Evaluating Transmission System Alternatives for Offshore Wind:

A Multi-Criteria Analysis of High-Voltage Solutions

Evaluating Transmission System Alternatives for Offshore Wind: A Multi-Criteria Analysis of High-Voltage Solutions

A Systems Engineering Evaluation of Export Options with a Focus on the Potential of Direct-to-Shore Configurations

By

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AEP	Annual Energy Production
BWM	Best-Worst Method
BWT	Best-Worst Tradeoff
CAPEX	Capital Expenditure
CoSEM	Complex Systems Engineering & Management
DM	Decision Maker
FEPM	Front End Park Model
FID	Final Investment Decision
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEA	International Energy Agency
MCA	Multi-Criteria Analysis
MCDM	Multi-Criteria Decision-Making
MVAC	Medium Voltage Alternating Current
ONS	Onshore Substation
OPEX	Operational Expenditure
OSS	Offshore Substation
PD	Project Director
SPOrgC	Single Point Organisation Chart
TPM	Technical Project Manager
TSO	Transmission System Operator
WTG	Wind Turbine Generator

Abstract

The global expansion of offshore wind energy has accelerated in recent years, driven by the increasing demand for clean electricity and advances in turbine technology. However, as projects grow in scale and move farther from shore, the challenge of cost-efficient power transmission becomes increasingly critical. Transmission infrastructure - including offshore substations and export cables - can account for up to 30% of a wind farm's capital expenditure, making design choices in this area a key determinant of overall project viability.

As offshore wind turbines continue to scale up, so do their electrical capabilities. Recent developments have enabled turbines to generate electricity at 132 kV, which raises a critical design question: can 132 kV also be used as the export voltage directly to shore eliminating the need for costly offshore substations (OSS)? In conventional offshore wind farm layouts, an OSS is used to collect the electricity generated by the turbines and step up the voltage before transmission to shore, reducing energy losses. This thesis explores whether such direct-to-shore configurations offer a viable alternative to conventional transmission systems with offshore voltage step-ups.

Although 132 kV systems are emerging in planned projects, the literature predominantly treats 132 kV as an infield voltage. The idea that it might also enable direct-to-shore transmission is mentioned only briefly, with no accompanying technical or economic evaluation. This lack of analysis likely stems from the novelty of the technology: turbines that can generate at 132 kV have only recently entered the market. Consequently, the opportunity to eliminate OSS, which is typically one of the most expensive and complex components of an offshore wind farm, has not been critically assessed.

This thesis addresses that knowledge gap through a multi-criteria decision-making (MCDM) approach that integrates technical, economic, environmental, regulatory, and implementation considerations. The Best-Worst Tradeoff (BWT) method is applied to ensure structured and consistent criteria weighting, reflecting stakeholder priorities. By applying this method to Vattenfall's Kattegatt Syd project - a planned 1.2 GW offshore wind farm in Sweden - the study demonstrates how the framework can be used as a decision-support tool for early-stage design evaluations.

Four transmission system alternatives were compared, including two with OSS and two direct-to-shore options. Stakeholder input was gathered through in-depth interviews with two key decision-makers (DMs) at Vattenfall: the Technical Project Manager (TPM) and the Project Director (PD). These stakeholders were asked to assess performance trade-offs

and weight the importance of seven criteria, including:

- **Economic:** CAPEX, OPEX, Revenue
- **Implementation:** Risk, Ease of Implementation
- **External:** Environmental & Permitting Impact
- **Future-readiness:** Innovation & Scalability

The results show that 132 kV direct-to-shore transmission outperforms OSS-based configurations on CAPEX, Revenue, Risk and Innovation & Scalability, mainly due to reduced infrastructure and supply chain uncertainty of the OSS. However, it scores lower on Ease of Implementation and Permitting Complexity, due to it being a less mature solution and requiring more cables to and on shore (complicating the permitting process). After combining stakeholder weightings and performance scores, the 132 kV direct-to-shore configuration emerged as the top-ranked alternative for both decision-makers.

This thesis contributes scientifically to the fields of offshore wind power and multi-criteria decision-making. It addresses a clear gap in the literature by evaluating 132 kV direct-to-shore systems across technical, economic, and regulatory dimensions. In doing so, it also introduces a previously undocumented system configuration (a 132 kV direct-to-shore setup with an onshore substation near landfall) developed during the research based on expert input. Furthermore, the study advances the application of the Best-Worst Trade-off (BWT) method by demonstrating its suitability for complex infrastructure decisions in the energy domain. As BWT is a relatively new method with limited application in real-world settings, this research contributes to its validation and showcases its potential as a transparent and structured decision-support tool. In this way, the thesis strengthens the scientific foundation for future offshore grid design and supports the continued development of robust multi-criteria evaluation methods.

Contents

1 Introduction

1.1 Context

The increasing demand for electric power and the growing consciousness towards the changing climate has led to a rapid development of renewable energy in recent years [36]. Since the installation of the first offshore wind turbine in 1991 [22], the offshore wind industry has experienced significant growth [20]. Offshore installations provide superior wind conditions compared to onshore sites, benefiting from reduced turbulence and higher average wind speeds, which make them particularly attractive for wind energy generation [22]. Additional advantages include minimizing visual and noise pollution impacts on nearby communities [2]. On a global scale, the offshore wind sector is projected to expand further, with the International Energy Agency (IEA) forecasting an annual growth rate of 13% through 2040 under their Stated Policies Scenario. By that time, the sector could reach nearly 340 GW of installed capacity, contributing approximately 3% of the predicted global electricity supply [15]. Moreover, projections by [20] show that offshore wind can deliver one-third of the required global power sector emissions reductions for a net zero world by 2050.

However, as offshore wind farms continue to increase in size and expand further from the coast, new technical and economic challenges arise. One of the main difficulties is managing the efficient transmission of power [36]. A considerable proportion of offshore wind project expenses comes from power transmission. For projects completed in 2018, these costs accounted for 20% to 30% of the total capital investment [15]. Of these transmission-related costs, an earlier estimate from [24] suggests that 85–90% stem from the export grid connection, linking the offshore substation (OSS) to the onshore grid. Thus, optimizing the export grid for offshore wind farms is critical to improving the financial viability of these projects.

1.2 Background Offshore Wind Transmission

An offshore wind farm consists of multiple wind turbines installed at sea to generate electricity. The wind moves the turbine blades, which drive a generator that converts kinetic energy into electrical energy. These turbines are securely anchored to the seabed using foundations [43].

The generated electricity follows a multi-step transmission process to efficiently transport power from the turbines to the onshore grid. First, inter-array cables connect individual wind turbines to an offshore substation. These cables currently typically operate at 33 kV or 66 kV and serve as the first stage of electricity transmission. Their key functions include:

- Collecting electricity generated by each wind turbine.
- Grouping turbines in clusters/strings and routing power to the offshore substation.

Without inter-array cables, power would need to be transmitted separately from each turbine, leading to inefficiencies and higher costs [49]. The electricity collected via inter-array cables arrives at the offshore substation. Here, voltage transformation occurs, typically stepping up the voltage from 33 kV or 66 kV to 132 kV, 220 kV, 400 kV or higher. The selection of voltage level can influence aspects such as transmission losses and suitability for longer distances [43]. To what level the voltage is typically stepped up is dependent on factors such as:

- Distance to shore
- Wind farm capacity
- Grid connection requirements
- Cost-benefit considerations, including infrastructure costs and energy losses [49].

Once stepped up in voltage, the electricity is transmitted via high-voltage export cables to an onshore substation (ONS). Upon reaching the ONS, the electricity undergoes further voltage transformation to match the onshore grid requirements before being connected to the grid and distributed to consumers [43]. A schematic representation of this process is given in Figure 1

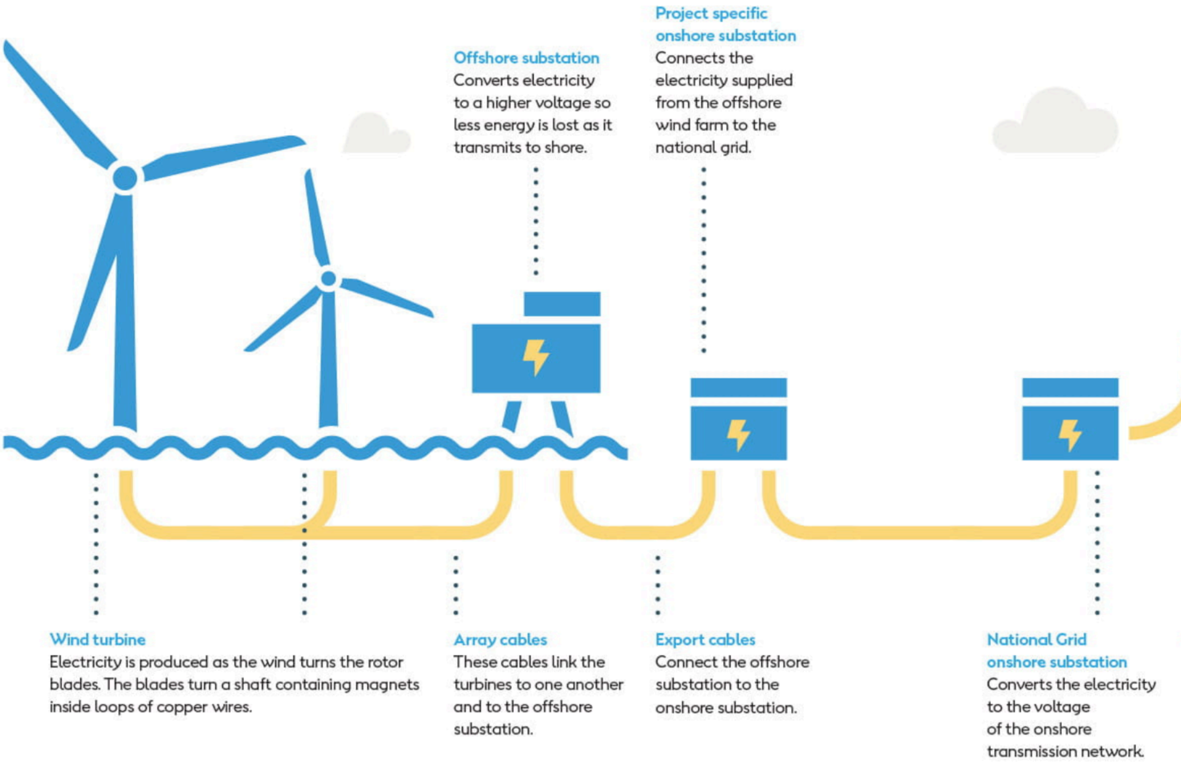

Figure 1: Schematic Representation Offshore Wind Farm [30]

1.3 Reasoning for this research

The voltage levels used in offshore wind farms have not remained static. To analyze trends in offshore wind farm transmission design, data from the TGS 4C Offshore database was used. TGS 4C Offshore is a widely recognized industry database that provides detailed information on offshore wind projects worldwide, including their status (concept, early planning, development, consent application, or fully commissioned) [28]. Using this database, a dataset was compiled containing offshore wind farms with their year of full commissioning (both past and planned) and their infield nominal voltage. The infield nominal voltage refers to the voltage level at which electricity is transmitted within the wind farm, specifically between individual wind turbines and the OSS [28]. Wind turbines typically generate electricity at this voltage level before it is transmitted through inter-array cables. Then, at the OSS the infield voltage is stepped up for transmission to shore. The year of full commissioning represents the year in which a wind farm is fully operational and connected to the grid, marking its official entry into commercial operation. By analyzing wind farms based on their full commissioning year, a clear evolution in infield voltage levels over time can be observed, as seen in Figure 2.

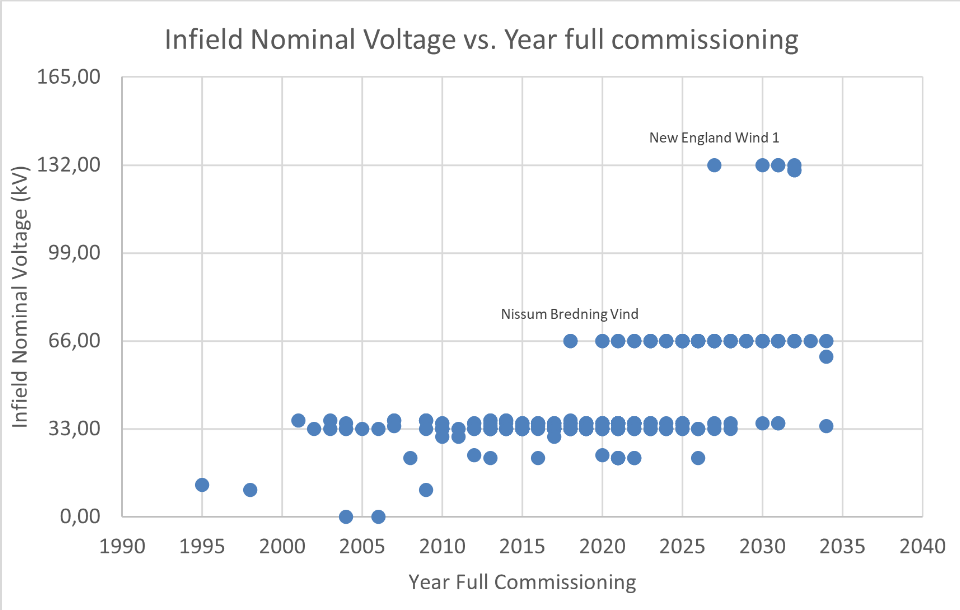

Figure 2: Infield Nominal Voltage

1.3.1 Observed Trends

The data reveals several key insights into the evolution of infield nominal voltages over time:

- **Limited offshore wind activity before 2000**: Before the year 2000, there were very few offshore wind farms, as offshore wind energy was still in its early stages. The few projects that existed primarily used low voltage levels.
- **Dominance of 33 kV for nearly three decades**: From 2000 onwards, most offshore wind farms adopted an infield voltage of around 33 kV, which remained the dominant standard for almost 30 years. This period was marked by steady growth in offshore wind capacity.
- **Transition to 66 kV (Post-2017)**: Around 2017, a shift toward 66 kV infield voltages began, marking an industry-wide transition. This development can primarily be attributed to two drivers:
  - **TSO requirements**: Transmission System Operators (TSOs) began setting voltage requirements for offshore wind farms. A notable example is the Borssele 1 & 2 wind farms in the Netherlands, commissioned in 2020, where TenneT required a 66 kV infield voltage. By defining voltage standards, TSOs played a crucial role in introducing this change and shaping industry adoption [42].
  - **Turbine scale-up**: The transition also correlates with the increasing deployment of larger wind turbines. Until 2015, offshore wind farms predominantly used turbines up to 4 MW [28], which corresponded with the use of 33 kV. The introduction of turbines above 5 MW (6–8 MW) around 2015 coincides with the adoption of 66 kV [28]. The increased power output necessitated higher

infield voltages to reduce electrical losses and improve efficiency. Now, with the industry moving toward 10 MW+ turbines [28], the emergence of 132 kV aligns with this trend [42].

- **Emergence of 132 kV (Post-2025)**: More recently, planned offshore wind projects indicate a shift toward 132 kV infield voltages. The trend in the industry is toward larger and more powerful turbines, driven by economic efficiencies. Original Equipment Manufacturers (OEMs) - companies that design and supply key components such as turbines, cables, and substations - have already announced new turbine models featuring 132 kV voltage levels for upcoming projects [7]. According to a Carbon Trust report as part of the Offshore Wind Accelerator (OWA) programme, doubling the array voltage from 66 kV to 132 kV will be critical to enabling the next generation of turbines (14-20 MW) and helping the global offshore wind industry scale up to 250 GW by 2030. Their Hi-VAS (High-Voltage Array Systems) project identified 132 kV as the "cost-optimal" choice among various candidates. According to this research, a 1.2 GW offshore wind farm could save between £32–50 million by using a 132 kV system instead of a 66 kV one, due to reduced cable lengths and more efficient power collection [26]. Despite these advantages, the transition from 66 kV to 132 kV is still in its early stages. The previous voltage shift, from 33 kV to 66 kV, took around 15 years, and it remains uncertain how long the shift to 132 kV will take. Contributing factors include political and regulatory developments, supply chain uncertainties, and economic conditions.

  Nevertheless, it is evident from the data depicted in Graph 2 that 132 kV systems are beginning to appear and will play a significant role in the future of offshore wind. Early projects in the pipeline featuring 132 kV include New England Wind 1 and Leading Light Wind in the United States [28]. Similar initiatives are also emerging in the UK, Germany, and France [28], indicating a broader international adoption of this higher voltage standard.
- **132 kV projects to gain dominance**: The data suggests that 132 kV projects are not only emerging but are on track to overtake 66 kV projects in the future, driven by advancements in turbine technology and evolving transmission system requirements.

1.4 Problem Description and Research Goal

In this section, the problem that the research is addressing is described and the goal of the research and specific objectives will be given.

1.4.1 Problem Description

These trends in voltage levels raise a critical question: if turbines are increasingly becoming capable of generating at 132 kV voltage level, does it remain necessary to add offshore substations to further step up the voltage - such as from 132 kV to 220 kV - or does this added complexity and cost outweigh the potential benefits? Offshore substations are major cost drivers in wind farm development, requiring significant investments in platform construction, installation, and maintenance [33]. This question becomes even more urgent considering the current challenges in the offshore wind sector. Financial pressures, rising construction costs, and unprofitable tender outcomes are putting the economic feasibility of new wind projects at risk [6], [27]. A notable example of this uncertainty in the offshore wind market is the Danish offshore wind tender in late 2024, which aimed to award licenses for three large-scale wind farms. However, the tender attracted no bids, mainly due to an unattractive subsidy-free financial model, rising costs, and high risk exposure for developers [34].

In this context, simplifying transmission system design by omitting offshore substations could offer a crucial cost advantage. This research aims to determine under what conditions direct-to-shore (without an OSS) 132 kV transmission is a viable alternative to conventional step-up configurations.

1.4.2 Goal of the Research

To achieve this, the study will conduct an analysis of offshore wind transmission systems by comparing configurations that include an offshore substation with direct-to-shore transmission to evaluate their technical feasibility and economic trade-offs. To ensure practical applicability, this study will focus on a selected offshore wind reference project within Vattenfall's portfolio, the specific project will be introduced in Chapter 3. This will serve as a case study to test the evaluation framework for the comparison between the transmission alternatives, which will be designed to be applicable to other offshore wind projects in the future as well.

This study will use the Best-Worst Tradeoff (BWT) method, a multi-criteria decision-making approach, to rank the different transmission alternatives based on key criteria. The BWT method will allow for a structured quantitative comparison, helping to establish the conditions under which direct-to-shore 132 kV transmission is the most advantageous choice.

Further details on the methodology, research approach, and sub-research questions will be elaborated in Chapter 3: Methodology.

1.4.3 Research Objectives

The objective of this thesis is to evaluate whether a 132 kV direct-to-shore transmission system is a viable alternative to using an offshore substation, specifically for selected offshore wind projects at Vattenfall. This evaluation is based on a multi-criteria framework that includes technical, economic, regulatory, environmental, and implementation-related aspects. The study compares the direct-to-shore configuration with the conventional setup involving an offshore substation, aiming to determine under which conditions the direct solution can be technically feasible, cost-effective, and advantageous. The findings will support Vattenfall in making informed design choices for future offshore wind developments.

1.5 Scope

In this section, a clear system boundary is determined and the different components of the systems are defined.

1.5.1 System Scope

This study focuses on the export system of an offshore wind farm, covering the transmission of electricity from the inter-array cables to the onshore grid connection. Two different system configurations are considered: a configuration including an OSS and a direct-to-shore configuration without an OSS. The system consists of the following key components:

- Inter-Array Cables (66 or 132 kV): Collect electricity from multiple turbines and deliver it to the next stage of the system.
- Offshore Substation (optional, depending on system choice): Voltage transformation before export to shore.
- Export Cables (132 kV or higher): Transmit power to the onshore grid.
- Onshore Grid Connection: Integration with the national transmission system.

The system boundary starts at the inter-array cables. Therefore, the design and selection of the wind turbine generators (WTGs) are considered outside the scope of this research. It is assumed that turbines deliver power at either 66 kV or 132 kV, depending on the project specifications, but different turbine technologies and variations are not assessed in this study.

The two different configurations are depicted in Figure 3 below.

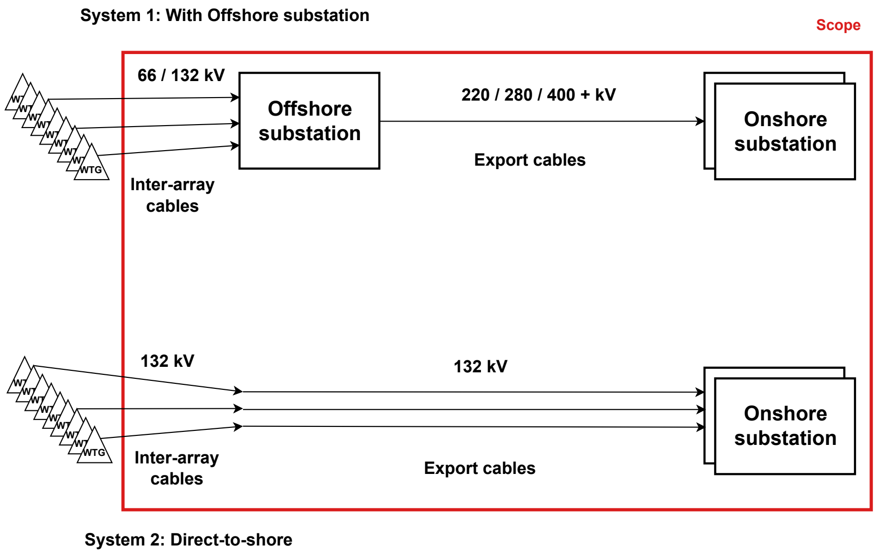

Figure 3: System Scope

1.5.2 Geographical Scope

Additionally, it is important to note that the responsibility for the construction and ownership of the OSS differs across countries. In some countries, wind farm developer is responsible for building the offshore substation [32], [12], [37], [8]. In other countries, this responsibility lies with the Transmission System Operator (TSO) [46].
This study specifically focuses on countries where the developer (i.e. Vattenfall) is responsible for building and maintaining the offshore substation and only projects within such regulatory frameworks are considered for analysis [46].

1.5.3 Scenario Scope

This study analyses a specific offshore wind project within Vattenfall's current portfolio to assess the practical applicability of different export system configurations. By evaluating real project scenarios, the study aims to ground the comparative analysis in realistic boundary conditions, such as distance to shore and expected power output. The selected case enables a context-specific assessment of the technical feasibility and relative performance of 132 kV export options, both with and without offshore substations.

1.6 Link to CoSEM program

The interdisciplinary nature of this research aligns closely with the objectives of the MSc program in *Complex Systems Engineering & Management (CoSEM)*, Energy track. Offshore wind transmission systems function within a highly complex socio-technical environment that spans not only technical engineering design but also regulatory, institutional, economic, and environmental dimensions.

This thesis does not merely aim to optimize technical system components such as voltage level, cable configuration, or substation design. It also takes into account the broader system-level challenges such as stakeholder alignment, the division of responsibilities between developers and TSOs, varying national regulatory regimes, permitting processes etc. These dimensions are essential for designing feasible and effective interventions that work not just in theory, but also in practice, an approach that is central to the CoSEM philosophy.

The research adopts a Systems Engineering approach to compare and evaluate transmission configurations, systematically identifying stakeholder, assessing trade-offs, and integrating both technical and non-technical constraints. This reflects the CoSEM program's emphasis on the design and governance of large-scale, interconnected systems.

Courses such as *Engineering Optimization and Integrating Renewables in Electricity Markets* (SEN1511), *Electricity and Gas: Market Design and Policy Issues* (SEN1522), and *Design of Integrated Energy Systems* (SEN1531) have equipped me with the analytical and design skills necessary to understand and optimize energy infrastructure from both a technical and market perspective. Furthermore, *Sociotechnology of Future Energy Systems* (SEN1541) deepened my understanding of the social and institutional dynamics that influence the success of energy transitions, which directly informs the stakeholder and regulatory analysis in this thesis.

By integrating these disciplinary perspectives and methodologies, this research contributes to the design of robust, future-proof offshore wind transmission solutions - fully in line with the CoSEM program's mission to educate engineers capable of intervening effectively in complex socio-technical systems.

1.7 Collaboration with Vattenfall

In this study, a request from Vattenfall to further explore alternative offshore wind transmission systems (specifically focusing on the potential of 132 kV direct-to-shore export configurations) was addressed. Vattenfall, a major European energy company, is actively engaged in the development and operation of offshore wind farms and is investigating new system designs to optimize efficiency, reduce costs, and support the future scalability of offshore grid connections. Based on internal considerations and future project ambitions, Vattenfall identified the evaluation of 132 kV direct-to-shore export systems as a relevant and timely topic [33].

The collaboration with Vattenfall provided essential industry insights and ensured the relevance of the study to real-world challenges, significantly enriching the academic depth and practical value of this thesis. Due to the inclusion of business-sensitive information, Vattenfall will review the final version of this thesis prior to publication. To protect proprietary data, all quantitative economic results in the public version of this thesis will be presented in a redacted form, rather than as absolute values derived from Vattenfall's internal business cases.

1.8 Structure of the thesis

This thesis is structured into six chapters. Chapter 1 introduces the context of offshore wind transmission, outlines industry trends, presents the research motivation, problem description, and defines the study's objectives and scope. Chapter 2 presents the literature review and identifies the knowledge gap. It also introduces the main research question and sub-research questions that guide the rest of the analysis. Chapter 3 outlines the research methodology, including the rationale for applying the Best-Worst Tradeoff (BWT) method, the structure of the multi-criteria decision-making process, and the overall research flow. This chapter also introduces the selected case study (Kattegatt Syd) which serves as the reference project for the analysis. Chapter 4 presents the results of the study. It begins with the regulatory context of the Kattegatt Syd project, followed by the stakeholder analysis, definition of transmission system alternatives, selection and validation of evaluation criteria, performance assessment, criteria weighting, and final multi-criteria scoring. Chapter 5 concludes the thesis by synthesizing the findings, discussing limitations and methodological reflections, validating the results, and providing recommendations for future research and offshore wind transmission planning. Lastly, Chapter 6 contains the appendices.

2 Literature Review and Knowledge Gap

To understand the current state of research in this field, a systematic literature review was conducted. This review provides a comprehensive overview of existing studies and insights. Based on the findings, the knowledge gap that forms the foundation of this thesis is identified and discussed.

