Towards an integrated offshore transmission system

A scenario-based modelling approach to assess mitigation schemes for hybrid offshore wind projects

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by

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Preface

This thesis is the result of months of hard but also gratifying work. I always have been fascinated in a way about the energy sector, and to get the chance to conduct this research at the Dutch TSO TenneT is something that I am very grateful for. However, this thesis would not have been possible without the help of the people around me and close to this research. To my first supervisor, Rudi Hakvoort, thank you for your clear guidance and sharp feedback remarks. In addition, I want to thank Simon Tindemans, my second supervisor, for the help, especially in the beginning, to help me to structure the process more clearly. In addition, I would like to thank my company supervisor Bryan Brard along with many other colleagues from TenneT, for all the knowledge I gained on the subject. I found myself fascinated by the offshore renewable energy integration, partly because of the projects that I could have joined in on.

As this report marks the end of an era, I can honestly say that I have learned a lot both on a professional- and personal level. Primarily since this research was meant to take place at the Dutch TSO TenneT, however, as a consequence of the COVID pandemic, the study was performed mainly from home. This was incredibly challenging at times, but the online coffee meetings with fellow SET students, supervisors and colleagues from TenneT helped me through the most challenging times.

To find my way in this extensive area of expertise was sometimes frustrating as it touches upon many different fields of expertise that were relatively unknown to me. However, I am proud of all the knowledge I have gained over the months, especially on the topic of regulations and policies. Hopefully, the findings of this research may help my fellow students, the academic field and the professional environment in any way possible.

Aernout Klokgieters
Delft, October 2021

Executive Summary

In earlier times the climate crisis was ignored. However, these days it is acknowledged as one of the most important challenges the world is facing. With increased awareness of anthropogenic emissions, most sectors are changing rapidly. One of those sectors is the offshore wind energy sector. As a consequence of the Paris Climate Agreement, the European Commission adopted an offshore renewable strategy that aims to install at least 60 GW of offshore wind by 2030 and up to 300 GW by 2050. With the increasing capacity of offshore wind being constructed, new wind farms will move gradually further offshore. This, therefore, requires a need for significant investments in large-scale wind farms and in the required grid infrastructure to be able to transmit the large amounts of electricity produced offshore to the consumers onshore. Thus the need for cost-efficient integration of the North Sea transmission arises. Currently, existing offshore wind farms are being investigated as potential gateways in order to achieve this offshore transmission network integration in a cost-efficient manner.

In this master thesis project, the effects of various future connection schemes and market setups on the business cases of offshore wind farms were investigated. The study focuses on a location in the North Sea close with similar geographical characteristics as a large sandbank called the Doggerbank. First, a literature study was performed to obtain background knowledge about the offshore situation. Relevant assets were identified, multiple offshore grid typologies were found and different offshore governance models and market setups have been identified.

In addition, the theoretical background of constructing a business case for offshore wind farms from a Dutch and British perspective was explored. The main cost drivers were identified and can be distinguished in capital expenditures and operational expenditures. In addition, these cost categories were quantified in order to set up a business case for an offshore wind farm at a specified location. The cost category taking up most of the investment was found to be the grid connection, taking approximately 30% of the total investments. In addition, British built wind farms require more initial investment with respect to the Dutch wind farms, due to a difference in governance models between the countries. Next, the methods by which a wind farm can collect income was explored. Various categories were identified being; revenue by selling the commodity, power purchase agreement, financial support schemes and green certificates. Historical wind data was used to determine a wind profile. In addition, the historical market data was added to quantify the cash flow of an offshore wind farm. Last,

an expression of the Levelized Cost of Energy (LCOE) was found for a Dutch and British constructed offshore wind farm respectively.

To obtain insights into the effects of the North Sea transmission integration on the business case of offshore wind farms, a scenario-based modelling & simulation approach was adopted. First, a conceptual model has been developed. This was done by, first, identifying the situation in which the problem occurs and second, determining the modelling scope. Next, the in- and outputs were explained and the simplifications used for the model were presented accordingly.

