[4] Marco Liserre et al. “Overview of multi-MW wind turbines and wind parks”. In: *IEEE Transactions on Industrial electronics* 58.4 (2011), pp. 1081–1095.

[5] European Comission. *REPowerEU Plan.* Communication From The Commission To The European Parliament, The European Council, The Council, The European Economic And Social Committee And The Committee Of The Regions. 2022.

[6] Xin Xiang, Michael MC Merlin, and Tim C Green. “Cost analysis and comparison of HVAC, LFAC and HVDC for offshore wind power connection”. In: (2016).

[7] Douglas Elliott et al. “A comparison of AC and HVDC options for the connection of offshore wind generation in Great Britain”. In: *IEEE Transactions on Power Delivery* 31.2 (2015), pp. 798–809.

[8] Thomas Skaanoey et al. “AC subsea power transmission architectures, design and challenges, the martin linge case”. In: *Offshore Technology Conference.* OTC. 2017, D031S038R006.

[9] ENTSO-E AISBL. “Offshore transmission technology”. In: *Report, November* (2011).

[10] Roland Ryndzionek and Łukasz Sienkiewicz. “Evolution of the HVDC link connecting offshore wind farms to onshore power systems”. In: *Energies* 13.8 (2020), p. 1914.

[11] AG Siemens. “Power engineering guide”. In: *Erlangen: Publicis Pixelpark* (2017).

[12] Eleni Tsotsopoulou et al. "Protection scheme for multi-terminal HVDC system with superconducting cables based on artificial intelligence algorithms". In: *International Journal of Electrical Power & Energy Systems* 149 (2023), p. 109037.

[13] María José Pérez-Molina et al. "Challenges for protection of future HVDC grids". In: *Frontiers in Energy Research* 8 (2020), p. 33.

[14] Abha Pragati et al. "A Comprehensive Survey of HVDC Protection System: Fault Analysis, Methodology, Issues, Challenges, and Future Perspective". In: *Energies* 16.11 (2023), p. 4413.

[15] Jonathan Ruddy, Ronan Meere, and Terence O'Donnell. "Low Frequency AC transmission for offshore wind power: A review". In: *Renewable and Sustainable Energy Reviews* 56 (2016), pp. 75–86.

[16] Thomas Worzyk and Thomas Worzyk. "Installation and Protection of Submarine Power Cables". In: *Submarine Power Cables: Design, Installation, Repair, Environmental Aspects* (2009), pp. 161–209.

[17] ENTSO-E. *Technology Factsheets.* https://eepublicdownloads.entsoe.eu/clean-documents/RDC%20documents/2021$_{T}echnology\%20Factsheet.pdf$. 2021.

[18] Nikolas Flourentzou, Vassilios G Agelidis, and Georgios D Demetriades. "VSC-based HVDC power transmission systems: An overview". In: *IEEE Transactions on power electronics* 24.3 (2009), pp. 592–602.

[19] Fu Mingyu, Zhang Aihua, and Xu Jinlong. "Robust adaptive backstepping path tracking control for cable laying vessel based on guidance strategy". In: *2012 IEEE International Conference on Mechatronics and Automation.* IEEE. 2012, pp. 1056–1061.

[20] Parsons Brinckerhoff. "Electricity transmission costing study". In: *Parsons Brinckerhoff* (2012).

[21] R Pletka et al. "Capital costs for transmission and substations: updated recommendations for WECC transmission expansion planning". In: *Black and Veatch PROJECT* 181374 (2014).

[22] Predrag Djapic and Goran Strbac. *Cost benefit methodology for optimal design of offshore transmission systems.* Department for Business, Enterprise & Regulatory Reform, 2008.

[23] N Barberis Negra, Jovan Todorovic, and Thomas Ackermann. "Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms". In: *Electric power systems research* 76.11 (2006), pp. 916–927.

[24] Hae-Il Jung and Yevgen Biletskiy. “Evaluation and comparison of economical efficiency of HVDC and AC transmission”. In: *2009 Canadian Conference on Electrical and Computer Engineering*. IEEE. 2009, pp. 41–44.

[25] Council of European Energy Regulators. *PROJECT CEER-TCB18: Pan-European cost-efficiency benchmark for electricity transmission system operators*. `https://www.ceer.eu/`. 2018.

[26] Kaushik Das and Nicolaos Antonios Cutululis. “Offshore Wind Power Plant Technology Catalogue-Components of wind power plants, AC collection systems and HVDC systems”. In: (2017).

[27] Goolge Maps. “Google maps”. In: *Dipetik Desember* 14 (2015), p. 2015.

[28] Bornholms Regionskommune. https://www.brk.dk/Sider/Forside.aspx. 2023.

[29] *Potencial de Energía Eólica Terrestre y Marina de Europa. Evaluación de las Restricciones Ambientales y Económicas.* Tech. rep. Agencia Europea de Medio Ambiente.

[30] Aymen Chaouachi, Catalin Felix Covrig, and Mircea Ardelean. “Multi-criteria selection of offshore wind farms: Case study for the Baltic States”. In: *Energy Policy* 103 (2017), pp. 179–192.

[31] S.A. Iberdrola. *Baltic Eagle, our second large offshore wind farm in Germany*. https://www.iberdrola.com/. 2023.

[32] Floriana Cerniglia and Francesco Saraceno. *Greening Europe: 2022 European Public Investment Outlook*. Open Book Publishers, 2022.

[33] ENTSO-E. https://www.entsoe.eu/data/map/. 2023.

[34] ArcGIS. https://www.arcgis.com/apps/mapviewer/index.html. 2023.

[35] United Nations. *Sustainable Development Goals*. 2024. URL: `https://sdgs.un.org/goals`.

[36] The United Nations. https://www.un.org/sustainabledevelopment/. 2023.

[37] Bastien Taormina et al. “A review of potential impacts of submarine power cables on the marine environment: Knowledge gaps, recommendations and future directions”. In: *Renewable and Sustainable Energy Reviews* 96 (2018), pp. 380–391.