2.1 Methodology literature review

The literature review was conducted using a systematic approach to identify relevant articles regarding transmission alternatives for offshore wind parks. First the articles are searched, screened and then selected based on relevancy for the review. To conduct a scoping literature review, key databases such as Mendeley, Google Scholar, and ScienceDirect were searched for relevant studies. The search terms included "offshore wind," "transmission," "export system", "direct-to-shore", "alternatives," "transmission systems", "grid connection," "voltage levels," "turbine voltage levels," "multi-criteria analysis." Initial results yielded over 100 articles, which were filtered down to 17 based on if the title seemed relevant to the subject, criteria such as publication date, article language and lastly duplicate articles were deleted. Finally, to ensure a comprehensive overview, a backward search was conducted on these articles by examining the references. Of these remaining articles the abstracts, introductions and conclusions were reviewed to confirm their relevance to the subject. The final selection comprised of 11 articles. The search and selection process is visualized in Figure 4.

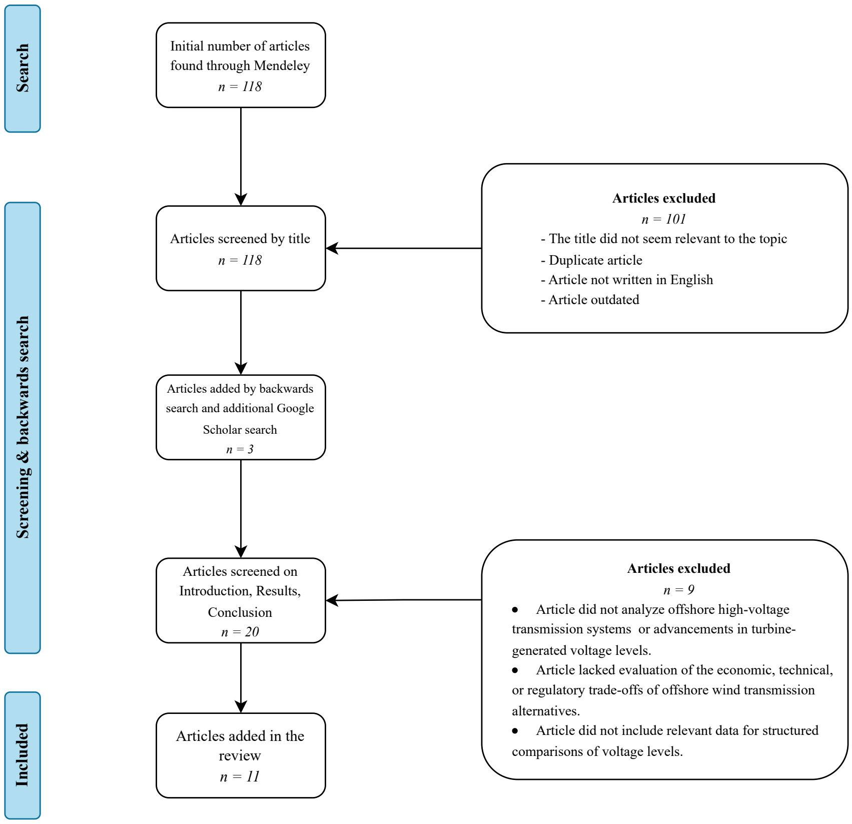

Figure 4: Search and selection process

2.2 Knowledge gap

To facilitate the comparative analysis of key literature on offshore wind transmission systems, an analytical table is constructed and presented as Table 1 below. The table evaluates each study based on the following core concepts: topic, technical depth, economic analysis, regulatory insights, consideration of turbine voltage advancements and relevance to the research. By using consistent criteria, the table highlights both the strengths and limitations of the studies, offering valuable insights that support the thesis' focus on optimizing transmission systems for offshore wind energy.

Reference	Topic	Technical Depth	Economic Analysis	Regulatory Insights	Considers Turbine Voltage Level Advances	Applicability to Thesis
Widuto (2024)	Wind energy and EU climate targets	Low	None	High	No	Provides policy context but lacks technical relevance.
Energinet (2023)	Offshore energy hubs and HVDC systems	High	Minimal	None	Yes	Examines transmission configurations and mentions eliminating substations.
Bergmann et al. (2018)	Policy and regulatory barriers for offshore meshed grids	Low	None	High	No	Provides insights into regulatory challenges for offshore grids.
JMSE (2023)	Offshore wind integration and transmission systems	Moderate	General trends	Limited	Partially	Provides industry-wide benchmarks for transmission design.
Schachner (2005)	AC transmission at wind farm voltage	Moderate	Minimal	Limited	No	Highlights challenges in lower voltage transmission.
Adeuyi (2020)	HVAC and HVDC technologies for GB offshore wind	Moderate	Minimal	Limited	No	Offers insights into transformer usage for offshore transmission.
Coffey et al. (2021)	MVDC technologies and applications	Low	None	None	No	Explores potential of MVDC but lacks practical examples.
Dakic et al. (2020)	HVAC systems with reactive power compensation	Moderate	Moderate	None	No	Provides technical and cost insights for HVAC optimization.
Larsson (2021)	Economic breakpoints for HVAC and HVDC systems	Moderate	Detailed cost breakpoints	None	No	Directly informs cost-distance trade-offs in transmission systems.
Datta (2022)	MVDC collection and HVDC transmission	High	Minimal	None	No	Supports comparisons of advanced transmission architectures.
Liang et al. (2022)	Best-Worst Tradeoff Method (BWT)	High	None	None	No	Provides decision-making model for evaluating transmission trade-offs.
Carbon Trust (2022)	Global offshore wind industry to increase voltage	Low	None	None	Yes	Identifies industry trend toward higher turbine voltage levels.

Table 1: Analytical Table

The analytical table offers a comparative overview of key literature on offshore wind transmission systems. These studies span regulatory, technical, and economic dimensions, each contributing differently to understanding transmission design. For instance, Widuto (2021) and Bergmann et al. (2018) offer policy-oriented perspectives, emphasizing how regulatory frameworks influence offshore system development. In contrast, technical contributions - such as Energinet (2023) and Datta (2022) - focus on transmission configurations and emerging architectures. Other works, like Larsson (2021) and Dakic et al. (2020), provide detailed cost analyses related to transmission distance thresholds (HVAC vs. HVDC) and technical optimization strategies for HVAC systems. Even though these articles do not focus specifically on direct-to-shore transmission, they are relevant to see how design trade-offs are addressed in comparable transmission contexts, and to identify variables that influence the choice between different system architectures. Lastly, Liang et al. (2022) introduces a structured evaluation method (Best-Worst Method) to support design decision-making. Together, these studies provide technical, economic, and regulatory insights that are highly relevant to offshore transmission planning. However, the analytical overview also reveals several important knowledge gaps.

While 132 kV turbine voltage levels are increasingly cited in recent reports (e.g., Energinet, 2023 and Carbon Trust, 2022) as an emerging industry standard, their broader implications for export system design - particularly the feasibility of direct-to-shore transmission - have not yet been systematically explored. The literature predominantly discusses 132 kV as an infield voltage, and the idea that it might enable direct-to-shore export appears only once, briefly mentioned in Energinet (2023), without further technical or economic assessment. This lack of in-depth analysis can largely be attributed to the novelty of this voltage level: offshore wind turbines capable of generating at 132 kV are a recent development. Consequently, the potential to eliminate offshore substations has not yet been critically assessed. In addition, current comparative studies of offshore transmission systems largely focus on standard HVAC versus HVDC configurations and are predominantly techno-economic in nature. They rarely assess broader criteria such as project risk, innovation potential, or environmental and permitting complexity in an integrated manner. Even fewer studies incorporate regulatory context or stakeholder preferences into the evaluation. As a result, no comprehensive, multi-dimensional framework currently exists for assessing non-standard configurations like 132 kV direct-to-shore export.

This study addresses that gap by conducting a multi-dimensional assessment that goes beyond traditional techno-economic analyses by integrating regulatory context and stakeholder perspectives. By applying this method to a real-life offshore wind case, the study demonstrates the practical applicability of this framework as a decision-support tool, especially for early-stage design evaluations.

2.3 Research Questions

This study aims to address the knowledge gap identified above through a main research question which is further divided into 5 sub-research questions. Together, these sub-research questions form the structure of the study as a whole. The main research question reads as follows:

For selected offshore wind projects in Vattenfall's portfolio, how can a high-voltage transmission system be selected?

To answer the main research question, the following sub-research questions have been formulated:

- SRQ 1: How do the regulatory cost allocation structures in countries where Vattenfall operates offshore wind projects affect the consideration and potential of direct-to-shore transmission solutions?
- SRQ 2: Which stakeholders are involved in the selection of a certain high voltage transmission system for a project in Vattenfall's portfolio?
- SRQ 3a: Which criteria should be considered when evaluating offshore wind transmission systems and how do the different transmission system alternatives perform on these criteria?
- SRQ 3b: What is the relative importance (weighting) assigned to each criterion by stakeholders involved in the decision-making process?
- SRQ 4: How does direct-to-shore transmission compare to transmission with an offshore substation when the performance scores assigned by experts are combined with the criteria weightings established by stakeholders to calculate final scores?

3 Methodology

This chapter outlines the methodology used to systematically address the research question. It presents the structured approach, including the methods, techniques, and key decisions made throughout the research process.

3.1 Main Research Approach

To evaluate offshore wind transmission system alternatives in a structured and transparent way, this study applies a Multi-Criteria Decision-Making (MCDM) approach. MCDM refers to a class of methods used to support decision-making when multiple, and often conflicting, evaluation criteria must be considered simultaneously. MCDM allows for the integration of both quantitative and qualitative criteria by assigning performance scores and determining the relative importance (weights) of each criterion. In this research, the Best-Worst Tradeoff (BWT) method is used, as it combines two well-established techniques: the Tradeoff procedure and the Best-Worst Method (BWM) [21].
Both methods bring valuable strengths to the table, but also have specific limitations that make them less suitable for use in isolation. By combining both methods, the BWT method enables a more reliable and nuanced weighting process.

3.1.1 Tradeoff Method

The Tradeoff procedure originates from Multi-Attribute Value Theory (MAVT) and is designed to ensure that criterion weights reflect actual trade-offs across different performance levels. In this method, decision-makers are asked how much of one *attribute*[1] they are willing to give up in return for gains in another. These trade-offs are made over the full performance range of each attribute, meaning that the range is explicitly considered in the weighting process [21]. This is important because the significance of an attribute often depends on the extent of variation it shows within the decision context. For example, when asked what the most important criterion is when buying a car, a decision-maker might initially say price. However, when comparing two concrete alternatives with only a small difference in price but a large difference in safety perception, the decision-maker may reconsider and prioritize safety instead. This illustrates how incorporating attribute ranges can lead to more realistic and context-sensitive preferences. The Tradeoff method thus enables decision-makers to express preferences while explicitly accounting for the performance span of each attribute. However, the method does not include a formal mechanism for checking the internal consistency of these judgments, which may lead to

[1] In decision analysis, a *criterion* refers to the dimension used to evaluate alternatives (e.g., CAPEX, risk), while an *attribute* refers to the measurable performance level of an alternative on that criterion (e.g., €700M, risk score 3/5).

subjective errors or contradictions in practice. Although some suggestions exist to improve robustness through additional questioning [19], there is no clear guidance on how to do this effectively [21].

3.1.2 Best-Worst Method

The BWM is an optimization-based approach designed to improve the consistency of weight elicitation in multi-criteria decision-making. It requires decision-makers to first identify the most important ("best") and least important ("worst") criteria among a predefined set. Pairwise comparisons are then conducted between the best criterion and all other criteria, as well as between the worst criterion and all other criteria. These comparisons generate a set of numerical weights that reflect the relative importance of each criterion, while also ensuring that decision-makers maintain internal consistency. Additionally, by incorporating the philosophy of BWM - using two vectors of pairwise comparisons based on two opposite references (best and worst) within a single optimization model - the method also helps mitigate anchoring bias, which is more common in approaches that rely on a single anchor point. However, BWM does not explicitly consider the range of each attribute, which can lead to weight distortions when criteria vary significantly in scale or impact [21].

3.1.3 Best-Worst Tradeoff (BWT) Method

The BWT method operationalizes a hybrid approach by combining the dual-reference structure of the Best-Worst Method with the explicit consideration of performance ranges from the Tradeoff method. In practice, decision-makers first select the most and least important criterion, and then express trade-offs in two directions: (1) how much of the best criterion's performance the decision-maker is willing to give up to gain full performance on another criterion (*best-to-others*), and (2) how much of another criterion's performance the decision-maker is willing to give up to gain full performance on the worst criterion (*others-to-worst*). These comparisons are made using real performance ranges, ensuring that the trade-offs reflect actual variation in system outcomes. This dual anchoring structure also helps reduce the risk of anchoring bias, as preferences are not tied to a single reference point. At the same time, like the Tradeoff procedure, the BWT method explicitly accounts for the range of attribute values. This ensures that criteria with substantial performance variations are appropriately weighted in the decision process [21].
As a result, the BWT method generates a set of criterion weights that are both internally consistent and sensitive to the relative impact of each criterion across its range. This combination makes the BWT method particularly well-suited for this research, where offshore wind transmission systems must be evaluated based on multiple conflicting criteria.

3.1.4 Motivation for the Chosen Method

The BWT method was selected for this study because it effectively addresses the complex, MCDM challenges involved in offshore wind transmission system planning. Such decisions require balancing multiple, often conflicting objectives, such as minimizing capital and operational expenditures, ensuring technical and regulatory feasibility, mitigating environmental impacts, and future-proofing infrastructure investments.

Offshore wind projects are also highly context-specific: factors such as the distance to shore, national regulations, wind farm size, and the maturity of available technologies can vary greatly between cases. As a result, a method was needed that combines analytical structure with enough flexibility to be applied across different project settings.

The BWT method meets these needs by offering:

- Consistent and comparable evaluation of alternatives across diverse projects.
- Structured incorporation of expert judgment while minimizing inconsistencies, just as in traditional methods such as the Analytic Hierarchy Process (AHP) or the Tradeoff Method.
- Clear and systematic analysis of trade-offs between competing system objectives.
- Transparency in decision-making, supporting validation, communication, and strategic planning.

Compared to other multi-criteria analysis methods, BWT enables a more consistent and transparent weighting of evaluation criteria, reducing biases in expert assessments and supporting better traceability of the final outcomes. Its structured nature is particularly suited for decisions where both quantitative performance and qualitative expert insights must be combined in a robust and reproducible way. Thus, BWT provides a structured yet adaptable framework that is well-aligned with the complex and context-specific nature of offshore wind transmission planning.

3.2 Research Flow of the Thesis

The overall research approach is structured in four sequential phases, aligned with the four sub-research questions (SRQs) of this thesis.

The research begins with an assessment of the regulatory context (SRQ 1), focusing on the cost allocation structures in countries where Vattenfall operates offshore wind projects. It investigates whether the offshore substation is typically financed by the developer or the Transmission System Operator (TSO), which directly influences the feasibility and relevance of direct-to-shore transmission options for Vattenfall.

The second phase consists of a stakeholder analysis (SRQ 2), in which relevant actors involved in the selection of offshore transmission systems for Vattenfall projects are identified. This step uses a Power-Interest grid to determine which stakeholders will be included in the preference elicitation process.

The third phase concerns the development of the multi-criteria decision making (MCDM) framework. This is addressed through two sub-questions. First, SRQ 3a identifies which evaluation criteria are relevant for the comparison and assesses how the different transmission alternatives perform on these criteria. This includes collecting real-world performance data on aspects such as CAPEX, OPEX, risks and permitting impacts. Second, SRQ 3b focuses on the relative importance of these criteria in the decision-making process as perceived by the key stakeholders. This is done through the Best-Worst Tradeoff method, which elicits weights that reflect stakeholder preferences.

In the fourth phase, the performance scores per criteria are combined with the elicited weights per criteria to compute an overall MCDM score for each transmission system alternative. This directly addresses SRQ 4, by evaluating how the direct-to-shore option compares to transmission via an offshore substation when both assessed performance and stakeholder preferences are taken into account. Through this final MCDM score a ranking of alternatives can be made based on their total scores.

These phases of this research are shown in the Research Flow Diagram in Figure 5 below.

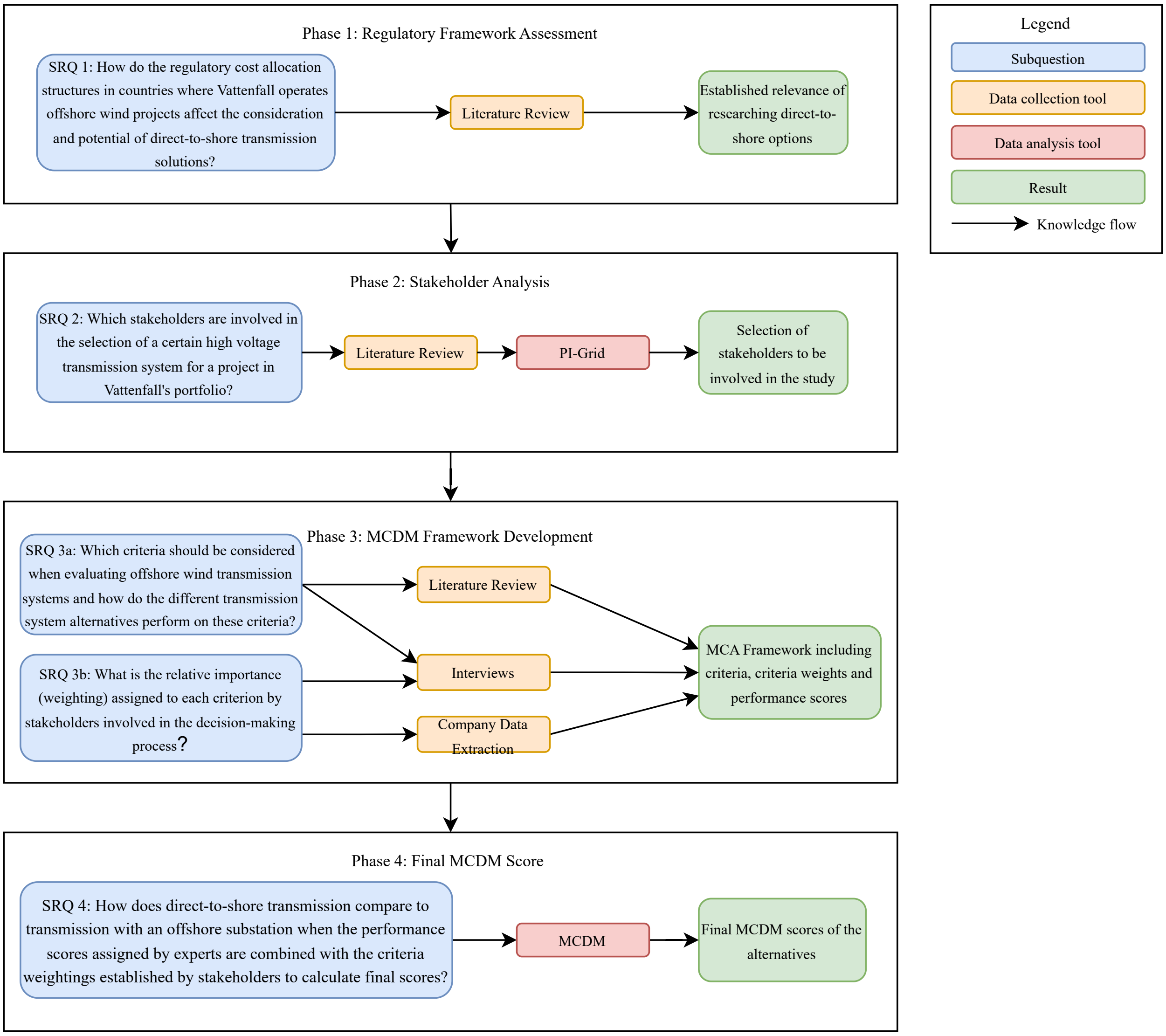

Figure 5: Research Flow Diagram for this Thesis

3.3 Steps of the (BWT) method

This subsection provides a more detailed overview of the steps of the (BWT) method and how they are applied in this thesis. The following steps are carried out:

1. **Regulatory framework assessment:** The permitting and legal environment is examined to understand how transmission costs are allocated between the developer and the TSO in the country of the selected project. In certain countries, building the offshore substation is the responsibility of the TSO, in which considering direct-to-shore would not be applicable for Vattenfall.

2. **Stakeholder analysis:** A Power-Interest (PI) grid is used to identify and categorize relevant stakeholders based on their influence and involvement in offshore wind

transmission system decisions. On the basis of this analysis it is decided which stakeholders are the decision makers in this study and therefore will be included in the analysis.

3. **Define alternatives:** The alternatives that are compared in this analysis are defined. These alternatives are evaluated using the criteria selected in Step 4.

4. **Criteria selection:** Relevant evaluation criteria are established based on a combination of literature, real-life bid criteria from offshore wind tenders, and Vattenfall's internal evaluation framework. These form the basis for applying the BWT method.

5. **Construct value functions for each criterion:** Because the evaluation criteria differ in units (e.g., euros, qualitative scales), all criteria are normalized to a 0–1 scale using value functions. A value function expresses how desirable a specific performance level is for a given criterion, translating heterogeneous units into a common preference scale. It reflects the perceived utility of a criterion's performance, where 0 represents the worst acceptable performance and 1 the best. These value functions are constructed using the mid-value splitting technique proposed by Keeney and Raiffa [19], as operationalized by Liang et al. [21].

   To define the lower and upper bounds of each value function, the performance levels of all alternatives are collected. These values, obtained from simulations of Vattenfall's internal technical models, expert input, or literature, form the observed performance range of each criterion, where the worst and best observed values correspond to $v_j(\underline{x}_j) = 0$ and $v_j(\overline{x}_j) = 1$.

   Next, the decision-maker estimates the mid-value point x_5 such that $v_j(x_5) = 0.5$. The process continues by identifying:

   - $x_{0.75}$, the midpoint between x_5 and $\overline{x}_j$, where $v_j(x_{0.75}) = 0.75$,
   - $x_{0.25}$, the midpoint between $\underline{x}_j$ and x_5, where $v_j(x_{0.25}) = 0.25$.

   This procedure allows for the construction of a value function that reflects potential nonlinearity in stakeholder preferences across the relevant performance range. In other words, it captures that stakeholders may not perceive improvements equally across the scale, for example, a cost reduction from €900M to €800M may be seen as more valuable than one from €600M to €500M.

   To ensure consistency, the decision-maker verifies that x_5 truly lies midway between x_{25} and x_{75}. If this is not the case, adjustments are made until the internal consistency of the value function is guaranteed.

   This procedure ensures that the final value functions accurately capture stakeholder perceptions and nonlinearity in value across the domain of each criterion.

6. **Identify the Importance Order:** The decision maker (DM) is presented with a set of hypothetical alternatives, each representing an extreme combination of attribute values. Each alternative corresponds to a combination where one attribute is at its best performance level, while all others are at their worst performance levels. Formally, for p attributes, the alternatives are represented as:

$$A_1 : (\overline{x}_1, \underline{x}_2, \ldots, \underline{x}_p), \quad A_2 : (\underline{x}_1, \overline{x}_2, \ldots, \underline{x}_p), \quad \ldots, \quad A_p : (\underline{x}_1, \underline{x}_2, \ldots, \overline{x}_p)$$

   where:

   - $\overline{x}_j$ denotes the best (most attractive) performance level of attribute j,
   - $\underline{x}_j$ denotes the worst (least attractive) performance level of attribute j.

   The DM is asked to rank these alternatives based on their perceived attractiveness. By ranking these alternatives based on their overall attractiveness, the DM implicitly indicates which individual criteria they value most. The criterion corresponding to the best-ranked alternative is identified as the "best" criterion, and the one corresponding to the lowest-ranked alternative as the "worst" criterion. These identified best and worst criteria serve as anchors for the subsequent trade-off elicitation step.

7. **Construct Indifference Pairs:** After identifying the best and worst criteria, the DM is asked to evaluate a series of hypothetical trade-offs to reveal how they value improvements across different attributes. In each comparison, the DM is presented with two hypothetical alternatives that differ only in the performance levels of two criteria: either the best criterion versus another, or another criterion versus the worst. All other criteria are held constant at their worst observed levels. This setup isolates the trade-off being evaluated and allows the DM to focus solely on the relative desirability of the two varying attributes. The objective is to identify an indifference point (a specific performance level at which the DM perceives two alternatives as equally attractive). These indifference points provide insight into how much of one attribute the DM is willing to sacrifice in exchange for gains in another. Two sets of indifference relations are constructed: one comparing the Best attribute to others, and one comparing others to the Worst.

   - **Best-to-Others (BO):** The DM is asked to compare an alternative where the *Best* attribute is at its full performance level $\overline{x}_B$ and all others are at worst levels, with an alternative where another attribute is at its best level $\overline{x}_j$ and all others at their worst level. The performance level of the Best attribute is gradually reduced until the DM is indifferent between the two alternatives. This process is repeated for each comparison attribute j. For example, if x_1 is ranked as the most important attribute, the indifference conditions are expressed as:

$$\begin{cases} P_1: & (\underline{x}_B, \overline{x}_2, \underline{x}_3, \ldots, \underline{x}_p) \sim (x_B^{B,2}, \underline{x}_2, \underline{x}_3, \ldots, \underline{x}_p) \\ P_2: & (\underline{x}_B, \underline{x}_2, \overline{x}_3, \ldots, \underline{x}_p) \sim (x_B^{B,3}, \underline{x}_2, \underline{x}_3, \ldots, \underline{x}_p) \\ & \vdots \\ P_{p-1}: & (\underline{x}_B, \underline{x}_2, \ldots, \overline{x}_p) \sim (x_B^{B,p}, \underline{x}_2, \ldots, \underline{x}_p) \end{cases} \tag{1}$$

where:

- $\overline{x}_j$ denotes the best performance level of attribute j,
- $\underline{x}_j$ denotes the worst performance level of attribute j,
- $x_B^{B,k}$ denotes the degraded level of the Best attribute B in the comparison with attribute k.

The decision-maker is thus asked to find values for all $x_B^{B,k}$, representing the degraded performance levels of the Best attribute B at which they are indifferent between receiving full performance on another attribute k and the reduced performance on B. These are called the indifference values.

Assuming an additive value function, and denoting the normalized utility of $x_B^{B,k}$ as $v_B(x_B^{B,k})$, the following equality must hold at the point of indifference:

$$w_B \cdot v_B(x_B^{B,k}) = w_k$$

We define:

$$a_{Bk} = \frac{w_B}{w_k}$$

or equivalently:

$$w_k = \frac{w_B}{a_{Bk}} \quad \text{and} \quad w_k a_{Bk} = w_B$$

The collection of all a_{Bk} values for each k forms the Best-to-Others vector $A^{BO} = (a_{B1}, a_{B2}, \ldots, a_{Bn})$.