Various scenarios were developed in order to be able to simulate distinct future situations in which a wind farm may be required to operate. These system changes are predominantly caused by different connection scenarios or by a change in market setups. First, a base model was developed, to understand the basic operations of a wind farm. Next, the reference case using a Dutch and British wind farm connected to their own national electricity market was simulated that represents the current situation of existing offshore wind farms. Then, a cross-border connection was added to the reference case under the current home market setup. Subsequently, a change in market setup, the offshore bidding zone, was introduced.

The first insights were obtained through simulation of the reference case, which represents the current situation. Large wind farm projects far from shore were found to be most likely still dependent on support through subsidy schemes. This holds for both a Dutch and British perspective regarding the construction. The first scenario on which the effects were simulated, describes a situation in which a connection to a foreign market is introduced to the reference case. The results of these simulations show no substantial changes in the cash flow of the offshore wind farms. However, large amounts of costs imposed on society were identified under this scenario. When the offshore bidding zone was introduced as a new market setups in a cross-border connection various results were found. First, for a Dutch wind farm in this connection and under this market setup, the revenues tent to increase with respect to the reference case. However, for a British wind farm a clear decline in the collected revenues by the wind farm developers was observed. Nevertheless, due to the regulatory conflicts that were identified in the cross-border connection scenario under the current home market setup, a change to the offshore bidding zone market setup seems desirable. This implies that under current regulation, the offshore bidding zone market setup shows no issues being compliant with EU legislation and National regulation.

An additional step was performed in this master thesis project, that adopts the objective to identify instruments that could mitigate these declines in revenues under an offshore bidding zone market setup. These instruments are regarded as mitigation options or mitigation schemes. The academic method of a policy scorecard was adopted, and additional desk research was performed to identify current proposals for mitigation schemes in the literature. Eight mitigation schemes were found from which seven were applicable to an offshore bidding zone market setup. These could be distinguished into support through operations and through regulatory changes. It was found that, within the scope of this research, which is looking into the economic effects and the feasibility of the identified mitigation schemes, the Contract for Difference scheme seems to be the best choice as it provides stability for the wind farm developers, and is the most cost-efficient option with respect to society. Good alternatives were identified to be the redistribution of congestion income and granting wind farm developers a so-called "Transmission System Operator -light" certificate that allows for a share in the congestion income.

However, there is a broader political impact, in terms of financial budget requirements on a member state level, general public support for support schemes and overall effectiveness of support schemes in broader policy objectives. As a consequence, it is recommended for future research to further investigate different domains than the economically and feasibility domains that have been presented in this research. In order to solve the current issue, these domains require additional investigated to obtain this broader perspective and to eventually be able to make political decisions.

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List of Abbreviations

ACER	Agency for the Cooperation of Energy Regulators
AEP	Annual Energy Production
CAPEX	Capital Expenditure
CEP	Clean Energy Package
CfD	Contract for Difference
CI	Congestion Income
EC	European Commission
EEZ	Exclusive Economic Zone
ENTSO-E	European Network of Transmission System Operators for Electricity
FIT	Feed-In-Tariff
HM	Home Market
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IC	Interconnector
LCCC	Low Carbon Contract Company
LCOE	Levelized Costs Of Energy
MOG	Meshed Offshore Grid
NRA	National Regulatory Authority

OBZ	Offshore Bidding Zone
OFTO	Offshore Transmission Owner
OPEX	Operational Expenditure
OWF	Offshore Wind Farm
PPA	Power Purchase Agreement
REC	Renewable Energy Certificate
RO	Renewbales Obligation
SDE++	Stimulering duurzame energieproductie en klimaattransitie
TNUoS	Transmission Network Use of System Charge
TSO	Transmission System Operator
WACC	Weighted Average Cost of Capital

Chapter 1

Introduction

In earlier times the climate crisis was ignored. However, these days it is acknowledged as one of the most important challenges the world is facing. Rising sea levels, record-breaking temperatures and extremer weather patterns are just some of the challenges we are facing (Health, 2020). As is seen in Figure 1-1, the world's emissions increased over the past decade. In 1980 the worlds' carbon emissions were just above 20 Megatonnes of CO_2. However, nowadays this is close to 35 Megatonnes. The biggest emitter is the power sector contributing to roughly 40 per cent of the worldwide carbon emissions.