- **Others-to-Worst (OW):** Similarly, the DM compares each remaining attribute at its best level $\overline{x}_j$ against the *Worst* attribute at its best level $\overline{x}_W$, with all other attributes at worst levels. The performance level of the comparison attribute is adjusted downward until indifference is reached. For example, if x_2 is ranked as the least important attribute, these comparisons are formulated as:

$$\begin{cases} P_1: & (x_1^{W,1}, \underline{x}_2, \underline{x}_3, \ldots, \underline{x}_p) \sim (\underline{x}_1, \overline{x}_W, \underline{x}_3, \ldots, \underline{x}_p) \\ P_2: & (\underline{x}_1, \underline{x}_2, x_3^{W,3}, \ldots, \underline{x}_p) \sim (\underline{x}_1, \overline{x}_W, \underline{x}_3, \ldots, \underline{x}_p) \\ & \vdots \\ P_{p-1}: & (\underline{x}_1, \underline{x}_2, \ldots, x_p^{W,p-1}) \sim (\underline{x}_1, \overline{x}_W, \underline{x}_3, \ldots, \underline{x}_p) \end{cases} \tag{2}$$

where $x_k^{W,k}$ denotes the reduced level of attribute k that leads to indifference with the scenario where the Worst attribute (e.g., attribute 2) is at its best. The decision-maker is thus asked to find values for all $x_k^{W,k}$

Assuming an additive value function, and letting $v_k(x_k^{W,k})$ denote the normalized utility of the degraded level $x_k^{W,k}$, the following equality must hold at the point of indifference:

$$w_k \cdot v_k(x_k^{W,k}) = w_W$$

We define:

$$a_{kW} = \frac{w_k}{w_W} \quad \text{or equivalently} \quad w_k = a_{kW} \cdot w_W \quad \text{and} \quad w_W = \frac{w_k}{a_{kW}}$$

The set of all a_{kW} values forms the Others-to-Worst comparison vector:

$$A^{OW} = (a_{1W}, a_{2W}, \ldots, a_{nW}) \quad \text{with} \quad k \neq W$$

This vector represents the decision maker's estimate of how much more important each attribute k is compared to the worst attribute W. These values are used, together with the Best-to-Others vector, to construct a consistent system of linear equations for determining the final criterion weights.

The set of indifference conditions collected through these comparisons forms the basis for constructing the pairwise comparison vectors A^{BO} and A^{OW}, which are used in step 9 to compute the final weights.

8. **Consistency Evaluation:** Prior to deriving the final weights, the consistency of the decision maker's inputs is assessed to ensure logical coherence between pairwise comparisons. Following [21], two types of consistency are evaluated: ordinal consistency and cardinal consistency.

   - **Ordinal Consistency:** Ordinal consistency is satisfied if the relative orderings implied by the Best-to-Others (BO) and Others-to-Worst (OW) comparisons are aligned. Formally, for any two attributes k and j, ordinal consistency holds if:

$$(a_{Bk} - a_{Bj})(a_{jW} - a_{kW}) > 0 \quad \text{or} \quad (a_{Bk} = a_{Bj} \,\text{and}\, a_{jW} = a_{kW})$$

where:

- a_{Bk} is the comparison value of Best to attribute k,
- a_{Bj} is the comparison value of Best to attribute j,
- a_{jW} is the comparison value of attribute j to Worst,
- a_{kW} is the comparison value of attribute k to Worst.

The degree of violation is quantified using the Ordinal Consistency Ratio (OR):

$$OR = \max_j \left(\frac{1}{n-1} \sum_{k=1}^{n} F(a_{Bk} - a_{Bj}, a_{jW} - a_{kW}) \right)$$

where $F(c, d)$ is a step function defined as:

$$F(c,d) = \begin{cases} 1, & \text{if } c \times d < 0 \\ 0.5, & \text{if } c \times d = 0 \text{ and } (c \neq 0 \text{ or } d \neq 0) \\ 0, & \text{otherwise} \end{cases}$$

and:

- $c = a_{Bk} - a_{Bj}$
- $d = a_{jW} - a_{kW}$

- **Cardinal Consistency:** Cardinal consistency is achieved if the strength of the preferences is internally coherent. Perfect cardinal consistency requires that for each attribute j:

$$a_{Bj} \cdot a_{jW} = a_{BW}$$

where a_{BW} is the implied comparison between the Best and Worst attributes. Deviations from perfect cardinal consistency are measured using the *Cardinal Consistency Ratio* (CR), defined as:

$$CR = \max_j CR_j$$

with:

$$CR_j = \begin{cases} \dfrac{|a_{Bj}a_{jW} - a_{BW}|}{a_{BW}(a_{BW} - 1)}, & \text{if } a_{BW} > 1 \\ 0, & \text{if } a_{BW} = 1 \end{cases}$$

Both consistency ratios are compared to predefined thresholds, which depend on the number of attributes and the strength of the Best-to-Worst comparison. If either the OR or CR exceeds the acceptable thresholds, the DM may be asked to revise the inconsistent pairwise judgments. This structured consistency evaluation ensures the robustness and reliability of the elicited weights.

9. **Compute Final Weights:** The indifference values and trade-off equations collected in the previous step are used to compute the final weights of each criterion through a linear programming optimization. These equations reflect how the DM values the Best attribute relative to others, and each attribute relative to the Worst.

   Formally, the following conditions are imposed:

$$\begin{cases} w_k a_{Bk} = w_B, & \forall k \neq B \\ w_k = a_{kW} w_W, & \forall k \neq W \\ w_1 + w_2 + \cdots + w_n = 1 \end{cases}$$

   where w_B and w_W denote the weights of the Best and Worst attributes respectively, and a_{Bk} and a_{kW} are the indifference-derived preference ratios.

   Since perfect consistency in judgements from the DMs is rarely achieved in practice, such an equation system does not have a solution. The final weights are obtained by minimizing the greatest absolute violation of the equations and thereby solving the following minimax optimization problem:

$$\min \xi$$

   subject to:

$$|w_B - a_{Bk} \cdot w_k| \leq \xi, \quad \forall k \neq B$$

$$|w_k - a_{kW} \cdot w_W| \leq \xi, \quad \forall k \neq W$$

$$w_1 + w_2 + \cdots + w_n = 1, \quad w_j \geq 0 \quad j = 1, 2, \cdots, n.$$

   Here, ξ represents the maximum absolute inconsistency tolerated in the solution.

   The result is a normalized weight vector, accurately reflecting the relative importance of each evaluation criterion, consistent with the stakeholder's elicited preferences.

10. **Compute Overall Scores:** The final step combines the normalized performance scores of each alternative (obtained in Step 5) with the weights of each criterion (derived in Step 9) to compute an overall score for each alternative. This is done by applying an additive aggregation function.

    Formally, for each alternative, the overall score is calculated as:

$$\text{Score}_{\text{Alt}} = \sum_{j=1}^{n} w_j \cdot v_{j,\text{Alt}}$$

where:

- w_j is the final weight of criterion j,
- $v_{j,\text{Alt}}$ is the normalized performance of the alternative on criterion i.

The alternative with the highest overall score is considered the most preferred, based on the stakeholder's elicited preferences and the observed performance of each option. This final score reflects both the importance of each criterion and how well each alternative performs on them.

Together, these steps enable a structured, stakeholder-informed comparison of offshore transmission system alternatives using the BWT method [21].

3.4 Introduction to Selected Offshore Wind Project

In this chapter, the offshore wind project that serves as the scenario for the MCDM framework is introduced. Additionally, the rationale behind selecting this specific project is explained. It is important to note that only one project is analysed in detail due to the time-intensive nature of information collection, stakeholder engagement, and business case simulations. As a result, further projects could not be included within the scope of this thesis. However, while the analysis focuses on a single project, the evaluation framework has been designed to be adaptable to other offshore wind projects in Vattenfall's portfolio.

3.4.1 Project Overview

This research currently focuses on one offshore wind project from Vattenfall's portfolio: Kattegatt Syd (located in Sweden). Kattegatt Syd was selected because it offers a realistic and relevant development context for assessing high-voltage offshore transmission system alternatives. The project is in an advanced planning stage with most key permits granted and is actively considering the use of a 132 kV inter-array voltage. With a capacity of 1.2 GW and a moderate distance to shore (approximately 25 km), it provides a suitable case for exploring the feasibility of direct-to-shore transmission.

Kattegatt Syd

Kattegatt Syd is a 1.2 GW offshore wind farm under development by Vattenfall, located approximately 25 km off the Swedish coast near Falkenberg, in Halland County. The project area spans 103 square kilometers and will include 60 to 80 wind turbines with a total height of 250 to 350 meters. The site is situated at water depths of 30-50 meters and will use bottom-fixed foundations, meaning the turbines are mounted directly to the seabed using monopiles or jackets, which are suitable for shallow to medium water depths and offer a stable, cost-effective solution for fixed installations. The wind farm is expected to generate around 5 TWh of electricity annually. This is equivalent to the consumption of 780,000 detached houses, or approximately 3% of Sweden's total electricity production. The final investment decision (FID) [2] for this Windfarm is expected in 2028, with commissioning planned for 2031 [44].

To support detailed design and planning, Vattenfall is currently conducting a range of technical investigations. These include geophysical and geotechnical surveys of the wind

[2] The FID refers to the point in a project's development at which the developer commits to fully fund and proceed with the construction and execution of the project, based on completed planning, permitting, and financial assessments.

farm area and the planned offshore cable route that will transmit electricity to shore, as well as land-based studies between the cable's landfall point and the future onshore grid connection. These studies aim to assess the geological conditions, environmental constraints, and technical feasibility for selecting suitable foundation types and installation methods for both foundations and cables [44].

Over the course of the project's development, the layout has been significantly adjusted to reduce environmental impact. The project area was reduced by over 40% to avoid conflicts with nearby Natura 2000 protected areas (Stora Middelgrund, Röde Bank, and Lilla Middelgrund), shipping lanes, and benthic habitats of ecological importance. The wind farm is designed to coexist with other marine activities, such as commercial fishing and recreational boating. Demersal fishing and pleasure boating will be permitted within the park and over the export cable [44].

The project received its main construction and operation permit from the Swedish government in 2023. Prior to that, Natura 2000 permits were granted by the County Administrative Board in 2022 and confirmed by the Land and Environment Court of Appeal in 2025. In addition to these, permitting is ongoing for the internal electrical infrastructure and export cable system. This includes applications under the Continental Shelf Act[3] and the Electricity Act[4], both of which are required for the installation and operation of offshore transmission systems[44].

Vattenfall is maintaining continuous dialogue with key stakeholders during development, including fisheries producer organisations, shipping authorities, the Armed Forces, and affected property owners. These discussions are intended to ensure coexistence, minimize conflicts, and support the long-term sustainability of the project in its surrounding marine and coastal environment [44].

[3] The Swedish Continental Shelf Act regulates the exploration and use of the seabed and subsoil beyond the territorial sea, including permits for submarine cables and other marine installations.

[4] The Swedish Electricity Act governs electricity production, transmission, distribution, and trading. It requires permits for connecting to the national grid and for operating transmission infrastructure.

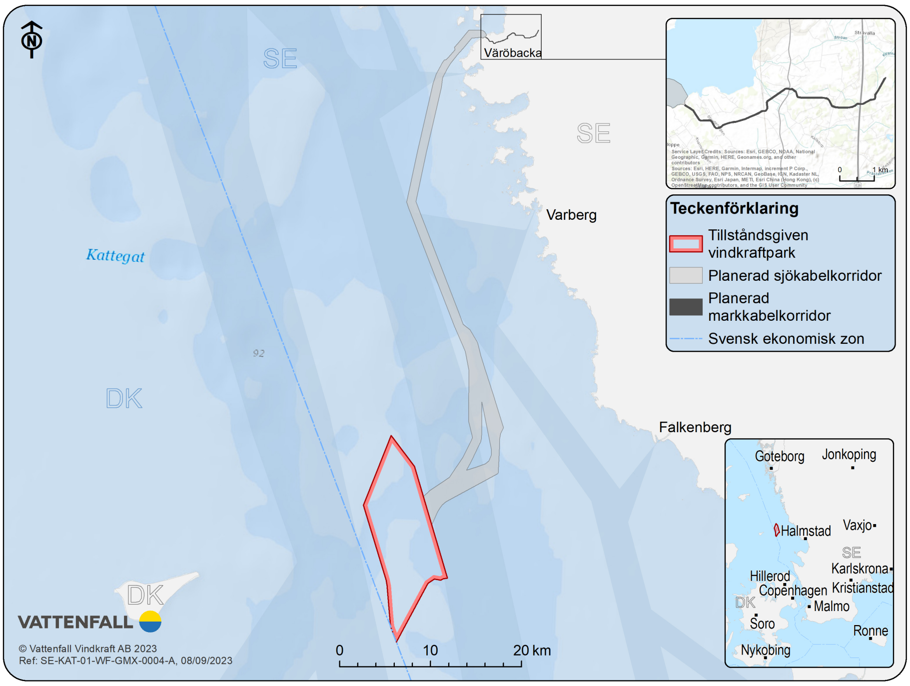

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Figure 6: Location of Kattegatt Syd [44]

4 Results

This chapter presents the results of the analysis and provides answers to the sub-research questions formulated in Chapter 2.3.

4.1 Regulatory Environment Kattegatt Syd (Sweden)

In this chapter, a literature-based investigation is conducted to understand how the allocation of costs for offshore transmission infrastructure is regulated in Sweden. The goal is to determine whether, under the current regulatory framework, it is relevant for Vattenfall to consider a direct-to-shore transmission configuration for the Kattegatt Syd project. Specifically, the chapter explores who is responsible for financing offshore grid components and who holds decision-making authority over system design. These insights will clarify whether such a configuration falls within Vattenfall's actual scope of options.

4.1.1 Background: Tendering Process for Offshore Wind Projects in Sweden

Sweden operates under an "open-door" permitting system, a decentralized approach in which developers are free to identify and apply for offshore wind project locations independently, rather than responding to government-defined zones or competitive tenders. In this model, there is no central planning or coordination of site allocation, meaning that multiple developers may submit overlapping proposals for the same sea areas. This creates significant friction in the permitting process, leading to delays, legal disputes, and uncertainty about project feasibility. Additionally, because permitting, environmental assessments, and grid connection responsibilities lie largely with the developer, there is limited government oversight or support in harmonizing the planning process. As a result, investment decisions are slowed, and grid infrastructure planning becomes reactive rather than proactive. To date, only 2 GW of over 100 GW in proposed capacity has been licensed under this system [8].

The Kattegatt Syd project has already secured several key permits: the Swedish government granted the main permit for the construction and operation of the wind farm in 2023, and the Natura 2000 permits were issued by the County Administrative Board in 2022 and subsequently upheld by the Land and Environment Court of Appeal in 2025. However, additional permits are still required before construction can proceed. These include permits for the internal array cables and the export cable.

4.1.2 Cost Allocation

Swedish policy currently places the financial burden of offshore grid connection entirely on developers - unlike in countries where governments co-fund or fully fund offshore infrastructure [8].

However, in 2022, the Swedish government took a major step toward streamlining offshore wind development by amending the Electricity Act. Under this amendment, Svenska kraftnät (Svk), the Swedish Transmission System Operator (TSO), was granted centralized authority to build six state-funded offshore grid connection points, with a combined capacity of 10 GW to be realized by 2035 [47] [37]. The aim was to reduce barriers to entry for offshore developers: projects situated within 15 km of a Svk connection hub and operating at or below 132 kV AC would benefit from subsidized grid infrastructure, eliminating the need to finance costly offshore substations themselves. However, these ambitious plans were short-lived. Following a change in government in autumn 2022, a new policy direction emerged. The new administration readopted the position that offshore wind developers should bear the full cost of grid connections. This reversal was formalized in a government memorandum issued on June 21, 2023, proposing to withdraw the previously granted mandate to Svk. The withdrawal was scheduled to take effect on October 1, 2023 [37].

In conclusion, developers in Sweden remain fully responsible for the costs of the entire offshore transmission system. This reinforces the relevance of exploring alternatives such as direct-to-shore transmission, which may offer cost advantages by avoiding the need for offshore substations. Given this cost allocation structure, projects like Kattegatt Syd in Sweden provide a meaningful context in which to consider the feasibility and potential of direct-to-shore solutions.

4.2 Stakeholder analysis

This chapter aims to determine which stakeholders should be actively involved in the selection of a high-voltage transmission system for the specific offshore wind project introduced in Chapter 3.4. To support this, a broad stakeholder analysis is conducted based on typical offshore wind transmission projects in Sweden, including the selected case. This general overview is then used to narrow down which actors are relevant for involvement in the decision-making process for a transmission system design for the selected Vattenfall project. Identifying the appropriate decision-makers is essential for the application of the BWT method, which requires input from those with authority over system selection.

4.2.1 Power Interest Grid

The development of offshore wind transmission systems involves a complex network of stakeholders with varying levels of influence and interest. To structure stakeholder engagement, this analysis applies the Power-Interest Grid, categorizing stakeholders into four groups: Players, Context Setters, Subjects, and Crowd, as in [1]. Each stakeholder is placed within this framework based on their ability to influence decision-making (power) and their level of vested interest in the project's outcomes (interest), as shown in Figure 7.

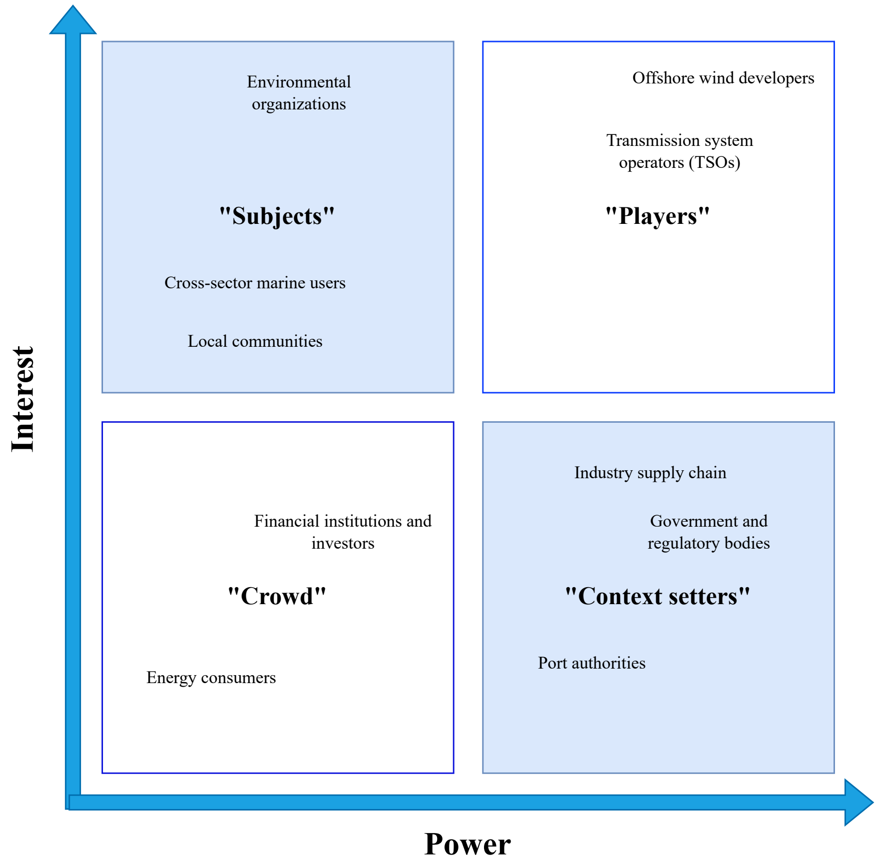

Figure 7: Power Interest Grid

- **Players**: These stakeholders are actively involved in decision-making and project execution.
  - **Transmission System Operators (TSOs)**: Svenska kraftnät, Sweden's national TSO, is responsible for the onshore grid and ensuring system stability. Although it does not build offshore infrastructure, Svk must approve offshore projects' connection points and ensure compliance with technical and capacity requirements [37]. TSOs also influence timelines and connection feasibility. Hence, they have high power due to their gatekeeping function and grid planning authority, and high interest in maintaining grid stability and achieving renewable integration targets [37].
  - **Offshore Wind Developers**: As concluded in Chapter 4.1, in Sweden, companies such as Vattenfall, are responsible for the design, financing, and construction of offshore wind farms, including the offshore transmission system up to the point of onshore connection. Based on information from Svenska kraftnät (Svk) [37], developers have the autonomy to choose between transmission system configurations, such as a 132 kV direct-to-shore connection or a higher-voltage setup with an OSS. Developers hold a high level of power due to

their ownership of the project and control over system design, and they have a strong interest because transmission choices affect profitability.

- **Context Setters**: These stakeholders have significant influence but are not directly engaged in day-to-day decisions. However, maintaining their support is crucial.
  - **Government and Regulatory Bodies**: The Swedish Energy Agency and the Ministry of Climate and Enterprise hold significant power in offshore wind development by defining the legal framework, issuing marine permits, and designating suitable areas through marine spatial planning. Their high interest lies in advancing Sweden's climate and energy goals, including the target to produce 100% fossil-free or climate-neutral electricity by 2040, with offshore wind as a key contributor. Their power is evident in their ability to approve or block projects, as seen when several offshore wind permits were denied due to national defense concerns [39], [40], [41].
  - **Industry Supply Chain**: This includes manufacturers of high-voltage cables (e.g., NKT), substations (e.g., Siemens Energy), and vessels for installation. They hold high power in offshore wind projects due to their technical expertise and their indispensable role in supplying critical sub-systems of the transmission infrastructure. Their commercial interest lies in optimising the design, cost, and delivery of their own components - not in the performance of the overall system. As such, they aim to influence technical choices in ways that favour their specific offerings. However, because they only deliver part of the total system, their optimised sub-solutions may not align with the best-performing overall configuration. It is therefore up to the wind farm developer (e.g., Vattenfall) to manage and integrate these interests, ensuring that system-level design choices (such as opting for a 132 kV direct-to-shore solution or one involving an offshore substation) result in a coherent and cost-effective end system [17] [33].
  - **Port Authorities**: Ports facilitate the transport, storage, and assembly of wind farm components, including heavy electrical infrastructure such as an OSS and export cables. Their power stems from their control over critical infrastructure and scheduling, which can influence project timelines [17]. While their direct interest in the transmission system design may be limited, the choice between an OSS and a direct-to-shore configuration can affect the complexity and volume of port activities. For example, an OSS can require larger and more complex components to be handled at the port, increasing logistical involvement. Additionally, port authorities often have an interest in regional economic development and job creation, which can be positively influenced by the scale and nature of offshore wind logistics and infrastructure handling [33].
- **Subjects**: These stakeholders have a vested interest in project outcomes but little

direct influence.

- **Local Communities**: Residents near landing points and cable routes may be affected by visual, noise, or environmental impacts. Their interest is high due to concerns about land use and ecological impact, especially in coastal municipalities. A direct-to-shore configuration may increase the need for larger onshore infrastructure, potentially heightening local resistance compared to a design that includes an OSS. However, they typically have low power, limited to influence through consultations and local political channels [17].
- **Environmental Organizations**: Groups such as the Swedish Society for Nature Conservation monitor offshore wind's environmental footprint. Their interest is high, particularly regarding seabed disturbance from cable routes and the placement of offshore infrastructure in ecologically sensitive areas. Transmission design choices influence the scale and location of these impacts. They lack formal power but can delay projects by pushing for stricter permit conditions or mobilizing public opinion [17].
- **Cross-Sector Marine Users**: Fishing organizations and shipping companies operate in the same maritime zones. Their high interest comes from concerns about potential disruptions to their operations. The choice of transmission system can influence the extent and nature of spatial interference at sea. However, their power is relatively low because regulatory bodies and developers ultimately make decisions regarding spatial planning and marine area allocations [17].

- **Crowd**: These stakeholders have minimal engagement but may be indirectly affected.
  - **Energy Consumers**: Energy consumers in Sweden have low power and low interest regarding the choice between direct-to-shore transmission and transmission via offshore substations. They possess low power because they are not involved in decisions for offshore wind transmission [11], [38]. Their interest is also low, because the specific choice of offshore transmission system has no visible or immediate impact on their daily electricity use or bills. Any financial effects are indirect and long-term, since offshore grid connection costs are socialized across all users via general grid tariffs, in line with current Swedish regulatory proposals [11]. As a result, consumers are neither directly involved in decision-making nor do they have much interest in the technical choices related to offshore wind transmission.
  - **Financial Institutions and Investors**: In Sweden, financial institutions and investors provide essential capital for offshore wind projects but do not participate directly in technical decision-making regarding the transmission system. Their formal power is moderate: although their funding is crucial, they typi-

cally lack influence over whether a direct-to-shore or OSS solution is selected [11], [38]. Their interest in these technical details is generally low, as they often lack the in-house expertise to assess such alternatives. Instead, they rely on developers and technical consultants to ensure that the selected design is technically sound and compliant with Swedish regulations. However, they can indirectly influence design choices by requiring higher risk premiums for investments in highly complex, time-critical infrastructure - such as transmission systems that carry all potential revenues from the wind farm - thereby shaping the financial attractiveness of certain configurations. Their primary concerns remain financial viability and favorable risk-return profiles [4], [11], [33], [38].

4.2.2 Selection of Stakeholders for this Study

In this study, only internal stakeholders from Vattenfall will be interviewed. This selection is based on two key considerations. First, the decision-making authority for the choice between the transmission alternatives under investigation - namely, a 66 kV OSS, a 132 kV OSS, and a 132 kV direct-to-shore connection - lies entirely within Vattenfall. This is because (as investigated in Chapter 4.1) in Sweden Vattenfall is responsible for the full offshore grid connection up to the ONS, from which point the TSO becomes responsible [37]. Consequently, the decision on how to transport the electricity to shore, including whether and how to use an OSS, falls within Vattenfall's scope, provided the necessary permits can be obtained. Second, the BWT method used in this research requires input from actual decision-makers, which further justifies focusing on those within Vattenfall.

While external stakeholders will not be interviewed, their perspectives are not overlooked. The evaluation criteria used to assess the transmission alternatives are partially derived from official bid criteria used in real offshore wind tenders. These bid criteria are specifically designed to reflect the interests and priorities of a wide range of stakeholders - including regulators, transmission system operators, environmental agencies, and market actors. In this way, the broader stakeholder landscape is indirectly represented within the evaluation framework.

4.2.3 Internal Stakeholder Selection

To determine the appropriate stakeholders for decision-making on the design of the export system within Vattenfall, this research refers to Vattenfall's standard Single Point Organisation Chart (SPOrgC) used for asset projects shown in Figure 8. This chart outlines the core structure of responsibilities in offshore wind development projects. Based on this structure - and confirmed through multiple internal discussions with experienced experts at Vattenfall - it was established that each project has exactly one Technical

Project Manager (TPM) and one Project Director (PD), who jointly hold the ultimate decision-making authority over the choice of grid connection concept.