Fortunately, as the global carbon emissions levels are increasing, signs of change are observed in the way energy is consumed and produced. Throughout the years several international agreements have been signed such as the Kyoto Protocol, the Copenhagen Accord and most recently the Paris agreement. The Paris agreement was unanimously signed by 196 countries aiming to limit global warming to well below 2 and preferably to 1.5 degrees Celsius, compared to the pre-industrial levels of 1990. In order to achieve this long term goal, the agreement mainly focuses on increasing the share of renewable energy sources (RES) and reducing the overall Greenhouse Gas (GHG) emissions (UNFCCC, 2016).

In 2015, the European Commission signed the European Green Deal, which states the ambitious goal for Europe to be the first climate-neutral continent by 2050. The European Commission adopted 5 main pillars in order to supply the EU consumers with sustainable, competitive and affordable energy (European Commission, 2020c). Decarbonising the economy, integration of the internal electricity market and research are the main drivers for the development of the power sector.

When analysing these developments, it is seen that renewable ways of producing electricity are on the rise. Harvesting the power of the wind and sun, large-scale solar plants and wind farms are emerging all around Europe. As seen in Figure 1-2, an enormous increase in renewable electricity production is seen. In the 90s renewable electricity generation was

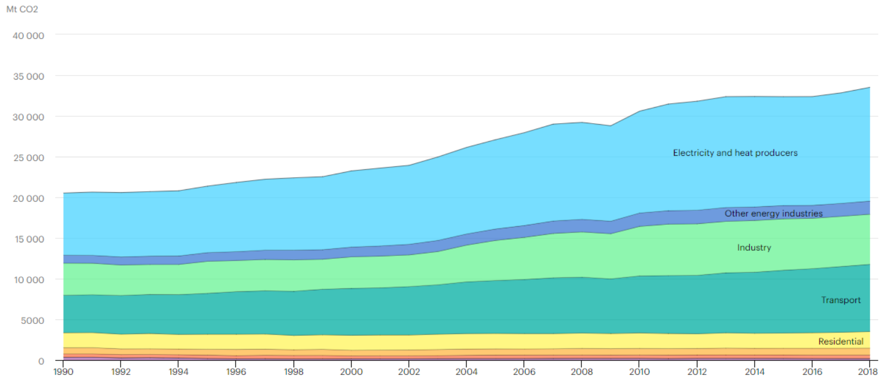


Figure 1-1: Global carbon emission per sector (1990 - 2018) (IEA, 2020a).

almost non-existent, however around the year 2000, this previously mentioned about shift is observed. Especially wind-generated electricity is increasing rapidly. Wind production levels just hit the level of 778 GWh in 1990 and this has increased to more than 400.000 GWh in 2018. In addition, this generation increase is expected to become even larger over the coming decades (Henderson et al., 2003).

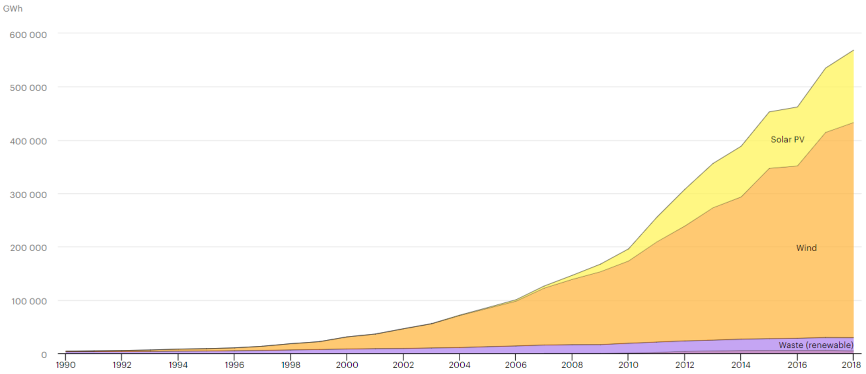


Figure 1-2: Share of low-carbon electricity generation by source, Europe 1990-2018 (IEA, 2020b).