These two roles are uniquely positioned to assess export system options across all relevant dimensions, including technical feasibility, economic implications, regulatory constraints, and system-wide project risks. Unlike other specialists involved in the project, such as electrical engineers, permitting advisors, or financial controllers, the TPM and PD are the only individuals with full oversight of how different aspects of the project interact. As repeatedly emphasized in discussions with Vattenfall experts, only these roles can judge how trade-offs between criteria (for example, higher CAPEX versus lower implementation risk, or technical innovation versus permitting complexity) affect the overall project outcome and alignment with strategic objectives.

While input from domain experts is essential, their focus is generally limited to a single area of expertise. Consequently, they often lack the broader context needed to meaningfully interpret project-wide metrics such as total CAPEX, risk budgets, or implementation timelines. For instance, a cable engineer may optimize a technical design without knowing whether its additional cost is acceptable at the project level. In many cases, such experts are also not aware of i.e. the total project CAPEX, making absolute cost figures largely meaningless in their context. Therefore, they are not suited to make the integrative value judgments that the BWT method requires [33].

In contrast, the TPM and PD are not only the most informed stakeholders across disciplines - they are also the final decision-makers who are formally responsible for selecting the export system design. Their system-level perspective and cross-functional accountability ensure that the BWT-based evaluation reflects real-world decision-making processes within offshore wind development at Vattenfall.

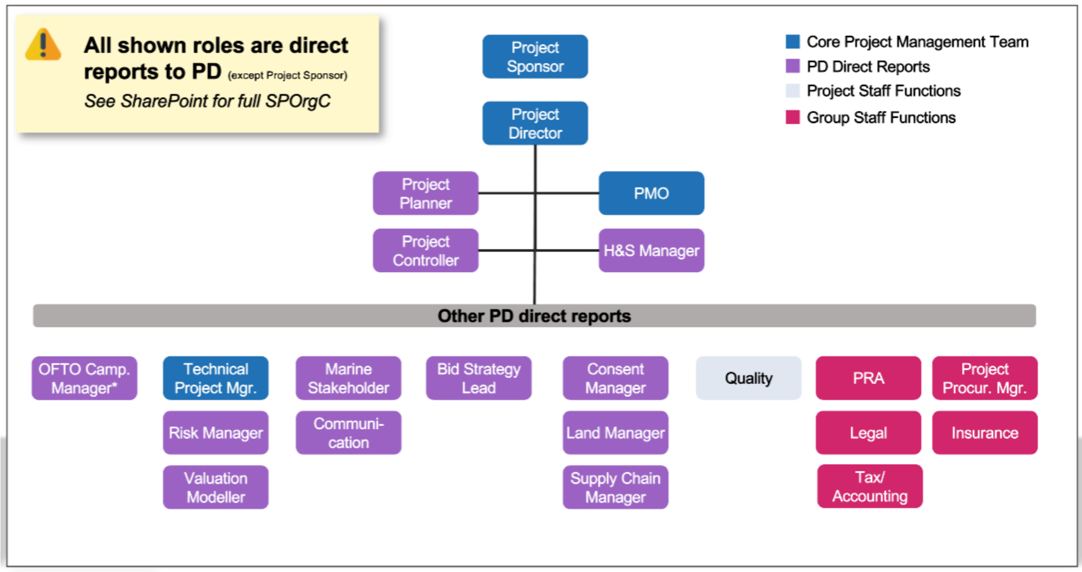

Figure 8: Single Point Organisation Chart Asset Projects Vattenfall

4.3 Alternatives considered

This study evaluates four alternative configurations for the grid connection of offshore wind farms. These alternatives differ in terms of the inter-array voltage level and the presence and location of voltage transformation within the overall system design. The selection of these four configurations was made in consultation with my company supervisor at Vattenfall, ensuring that the proposed alternatives are both relevant and reflective of current strategic considerations in offshore grid development within Vattenfall. At the same time, the configurations are based on distinctions that are most relevant for this study's comparison between OSS and direct-to-shore solutions. During the research process, the fourth configuration - the 132 kV direct-to-shore variant with an onshore substation near landfall - was developed and added. Expert interviews and internal discussions indicated that this variant differs substantially from the fully direct-to-TSO configuration in terms of system layout and permitting implications, and should therefore be evaluated as a separate alternative. The following four configurations are compared:

1. **66 kV inter-array with OSS (Base case):** This configuration, which is currently the most widely used in the offshore wind industry, serves as the reference or base case. It uses 66 kV inter-array cables to connect the turbines to an OSS, where the voltage is stepped up before export to the onshore grid. The OSS aggregates the power and transmits it through approximately three 275 kV export cables to shore.

2. **132 kV inter-array with OSS:** A variant that applies a higher 132 kV voltage level within the inter-array network. This can reduce electrical losses and decrease the number of required inter-array cables. As in the base case, the voltage is stepped up at an offshore substation before being transmitted to shore - again approximately using three 275 kV export cables.

3. **132 kV direct-to-shore with only TSO onshore substation (ONS):** In this configuration, 132 kV export cables run directly from the offshore wind turbines to the TSO point of connection onshore. No OSS is used. The voltage is stepped up only at the onshore TSO point of connection to the main grid. Because there is no offshore voltage step up, each turbine string requires its own export cable, resulting in approximately six to seven parallel 132 kV cables running to the TSO substation.

4. **132 kV direct-to-shore with ONS near landfall:** An alternative direct-to-shore setup in which 132 kV cables reach shore and connect to an ONS located near the landfall point. The voltage is stepped up at this substation before continuing to the TSO grid connection point. Similar to the previous variant, this setup requires approximately six to seven separate export cables from offshore, but from the ONS onwards, the number of cables is reduced to approximately 3.

The options are visualized in Figure 9.

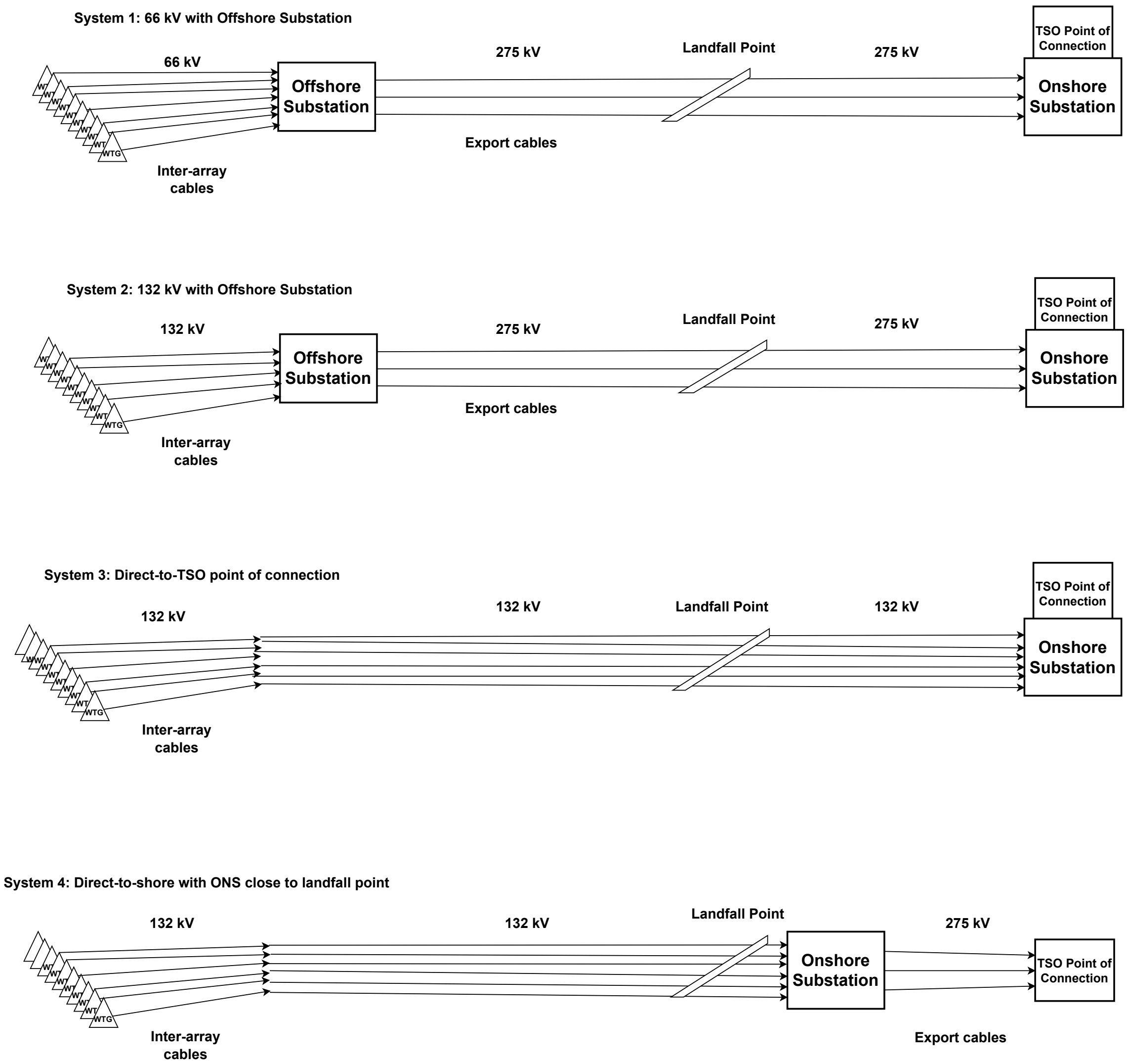

Figure 9: Alternatives considered for comparison

4.4 Establishment of Evaluation Criteria

This chapter presents the set of criteria, which serve as the building blocks of the MCDM framework.

4.4.1 Criteria Selection method

Firstly, the evaluation criteria used in this study are established based on a review of existing literature comparing alternative offshore wind transmission systems. Although most of the reviewed studies focus on comparisons between HVAC and HVDC technologies, rather than specifically on 132 kV direct-to-shore options, they still provide a solid foundation for identifying relevant evaluation dimensions. To identify relevant literature, the following search string was used in Scopus: *(TITLE-ABS-KEY ("offshore wind" AND ("grid connection" OR "export system" OR "transmission system" OR "electrical infrastructure") AND ("multi-criteria analysis" OR "mca" OR "decision-making" OR "multi-criteria decision-making" or "mcdm" or "evaluation method"))).* A comprehensive overview of the criteria used in each reviewed article is provided in Table 14 in Appendix A. Criteria that appeared frequently were considered the most relevant for the MCDA of this study. In addition, the feasibility of analysing each criterion was reviewed to ensure that the analysis could be completed within the limited timeframe of this study. In addition to the literature review, bid criteria for tenders in actual offshore wind projects were also considered, these could be accessed through Vattenfall's internal network. These bid criteria offer valuable insights into the practical and contractual priorities in transmission system selection and encorporate different stakeholder perspectives. Furthermore, input was gathered from Vattenfall, which applies a standardized set of internal criteria when evaluating transmission systems as part of the business case for offshore wind farm development. These criteria are used to assess the strength of a business case regardless of the options being considered and provide a relevant structure for comparing the transmission options considered in this thesis.
Based on the combination of literature, real-life tender practices, and Vattenfall's internal evaluation framework, a set of seven evaluation criteria was selected for the BWT method.

4.4.2 Criteria Definition

1. Capital Expenditure (CAPEX)
The initial investment required to implement the transmission system. This includes the cost of cables, transformers, offshore substations (if applicable), installation, and engineering services. CAPEX is a very influential factor in offshore infrastructure business cases and is referenced in nearly all reviewed articles.
Formula: $\text{CAPEX} = C_{\text{installation}} + C_{\text{equipment}} + C_{\text{engineering}}$
Unit: million euros (€M)

2. Operational Expenditure (OPEX)

The recurring annual costs during the operational lifetime of the system. This includes inspection, repair, maintenance, and asset management. OPEX affects annual cash flow and long-term project profitability.

Formula: $\text{OPEX} = C_{\text{maintenance}} + C_{\text{inspection}} + C_{\text{asset management}} + C_{\text{repairs}}$

Unit: million euros (€M)

3. Revenue

This criterion represents the total expected revenue generated by the offshore wind farm over its lifetime. It is primarily driven by the Annual Energy Production (AEP), which captures the effective amount of electricity delivered to the grid. AEP reflects not only the gross production capacity of the wind farm, but also incorporates technical factors such as electrical efficiency, transmission losses, and periods of unavailability. These losses affect the quantity of electricity sold and thus influence revenue directly.

Unit: present value in € million

4. Risk Associated with Project

Reflects the level of uncertainty and potential for unforeseen events that could impact the project timeline, cost, or feasibility. These risks may stem from weather conditions, regulatory changes, or the use of unproven technology. Higher risk typically requires larger contingencies and mitigation planning. One way to reflect this in the analysis is by using a risk budget (an amount of money set aside to cover unexpected costs). Vattenfall already includes such reserves in its project planning to account for technical, logistical, and external uncertainties.

Unit: million euros (€M)

5. Ease of Implementation

This criterion reflects the overall ease and maturity of implementing the transmission system from specification and procurement to installation and operational integration. It captures four key aspects:

- Technical feasibility: Whether the system is technically viable under project-specific conditions, such as distance to shore, voltage level, and the number of required circuits. If the solution is not technically feasible, it should receive the lowest possible score.
- Combined technical complexity and project maturity: The degree to which the system is technically challenging and the extent to which design, engineering, and planning are already developed.
- Supply chain availability: How many capable suppliers exist to deliver the full system? Limited supplier options may increase costs, reduce redundancy, or cause delays.
- Internal knowledge requirements: The level of detail and expertise needed to specify,

procure, and operate the system.

Scoring guide:

- 5 - Very High: Technically feasible under all project conditions, mature solution, multiple suppliers, suppliers knowledgeable to deliver competent solution, high internal familiarity.
- 4 - High: Technically feasible with minor constraints, mature or near-mature solution, good supplier base, strong internal familiarity.
- 3 - Moderate: Some technical constraints but feasible, moderate complexity, limited supplier base, moderate experience.
- 2 - Low: Technically feasible but with considerable complexity or immaturity, few suppliers, low internal familiarity.
- 1 - Very Low: Not technically feasible (e.g. due to excessive cable distance or circuit requirements), highly complex, few suppliers, low availability, low internal knowledge and experience.

Unit: Qualitative score (1–5)

6. Environmental Impact and Permitting Complexity

This criterion assesses the overall ecological and spatial impact of the transmission system, as well as the feasibility of obtaining the necessary permits within the required timeframe. It considers both offshore and onshore factors, including potential effects on marine ecosystems, seabed disturbance, required space for cable corridors, visual impact, and proximity to protected areas. Onshore restrictions such as land-use limitations, proximity to residential zones, and availability of suitable routes for cabling can significantly influence permitting complexity. A high environmental or spatial impact typically leads to greater stakeholder resistance and longer approval processes. Therefore, this criterion also captures the likelihood that all required permits will be secured on time, taking into account the project's location, spatial constraints, existing regulatory procedures, and any known site-specific challenges.

Scoring guide:

- 5 - Very Low: Permitting expected to proceed smoothly with low stakeholder resistance.
- 4 - Low: Permitting challenges expected to be limited.
- 3 - Moderate: Permitting challenges are present but manageable.
- 2 - High: Permitting expected to be difficult and time-consuming.
- 1 - Very High: Permitting likely to be highly complex, delayed, or constrained.

Unit: Qualitative score (1–5)

7. Innovation and Scalability for Future Offshore Systems

Evaluates the degree to which the transmission system is innovative, contributes to future-proof grid development, and supports integration of offshore wind farms in a scalable and flexible way.

Includes the following aspects:

- Innovativeness & originality: How new or disruptive is the concept compared to current practice?
- Contribution to future integration: Does the system allow for future wind park expansion or modular connection?
- Flexibility & scalability: Can the system interface with future energy storage or hybrid grid concepts?

Scoring guide:

- 5 - Very High: Groundbreaking or highly innovative concept with clear added value and strong potential for scalable offshore grid integration.
- 4 - High: Innovative system with several new or adaptive features, strong potential for modularity and future grid compatibility.
- 3 - Moderate: Some innovative or adaptive elements, promising but with unclear feasibility or scalability.
- 2 - Low: Minor improvements over conventional systems, limited contribution to future integration.
- 1 - Very Low: Conventional solution with little or no innovation. No significant contribution to future system needs.

Unit: Qualitative score (1–5)

Together, these seven criteria form the core evaluation framework for comparing the transmission system alternatives using the BWT method. Each criterion reflects a distinct and meaningful dimension of business case performance and is evaluated using a normalized value function to enable structured trade-off analysis with stakeholders. The selected criteria, organized by dimension and their respective units of measurement, are presented in Table 2.

Dimension	Criteria	Unit
Economic	CAPEX	Million euros (€M)
	OPEX	Million euros per year (€M/year)
	Revenue	Million euros (€M)
	Risk Associated with Project	Million euros (€M), based on risk budget
Technical & Implementation	Ease of Implementation	Qualitative score (1–5)
External	Environmental Impact and Permitting Complexity	Qualitative score (1–5)
Systemic Innovation & Future Readiness	Innovation and Scalability for Future Offshore Systems	Qualitative score (1–5)

Table 2: Evaluation criteria for offshore wind transmission systems

4.4.3 Criteria Validation

The selection and formulation of the evaluation criteria were validated through expert consultations within Vattenfall. In total, four experts from the Offshore Wind Development Department provided feedback, each contributing insights from their specific area of expertise.

The first expert works in Electrical Project Engineering and is involved in projects such as Kattegatt Syd, providing input on practical and technical aspects of high-voltage export systems. The second expert is part of the Systems Concepts team, focusing on the technical solution development side of offshore wind and ensuring the criteria aligned with broader systems thinking. The third expert specializes in System Design and is particularly involved in the development of business cases for offshore wind projects, offering key perspectives on financial feasibility and strategic decision-making. The fourth expert focuses on Modelling and Optimization of system designs, contributing to the assessment of technical performance, efficiency, and system-wide impacts.

Based on their feedback, the initial criteria were iteratively refined - through rewording for clarity, the addition of new dimensions, and improved alignment with real-world offshore wind development practices. As a result, the final evaluation framework better captures the technical, economic, and strategic considerations essential to the design and implementation of offshore wind export transmission systems.

4.4.4 Reasoning for Separating Economic Criteria

Although it is theoretically possible to reduce all monetary values in a project (such as CAPEX, OPEX, revenue, and risk budget) into a single financial metric using discounted cash flow (DCF) or net present value (NPV) analysis, this approach does not sufficiently capture the complexity of real-world investment decisions in offshore wind projects. In particular, the timing, structure, and uncertainty of financial flows affect project feasibility, risk exposure, and stakeholder acceptance in ways that a single aggregated value cannot reflect. Therefore, treating CAPEX, OPEX, revenue, and risk budget as distinct criteria in a MCDM framework like the BWT Method is both justified and necessary.

First, high upfront capital costs are one of the main practical barriers to offshore wind deployment. Even if a project is economically sound in NPV terms, the inability to raise sufficient capital may render it infeasible. As Gatti (2012) notes in [9], "the magnitude and timing of capital expenditures are often the most critical factors in project finance, affecting not only feasibility but also risk allocation and the ability to attract investors." This is echoed by the International Energy Agency [14], which highlights that "high upfront capital costs remain the principal barrier to offshore wind deployment, even when long-term returns are attractive."

Second, the risk profile of different types of expenditures varies significantly. CAPEX is typically sunk and irreversible, exposing investors to high upfront risk. OPEX and revenue-based risks, in contrast, can often be managed dynamically over time. This distinction is especially relevant in offshore wind, where long asset lives and regulatory uncertainty increase the stakes. As Brealey, Myers, and Allen (2020) [5] explain, "the risk profile of capital expenditures is fundamentally different from that of operating expenditures, particularly in industries with long asset lives and uncertain regulatory environments." Including a risk budget as a separate criterion helps capture these differences and allows decision-makers to explicitly address cost uncertainties that would otherwise be hidden in aggregate metrics.

Third, strategic and stakeholder preferences reinforce the need to distinguish between these cost types. Stakeholders often explicitly prefer lower CAPEX, even if it results in higher OPEX or longer payback periods. Infrastructure Australia (2018) [13] emphasizes that "stakeholders may prioritize lower upfront capital requirements to reduce financing risk, even if this increases operational costs over time." Similarly, IRENA (2023) [16] points out that reducing CAPEX is crucial in offshore wind projects for "accelerating project timelines and securing necessary permits and financing."

A multi-criteria framework is particularly well-suited to capture these real-world considerations, where trade-offs between economic criteria cannot be ignored. While financial metrics like NPV combine CAPEX, OPEX, revenue, and risk into a single discounted value, they do not reflect the different implications these costs have in practice - such as financing requirements, sunk risk, or stakeholder sensitivity to upfront investments, especially in capital-intensive sectors like offshore wind. Splitting these components enables a more transparent evaluation of trade-offs and ensures that decision-makers can consider timing, risk exposure, and capital intensity explicitly in their assessments.

4.5 Performance Scores of Alternatives Based on each Criterion

In this section, each transmission alternative is scored based on their performance on all seven criteria. Furthermore, it will be explained how each criterion was scored, including the data sources, assumptions, and expert input used.

4.5.1 Quantitative Criteria

With support from the System Design team, Vattenfall's Front-End Park Model (FEPM) was used to establish performance scores for the quantitative criteria by simulating tailored scenarios, allowing for a consistent and realistic comparison of the alternatives. The FEPM is an internal modelling tool used within Vattenfall to develop business cases and calculate technical parameters and costs for offshore wind projects [33].

The model outputs used in this study were primarily based on Kattegatt 2, an ongoing business case with comparable project characteristics, including a similar offshore distance and a similar capacity of around 1GW. Kattegatt 2 is currently an active project under development of which there was significant ongoing work related to this project at the time of the analysis. As a result, detailed model outputs and technical information were more readily accessible. However, one notable difference between the projects is the location of the TSO point of connection: in Kattegatt 2, the TSO grid connection is located 53 km inland, while for Kattegatt Syd this distance is only around 7 km. The FEPM simulation was based on the direct-to-shore alternative that includes an ONS located near the landfall point. However, due to the very short onshore distance between the landfall and the TSO grid connection for Kattegatt Syd, the two direct-to-shore configurations (with and without an ONS near landfall) are assumed to have equivalent outcomes in terms of infrastructure requirements, losses, and costs. Consequently, CAPEX, OPEX, and Revenue values were treated as equal for both configurations.

Both discounted (present value) and nominal financial outputs were produced by the simulation model. For this assessment, nominal values are used, in line with internal practice at Vattenfall, where costs and revenues are commonly expressed in nominal terms [33]. Using nominal values ensures consistency with how financial figures are typically communicated and compared within the organization, making the trade-offs between alternatives more meaningful and actionable for decision-makers.

CAPEX

CAPEX reflects all initial investment costs related to each export system configuration, expressed in nominal terms. The CAPEX values are as follows:

- 66 kV OSS: €[redacted] million
- 132 kV OSS: €[redacted] million
- Direct-to-shore (both options): €[redacted] million

OPEX

OPEX represents the total nominal sum of all expected operational and maintenance costs over the full project lifetime. The following values were used:

- 66 kV OSS: €[redacted] million
- 132 kV OSS: €[redacted] million
- Direct-to-shore (both options): €[redacted] million

Revenue

Revenue is calculated as the total nominal income from electricity sales, Guarantees of Origin (GoOs), and market prices based on the LTMO (Long-Term Market Outlook) curves. The expected revenue values are:

- 66 kV OSS: €[redacted] million
- 132 kV OSS: €[redacted] million
- Direct-to-shore (both options): €[redacted] million

Risk Budget

For the contingency budget, within Vattenfall's business cases taking a contingency of 5% of total CAPEX of the project is standard practice. However, Vattenfall has not developed an offshore wind project in a country where the developer is responsible for the OSS within their scope for more than 10 years. The last time they got to the negotiation phase regarding an OSS, during the course of negotiations, the price had already tripled [33]. Moreover, a Risk and Opportunity Manager from the "Controlling Offshore" department of the company was interviewed. Her specific focus is on products (i.e. OSS) and concepts. She could adhere to the fact that having an OSS in scope brings a lot of uncertainty into the project. She drew from her own experiences where she was involved in supplier negotiations regarding a substation. However, she mentioned that although removing the OSS would eliminate much of the complexity, it would result in more export cables, which may introduce new technical/supply risks.

Moreover, based on the Single Point Organisation Chart shown in Figure 8, the Risk

Manager responsible for Kattegatt Syd was identified and consulted as part of this research. He explained that the company has not actively scoped full transmission systems in years, and as a result, the risk register for Kattegatt Syd is still under development. For example, risk has only been assessed for the base case (66 kV OSS), while other transmission configurations have not yet been formally analysed. He acknowledged that removing the OSS would eliminate many typical offshore risks (such as weather windows, vessel size and availability, installation complexity), but also expressed uncertainty around whether long export cable configurations without an OSS might introduce new, as-yet-unquantified risks. "That is why I cannot speak confidently to the difference in risk between these configurations," he noted, emphasizing that the company lacks recent examples or product-level risk data for these alternatives [33].

Moreover, a literature search was conducted. Spinergie (2024) mentions significant supply chain bottlenecks in OSS demand and even say 35% of global demand is already at risk [35]. Further literature research supports that inclusion of an OSS in the scope of the developer increases the risk profile of the project [3], [29], [23].
Based on this combination of internal insights and external sources and in consultation with my Vattenfall supervisor who has been involved in the most recent company negotiations regarding an OSS, differentiated risk assumptions were applied. A contingency of 25% was allocated to all alternatives that include an OSS, reflecting the high supplier-side uncertainty and multi-interface complexity. For the direct-to-shore configurations, a reduced but still conservative 10% contingency was assumed of twice the standard level. This is done to account for the relative novelty of these systems, possible export cable vulnerabilities at extended lengths, and the potential for new risks to emerge as uptake of these solutions increases.

4.5.2 Qualitative Criteria

To evaluate the performance of different export system designs on qualitative criteria, interviews were conducted with internal Vattenfall experts involved with Kattegatt Syd. Each interviewee was selected based on their expertise and role relevance to the specific criterion. A 5-point Likert scale was used to capture performance scores, reflecting expert judgment. This is a commonly applied method in MCDM, in which respondents indicate their level of agreement or assessment on a fixed scale (in this case: from 1 - very low to 5 - very high) [19]. Prior to the interview, the interviewees were provided with detailed background information on all four transmission system alternatives, as well as the scoring guide.

To decide which experts should be interviewed for scoring these criteria in this scenario, I referred back to the Single Point Organisation Chart (SPOrgC) in Figure 8 used within Vattenfall for offshore wind asset projects. For each qualitative criterion, it was identified which role holds relevant expertise or responsibility within certain asset projects and then these stakeholders were contacted specifically for the Kattegatt Syd project. This ensures that each score is grounded in first-hand project knowledge.

The following roles were interviewed:

- **Consent Manager**: Provided input for the *Permitting Complexity & Environmental Impact*. As this role is responsible for navigating the permitting process and engaging with environmental regulators, it offers critical insight into permitting risks and ecological implications.
- **Electrical Project Engineer**: Reporting to the TPM, this role is not shown explicitly in the SPOrgC but is part of the TPM's extended technical team. Selected for the *Ease of Implementation* and *Innovation & Scalability* criteria due to direct involvement in designing and integrating grid connection systems.
- **Procurement Specialist**: Since this project did not include a Supply Chain Manager as is shown in the SPOrgC, a procurement expert from Business Area Wind with Swedish market experience was interviewed to support the *Ease of Implementation* criterion. This stakeholder contributes valuable insight into supplier availability and logistical challenges.

This selection ensures that all performance scores for the qualitative criteria are provided by stakeholders who are directly involved in, or accountable for, the underlying aspects of each criterion.

Ease of Implementation

To assess the Ease of Implementation criterion, interviews were conducted with an experienced electrical engineer and a procurement manager from Vattenfall. This criterion captures the combined assessment of technical feasibility, project maturity, supply chain availability, and internal knowledge requirements necessary to implement the transmission system alternatives.

The procurement expert, with experience in the Swedish offshore wind market, provided scores that reflect current industry practice and supplier landscape maturity:

- 66 kV with OSS and 132 kV with OSS both received the highest score of 5, described as "current practice and fully mature." These systems are the current standard for offshore wind farms.
- The 132 kV direct-to-shore (TSO point of connection) and 132 kV direct-to-shore (ONS near landfall) both received a score of 3. According to the expert, these are not

standard practice. The installation of multiple cables to shore can face site-specific challenges, possibly requiring installation to be done over 2 seasons. However, these solutions will be increasingly attractive to cable suppliers due to larger installation scopes.

The electrical engineer, part of the technical team under the TPM, also assessed all four alternatives based on technical feasibility and design integration:

- Both 66 kV with OSS and 132 kV with OSS received a score of 3. Although feasible, the engineer highlighted the increased complexity and high cost of involving both OSS and ONS (as would be the case in Sweden) both are highly expensive components with very long lead-times.
- The 132 kV direct-to-shore option connecting directly to the TSO point of connection also received a score of 3. The engineer emphasized that, assuming technological maturity of high-voltage turbine and array cable connections, the solution is technically feasible. One noted advantage is the potential to connect directly to the Distribution System Operator (DSO) network. This setup can offer increased redundancy because the DSO grid often has multiple feeders and is typically more meshed and distributed than the TSO grid. As a result, faults or outages in one part of the grid can more easily be isolated, while maintaining supply from alternative paths. This enhances the operational flexibility and fault resilience of the export system. Additionally, the expert noted that removing a substation - particularly an offshore one - would be highly beneficial from a cost and complexity standpoint. As he stated: "We all know, in terms of cost and complexity, we should try to avoid equipment offshore."
- The 132 kV direct-to-shore alternative (with an ONS located near the landfall point) received a slightly higher score of 4, due to several practical advantages. The ONS is positioned relatively close to the offshore site and is built on a less complex onshore location, which simplifies construction and grid integration. Additionally, when connecting directly to the DSO grid, having an ONS allows for greater flexibility in system operation, particularly from a redundancy and operational strategy perspective. Normally, export cables have thermal limits - meaning that in warmer conditions, the amount of current they can carry is limited to prevent overheating. However, for most of the year, the underground environment in northern regions remains very cold. This makes it possible to use one of the two export cables for a larger share of the transmission load without exceeding thermal limits. In case of failure, the second cable can be activated. This is only possible if switching capacity exists at the landfall point, which is enabled by the presence of the onshore substation. Without it, such operational flexibility and redundancy would not be achievable.

Environmental Impact and Permitting Complexity

To assess the criterion Environmental Impact and Permitting Complexity, an expert interview was conducted with the consent manager of the Kattegatt Syd offshore wind project. She is an experienced permitting specialist, particularly in offshore cable routing and onshore planning. Using the Likert scale, she assigned a score to each alternative and provided qualitative reasoning based on her permitting experience.

- The 66 kV with OSS and the 132 kV with OSS alternatives both received a score of 3 - Moderate. According to the expert, finding an acceptable onshore route is manageable. The cable corridor on land would be approximately 30 meters wide and could face some resistance from property owners. Appeals may occur but are considered manageable in both cases.
- The 132 kV direct-to-shore option with export cables connecting directly to the TSO point received the lowest score: 1 - Very High. The expert explained that securing an offshore route for this many cables is particularly challenging due to the presence of sensitive benthic habitats and protected archaeological sites. At the landfall point, corridor space is limited due to the presence of another developer. Furthermore, onshore routing would require a corridor at least 60 meters wide over a 7 km stretch, resulting in significant impact on the landscape, environment, and archaeology (e.g., extensive excavations). Gaining voluntary agreements from property owners would be very difficult, and the likelihood of appeals is assessed as very high.
- The 132 kV direct-to-shore alternative with export cables connecting to an onshore substation near the landfall scored slightly better: 2 - High. While it faces the same offshore challenges as the previous option, having the substation closer to shore may reduce the footprint onshore and opposition from property owners slightly. Still, the impact remains high. In addition, the higher electromagnetic field (EMF) of this configuration requires increased distance from residential areas, which could be problematic in narrower parts of the onshore corridor.

The expert also states that it is important to note that these scores reflect only the permitting complexity related to the cable systems. The presence of an OSS does not influence the permitting score, as the OSS is generally included in the wind farm's overall permit and does not receive separate attention during the permitting process. If the assessment had covered permitting for the wind farm as a whole, all alternatives would have scored 1, due to the high complexity of full wind farm permitting - not because of the OSS specifically.

Innovation and Scalability

To evaluate the Innovation and Scalability criterion, an interview was conducted with the electrical engineer of Kattegatt Syd. This criterion reflects the potential of each system to support technological advancements and to scale effectively with future offshore wind developments.

- The 66 kV with OSS configuration has the lowest innovation potential (score 1) according to the electrical engineer, as it is a fully conventional solution.
- The 132 kV with OSS option received a 3, slightly better due to a reduction in the number of cables.
- Both 132 kV direct-to-shore alternatives were rated 4. The expert emphasized the advantage of skipping the OSS and the ability to consider multiple onshore connection points. This makes it easier to scale the solution to different project conditions, especially in cases where even the ONS could be avoided.

4.5.3 Final Performance Scores per Criteria

The final scores per alternative are given in Table 3 below. As the Ease of Implementation criterion has been scored by two people, the average of their scorings is taken as the final score.

Criteria	**66 kV with OSS**	**132 kV with OSS**	**132 kV direct-to-TSO**	**132 kV direct-to-shore with ONS near Landfall**
CAPEX	[redacted]	[redacted]	[redacted]	[redacted]
OPEX	[redacted]	[redacted]	[redacted]	[redacted]
Revenue	[redacted]	[redacted]	[redacted]	[redacted]
Risk Associated with Project	25	25	10	10
Ease of Implementation	4	4	3	3.5
Environmental Impact and Permitting Complexity	3	3	1	2
Innovation and Scalability	1	3	4	4

Table 3: Performance scores of the Four Offshore Transmission System Alternatives

4.6 Criteria Weighting

This section presents the criteria weightings derived from the stakeholder interviews, following the methodological steps outlined in Section 3.3.

4.6.1 Mutual Preferential Independence

Mutual preferential independence (MPI) is a core concept in MCDM. It implies that the preferences or trade-offs between any subset of criteria are not affected by the specific levels of the remaining criteria. This condition is important to justify the use of additive value models [18], [48].

In this thesis, the weights obtained through the BWT method are applied in an additive value model to calculate the final scores of the alternatives. In principle, for a valid application of an additive model, the assumption of MPI among the criteria should be formally tested. In this study, such a formal test was not conducted. This choice is supported by the literature: although classical sources emphasize the importance of MPI [18], practice-oriented applications suggest that when the variation ("range") of the attributes is limited, the effect of any potential dependencies between attributes can often be considered negligible in practice. For instance, Rezaei (2021) describes that in their own experimental case the additive model was considered valid because "the range of the attributes in their experiment was small" and refers to literature from von Winterfeldt & Edwards (1986) and Watson et al. (1987) to justify this [45], [48].

In this thesis, all performance scores were normalized and based on realistic, bounded ranges derived from expert interviews and internal Vattenfall data. The variation between attributes was relatively small: for instance, CAPEX values among alternatives differed by only 6.4%, OPEX by less than 2.4%, and revenue differences were extremely limited at 0.45%. The qualitative scores (on a 1–5 scale) for implementation, environmental impact, and innovation also showed limited spread. Given these narrow ranges (and supported by the literature cited above) the use of an additive aggregation model is considered justified in this case, despite the absence of a formal MPI test.

4.6.2 Stakeholders interviewed

Through the stakeholder selection in Chapter 4.2 it was defined that the decision-making authority for the transmission system design of a specific offshore wind asset project lies with the Technical Project Manager (TPM) and the Project Director (PD). These two individuals were interviewed for the reference project Kattegatt Syd.

4.6.3 Interview Design

The interview design is based on a structured survey developed in Qualtrics, which is administered in a one-on-one interview setting due to the complexity of the decision-making problem and the BWT method. All procedures follow TU Delft's Human Research Ethics Committee (HREC) guidelines. The informed consent form is included at the start of the survey and can be found in Appendix B. The outcomes of the different steps of the stakeholder interviews are presented in the following subsections.

Although this thesis applies the BWT method as its primary elicitation framework, the final analysis is operationalized using a BWM Excel solver. This solver is a spreadsheet-based implementation of the Best-Worst Method, commonly used to compute optimal criterion weights and check the consistency of pairwise comparisons. While the BWT method extends BWM by incorporating attribute ranges through value functions, it ultimately generates comparison inputs that are structurally compatible with the BWM format. Specifically, each BWT trade-off question results in a numerical value derived from a normalized value function, which is then translated into a reciprocal pairwise comparison between criteria. Because of this compatibility, the BWM solver can be reliably used to process the BWT-derived comparison vectors, allowing for the efficient calculation of both consistency ratios and final criterion weights.

To support this process, an Excel sheet was prepared in advance. This sheet includes a template for all value functions needed for the BWT procedure. These functions are defined based on midpoints elicited during the interview - specifically, values corresponding to utility levels 0.25, 0.5, and 0.75. During the interview, the decision-maker is asked to indicate these midpoints directly, and the interviewer fills in the corresponding values in the Excel sheet. Using this input, piecewise linear value functions are constructed dynamically within the sheet. As the expert then provides an indifference judgment between two trade-off alternatives, the corresponding numerical input is entered. This value is automatically interpolated using the constructed value functions. The reciprocal of the resulting utility ratio is then used as the pairwise comparison input, which is directly linked to the corresponding cell in the BWM solver sheet configured for a 7-criteria problem. This setup enables real-time consistency checking: the solver continuously updates the overall consistency ratio. If inconsistency is detected, the interviewer can immediately identify problematic trade-offs and discuss potential revisions with the expert.

Each part of the interview and its corresponding output data are given in the subsections below.

Introduction

At the start of each interview, the informed consent form was read aloud together with the participant, after which they were given the opportunity to ask questions and indicate whether they agreed to proceed under the conditions outlined. I explicitly asked whether they were comfortable being referenced in a non-identifying way in the final thesis.

Next, I introduced the project and explained the objective of the research, including the role of expert input in evaluating offshore transmission alternatives. I then presented the seven evaluation criteria and their respective performance scores, clarifying how these scores had been determined. I also explained the overall evaluation method and how the interview contributed to this process.

Before each key part of the interview, such as the elicitation of value functions and the trade-off questions, I provided a separate, focused explanation to ensure the expert fully understood the goal and approach of that specific step.

Value Functions

In the first part of the stakeholder interviews, participants are guided through a structured process to define value functions for each evaluation criterion. They are first presented with the best and worst performance levels, based on the performance scores established in Chapter 4.5. Then, they are asked to estimate the intermediate performance levels that they perceive as being 25%, 50%, and 75% as attractive as the best-case value. An example of how these questions are phrased to the decision-maker is given in Appendix C. This subjective assessment helps capture how improvements are valued across the performance range, using the mid-value splitting method by Keeney and Raiffa [19]. These responses form the basis for constructing (nonlinear) value functions that reflect stakeholder preferences. In Table 4 and Table 5 the mid-value points given by both the TPM and the PD (respectively) are depicted. The different criteria are shown as: C_1 = CAPEX, C_2 = OPEX, C_3 = Revenue, C_4 = Risk, C_5 = Ease of Implementation, C_6 = Permitting Complexity, C_7 = Innovation.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7
Worst (0)	[redacted]			25	3.00	1	1
0.25				23	3.25	1.5	2
0.5				20	3.5	2	3
0.75				15	3.75	2.5	3.5
Best (1)				10	4.00	3	4

Table 4: Mid-value points for each criterion (TPM)

	C_1	C_2	C_3	C_4	C_5	C_6	C_7
Worst (0)	[redacted]			25	3.00	1	1
0.25	[redacted]			23	3.25	1.5	1.75
0.5	[redacted]			20	3.5	2	2.5
0.75	[redacted]			17	3.75	2.5	3.25
Best (1)	[redacted]			10	4.00	3	4

Table 5: Mid-value points for each criterion (PD)

These elicited values are then used to construct piecewise linear value functions, which are shown in Figure 10 and 11 below. When a criterion performance value is provided, its corresponding normalized value is derived from this function.

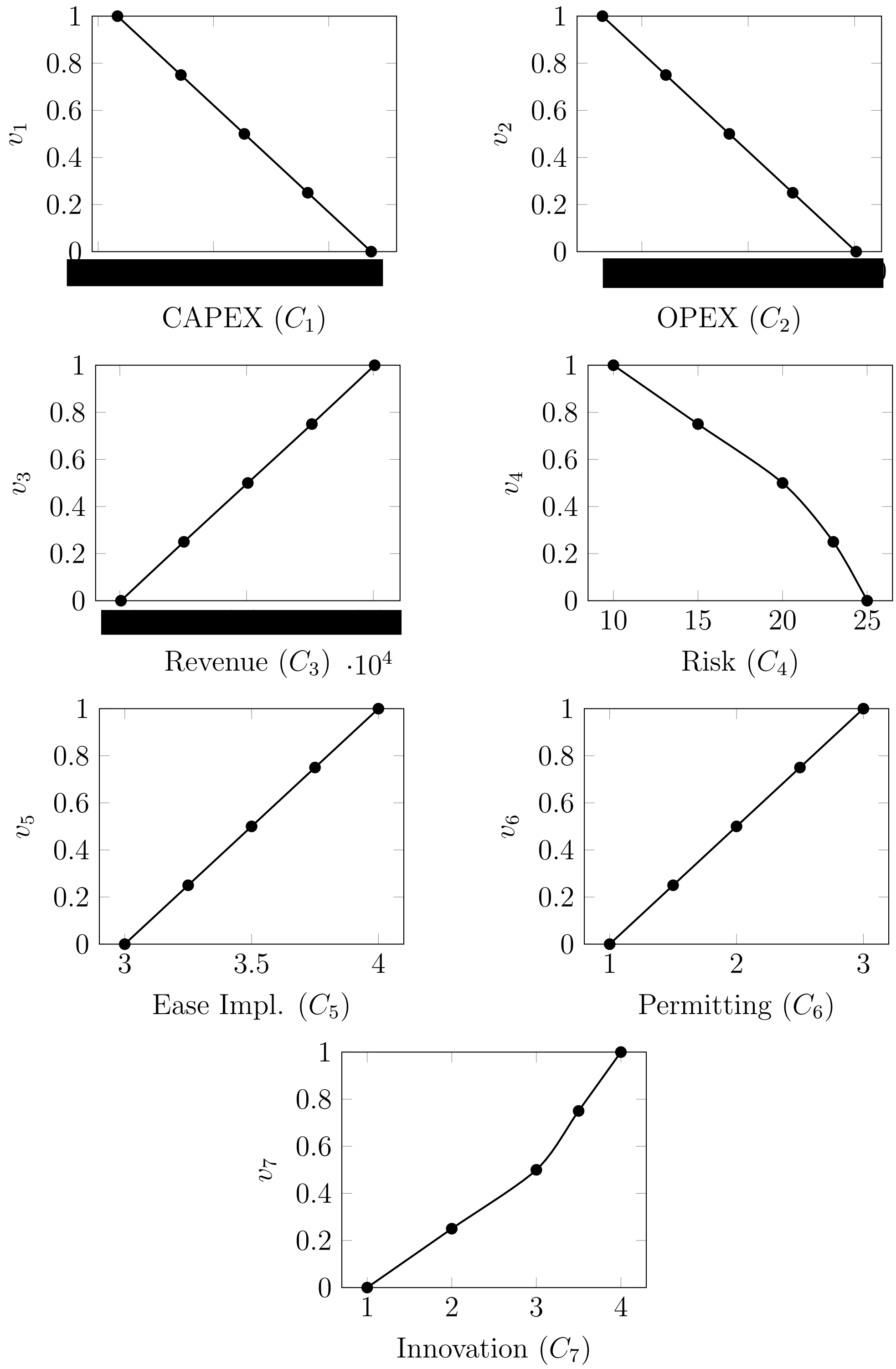

Figure 10: Assessed value functions for criteria C_1 to C_7 based on TPM mid-values.

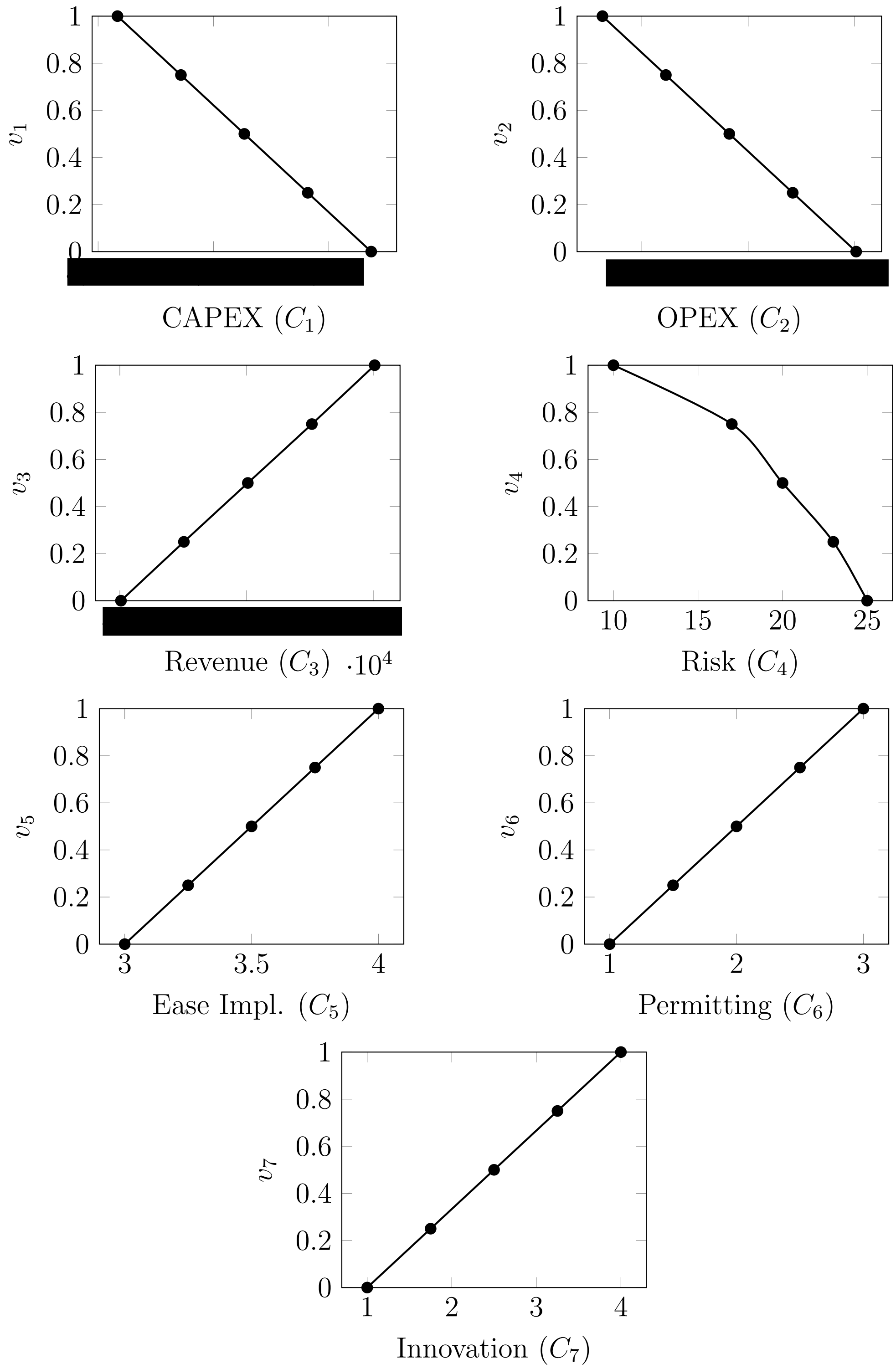

Figure 11: Assessed value functions for criteria C_1 to C_7 based on PD mid-values.

Best and Worst Criterion Selection

To determine the relative importance of each evaluation criterion, stakeholders are presented with seven hypothetical alternatives. In each alternative, one criterion is set to its best performance level, while all others are fixed at their worst. Participants are then asked to rank the alternatives from most to least favorable. Since each alternative highlights the effect of improving just one criterion, the resulting ranking directly reflects the decision-maker's perceived importance of each criterion in isolation. This ranking is used to identify the best and worst criterion in the subsequent BWT analysis. From the ranking during the TPM interview, it can be concluded that Revenue (C_3) is the most important (Best) criterion and Innovation & Scalability (C_7) is the least important (Worst) criterion. For the PD, Permitting Complexity (C_5) is most important (Best) and Risk (C_4) is the least important (Worst).

Best to others tradeoffs

To tradeoff the best attribute to the other attributes, 6 hypothetical consequences are created as explained in Chapter 3.3. For the TPM, who selected the criterion Revenue (C_3) as best criterion, the following hypothetical consequences were presented, the TPM was asked to provide the undetermined values $\left(x_3^{3,1},\ x_3^{3,2},\ x_3^{3,4},\ x_3^{3,5},\ x_3^{3,6},\ x_3^{3,7}\right)$.

$$\left(\text{[redacted]},\ x_3^{3,1},\ 25,\ 3.0,\ 1.0,\ 1.0\right) \sim (\text{[redacted]},\ 25,\ 3.0,\ 1.0,\ 1.0)$$
$$\left(\text{[redacted]},\ x_3^{3,2},\ 25,\ 3.0,\ 1.0,\ 1.0\right) \sim (\text{[redacted]},\ 25,\ 3.0,\ 1.0,\ 1.0)$$
$$\left(\text{[redacted]},\ x_3^{3,4},\ 25,\ 3.0,\ 1.0,\ 1.0\right) \sim (\text{[redacted]},\ 10,\ 3.0,\ 1.0,\ 1.0)$$
$$\left(\text{[redacted]},\ x_3^{3,5},\ 25,\ 3.0,\ 1.0,\ 1.0\right) \sim (\text{[redacted]},\ 25,\ 4.0,\ 1.0,\ 1.0)$$
$$\left(\text{[redacted]},\ x_3^{3,6},\ 25,\ 3.0,\ 1.0,\ 1.0\right) \sim (\text{[redacted]},\ 25,\ 3.0,\ 3.0,\ 1.0)$$
$$\left(\text{[redacted]},\ x_3^{3,7},\ 25,\ 3.0,\ 1.0,\ 1.0\right) \sim (\text{[redacted]},\ 25,\ 3.0,\ 1.0,\ 4.0)$$

The TPM assessed the following equivalent values for Revenue (C_3):

$$\left(x_3^{3,1},\ x_3^{3,2},\ x_3^{3,4},\ x_3^{3,5},\ x_3^{3,6},\ x_3^{3,7}\right) = (\text{[redacted]})$$

By using the value functions from the last step and following the method described in Chapter 3.3, the following A^{BO} vector is obtained:

$$A^{BO} = (a_{B1},\ a_{B2},\ a_{B4},\ a_{B5},\ a_{B6},\ a_{B7}) = (1.68,\ 2.02,\ 2.53,\ 3.37,\ 5.08,\ 8.24)$$

The same was done in the PD interview, while reflecting the criterion he selected as most important in the tradeoffs, namely Permitting Complexity (C_6). The hypothetical consequences and equivalent values of the PD interview can be found in Appendix D. This resulted in the following A^{BO} vector:

$$A^{BO} = (a_{61},\ a_{62},\ a_{63},\ a_{64},\ a_{65},\ a_{67}) = (1.67,\ 1.82,\ 1.33,\ 2.00,\ 1.25,\ 1.18)$$

Others to worst tradeoffs

To tradeoff the other criteria to the least important criterion, once again 6 hypothetical alternatives were created as explained in Chapter 3.3. The TPM identified Innovation & Scalability as the worst criterion and was therefore presented with the following alternatives. He was asked to determine the values for $\left(x_1^{1,7},\ x_2^{2,7},\ x_3^{3,7},\ x_4^{4,7},\ x_5^{5,7},\ x_6^{6,7}\right)$.