1-1 Wind generation in Europe

Renewable energy sources will play an increasing role in decarbonising the energy systems of many EU Member States (EUMSs). For the northern part of Europe especially wind generation is favourable due to its high wind potential along the northern coasts. As displayed in Figure 1-3, the annual full-load hours for onshore wind generation reaches levels of over 3000 hours per year for the North Sea and Baltic Sea regions, whereas the southern regions are hardly suitable for onshore large-scale wind generation (Held et al., 2011).

Over the past years electricity generation by means of offshore wind turbines has emerged

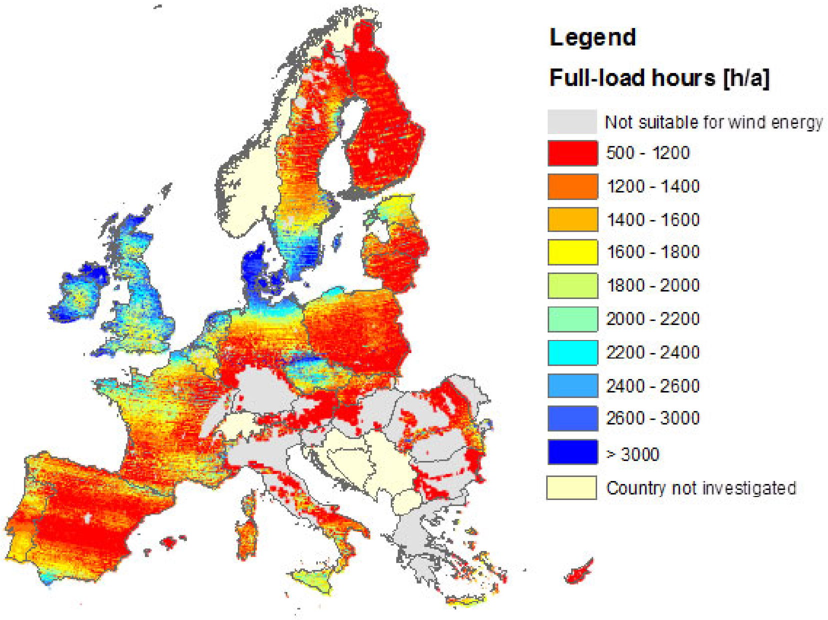


Figure 1-3: Annual full load hours for onshore wind energy in the EU (Held et al., 2011).

as one of the most promising ways to increase the share of renewables in power generation. (Nikitas, Bhattacharya, & Vimalan, 2020) discusses some of the advantages that offshore wind has over traditionally onshore wind. First of all, the average wind speed on sea is generally higher and more consistent than wind onshore resulting in a greater yield of wind generation. Second, as there is more free space available in the sea, offshore wind farms (OWFs) can be more versatile and scalable. Furthermore, the transition from shore to the sea makes it possible for the turbines to increase in size. Because of this, large proportions of future projection scenarios will expect an enormous increase in offshore wind.

In order to exploit the offshore wind potential the European Commission presented an EU Strategy on offshore renewable energy in 2020. This strategy aims to install at least 60 GW of offshore wind by 2030 and up to 300 GW by 2050 (European Commission, 2020a). As shown in Figure 1-4, the offshore wind development over the past decade has exceeded the bar of 20 GW installed capacity. Last year, Europe installed almost 0.5 GW of new capacity mostly located in the North Sea region (Wind Europe, 2021). Projects in the Northern Seas alone are projected to install 90 to 205 GW of offshore wind capacity by 2050 to contribute to the climate targets (Wouters, Van Der Veen, Henneaux, & Van Blijswijk, 2019). The North Sea is favourable with developers because of the relatively shallow water depth, making it less expensive compared to construction in deeper waters.