$\left(x_1^{1,7},\right.$ [redacted], 25, 3.0, 1.0, 1.0$\left.\right) \sim ($[redacted], 25, 3.0, 1.0, 4.0$)$

$\left(\right.$[redacted], $x_2^{2,7}$, [redacted] 25, 3.0, 1.0, 1.0$\left.\right) \sim ($[redacted], 25, 3.0, 1.0, 4.0$)$

$\left(\right.$[redacted], $x_3^{3,7}$, 25, 3.0, 1.0, 1.0$\left.\right) \sim ($[redacted], 25, 3.0, 1.0, 4.0$)$

$\left(\right.$[redacted], $x_4^{4,7}$, 3.0, 1.0, 1.0$\left.\right) \sim ($[redacted], 25, 3.0, 1.0, 4.0$)$

$\left(\right.$[redacted], 25, $x_5^{5,7}$, 1.0, 1.0$\left.\right) \sim ($[redacted], 25, 3.0, 1.0, 4.0$)$

$\left(\right.$[redacted], 25, 3.0, $x_6^{6,7}$, 1.0$\left.\right) \sim ($[redacted], 25, 3.0, 1.0, 4.0$)$

The TPM assessed the following equivalent values:

$\left(x_1^{1,7},\ x_2^{2,7},\ x_3^{3,7},\ x_4^{4,7},\ x_5^{5,7},\ x_6^{6,7}\right) = ($[redacted], 19, 3.5, 2.5$)$

By using the value functions and following the method described in Chapter 3.3, the following A^{OW} vector is obtained:

$$A^{OW} = (a_{1W},\ a_{2W},\ a_{3W},\ a_{4W},\ a_{5W},\ a_{6W}) = (2.86,\ 1.57,\ 4.50,\ 1.82,\ 2.00,\ 1.33)$$

The same was done in the PD interview, while reflecting the criterion he selected as least important in the tradeoffs, namely Risk (C_4). This process is shown in Appendix D. This resulted in the following A^{OW} vector:

$$A^{OW} = (a_{1W},\ a_{2W},\ a_{3W},\ a_{5W},\ a_{6W},\ a_{7W}) = (1.62,\ 1.61,\ 1.35,\ 1.25,\ 1.33,\ 1.20)$$

Consistency check

To evaluate the reliability of the elicited preferences, the BWM solver was used to compute the consistency level associated with the A^{BO} and A^{OW} vectors. The solver determines whether the pairwise comparisons provided by the decision-maker align coherently with one another by calculating a consistency ratio. More information on how this consistency is calculated can be found in Chapter 3.3. If the consistency level exceeds a predefined threshold, the solver flags the input for potential revision. However, for both the TPM and PD interviews, the solver indicated that the pairwise comparison data met the consistency requirements. Therefore, no revisions to the preference information were necessary.

4.6.4 Calculate the Optimal Weights for Each Criterion

Next, the BWT model as discussed in Chapter 3.3 is applied to compute the optimal weights for each criterion. In this study, the BWM Excel solver is used to perform this calculation by inputting the pairwise comparison values derived from the BWT interviews. The solver provides the set of weights that best fit the expert's preferences while maintaining consistency.

For the TPM interview, the resulting weights are:

$$w^{TPM} = (0.207,\ 0.150,\ 0.279,\ 0.143,\ 0.107,\ 0.071,\ 0.044)$$

For the PD interview, the resulting weights are:

$$w^{PD} = (0.128,\ 0.118,\ 0.160,\ 0.099,\ 0.164,\ 0.172,\ 0.159)$$

These weights reflect the relative importance each stakeholder assigns to the seven criteria under evaluation. The weights of both decision-makers are visualized in the chart in Figure 12 below.

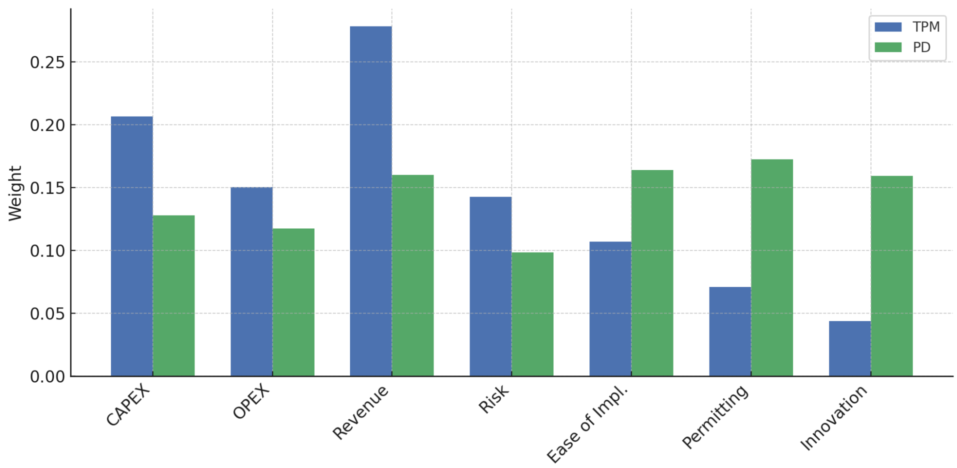

Figure 12: Weights per criterion for TPM and PD decision makers

4.7 Final MCDM scores

In this section, the performance scores per criterion are combined with the criteria weightings assigned by the decision-makers to establish final MCDM scores per alternative. Scores were first calculated for the TPM and PD individually, and then aggregated into a final combined evaluation.

4.7.1 Final Scores for the TPM

To determine the overall preference for each transmission system alternative, the normalized performance scores of each criterion (as shown in Table 7) are calculated as explained in Chapter 3.3. These values are then aggregated with the criteria weights using the additive formula equation also introduced in Chapter 3.3.

The weights used for the TPM are summarized below:

Criterion	CAPEX	OPEX	Revenue	Risk	Ease of Impl.	Permitting	Innovation
Weight	0.2069	0.1505	0.2785	0.1426	0.1069	0.0709	0.0437

Table 6: TPM Criteria Weights (rounded to 4 decimals)

The normalized performance scores of the TPM for each alternative are:

Alternative	**CAPEX**	**OPEX**	**Revenue**	**Risk**	**Ease of Impl.**	**Permitting**	**Innovation**
Alt 1	0.00	1.00	0.00	0.00	1.00	1.00	0.00
Alt 2	0.02	0.00	0.78	0.00	1.00	1.00	0.50
Alt 3	1.00	0.36	1.00	1.00	0.00	0.00	1.00
Alt 4	1.00	0.36	1.00	1.00	0.50	0.50	1.00

Table 7: Normalized Performance Scores for TPM

Using these values, the final scores are computed. The calculations of these scores can be found in Appendix E. The final MCDM scores are as follows:

Alternative	**Final Score (TPM)**
Alt 1: 66 kV with OSS	0.3283
Alt 2: 132 kV with OSS	0.4211
Alt 3: 132 kV direct to TSO	0.7260
Alt 4: 132 kV direct to ONS	0.8149

Table 8: Final Scores for TPM

Based on the TPM's preferences, the **132 kV direct-to-shore with ONS near landfall (Alt 4)** is the most preferred alternative, followed by the 132 kV direct-to-TSO configuration.

4.7.2 Final Scores for the PD

The same methodology is used to compute the final scores for each alternative from the perspective of the PD, by multiplying the normalized performance scores (Table 10) with the corresponding elicited weights. The weights of the PD are summarized below:

Criterion	CAPEX	OPEX	Revenue	Risk	Ease of Impl.	Permitting	Innovation
Weight	0.1280	0.1174	0.1601	0.0986	0.1642	0.1724	0.1593

Table 9: PD Criteria Weights (rounded to 4 decimals)

The normalized performance scores of the PD for each alternative are:

Alternative	CAPEX	OPEX	Revenue	Risk	Ease of Impl.	Permitting	Innovation
Alt 1	0.00	1.00	0.00	0.00	1.00	1.00	0.00
Alt 2	0.02	0.00	0.78	0.00	1.00	1.00	0.67
Alt 3	1.00	0.36	1.00	1.00	0.00	0.00	1.00
Alt 4	1.00	0.36	1.00	1.00	0.50	0.50	1.00

Table 10: Normalized Performance Scores for PD

Using these values, the final scores are computed. The computations can be found in Appendix E. The final MCDM scores of the PD are as follows:

Alternative	Final Score (PD)
Alt 1	0.454
Alt 2	0.571
Alt 3	0.588
Alt 4	0.756

Table 11: Final Scores for PD

4.7.3 Collective Evaluation and Final Scores

To derive an overall preference ranking that reflects both stakeholders' perspectives, the individual scores of the TPM and PD are aggregated into a collective score. Both stakeholders are assigned equal importance because both hold equal decision-making authority within the context of offshore grid connection development at Vattenfall. This assumption was confirmed in conversations with Vattenfall stakeholders, who indicated that both the TPM and PD play a decisive and equally weighted role in the approval process of system design options [33]. Table 12 presents the combined results.

Alternative	TPM Score	PD Score	Final Score (Average)
Alt 1	0.3283	0.4540	0.3912
Alt 2	0.4211	0.5714	0.4963
Alt 3	0.7260	0.5880	0.6570
Alt 4	0.8149	0.7559	0.7854

Table 12: Combined Stakeholder Scores and Final Ranking

The final scores are visualized in the chart in Figure 13 below:

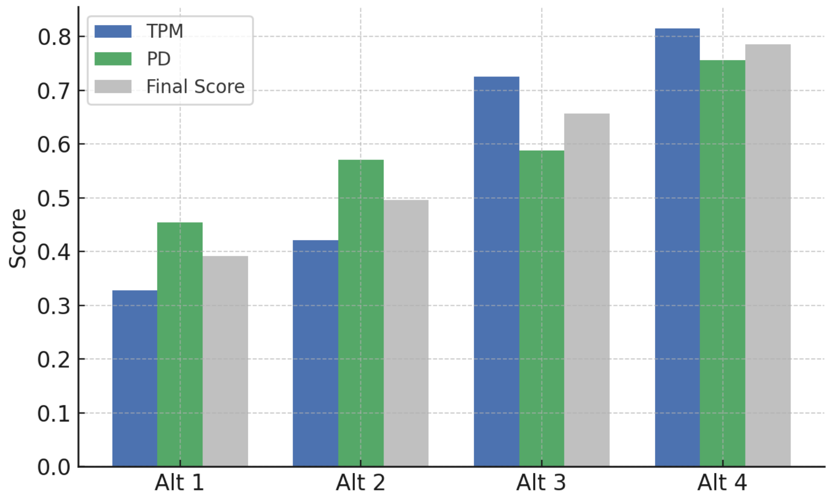

Figure 13: Final MCDM scores

Summarised again below are the four alternatives:

- **Alt 1:** 66 kV inter-array with OSS - the industry-standard base case.
- **Alt 2:** 132 kV inter-array with OSS.
- **Alt 3:** 132 kV direct-to-shore with only TSO substation - no OSS, directly to ONS at TSO connection point.
- **Alt 4:** 132 kV direct-to-shore with ONS near landfall - voltage stepped up before going to TSO connection point.

Based on these final scores, Alternative 4 is the most preferred solution overall, followed by Alternative 3. These results suggest a clear stakeholder preference for solutions that avoid offshore substations and reduce complexity and cost, while still enabling effective implementation and permitting processes.

4.7.4 Sensitivity Analysis

To assess the robustness of the MCDM results, a sensitivity analysis was conducted on both the input performance values and the applied weightings. While the main analysis of the weightings already incorporates different stakeholder perspectives through the BWT method - producing distinct weight sets for the TPM and PD decision-makers - an additional scenario was included in which all criteria were assigned equal weights. This equal weights scenario simulates a situation where no stakeholder-specific prioritization is applied, and each criterion is considered equally important.
The selection of performance scores of criteria for this sensitivity analysis was based primarily on their relative importance (i.e., weight) in the decision-making process. The two most heavily weighted criteria were included, as these have the greatest influence on the final MCDM results. Analyzing the sensitivity of high-impact criteria allows us to assess whether moderate changes in their input values could alter the ranking outcome. In addition to importance, it is assumed that qualitative performance scores are inherently more uncertain, as they rely on expert judgment and subjective interpretation. Therefore, the most heavily weighted qualitative criterion is also included in the sensitivity analysis, to assess whether plausible changes in expert judgment could meaningfully affect the rankings.

Based on the average weight across both decision-makers, the following three criteria were selected:

- **Revenue** (Average weight: 0.220): This is the most heavily weighted criterion based on the average weight of the TPM and the PD and is based on quantitative input. The observed difference in revenue between the highest and lowest scoring alternative is approximately 0.5% in absolute terms. To assess the sensitivity beyond this narrow range, a variation of 1% in revenue values was applied.
- **CAPEX** (Average weight: 0.168): Also a key economic indicator, CAPEX exhibits a relative difference of 6.84% across alternatives. A 7% variation was applied to test its impact on rankings.
- **Ease of Implementation** (Average weight: 0.136): This is the most important qualitative criterion and was included to capture the uncertainty related to expert-based scoring. A variation of 1 point was applied to reflect plausible variation in stakeholder judgment.

All other criteria were excluded due to their relatively lower weights.

Equal Weights Scenario

The sensitivity analysis shows that applying equal weights to all criteria does not substantially alter the overall ranking of alternatives. Alt 4 remains the highest-ranked option with a final score of 0.7657, followed by Alt 3 (0.6229), Alt 2 (0.4836), and Alt 1 (0.4286). This ranking is fully consistent with the original MCDM results based on stakeholder-derived weights. This analysis demonstrates that the overall MCDM outcome is robust to changes in the weighting structure. Even when all stakeholder preferences are removed and each criterion is given equal importance, the ranking of alternatives remains identical to the original result. Alt 4 continues to outperform all other options, while Alt 1 remains the least favorable. This indicates that the strong performance of Alt 4 is not an artefact of the stakeholder-derived weightings, but is instead driven by consistently high scores across multiple criteria. Although the use of equal weights slightly reduces the score differences between alternatives, it does not change the relative order. This confirms that the MCDM results are not overly sensitive to the weighting approach, and that the conclusion in favor of Alt 4 holds even under a neutral, preference-free evaluation. The final scores for this scenario can be found in Table 13, and all underlying calculations are provided in Appendix F.

Revenue

To assess the robustness of the MCDM outcomes regarding the revenue performance score, a sensitivity scenario was conducted in which the revenue values of the two direct-to-shore alternatives (Alt 3 and Alt 4) were decreased by 1%. These two alternatives originally had the highest revenue values and thus received a normalized score of 1.00. If a +1% increase had been applied instead, it would not have altered their relative position in the normalization, and their scores would have remained at 1.00. Therefore, a +1% variation would have had no effect on the final rankings, and only the –1% case was further investigated. By applying a 1% decrease in revenue, both direct-to-shore alternatives shift from being the best-performing to the worst-performing options on this criterion, resulting in a normalized score of 0.
Following the approach used in the rest of the analysis, scores were calculated using each stakeholder's value functions, and their respective final scores were computed using their own weight vectors. The final MCDM scores for each alternative were then averaged across the TPM and PD perspectives. The calculations can be found in Appendix F.

For the revenue criterion specifically, both decision-makers indicated during the midvalue splitting interviews that they perceived it as linearly increasing in value. Therefore, in this sensitivity scenario, we assume a linear value function and apply linear interpolation over the newly observed range. The results are summarized in Table 13.

The sensitivity analysis shows that while Revenue is an influential criterion, the overall MCDM rankings are relatively robust to a –1% decrease in revenue for the direct-to-shore

alternatives. Also, the analysis significantly narrows the spread between the alternatives' final scores. While Alt 4 remains the top-ranked option, however the margin by which it outperforms the others is noticeably reduced. Most notably, Alt 3, which was previously ranked second, drops to last place. Meanwhile, Alt 1 and Alt 2 move up relatively in the ranking, as their scores are unaffected by the revenue change and become more competitive in relative terms.
This shift highlights that although Alt 4 is robust to moderate reductions in revenue, the overall ranking is somewhat sensitive to changes in this high-weight economic criterion, especially for alternatives like Alt 3 that derive a large portion of their score from revenue performance. This suggests that the MCDM outcome is not overly dependent on minor revenue fluctuations, but also underscores the importance of accurate revenue estimates.

CAPEX

To assess the influence of CAPEX on the MCDM results, a sensitivity analysis was conducted by applying a +7% increase to the CAPEX values of the two direct-to-shore alternatives (Alt 3 and Alt 4). This adjustment was chosen because the original range of CAPEX values between alternatives is approximately 6.4%, meaning that a 7% shift falls just beyond the existing spread. By taking a range of +7%, it is ensured that the direct-to-shore alternatives, which were the best-performing alternatives in terms of CAPEX (normalized performance score of 1), become the worst-performing options, thereby testing the robustness of their ranking under less favorable cost assumptions. A –7% variation was not considered, since Alt 3 and Alt 4 already had the lowest CAPEX values in the original input data. Lowering these further would not affect their normalized score, which was already at the maximum value of 1.00 (i.e., best possible performance on this criterion).
As with the Revenue criterion, CAPEX was treated as a linear value function based on the midvalue splitting assessments. Both decision-makers indicated a consistent preference structure for lower CAPEX values during the interviews, justifying the use of linear interpolation for recalculating normalized scores based on the new range. The new CAPEX scores were then used to recompute the final MCDM scores for each stakeholder separately. The calculations and results can be found in Appendix F and the results are summarized in Table 13

The sensitivity analysis for CAPEX shows that the MCDM results are meaningfully affected by variations in capital cost assumptions. Increasing the CAPEX of Alt 3 and Alt 4 by 7% leads to a significant decrease in their final scores. Most notably, Alt 4 is no longer the top-ranked alternative, allowing Alt 2 to take over the lead with a final score of 0.6604. This outcome demonstrates that the MCDM ranking is not fully robust to moderate-to-high CAPEX variation, particularly when it affects the top-performing alternative. Alternatives that are cost-sensitive, like direct-to-shore configurations, are more vulnerable to these assumptions.

That said, it is important to note that this scenario reflects an extreme variation. A 7% increase in CAPEX pushes the cost of the direct-to-shore alternatives above that of OSS-based configurations. In practice, such a reversal is highly unlikely, since offshore substations are typically one of the most expensive components in the system—and direct-to-shore options intentionally avoid them. Therefore, while the ranking shifts under this scenario, the likelihood of this cost configuration occurring is limited.

Ease of Implementation

This sensitivity analysis focuses on lowering the Ease of Implementation score for Alt 4 by one point to test whether this affects the overall ranking outcome. Alt 4 is currently the top-ranked alternative, and unlike the other direct-to-shore option (Alt 3), it does not yet receive the lowest possible normalized score on this criterion. Lowering its score allows us to examine whether increased implementation complexity would reduce its performance sufficiently to change the final ranking.

No adjustments were made to Alt 1, Alt 2, or Alt 3 because doing so would not meaningfully affect the final ranking. Alt 1 and Alt 2 already receive the maximum normalized score (1), so increasing their raw input would not improve their ranking. Only a downward adjustment for Alt 4 has the potential to impact the overall ranking and is therefore the only relevant sensitivity case for this criterion. As with the Revenue and CAPEX criteria, Ease of Implementation was treated as a linear value function based on the midvalue splitting assessments done by the TPM and PD.

The calculations and results can be found in Appendix F and the results are summarized in Table 13. The sensitivity analysis for Ease of Implementation shows that reducing the input score of Alt 4 by one point has a limited impact on the overall ranking. Alt 4 remains the top-ranked alternative across both stakeholder perspectives, although its final score slightly decreases from 0.7854 to 0.7636. The relative position of the other alternatives remains unchanged. Alt 3 stays in second place, Alt 2 in third, and Alt 1 in last. This indicates that the overall MCDM outcome is robust to moderate uncertainty in the implementation complexity of Alt 4. The results also confirm that while Ease of Implementation has moderate weight in both the TPM and PD perspectives, the strong performance of Alt 4 on other high-weight criteria such as Revenue, CAPEX, and Innovation ensures that its leading position remains stable even under less favorable assumptions.

Comparison of Sensitivity Outcomes

Across all sensitivity analyses shown in Table 13, the MCDM results are most sensitive to variations in CAPEX. A 7% increase causes a shift in the ranking: Alternative 2 overtakes Alternative 4 as the top-ranked option. It should be noted, however, that the CAPEX scenario reflects an unlikely situation in which the cost of direct-to-shore alternatives exceeds that of OSS-based configurations. Since offshore substations are typically the most expensive component in such systems, this outcome is not expected in practice.

Revenue variation also has a notable impact. A 1% decrease leads to a significant change in the relative ranking of Alternatives 1, 2, and 3 - Alternative 3 drops from second to fourth place, while Alternatives 1 and 2 move up. However, Alternative 4 still achieves the highest score, indicating that its top position is robust against changes in expected revenue. In contrast, Ease of Implementation has only a limited effect on final scores and does not alter the ranking.

Finally, the Equal Weights scenario confirms the robustness of the overall outcome: even when all criteria are weighted equally, the ranking remains identical to the original result, with Alternative 4 consistently emerging as the preferred option. This strengthens confidence in the conclusion, as it demonstrates that the outcome is not dependent on stakeholder-specific weighting assumptions.

Alternative	**Original**	**Equal Weights**	**Revenue –1%**	**CAPEX +7%**	**Ease Impl. –1 pt**
Alt 1	0.3912	0.4286	0.5243	0.4796	0.3910
Alt 2	0.4963	0.4836	0.5446	0.6604	0.4963
Alt 3	0.6570	0.6229	0.4381	0.4902	0.6577
Alt 4	0.7854	0.7657	0.5668	0.6188	0.7636

Table 13: Comparison of Final Scores Across Sensitivity Analyses

5 Conclusion and Discussion

This final chapter presents the conclusions of the study. By revisiting the sub-research questions, it synthesizes insights gained throughout the thesis. In addition, it discusses the limitations of the research and highlights directions for future work.

5.1 Conclusion

This thesis applied a MCDM framework to evaluate offshore wind transmission alternatives and determine under what conditions a direct-to-shore high-voltage solution is viable. The study's findings are organized below by each sub-research question, providing concise answers based on the analysis. This structured approach ensures each aspect of the research objective is addressed clearly.

5.1.1 Answered Research Questions

SRQ 1: Impact of regulatory cost allocation on direct-to-shore solutions
Regulatory cost allocation structures in different countries significantly affect the feasibility and attractiveness of direct-to-shore transmission solutions for developers. In markets where the offshore grid infrastructure (including any OSS) is funded and built by the TSO - for example, under the centralized offshore grid models used in the Netherlands and Germany - developers do not directly bear those capital costs, so there is no economic incentive to pursue direct-to-shore designs.
By contrast, in countries where developers are responsible for the full cost of grid connection, a direct-to-shore approach can offer cost advantages and thus becomes far more appealing. In Sweden, policy reversals in 2022–2023 reaffirmed that developers must pay for the entire offshore transmission system, which reinforces the relevance of exploring alternatives such as direct-to-shore transmission that eliminate expensive offshore platforms for projects like Kattegatt Syd. Therefore, the potential of direct-to-shore is highest in regulatory environments where developers are responsible for grid connection costs, whereas in contexts with TSO-funded offshore grids, such solutions are not likely to be considered by Vattenfall due to the lack of direct cost benefit for the developer.

SRQ 2: Stakeholders involved in selecting a high-voltage transmission system
The selection of a high-voltage transmission configuration for a Vattenfall offshore wind project involves a broad range of stakeholders. These include internal actors such as Vattenfall's project teams, as well as external stakeholders like the TSO, government regulators, permitting authorities, equipment suppliers, and environmental organizations. Each group holds varying degrees of influence over the design process and its enabling conditions.

For this study, only internal stakeholders from Vattenfall were selected to participate in the preference elicitation process. This selection was based on the specific decision-making structure applicable to countries like Sweden, where the developer holds full responsibility for the choice of the transmission system design (granted that the necessary permits are obtained). Under such a regulatory framework, external actors such as the TSO or permitting authorities provide input or approvals but do not determine the transmission design itself. As such, the internal decision-makers at Vattenfall are solely accountable for evaluating alternatives and committing to a design direction.
Specifically, two internal decision-makers were chosen: the TPM and the PD. These roles were selected because they are jointly responsible for selecting the transmission system design of a specific project. The TPM brings a technical and performance-focused viewpoint, while the PD integrates strategic, financial, and permitting considerations into the project scope. Their combined inputs reflect the key internal trade-offs that guide system configuration choices at Vattenfall.

SRQ 3a: Evaluation criteria and performance of transmission alternatives
The study identified a set of seven criteria to evaluate offshore wind transmission systems, drawing from literature, industry practice (bid criteria for real-life tenders), and Vattenfall's internal project evaluation framework. These key criteria are: *CAPEX* (capital expenditure), *OPEX* (operational expenditure), *Revenue* (energy delivery and losses affecting project income), *Risk* (technical and project execution risk), *Ease of Implementation* (practicality and complexity of construction/operation), *Permitting* (regulatory and environmental consent difficulty), and *Innovation* (degree of novelty and future-oriented benefit).

Each transmission alternative's performance was assessed against these criteria. The direct-to-shore configurations showed clear strengths in several areas: by design they eliminate the offshore substation, achieving the lowest CAPEX and reducing certain risks (fewer offshore operations and a simpler system architecture). The direct-to-shore options also scored highest on energy delivery (revenue). Moreover, these configurations were considered highly innovative. However, the direct-to-shore designs underperformed on ease of implementation and permitting criteria, as they require multiple parallel export cables to shore and novel design aspects that can complicate installation logistics and regulatory approvals.

In contrast, the conventional approach with an OSS (66 kV inter-array with step-up to high voltage offshore) was the easiest to implement and permit (being the industry-standard solution), but it had the highest cost and incurred greater energy losses, making it the weakest on CAPEX and revenue metrics. The 132 kV with OSS variant offered moderate improvements in losses and slight CAPEX differences, but still carried the drawbacks of an offshore platform. Overall, this multi-criteria assessment highlighted the trade-offs: avoiding the OSS yields benefits in cost, revenue, and risk, at the expense of added complexity in implementation and permitting.

SRQ 3b: Stakeholder weighting of each evaluation criterion

Using the BWT method, the research captured how different stakeholders prioritize the above criteria. The resulting weightings revealed a contrast between technical and project leadership perspectives. For the TPM, energy revenue was the most important factor ($\sim$28% of total weight), followed by CAPEX ($\sim$21%), reflecting a strong focus on maximizing output and minimizing upfront costs. This stakeholder gave substantially less weight to criteria like Permitting ($\sim$7%) and Innovation ($\sim$4%), indicating that regulatory ease and novelty were lower priorities.

On the other hand, the PD placed highest importance on Permitting and Ease of Implementation (each roughly 16-17% weight), as well as a notable emphasis on Innovation ($\sim$16%), signaling a greater concern for ensuring the project can secure approvals and align with strategic innovation goals. In this view, CAPEX and OPEX were comparatively less emphasized (each around 12-13% weight). These weightings demonstrate that stakeholders value criteria differently: the technical role is more cost-and-performance driven, whereas the project director prioritizes smooth project delivery and long-term strategic considerations. The PD's weights were also more evenly distributed across all criteria, reflecting a need to consider the full spectrum of project requirements. This broader and more balanced perspective aligns with the PD's role, which involves overseeing and balancing the overall success of the project across all dimensions. Such differences underscore the need to balance multiple perspectives in the decision-making process.