1-2 The offshore electricity grid

With the increasing capacity of offshore wind being constructed, new wind farms will move gradually further offshore. This, therefore, requires a need for significant investments in large-scale wind farms and in the required grid infrastructure to be able to transmit the large

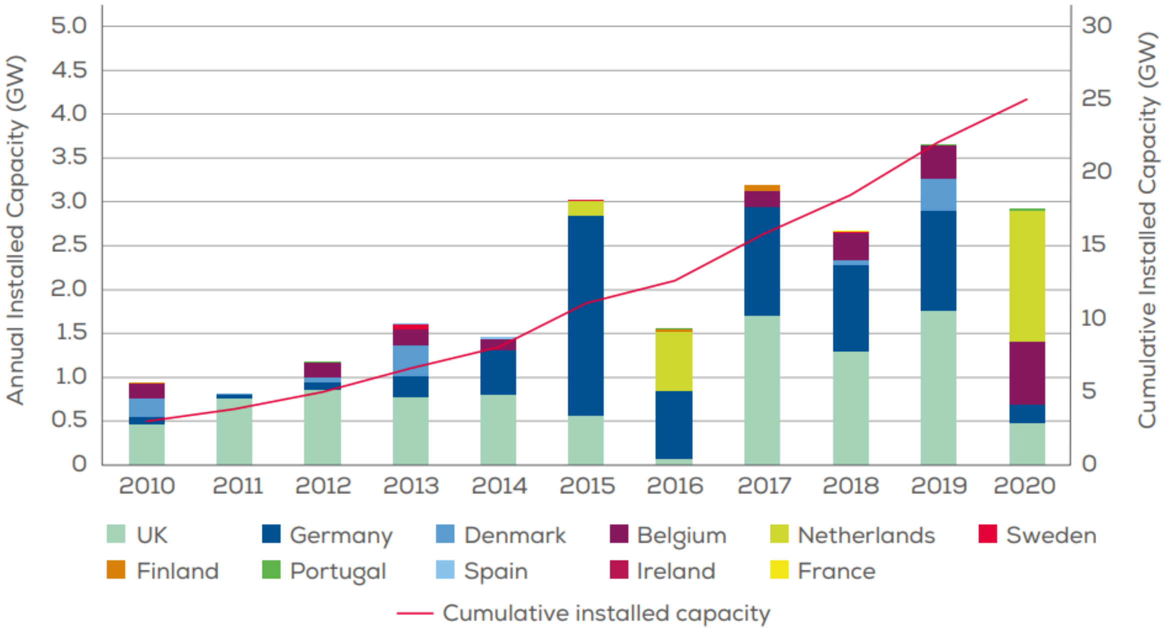


Figure 1-4: Annual offshore wind installations by country (left axis) and cumulative capacity (right axis) (Wind Europe, 2021).

amounts of electricity produced offshore to the consumers onshore. The need for cost-efficient electricity transmission infrastructure arises, including transnational links supporting cross-border electricity. (Wiggelinkhuizen, 2017) The strategy developed by the European Commission for harvesting the potential of offshore renewable energy estimates an annual investment of 800 billion will be required until 2050 (European Commission, 2020b).

The current offshore transmission infrastructure in the North Sea has two main functions: The interconnection of onshore electricity systems by means of interconnectors (ICs), and the connection of offshore power generation units usually being OWFs to shore (Gorenstein Dedecca & Hakvoort, 2016). Nevertheless, according to the EU, this needs to change in order to reach the full potential of these resources. Furthermore, the construction of offshore networks is often delayed by long lead times and the lack of developing capacity (Hektor, 2019). The EU-funded project "Progress on Meshed HVDC offshore transmission networks" (PROMOTioN) investigates how this current offshore grid can be integrated in order to move to a fully EU integrated offshore grid.

A solution to this problem is found in Meshed Offshore Grid (MOG) configurations. This solution has the ability to connect OWFs, interconnectors and shore connections. In addition, it could provide economic, technical and environmental benefits to the European electricity market (PROMOTioN, 2016). However, because of the early stage in the development of such solutions, these projects are still very scarce. As of today solely one is fully operational. The project named "Kriegers Flak Combined Grid Solution" (KF CGS) is the first project ever to connect the different electricity markets of Germany and Denmark by means of the interconnection using multiple OWFs. A representation of the project's physical layout is seen in Figure 1-5. According to 50Hertz, the German Transmission System Operator (TSO), the new interconnector will be able to provide the cheapest forms of generation in both countries to cover electricity demand (50Hertz, 2020). This interconnector has a capacity of 400MW in both directions and the integration of the two Danish wind farms Kriegers Flak is planned for 2021.

Figure 1-5: The Kriegers Flak - Combined Grid Solution project (Energinet, 2020).

1-3 Problem statement & research question

Despite the fact that one of these so-called meshed projects has been realized, there are still many crucial aspects left untouched about its development. One of them is the lack of a combination of the national regulatory frameworks. Furthermore, there is a lack of current technologies to operate the network safely, since it will most likely be operated through the relatively new HVDC technology. In addition, the nature of these projects includes international collaborations, requiring guidelines and standards for combining different building blocks constructed by the different parties involved.

In many cases a meshed offshore grid includes a transnational network, which has regulatory implications and implications for the business models, governance and financing (Hektor, 2019). Although there are some benefit studies conducted on combined grid solutions, these are always from the perspective of TSO or from/to society. However, in many cases in which for example an offshore bidding zone (OBZ) is introduced, the wind developers are not always motivated to collaborate in such projects. When the offshore wind developers are not incentivized to participate in the efficient integration of the offshore transmission network, these wind farm owners could act as barriers against the goal to integrate the European electricity market.

This research is supported by means of an internship at the Dutch TSO TenneT. TenneT is working on a similar case called the WindConnector project, a possible new combined grid solution between the Netherlands and the United Kingdom. This project is a collaboration between the Dutch TSO TenneT, the British TSO National Grid and the OWF developer Vattenfall, in which scenarios are being investigated to combine the radial connected OWF with a connection to the foreign shore and/or a British wind farm.

The scope of this research is to develop a model which allows simulations of certain future scenarios regarding the offshore electricity system from the perspective of an offshore wind farm developer. In addition, current policies and favourable concept policies should be able to be assessed against the expected effects of the different scenarios. Therefore, the main question this research tries to solve can be stated as follows:

How does the North Sea transmission infrastructure integration impact the business cases of offshore wind farms under different market designs and how can these be protected for future grid development?

1-4 Research approach

In order to formulate an answer to the research question, a well-designed approach must be formulated. When looking at the research question certain sub-questions can be formulated. These sub-questions have to be answered first in order to create the foundation for the next sub-question. In addition, all answers to the sub-questions combined should provide a foundation on which the conclusion can be formulated. Three main components can be distinguished in this research. First, the comprehension of the effects of grid and market developments on the business case of an OWF. Second, the analysis of these effects on the business case of an OWF must be understood properly and quantified. Third, simulated effects must be analysed further in order to assess possible mitigation options, if needed.

1-4-1 Type of research question

In order to formulate a research approach, the nature of the research question is analysed. This problem has arisen recently with the increasing developments in the offshore wind energy sector. Limited academic research in this specific field of research has been conducted so far. Nevertheless, certain theoretical frameworks identified in other contexts with problem statements of similar nature may be applied to the identified research problem. In the case of this research, a system will be set up and analysed together with the effects of external variables or constraints on the system. In addition, an assessment must be done in order to comprehend these effects and to find possible options for mitigation. As a consequence, a combination of a scenario-based approach along with a modelling and simulation approach is adopted in this study. Together, this results in a scenario-based simulation modelling approach. This will be carried out for a case study of a wind farm located at the Doggerbank.

1-4-2 Scenario-based approach

The scenario-based approach is defined according to Quade and Carter (1989) as: "A description of the conditions under which the system or policy to be designed, tested, or evaluated is assumed to perform". Scenarios can be seen as a set of situations with possible futures, based upon logical, consistent sets of assumptions, and fleshed out in sufficient detail to provide a useful context for engaging planners and stakeholders (TU Delft wiki, 2010b). These different situations are used for example by policymakers. To assess the new policy, multiple scenarios are defined to identify possible future problems and to identify robust (static) policies for dealing with the problems. Furthermore, scenarios have an explanatory function, they do not predict the future but rather explain what the future could look like. TU Delft wiki (2010b) describes an approach to formulate a scenario based on several steps that will be used as reference.