SRQ 4: Combined stakeholder evaluation - direct-to-shore vs. offshore substation

By combining the alternatives' performance scores with the above stakeholder weightings, the study computed final weighted scores for each transmission option. First, separate rankings were generated based on the individual preferences of the TPM and the PD. In both cases, the direct-to-shore configurations outperformed the traditional options involving an offshore substation, indicating that both stakeholders (despite their differing priorities) favored the direct-to-shore approach. These individual results were then merged into a combined ranking to reflect a balanced perspective. In this integrated outcome, the 132 kV direct-to-shore alternative with an onshore step-up substation (near the landfall) achieved the highest overall score, emerging as the most preferred solution. The second-ranked option was the 132 kV direct-to-shore to the TSO connection point,

while the OSS-based configurations ranked lower in all evaluations.
This outcome indicates a strong combined stakeholder preference for transmission designs that avoid OSS, thereby reducing cost and complexity, while still maintaining acceptable implementability. In other words, when expert-assessed performance on each criterion is weighted by actual stakeholder priorities, the direct-to-shore approach proves superior to the conventional OSS approach for the case examined. The analysis thus suggests that a direct-to-shore high-voltage connection can be a viable and even preferable alternative for future offshore wind projects.

5.1.2 Final Reflections

This study demonstrates how Vattenfall can make well-informed decisions when selecting a high-voltage transmission system by applying a structured multi-criteria framework combined with stakeholder-informed weighting. Rather than providing a universal answer, the results show that the optimal export system is highly project-specific, shaped by regulatory responsibility, technical context, and strategic priorities.
In the case of Kattegatt Syd, the analysis shows that a 132 kV direct-to-shore configuration can be the most attractive option in developer-led regulatory environments like Sweden where offshore substations represent a significant cost and risk. However, the same configuration also introduces implementation and permitting challenges, such as the need for more export cables and limited precedent in the industry. These trade-offs must be assessed within each project's unique context.

Crucially, this study shows that effective system selection depends on three factors:

- **Responsibility for offshore grid infrastructure** - whether the developer or the TSO is accountable for offshore assets, which influences who bears cost and risk.
- **Physical and spatial project constraints** - such as the distance to shore, landfall limitations, and available space for routing export cables. This influences the performance scores of the evaluation critera.
- **Decision-maker priorities** - including the relative importance assigned to minimizing costs, mitigating risks, enabling innovation, or simplifying permitting processes.

While this outcome applies specifically to Kattegatt Syd, the developed evaluation method can serve as a decision-support tool in future projects. The positive performance of the direct-to-shore configuration in this study encourages developers and policymakers to actively include this option in early-stage design evaluations, rather than overlooking it in favor of conventional OSS-based systems. In that sense, this thesis not only supports project-specific decision-making, but also contributes to a broader shift in offshore wind transmission planning: encouraging a more open and criteria-driven assessment of emerging alternatives, rather than defaulting to conventional OSS designs.

5.2 Discussion

This thesis applied the BWT method to evaluate offshore transmission system alternatives for offshore wind, with a focus on assessing the feasibility of a 132 kV direct-to-shore configuration. The structured approach, built on stakeholder-weighted criteria and system-specific performance scores, enabled a transparent and consistent decision-making process. To assess the robustness of the outcomes, expert validation was conducted, confirming the plausibility and practical relevance of the results. These reflections are presented in the first section of this chapter. The study also encountered several limitations (ranging from methodological assumptions to case-specific constraints and data uncertainties) that influence the interpretation and generalisability of the findings. These limitations are discussed in detail in the following sections, along with recommendations for future research and reflections on the scientific contributions of this work.

5.2.1 Validation of Results: Expert Reflections and MCDM Credibility

This section validates the outcomes of the MCDM approach by presenting insights from two expert interviews: one with a System Design Expert from the Kattegatt Syd offshore wind project, and another with the Concept Director for Offshore Wind Development. These experts reflected on the logic of the final performance scores, the relevance of the applied criteria weights, the ranking of the alternatives, and the practical usefulness of the outcomes for future project decisions.

Expert Reflections on Performance Scores

Both experts noted that the performance scores were broadly in line with what they had expected based on their project experience and technical understanding. A key discussion point in both interviews was the surprisingly strong performance of the direct-to-shore alternatives in terms of revenue. At first glance, both experts acknowledged that higher losses might be expected from a 132 kV direct-to-shore connection compared to configurations with OSS voltage step up. However, after consideration, they also recognized why direct-to-shore ultimately scored higher on this criterion in the analysis. The Concept Director pointed out two mechanisms that justify this result. First, offshore substations introduce transformer losses, which are avoided in direct-to-shore configurations. Second, systems with only two or three large export cables (as in OSS-based designs) suffer greater availability losses during cable maintenance or faults. Direct-to-shore systems typically involve more parallel cables, so an outage of one line has a smaller impact on total energy delivery. The System Design Expert agreed with this reasoning. The System Design Expert also mentioned that he had initially assumed that direct-to-shore configurations would be associated with higher risk due to their novel character. However, after reviewing the rationale provided through the interviews with risk experts and procurement managers - as incorporated into the qualitative criteria scores - he agreed that the overall offshore risk is indeed lower when eliminating the OSS, particularly due to the reduction in offshore equipment and construction complexity. Ultimately, both experts found the performance scores to be plausible and justifiable, despite some initial doubts.

Reflections on Criteria Weights

The experts were also asked whether the criteria weights, as derived through the BWT method, aligned with what they would expect from the respective stakeholder roles (Project Director and Technical Project Manager).
The System Design Expert confirmed that the TPM placing revenue and CAPEX as the most important criteria made complete sense. As he explained, these two criteria directly shape the business case. He also understood why revenue is places above CAPEX: "You can have low costs, but if you don't generate anything, you still do not have a strong business case." He emphasized that for technical project management, ensuring energy production and cost-efficiency are always paramount. The Concept Director similarly agreed with the PD's weighting profile, in which permitting and ease of implementation were prioritized. He explained that this strongly reflects the early-phase context of most offshore wind projects: at the start, permitting is the key hurdle, and technical procurement or cost concerns become more relevant later. In fact, he noted that the MCDM analysis captured this timing well: "This is very valid for a project in its early phase, at that point permitting is the key concern." He also highlighted that PDs must maintain deliverability across many dimensions, so a more balanced weighting (compared to the TPM's sharper focus on financials) is expected.

Beyond validating the individual profiles, both experts found the combined weighting set used for the final ranking to be well-reasoned. They appreciated that the final ranking was based on an average of both stakeholder weightings, as this approach reflects a realistic balance between strategic deliverability concerns (PD) and technical-financial feasibility (TPM). In their view, this averaging captured the two key perspectives typically involved in offshore transmission decisions, making the final outcome more credible and representative of actual project dynamics.

Reflections on the Final Ranking and Outcome

Regarding the overall outcome of the MCDM approach, both experts found the final ranking logical and consistent with their professional expectations.
The System Design Expert had hoped that Alternative 4 would come out on top and was pleased to see this confirmed. He noted that the inclusion of an ONS near landfall in alternative 4 (the second direct-to-shore alternative) offers clear operational and technical benefits without the permitting challenges of multiple inland cables. He had expected Alternatives 3 and 4 (both OSS-free) to outperform those with OSS (Alternatives 1 and 2), particularly due to their CAPEX advantage and simpler offshore execution. However, he was surprised that the 66 kV base case (Alternative 1) performed so poorly compared to 132 kV with OSS (Alternative 2), as the industry has historically favored 66 kV for its familiarity and simplicity. He explicitly stated that he had not expected 132 kV to outperform 66 kV and questioned: "If this is so clearly better, why aren't we already doing it? It's such a small change." Still, he acknowledged that 132 kV systems inherently have lower electrical losses, which could justify their better performance despite being less commonly implemented.

The Concept Director described the final scores as a clear preference for the OSS-free designs. He was "positively surprised" by the magnitude of the difference in total scores, calling the 40–50% performance gap between lowest and highest alternatives "a big difference." He found it convincing that even at ∼60 km offshore (the total cable route of Kattegatt Syd), direct-to-shore configurations could clearly outperform OSS-based systems. He added that he had expected a kind of performance curve - where direct-to-shore would outperform OSS-based solutions only up to a certain distance - and was pleased to see that at around 60 km, direct-to-shore still emerged as the top-performing option. This confirmed his view that such alternatives remain attractive for medium-range distances and that the break-even point lies somewhere further offshore.

What stands out from both expert reflections is the notable disconnect between expectation and implementation. While both stakeholders expected the OSS-free alternatives to perform better - and were ultimately not surprised by the results - these configurations are still not widely considered in actual project practice. This paradox highlights the persistence of institutional path dependency in offshore wind design: standard configurations continue to dominate, not necessarily because they are optimal, but because they represent the familiar, the proven, and the historically evolved status quo. The findings suggest that breaking away from these conventions requires more than just showing that an option performs better; it also takes clear internal support and a willingness to challenge established routines within project teams.

Usefulness and Future Application

When asked whether the MCDM outcomes were useful and actionable, both experts responded positively and with concrete implications.
The System Design Expert said the thesis made “a good case” for direct-to-shore transmission and that the MCDM ranking could help push the conversation forward internally. He noted that many industry players still default to OSS designs because “that’s how it’s always been done,” but the analysis shows that smarter, simpler alternatives deserve serious consideration - particularly as turbine voltages increase and offshore cost pressures rise. The System Design Expert indicated that direct-to-shore will be included as an explicit option in the next business case analysis for Kattegatt Syd, as a direct result of the insights gained through this research.

The Concept Director echoed this sentiment, stating that the results provided strong support for further exploring direct-to-shore designs. He considered the ranking “very useful” for early-phase decision-making and emphasized that the thesis presents a well-reasoned foundation to challenge TSO-driven standardization. He saw potential for the insights to be used in future project evaluations and internal development discussions, especially where offshore distances and land availability support such configurations.

Both experts concluded that, although the widespread adoption of direct-to-shore will take time, this thesis delivers a valuable analytical basis to support that shift. They indicated that the results will be taken into account in internal explorations of electrical infrastructure innovations for offshore wind.

5.2.2 Limitations of this research

This section outlines the main limitations of the research.

Limitations in Scope

A limitation of this thesis lies in its single-case study approach. The analysis was focused on the Kattegatt Syd offshore wind project, which served as a realistic and data-accessible example. However, system designs and feasibility outcomes are highly context-dependent; factors such as distance to shore, environmental constraints, and national grid requirements significantly affect the viability of transmission alternatives. As such, the results (particularly the favorable ranking of the 132 kV direct-to-shore configuration) should not be interpreted as universally applicable. Instead, they illustrate how the evaluation framework performs under one specific set of conditions. While this limits the generalizability of the conclusions, it strengthens their relevance for near-shore projects in similar regulatory contexts and invites further application and testing of the framework for other offshore wind projects. Importantly, the findings aim to spark discussion and exploration of 132 kV solutions in future offshore wind developments.

Moreover, the scope of alternatives evaluated in this thesis was intentionally limited to four transmission system configurations that were deemed most relevant to the Kattegatt Syd case. These options were selected based on their practical feasibility, internal strategic relevance, and availability of performance data. However, other potentially relevant variations were not considered, which inherently narrows the exploration space. For example, different voltage levels of the export cables (i.e. 400 kV) or designs with a shared OSS serving multiple projects are not considered. This restriction may affect the robustness of the final ranking, as some system concepts that might outperform the selected alternatives under different conditions were not included.

In addition to this limitation, certain elements were explicitly excluded from the system boundary. For instance, variations in wind turbine design were not analyzed, nor were different internal array layouts within the wind farm.
Although this focused scope allowed for a more detailed assessment of configurations, future research could apply the framework to a wider set of system concepts as offshore grid architectures evolve.

Methodological Limitations and Reflections Based on Expert Feedback

This section presents a combined reflection on the methodological limitations of the BWT approach, based both on its theoretical structure and on feedback gathered from experts during the tradeoff process. While the BWT method offered a structured, transparent, and relatively consistent framework for capturing stakeholder preferences, its practical application in this study highlighted several challenges and assumptions that deserve closer consideration.

One methodological consideration concerns the difficulty experienced by the stakeholders during the construction of value functions. While the mid-value splitting method applied in this thesis enables the modeling of nonlinear stakeholder preferences, most value functions ultimately resulted in linear or near-linear shapes. This outcome does not necessarily imply that stakeholders perceive utility in a strictly linear way; rather, it reflects the fact that the performance ranges (although large in absolute terms) were perceived as relatively modest in terms of real project impact. For example, differences of €200 million in CAPEX may seem substantial numerically, but within the context of a multi-billion-euro infrastructure project, this may be seen as only a marginal difference. Several stakeholders expressed difficulty identifying meaningful midpoint or indifference values for such criteria, which directly affected the shape and interpretability of their value functions. This suggests that the framing and perceived importance of performance ranges play a significant role in how value functions develop in practice.

Another issue that emerged from these relatively narrow value ranges across the alternatives was that experts noted that such small differences were difficult to evaluate meaningfully during the trade-off exercises. In some cases, participants explicitly stated that adjusting the value of an attribute (i.e. OPEX) down during the others-to-worst tradeoffs had virtually no impact on their perception of the alternative. This limited discriminative power reduced the reliability of the elicited trade-offs for these criteria and introduced uncertainty into the weighting process. In future applications, it may be beneficial to either reframe or aggregate such flat criteria, or exclude them from the trade-off phase if they do not meaningfully differentiate between alternatives in the specific decision context.

A central element of the BWT method is that trade-offs are made by adjusting actual performance rather than by comparing abstract importance ratios. This introduces a certain cognitive load: experts are required to judge the attractiveness of precise numerical changes between criteria that may differ in unit, scale, and perceived relevance. In several cases, experts indicated that such absolute value shifts were not always easy to interpret. While they fully understood the underlying criteria and ranges, they noted that in practice, they rarely assess project trade-offs using isolated absolute figures like a €100 million CAPEX change. Instead, they are more accustomed to reasoning in terms of relative differences between options or through indicators that integrate multiple dimensions (e.g., Levelised Energy Cost (LEC)). Moreover, they rarely consider two individual criteria in isolation; rather, their judgments typically involve balancing multiple factors simultaneously, often shaped by broader project context or strategic considerations. When confronted with a trade-off such as "€X M CAPEX versus permitting score 2.5", the comparison lacked intuitive clarity. Experts found it difficult to judge how much a shift in one criterion "should be worth" relative to a shift in another. This occasionally led to hesitation or uncertainty in their input, not due to lack of knowledge, but due to the unfamiliar and abstract nature of the trade-off format itself.

Moreover, while this thesis assumes mutual preferential independence (MPI) between criteria - a necessary condition for using additive value functions - this assumption was not always perceived as valid by the experts. During the interviews, particularly with the PD, it became clear that certain criteria are seen as directly linked in practice. For instance, increasing CAPEX may be associated with tighter implementation timelines, which in turn can influence both perceived risk and permitting complexity. This interdependence complicated the trade-off exercise, as the PD struggled to isolate the effect of one criterion without implicitly accounting for another. As he noted for example, "Reducing risk almost always costs money - it's hard to imagine that change in isolation." Although the criteria were constructed to minimize conceptual overlap, this feedback suggests that perceived interdependencies can affect the confidence and internal consistency of preference expressions. Future applications might benefit from explicitly acknowledging such relationships during the elicitation process or exploring more advanced modeling approaches that allow for interaction effects.

Finally, the methodological separation between scoring and weighting (while aligned with how many organisations structure their internal decision-making processes) may introduce internal inconsistencies. For example, scoring was performed by technical/consent/ procurement experts, while weighting was conducted by decision-makers. Although both groups were internally aligned, their interpretation of criteria may differ. This reinforces the importance of carefully designing and documenting criteria definitions and scoring rubrics, and suggests that future applications could benefit from integrated or joint stakeholder sessions to align interpretations across both dimensions.

Based on the expert feedback in this study, several suggestions can be made to improve the application of the BWT method in future decision-making contexts. First, it is recommended to frame performance levels more intuitively by including relative differences or project-relevant interpretations (e.g., percentage change, effect on LEC). This could help experts better understand the trade-off magnitude. Second, criteria with minimal discriminative power (such as OPEX in this case) should either be redefined, combined with other dimensions, or excluded if they do not add meaningful contrast between alternatives. Third, it may be beneficial to precede the trade-off elicitation with a brief discussion to align understanding and surface possible interdependencies. This would help participants engage more confidently with the quantitative exercise. Finally, when perceived interactions between criteria are likely, future studies could consider using grouped or hierarchical criteria structures to reflect the interconnected nature of real-world decisions. These measures would help reduce cognitive burden, improve interpretation, and ultimately enhance the decision-support value of the BWT framework.

Limitations in Stakeholder Scope and Input Data Quality

A key strength of this thesis lies in the involvement of relevant Vattenfall stakeholders across the scoring and weighting phases of the analysis. This included internal experts in scoring the system alternatives, as well as the two designated decision-makers of the Kattegatt Syd project team for the weighting of criteria. Given that decision-making authority for offshore grid connection strategies lies within Vattenfall itself, the choice to limit stakeholder participation to internal experts is justified in the context of this case. The evaluation criteria were designed to reflect a broad set of stakeholder needs by drawing on bid requirements from real-life offshore wind tenders. These were validated by internal Vattenfall experts to ensure relevance and internal coherence. Although external actors such as TSOs, regulators, or environmental organisations were not directly consulted, their priorities were indirectly embedded through the structure of the criteria themselves. Nevertheless, the absence of direct engagement limits the ability to capture contested viewpoints or cross-sectoral dynamics in how those criteria are understood and valued.

The performance scoring of qualitative criteria such as ease of implementation, environmental and permitting impact, and innovation was based on expert input from members of the Kattegatt Syd project team. This ensured that assessments were context-specific and grounded in project experience. However, it also introduces a significant limitation: the resulting scores are highly dependent on the specific individuals consulted. Differences in background, role, or interpretation among experts can lead to different evaluations of the same alternative. This subjectivity is inherent to the assessment of qualitative criteria, but it is amplified when the expert sample is narrow. In this study, each qualitative criterion was evaluated by only one or two internal experts, making the resulting scores highly sensitive to individual perspectives, knowledge, and assumptions. This increases the risk of bias or narrow framing, especially in areas where performance cannot be measured objectively and expert judgment plays a central role. As a consequence, the output of the decision model reflects not only the characteristics of the system alternatives but also the specific assumptions embedded in the scoring process. While it is not possible to determine in which direction broader input would have shifted the results, the analysis highlights that the final ranking is contingent upon a limited set of expert judgments and should therefore be interpreted with caution. Future research could mitigate this limitation by involving a broader and more diverse group of experts in the scoring process, potentially including external or independent reviewers. Additionally, structured group decision-making techniques, such as expert panels or Delphi studies, could be employed to reduce individual bias and enhance the robustness of qualitative performance assessments.

Moreover, in terms of input data for the quantitative criteria, the technology maturity the 132 kV direct-to-shore system remains relatively novel. While conceptually feasible, many performance and feasibility estimates are still based on theoretical designs or projected engineering models. Unlike conventional configurations with an OSS, there is little operational experience to draw from. This introduces additional uncertainty in areas such as reliability, long-term asset performance, and expected energy yields, particularly affecting the accuracy of risk assessments and revenue projections.

Regulatory and Temporal Assumptions

This study was conducted under the assumption of a stable regulatory and cost allocation framework, reflecting current Swedish policy in which developers bear full responsibility for offshore transmission. However, policy environments are subject to change. Several North Sea countries are moving toward more centralised, state-led or hybrid transmission solutions. Should Sweden shift in this direction, the attractiveness and feasibility of direct-to-shore systems could change dramatically.

Although the analysis considers a long-term operational timeframe and includes assumptions about future costs and system performance, these projections inherently involve a high degree of uncertainty. Estimating cost components such as Revenue, OPEX, and implementation risk over a 35-year period (lifetime of the windfarm) is particularly challenging, given potential changes in technology, supply chains, and market conditions. As a result, the evaluation may not fully reflect the range of plausible future developments.

5.2.3 Recommendations for Future Research

Building on the methodological and contextual limitations discussed above, several directions for future research can be identified to further strengthen the application of the BWT method in evaluating offshore grid connection strategies.

Firstly, the construction of value functions (particularly for criteria with relatively narrow performance ranges) could be enhanced by exploring alternative elicitation techniques. While stakeholders in this thesis generally provided linear value assessments, this may have been influenced by the perceived limited impact of differences. Future studies could test whether different framing methods lead to more nuanced value curves.

Secondly, future applications of BWT in this domain could benefit from additional support tools to assist stakeholders in making complex trade-offs between criteria. As aforementioned, the process of identifying and ranking evaluation criteria proved cognitively demanding for stakeholders, even when consistency ratios were statistically acceptable. Future research should explore how such cognitive demands can be mitigated - for example, by testing the effectiveness of visual aids or interactive tools in improving stakeholder understanding, engagement, and input quality.

Thirdly, the subjectivity observed in qualitative performance scoring highlights the importance of involving a broader and more diverse pool of experts, including independent reviewers. This would improve robustness, reduce individual bias, and enable a more balanced representation of views, especially when evaluating context-sensitive criteria like permitting risk or innovation potential.

Fourthly, future research could explore decision-making approaches that explicitly account for interactions between criteria. Instead of relying on an additive value function, methods such as the Choquet integral or multiplicative utility models could be considered, as these allow for modeling interdependencies and synergies between attributes. This would provide a more nuanced representation of stakeholder preferences in complex infrastructure decisions [10], [25], [31]

Furthermore, future studies could aim to combine internal and external stakeholder input more explicitly. While this thesis justifiably focused on Vattenfall's internal decision logic, a broader multi-actor approach may be particularly valuable in settings where decision-making authority is distributed or where regulatory and public interests are highly influential.

Moreover, regarding the technical scope of the evaluated alternatives, further research could consider the feasibility of even higher voltage levels within the same voltage class. While this thesis focused on 132 kV configurations, offshore wind export cables have commonly operated at 155 kV or 170 kV for decades. These voltage levels are already widely deployed in offshore environments, meaning that subsystem components (such as cables and transformers) are commercially available and technically proven. Integrating these levels into the assessment could further improve the performance of direct-to-shore configurations (Alt. 3 and Alt. 4), especially when optimizing the system at the scale of the full wind farm. Currently, subsystem suppliers (e.g., cable or transformer manufacturers) often optimize their individual components in isolation, which may overlook system-wide benefits achievable through coordinated design. Therefore, further research should evaluate the enablers that could support a shift towards integrated optimization at higher voltage levels - such as improved collaboration across the supply chain, cross-component design standardization, and clearer regulatory pathways. Updating the study to include these perspectives will offer a more future-oriented assessment of offshore transmission strategies [33].

Additionally, future research could apply the developed evaluation framework to offshore wind projects with different geographical, technical, and regulatory characteristics. This would help assess whether the observed benefits of 132 kV direct-to-shore transmission in the Kattegatt Syd case hold under varying conditions, such as greater distances to

shore, deeper waters, or alternative grid ownership models. Comparative studies across multiple projects and jurisdictions could provide a more comprehensive understanding of the potential role and limitations of direct-to-shore configurations in the broader offshore wind industry.
Finally, it may be valuable to explore whether alternative, less time-consuming MCDM methods could be used in similar contexts. While the BWT method provides structured and consistent stakeholder input, its application may be constrained in situations with limited time, resources, or data. Investigating alternative approaches could help clarify the balance between methodological robustness and practical feasibility in early-stage decision processes.

5.2.4 Scientific Contribution

This thesis contributes scientifically to two distinct scientific fields: offshore wind power and multi-criteria decision-making, with a particular focus on the BWT method.

In the field of offshore wind power, this study addresses a concrete knowledge gap in the academic literature on transmission system design. While most existing studies compare high-level export technologies such as HVAC and HVDC, they do not consider how recent technological developments - specifically the emergence of 132 kV inter-array voltage levels - could reshape system architecture choices. A small number of publications acknowledge this new voltage level, but none investigate its implications for enabling direct-to-shore transmission without an offshore substation. At best, the concept is briefly mentioned; however, no systematic analysis exists that evaluates this configuration across technical, economic, and regulatory dimensions. This thesis addresses that gap by applying a systems engineering perspective to evaluate 132 kV direct-to-shore export configurations. Using a real offshore wind case study (Kattegatt Syd), it conducts a structured multi-criteria comparison of four transmission alternatives. Importantly, the evaluation incorporates input from actual decision-makers within a leading developer organization (Vattenfall), ensuring that the analysis reflects both system-level performance and the priorities of those responsible for offshore transmission design choices in practice.

In addition, this study makes a novel contribution by developing and introducing a fourth transmission alternative that had not previously been defined in either literature or internal practice. Based on expert interviews and internal discussions, the option of a 132 kV direct-to-shore connection with an onshore substation near landfall was identified as a distinct variant. This configuration was therefore explicitly added to the analysis to allow a more accurate assessment of its implementation and permitting implications. By doing so, the study not only compares existing alternatives but also contributes to system architecture development in offshore wind by proposing a refined and previously undocumented option.

In the field of MCDM, the study introduces and applies the BWT method to the domain of offshore wind infrastructure planning. BWT was introduced in 2022 by Liang, Brunelli, and Rezaei in Information Sciences [21]. In the original article, BWT is applied in a case study comparing ports, showcasing its practical feasibility and potential for complex decision problems. To date, there are still very few scientific publications applying BWT to complex, real-world decision problems outside of the initial case study. The literature on multi-attribute decision methods mainly focuses on BWM and classical Tradeoff, with BWT remaining relatively new and understudied in practical applications. This thesis addresses this gap in the literature by applying BWT to a current and societally relevant challenge: the selection of optimal transmission infrastructure for offshore wind energy. By systematically employing BWT in a multi-criteria analysis, it demonstrates that this method is suited for complex decisions involving technical, economic, environmental, and implementation considerations. Moreover, it shows how BWT can be used to explicitly translate stakeholder priorities into weights and to underpin consistent, transparent choices - even for innovative and less mature technologies such as direct-to-shore 132 kV transmission. In this way, this thesis not only contributes to further validating BWT as a practical decision-making method but also provides a useful framework for future applications in the energy sector and beyond. This enhances the scientific relevance of this research for the field of multi-criteria decision-making and supports the ongoing development of BWT as a decision-making tool.

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6 Appendix

6.1 Appendix A - Analytical Table for Criteria Establishment

Article & Citation	Economic Criteria	Technological Criteria	Other Criteria / Environmental
Applying Hybrid MCDM Methods for Power Transmission System Evaluation and Selection – Xia Li et al. (2023)	• Initial investment cost • Operation loss cost (transformer loss, line loss) • Maintenance cost	• Voltage support capacity • Transmission reliability • Technology maturity • Fault-ride through capability • Controllability	
Benefit Evaluation of HVAC and HVDC for Offshore Wind Power Transmission System – Yuanzheng Lyu et al. (2024)	• Initial construction cost • Operating loss costs (Transformer, Converter, Submarine cable losses) • Maintenance costs • Fault repair costs • IRR Index (Initial Rate of Return)		• Carbon index
A Comparison Review on Transmission Mode for Onshore Integration of Offshore Wind Farms: HVDC or HVAC – Syed Rahman et al. (2021)	• Installation cost • Operational & maintenance costs • Efficiency & losses • ROI	• Power transmission capability • Converter & control complexity • Reliability & fault handling • Submarine cable requirements • System design & scalability	

Article & Citation	Economic Criteria	Technological Criteria	Other Criteria / Environmental
Comprehensive Evaluation Model and Methodology for Offshore Wind Farm Collection and Transmission Systems – Song, Chang, Wang (2023)	• Losses (Cable, Transformer, Converter) • Initial investment • Operation cost • Maintenance cost • Failure cost • Decommission & disposal cost • Failure opportunity cost	• Expected energy not supplied • Average availability • Transmission efficiency	• Sea resource occupation • Electromagnetic pollution
Transmission Systems for Grid Connection of Offshore Wind Farms: HVAC vs HVDC Breaking Point – J. Larsson (2021)	• Levelized Cost of Energy (LCOE) • Net Present Value (NPV) • Investment Costs • O&M Costs	• System Efficiency & Losses • Component Unavailability & Reliability • Scalability of Export Systems • Flexibility in System Design	• Lead Time for Deployment • Standardization & Market Maturity • Iterative Design Possibilities
Offshore Wind Power Transmission Decision-Making Based on Grey Correlation and TOPSIS – Z. Li et al. (2023)	• Construction Period Costs • Initial input cost • Running cost • Maintenance cost • Operating Period Costs • Failure, Tax, Abandonment • Operating Losses	• Reliability Indicators	• Marine water quality • Marine sediment • Marine ecology • Risk: Policy (Tax, Subsidy, Military) • Natural (Geographic risks) • Security (Marine traffic, Engineering operation)
Uncertain Hybrid Multiple Attribute Group Decision of Offshore Wind Power Transmission Mode Based on the VIKOR Method – Nansheng Pang, Wenjing Guo (2019)	• Project Cost • Construction Difficulty Degree	• Voltage Level • Transmission Distance • Transmission Capacity • Line Losses • Reliability • Technology Maturity	• Impact of Noise • Impact of Radiation

Article & Citation	Economic Criteria	Technological Criteria	Other Criteria / Environmental
Multi-Criteria Decision Analysis for Future Offshore Wind Farms in Italy – Chiara Virano (2023)	• Initial Cost of Investment (CAPEX)	• Energy Production • Water Depth • Proximity to Grid	• Environmental & Social: Area used • Environmental impact index • Visual impact index • Ship interaction • Job opportunities • Social acceptance index
Multi-Criteria Analysis for the Electrical Integration of Floating Offshore Solar Parks with Offshore Wind Parks – Houwing, Wiggelinkhuizen, Chrysochoidis-Antsos (2021)	• Economic Risks • CAPEX & OPEX of electrical integration • Market Maturity	• Flexibility • Scalability • Reliability • Installation, Operation & Maintenance complexity	• Societal acceptance • Legal & safety risks • Electromagnetic impact on fauna & flora • Noise pollution • Pollution potential • Seabed impact
Cleary, C., McFadzean, G., Hay, S., & Dixon, S. (2015). The potential benefits of direct-to-shore MVDC connections for offshore wind. Poster at EWEA Offshore 2015	• CAPEX • NPV	• Electrical losses • Unavailability • Energy yield	

Table 14: Evaluation Criteria Literature

6.2 Appendix B - Informed Consent Form

Thank you for participating in this interview. This study is conducted by Susan Janssen, a Master's student at TU Delft, in collaboration with Vattenfall as part of a research internship. The goal of the project is to evaluate different offshore wind transmission systems for wind farms specifically focusing on projects like Kattegatt Syd, where 132 kV export systems are viable options. More specifically, three alternatives are compared:

- 66 kV export via an offshore substation (benchmark alternative)
- 132 kV export via an offshore substation
- 132 kV direct-to-shore cables connecting directly to TSO Grid: No offshore substation is used. 132 kV export cables run all the way from the offshore wind farm directly to the TSO point of connection. Only onshore substation at TSO point of connection is used to step up the voltage.
- 132 kV direct-to-shore with Onshore Substation near Landfall: No offshore substation is used. 132 kV cables run directly from the offshore wind turbines to an onshore substation located near the landfall point. At this onshore substation, the voltage is stepped up to TSO voltage level before continuing to TSO point of connection.

The objective is to assess these options using a structured multi-criteria approach that considers a variety of stakeholder perspectives. To do this, I'm applying the Best-Worst Tradeoff (BWT) method - a decision-making approach that involves identifying which criteria stakeholders value most and least, and then eliciting trade-offs between them. While Kattegatt Syd is currently the reference project, the evaluation framework is designed to be flexible, meaning it can support comparison and decision-making across a wide range of offshore wind transmission projects. Your input will directly help determine how these criteria are weighted and applied to evaluate the transmission alternatives. The results will be used to identify which configuration is most favorable.

To the best of our ability, your responses in this study will remain confidential. No personal identifiers such as your name will be collected, and data will be anonymized for analysis unless you agree to be referenced in a general, non-identifying way (e.g., "an expert on Electrical Engineering from Vattenfall"). All data will be securely stored on TU Delft's research servers with encrypted access, restricted to the researcher and supervisors. Before any results based on the interviews are made publicly available, participants will have the opportunity to review how their input has been incorporated into the study. This ensures that the interpretation accurately reflects their expert insights.

Your participation is entirely voluntary, and you may withdraw at any time. If you have any questions about this research, please contact:

- Susan Janssen

(Primary Researcher)
- Jafar Rezaei – (Responsible Researcher at TU Delft)
- Petr Kadurek – (Supervisor at Vattenfall)

Q1

I confirm that I have read this participant information statement and consent to participate in this study.

- Yes
- No *(End of survey if selected)*

Q2

I agree to be referenced in a non-identifying way.

- Yes
- No *(End of block if selected)*

Q3

What is your role/area of expertise within Vattenfall?

6.3 Appendix C - Elicitation Questions for Value Function Construction

Q146

Imagine that improving the CAPEX of the system (i.e., lowering the investment cost) results in a trade-off: it leads to a decrease in the performance of all other criteria. However, this trade-off is equal in every case — the total sacrifice in the other criteria remains the same for all scenarios described below. We now ask you to compare two CAPEX improvements in terms of how valuable they feel to you.

- Scenario A: CAPEX improves from level €[redacted] M to level m_1.
- Scenario B: CAPEX improves from level m_1 to level €[redacted] M.

Question: At what level of m_1 do you feel indifferent between these two scenarios? In other words, at which CAPEX value does the first improvement (from €[redacted] M to m_1) feel just as beneficial to you as the second improvement (from m_1 to €[redacted] M)?

Q147

Now let's zoom in on the first part of the CAPEX range.

- Scenario C: CAPEX improves from level €[redacted] M to level m_2.
- Scenario D: CAPEX improves from level m_2 to level m_1.

In both cases, the cost (the decrease in all other criteria) is the same.
Question: At what value of m_2 would these two improvements feel equally valuable to you?

Q148

Now let's zoom in on the second part of the range.

- Scenario E: CAPEX decreases from m_1 to m_3.
- Scenario F: CAPEX decreases from m_3 to €[redacted] M.

In both cases, the cost (the decrease in all other criteria) is the same.
Question: At what value of m_3 would these two improvements feel equally valuable to you?

Q150 — Consistency Check

Now we want to check if m_1 is truly the "center" between m_2 and m_3 in terms of value.

- Scenario G: CAPEX decreases from m_2 to m_1.
- Scenario H: CAPEX decreases from m_1 to m_3.

Question: Do these two improvements feel equally valuable to you? In other words: is the improvement from m_2 to m_1 just as valuable to you as the improvement from m_1 to m_3?

- If yes, then m_1 is the correct midpoint.
- If no, we'll ask for a revised m_1 in the next question.

Q151 — Midpoint Adjustment

If the previous answer was **no**, we now ask you to adjust m_1.

Question: What value of m'_1 would make you feel indifferent between:

- A CAPEX improvement from m_2 to m'_1, and
- A CAPEX improvement from m'_1 to m_3?

In other words: What revised CAPEX value would split the value difference between m_2 and m_3 into two equally valuable improvements?

6.4 Appendix D - Tradeoffs PD

6.4.1 Best to others tradeoffs

To tradeoff the best attribute to the other attributes, 6 hypothetical consequences are created as explained in Chapter 3.3. For the PD, who selected the criterion Permitting Complexity (C_6) as best criterion, the following hypothetical consequences were presented, the PD was asked to provide the undetermined values $\left(x_6^{6,1},\ x_6^{6,2},\ x_6^{6,3},\ x_6^{6,4},\ x_6^{6,5},\ x_6^{6,7}\right)$.

([redacted], $25,\ 3.0,\ x_6^{6,1},\ 1.0) \sim ($ [redacted], $25,\ 3.0,\ 1.0,\ 1.0)$
([redacted], $25,\ 3.0,\ x_6^{6,2},\ 1.0) \sim ($ [redacted], $25,\ 3.0,\ 1.0,\ 1.0)$
([redacted], $25,\ 3.0,\ x_6^{6,3},\ 1.0) \sim ($ [redacted], $10,\ 3.0,\ 1.0,\ 1.0)$
([redacted], $25,\ 3.0,\ x_6^{6,4},\ 1.0) \sim ($ [redacted], $25,\ 4.0,\ 1.0,\ 1.0)$
([redacted], $25,\ 3.0,\ x_6^{6,5},\ 1.0) \sim ($ [redacted], $25,\ 3.0,\ 3.0,\ 1.0)$
([redacted], $25,\ 3.0,\ x_6^{6,7},\ 1.0) \sim ($ [redacted], $25,\ 3.0,\ 1.0,\ 4.0)$

The PD assessed the following equivalent values for Permitting Complexity (C_6):

$$\left(x_6^{6,1},\ x_6^{6,2},\ x_6^{6,3},\ x_6^{6,4},\ x_6^{6,5},\ x_6^{6,7}\right) = (2.2,\ 2.5,\ 2.1,\ 2,\ 2.6,\ 2.7)$$

6.4.2 Others to worst tradeoffs

To tradeoff the other criteria to the least important criterion, once again 6 hypothetical alternatives were created as explained in Chapter 3.3. The PD identified Risk as the worst criterion and was therefore presented with the following alternatives. He was asked to determine the values for $\left(x_1^{1,4},\ x_2^{2,4},\ x_3^{3,4},\ x_5^{5,4},\ x_6^{6,4},\ x_7^{7,4}\right)$.

$(x_1^{1,4},$ [redacted], $25,\ 3.0,\ 1.0,\ 1.0) \sim ($ [redacted], $10,\ 3.0,\ 1.0,\ 1.0)$
([redacted] $x_2^{2,4},$ [redacted] $25,\ 3.0,\ 1.0,\ 1.0) \sim ($ [redacted], $10,\ 3.0,\ 1.0,\ 1.0)$
([redacted], $x_3^{3,4},\ 25,\ 3.0,\ 1.0,\ 1.0) \sim ($ [redacted], $10,\ 3.0,\ 1.0,\ 1.0)$
([redacted], $x_5^{5,4},\ 3.0,\ 1.0,\ 1.0) \sim ($ [redacted], $10,\ 3.0,\ 1.0,\ 1.0)$
([redacted], $25,\ x_6^{6,4},\ 1.0,\ 1.0) \sim ($ [redacted], $10,\ 3.0,\ 1.0,\ 1.0)$
([redacted], $25,\ 3.0,\ x_7^{7,4},\ 1.0) \sim ($ [redacted], $10,\ 3.0,\ 1.0,\ 1.0)$

The PD assessed the following equivalent values:

$\left(x_1^{1,4},\ x_2^{2,4},\ x_3^{3,4},\ x_5^{5,4},\ x_6^{6,4},\ x_7^{7,4},\ x_6^{6,7}\right) = ($ [redacted], $3.8,\ 2.5,\ 3.5)$

6.5 Appendix E - Final MCDM Scores Calculation

The final score for each alternative is calculated as:

$$\text{Score}_{\text{Alt}} = \sum_{i=1}^{7} w_i \cdot v_{i,\text{Alt}}$$

where:

- w_i is the weight of criterion i,
- $v_{i,\text{Alt}}$ is the normalized performance score of alternative Alt on criterion i.

By implementing the final weights of the critera (TPM) and the normalized performance scores, the values are calculated as follows for the TPM:

- **Alt 1**: $0 + 0.1505 + 0 + 0 + 0.1069 + 0.0709 + 0 =$ **0.3283**
- **Alt 2**: $0.0041 + 0 + 0.2172 + 0 + 0.1069 + 0.0709 + 0.0219 =$ **0.4211**
- **Alt 3**: $0.2069 + 0.0542 + 0.2785 + 0.1426 + 0 + 0 + 0.0437 =$ **0.7260**
- **Alt 4**: $0.2069 + 0.0542 + 0.2785 + 0.1426 + 0.0535 + 0.0355 + 0.0437 =$ **0.8149**

The same can be done for the PD:

- **Alt 1:** $0 + 0.1174 + 0 + 0 + 0.1642 + 0.1724 + 0 =$ **0.454**
- **Alt 2:** $0.0026 + 0 + 0.1249 + 0 + 0.1642 + 0.1724 + 0.1067 =$ **0.571**
- **Alt 3:** $0.1280 + 0.0423 + 0.1601 + 0.0986 + 0 + 0 + 0.1593 =$ **0.588**
- **Alt 4:** $0.1280 + 0.0423 + 0.1601 + 0.0986 + 0.0821 + 0.0862 + 0.1593 =$ **0.756**

6.6 Appendix F - Sensitivity Analysis

6.6.1 Equal weights scenario

Under the equal weighting scenario, each criterion receives a weight of $w_i = \frac{1}{7} \approx 0.142857$, since there are 7 criteria in total.

The normalized performance scores for TPM are taken from Table 15:

Alternative	CAPEX	OPEX	Revenue	Risk	Ease Impl.	Permitting	Innovation
Alt 1	0.00	1.00	0.00	0.00	1.00	1.00	0.00
Alt 2	0.02	0.00	0.78	0.00	1.00	1.00	0.50
Alt 3	1.00	0.36	1.00	1.00	0.00	0.00	1.00
Alt 4	1.00	0.36	1.00	1.00	0.50	0.50	1.00

Table 15: Normalized Performance Scores for TPM

The final MCDM scores were computed using equal weights of $\frac{1}{7} \approx 0.142857$ per criterion:

- **Alt 1:** $0.142857 \cdot (0 + 1 + 0 + 0 + 1 + 1 + 0) = 0.142857 \cdot 3 = \mathbf{0.4286}$
- **Alt 2:** $0.142857 \cdot (0.02 + 0 + 0.78 + 0 + 1 + 1 + 0.5) = 0.142857 \cdot 3.3 = \mathbf{0.4714}$
- **Alt 3:** $0.142857 \cdot (1 + 0.36 + 1 + 1 + 0 + 0 + 1) = 0.142857 \cdot 4.36 = \mathbf{0.6229}$
- **Alt 4:** $0.142857 \cdot (1 + 0.36 + 1 + 1 + 0.5 + 0.5 + 1) = 0.142857 \cdot 5.36 = \mathbf{0.7657}$

The same is done for the PD. The normalized performance scores for the PD perspective are shown in Table 16:

Alternative	CAPEX	OPEX	Revenue	Risk	Ease Impl.	Permitting	Innovation
Alt 1	0.00	1.00	0.00	0.00	1.00	1.00	0.00
Alt 2	0.02	0.00	0.78	0.00	1.00	1.00	0.67
Alt 3	1.00	0.36	1.00	1.00	0.00	0.00	1.00
Alt 4	1.00	0.36	1.00	1.00	0.50	0.50	1.00

Table 16: Normalized Performance Scores for PD

Applying equal weights of $\frac{1}{7} \approx 0.142857$, the scores are computed as follows:

- **Alt 1:** $0.142857 \cdot (0 + 1 + 0 + 0 + 1 + 1 + 0) = 0.142857 \cdot 3 = \mathbf{0.4286}$
- **Alt 2:** $0.142857 \cdot (0.02 + 0 + 0.78 + 0 + 1 + 1 + 0.67) = 0.142857 \cdot 3.47 = \mathbf{0.4957}$
- **Alt 3:** $0.142857 \cdot (1 + 0.36 + 1 + 1 + 0 + 0 + 1) = 0.142857 \cdot 4.36 = \mathbf{0.6229}$
- **Alt 4:** $0.142857 \cdot (1 + 0.36 + 1 + 1 + 0.5 + 0.5 + 1) = 0.142857 \cdot 5.36 = \mathbf{0.7657}$

The final scores for the sensitivity analysis under the equal weights scenario are given below and calculated by averaging the TPM and PD scores.

Alternative	TPM Score	PD Score	Final Score (Average)
Alt 1	0.4286	0.4286	0.4286
Alt 2	0.4714	0.4957	0.4836
Alt 3	0.6229	0.6229	0.6229
Alt 4	0.7657	0.7657	0.7657

Table 17: Combined MCDM Scores (Equal Weights Sensitivity Analysis)

6.6.2 Revenue

The table below shows the updated normalized performance scores for the TPM, in which only the Revenue scores for Alt 3 and Alt 4 have been adjusted to reflect a 1% decrease. All other values remain as in the original analysis.

Alternative	CAPEX	OPEX	Revenue	Risk	Ease of Impl.	Permitting	Innovation
Alt 1	0.00	1.00	0.607	0.00	1.00	1.00	0.00
Alt 2	0.02	0.00	1.000	0.00	1.00	1.00	0.50
Alt 3	1.00	0.36	0.000	1.00	0.00	0.00	1.00
Alt 4	1.00	0.36	0.000	1.00	0.50	0.50	1.00

Table 18: Normalized Performance Scores for TPM (Revenue Sensitivity Analysis)

Using the TPM weight vector, the final MCDM scores for each alternative are calculated as follows.

- **Alt 1:** $0 + 0.1500 + 0.1693 + 0 + 0.1070 + 0.0710 + 0 = \mathbf{0.4973}$
- **Alt 2:** $0.0041 + 0 + 0.2790 + 0 + 0.1070 + 0.0710 + 0.0220 = \mathbf{0.4831}$
- **Alt 3:** $0.2070 + 0.0540 + 0 + 0.1430 + 0 + 0 + 0.0440 = \mathbf{0.4480}$
- **Alt 4:** $0.2070 + 0.0540 + 0 + 0.1430 + 0.0535 + 0.0355 + 0.0440 = \mathbf{0.5370}$

The table below shows the updated normalized performance scores for the PD, in which only the Revenue scores for Alt 3 and Alt 4 have been adjusted to reflect a 1% decrease. All other values remain as in the original analysis.

Alternative	CAPEX	OPEX	Revenue	Risk	Ease of Impl.	Permitting	Innovation
Alt 1	0.00	1.00	0.607	0.00	1.00	1.00	0.00
Alt 2	0.02	0.00	1.000	0.00	1.00	1.00	0.67
Alt 3	1.00	0.36	0.000	1.00	0.00	0.00	1.00
Alt 4	1.00	0.36	0.000	1.00	0.50	0.50	1.00

Table 19: Normalized Performance Scores for PD (Revenue Sensitivity Analysis)

Using the PD weight vector, the final MCDM scores for each alternative are calculated as follows.

- **Alt 1:** $0 + 0.1174 + 0.0971 + 0 + 0.1642 + 0.1724 + 0 = \mathbf{0.5512}$
- **Alt 2:** $0.0026 + 0 + 0.1601 + 0 + 0.1642 + 0.1724 + 0.1067 = \mathbf{0.6060}$
- **Alt 3:** $0.1280 + 0.0423 + 0 + 0.0986 + 0 + 0 + 0.1593 = \mathbf{0.4282}$
- **Alt 4:** $0.1280 + 0.0423 + 0 + 0.0986 + 0.0821 + 0.0862 + 0.1593 = \mathbf{0.5965}$

The final scores for the sensitivity analysis of revenue are given below and calculated by averaging the TPM and PD scores.

Alternative	TPM Score	PD Score	Final Score (Average)
Alt 1	0.4973	0.5512	0.5243
Alt 2	0.4831	0.6060	0.5446
Alt 3	0.4480	0.4282	0.4381
Alt 4	0.5370	0.5965	0.5668

Table 20: Combined MCDM Scores (Revenue Sensitivity Analysis)

6.6.3 CAPEX

The table below presents the updated normalized performance scores for the TPM, where only the CAPEX scores for Alt 3 and Alt 4 have been adjusted to reflect a 10% increase. All other performance scores remain unchanged.

Alternative	CAPEX	OPEX	Revenue	Risk	Ease of Impl.	Permitting	Innovation
Alt 1	0.529	1.00	0.00	0.00	1.00	1.00	0.00
Alt 2	1.000	0.00	0.78	0.00	1.00	1.00	0.50
Alt 3	0.000	0.36	1.00	1.00	0.00	0.00	1.00
Alt 4	0.000	0.36	1.00	1.00	0.50	0.50	1.00

Table 21: Normalized Performance Scores for TPM (Sensitivity Analysis CAPEX)

The final MCDM scores for each alternative are calculated using the TPM weights and the updated normalized scores.

- **Alt 1:** $0.1096 + 0.1500 + 0 + 0 + 0.1070 + 0.0710 + 0 = \mathbf{0.4375}$
- **Alt 2:** $0.2070 + 0 + 0.2176 + 0 + 0.1070 + 0.0710 + 0.0220 = \mathbf{0.6246}$
- **Alt 3:** $0 + 0.0540 + 0.2790 + 0.1430 + 0 + 0 + 0.0440 = \mathbf{0.5200}$
- **Alt 4:** $0 + 0.0540 + 0.2790 + 0.1430 + 0.0535 + 0.0355 + 0.0440 = \mathbf{0.6090}$

Now the same is done for the PD.

Alternative	CAPEX	OPEX	Revenue	Risk	Ease of Impl.	Permitting	Innovation
Alt 1	0.529	1.00	0.00	0.00	1.00	1.00	0.00
Alt 2	1.000	0.00	0.78	0.00	1.00	1.00	0.67
Alt 3	0.000	0.36	1.00	1.00	0.00	0.00	1.00
Alt 4	0.000	0.36	1.00	1.00	0.50	0.50	1.00

Table 22: Normalized Performance Scores for PD (Sensitivity Analysis CAPEX)

The final MCDM scores for the PD are calculated by combining the PD weights with the corresponding normalized performance scores as follows:

- **Alt 1:** $0.0677 + 0.1174 + 0 + 0 + 0.1642 + 0.1724 + 0 = \mathbf{0.5217}$
- **Alt 2:** $0.1280 + 0 + 0.1249 + 0 + 0.1642 + 0.1724 + 0.1067 = \mathbf{0.6962}$
- **Alt 3:** $0 + 0.0423 + 0.1601 + 0.0986 + 0 + 0 + 0.1593 = \mathbf{0.4603}$
- **Alt 4:** $0 + 0.0423 + 0.1601 + 0.0986 + 0.0821 + 0.0862 + 0.1593 = \mathbf{0.6286}$

Alternative	TPM Score	PD Score	Final Score (Average)
Alt 1	0.4375	0.5217	0.4796
Alt 2	0.6246	0.6962	0.6604
Alt 3	0.5200	0.4603	0.4902
Alt 4	0.6090	0.6286	0.6188

Table 23: Combined MCDM Scores (Sensitivity Analysis CAPEX)

6.6.4 Ease of Implementation

The table below presents the updated normalized performance scores for the TPM. Only the Ease of Implementation score for Alt 4 has been adjusted, reflecting a one-point reduction in the raw input (from 3.5 to 2.5). All other scores remain unchanged.

Alternative	CAPEX	OPEX	Revenue	Risk	Ease of Impl.	Permitting	Innovation
Alt 1	0.00	1.00	0.00	0.00	1.000	1.00	0.00
Alt 2	0.02	0.00	0.78	0.00	1.000	1.00	0.50
Alt 3	1.00	0.36	1.00	1.00	0.000	0.00	1.00
Alt 4	1.00	0.36	1.00	1.00	0.333	0.50	1.00

Table 24: Normalized Performance Scores for TPM (Sensitivity Analysis Ease of Impl.)

The final MCDM scores for each alternative are calculated using the TPM weights and the updated normalized scores.

- **Alt 1:** $0 + 0.1500 + 0 + 0 + 0.1070 + 0.0710 + 0 = \mathbf{0.3280}$
- **Alt 2:** $0.0041 + 0 + 0.2176 + 0 + 0.1070 + 0.0710 + 0.0220 = \mathbf{0.4217}$

- **Alt 3:** $0.2070 + 0.0540 + 0.2790 + 0.1430 + 0 + 0 + 0.0440 = \mathbf{0.7270}$
- **Alt 4:** $0.2070 + 0.0540 + 0.2790 + 0.1430 + 0.0356 + 0.0355 + 0.0440 = \mathbf{0.7981}$

The table below presents the updated normalized performance scores for the PD.

Alternative	CAPEX	OPEX	Revenue	Risk	Ease of Impl.	Permitting	Innovation
Alt 1	0.00	1.00	0.00	0.00	1.000	1.00	0.00
Alt 2	0.02	0.00	0.78	0.00	1.000	1.00	0.67
Alt 3	1.00	0.36	1.00	1.00	0.000	0.00	1.00
Alt 4	1.00	0.36	1.00	1.00	0.333	0.50	1.00

Table 25: Normalized Performance Scores for PD (Sensitivity Analysis Ease of Impl.)

The final MCDM scores for each alternative are calculated using the PD weights and the updated normalized scores.

- **Alt 1:** $0 + 0.1174 + 0 + 0 + 0.1642 + 0.1724 + 0 = \mathbf{0.4540}$
- **Alt 2:** $0.0026 + 0 + 0.1249 + 0 + 0.1642 + 0.1724 + 0.1067 = \mathbf{0.5708}$
- **Alt 3:** $0.1280 + 0.0423 + 0.1601 + 0.0986 + 0 + 0 + 0.1593 = \mathbf{0.5883}$
- **Alt 4:** $0.1280 + 0.0423 + 0.1601 + 0.0986 + 0.0547 + 0.0862 + 0.1593 = \mathbf{0.7291}$

The table below shows the combined MCDM scores from both stakeholders, including the final score based on the average of TPM and PD results.

Alternative	TPM Score	PD Score	Final Score (Average)
Alt 1	0.3280	0.4540	0.3910
Alt 2	0.4217	0.5708	0.4963
Alt 3	0.7270	0.5883	0.6577
Alt 4	0.7981	0.7291	0.7636

Table 26: Combined MCDM Scores (Sensitivity Analysis Ease of Impl.)