Many examples of this approach can be found throughout the literature. To take an example, the article by Hashemi et al. (2014) uses this approach to design the renewable energy system of Korea based on 6 different scenarios. The scenario development was based on a reference case, and with each scenario, different variables or boundaries were introduced. After the scenarios were developed, the effects were optimized to come to the conclusion of the article. For this research, different perspectives, connection typologies and market designs result in various scenarios that could be a representation of the future once such a decision is made by the European Commission.

1-4-3 Simulation and Modelling

In this research, the behaviour of the system (in this case the business case of a wind farm) must be analysed. For that part the Modelling and Simulation approach is applicable. According to TU Delft wiki (2010a), Modelling and Simulation is considered both a method and a tool and has become a conventional way for developing complex systems. More specifically, modelling refers to obtaining or developing a simplified representation of reality.

One of the reasons why this approach is better suited compared to its alternative called analytical approaches is because of the many system uncertainties. This includes future development regarding grid construction, market design and policy design. This is a complex system in which various stakeholders can influence the behaviour of the system. For the audience of this research, wind farm developers, (offshore) policymakers and TSOs the exact numbers and numerical results related to the analytical approach are not the most important outcome. The Simulation and Modelling approach is most suitable because it allows gaining important different insights into this complex situation.

An example of a similar usage of this method is conducted in the article by van den Burg et al. (2017). The article focuses on the development of a business case for mussel aquaculture in offshore wind farms in the North Sea area. An economic model was developed in order to analyse the financial feasibility of mussel banks located at offshore wind farms. The model represented a business case formulation of the mussel bank. Data of project costs and revenue streams were accumulated from various sources on which the financial modelling was performed. This conceptual model about a business case is similar to what will be performed in this research and consequently makes this approach suitable.

1-4-4 Scenario-based Simulation and Modelling

As is explained, both of the previously mentioned approaches are applicable to this research. However, on their own, they would not suffice to provide a proper result because both factors, simulations and scenarios, are important to be able to answer every aspect of the research question. Therefore, the two approaches will be combined. Prior literature has adopted such a combination before. According to Reilly and Willenbockel (2010): "Scenario modelling is a combination of scenario analysis and system modelling". In this combined approach, quantitative scenarios are constructed to enable a computational analysis of the system. Furthermore, the combination is used by Candy, Biggs, Larsen, and Turner (2015) to analyse the food system of Australia on futuristic shocks and adaptations. The reasoning behind this combined approach was because of the complex, socio-ecological nature of the problem, in some ways similar to the research present here.

A different example is given in the article by Hashemi et al. (2014). In this article, a new method is proposed for analysing the minimum storage capacity for low-voltage grid security. This was done by conducting a sensitivity analysis on various scenarios associated with the power injected by the customers connected to the grid. According to Hashemi et al. (2014), the proposed method is capable of modelling multiple scenarios where electricity from various resources is injected into the grid.

1-5 Sub research questions

As is stated earlier, in order to answer the main research question several sub-questions were created. Answering these questions is necessary in order to carry out the proposed research. The proposed sub research questions are as follows:

1. *What is the business case of an offshore wind farm from a Dutch and British perspective?*
2. *How do different grid connection scenarios impact the business case of offshore wind farms?*
3. *How does the offshore grid market design impact the business case of offshore wind farms?*
4. *How can the business cases of offshore wind farms be protected if a scenario yields negative effects?*

1-6 Project overview

This research will be carried out by developing a model that represents the business case of a Dutch- and British built wind farm located at the Doggerbank. In order to develop such a model, extensive desk research is carried out to identify the context of this research and to create a foundation on which the model and scenarios will be developed. After the data is gathered the model will be developed which will result in two reference cases (the Dutch and British business case) and a simulation model on which the future developed scenarios will be performed. In addition, scenarios will be set up to imply extra constraints on the model. In the last phase of this research, certain effects will be assessed and further research in possible mitigation options will be carried out. The next section will explain each research phase in more detail.

1-7 Research Phases

The theoretical framework that is used to answer the main research question can be formulated in certain phases. The sub research questions are set up in a way that these phases will be carried out. In addition, the output after each phase is considered a milestone which is crucial for the next phase. Next, the outline of these research phases is represented with corresponding sub research questions.

Phase 1: Information and data collection

In order to get familiar with the subject and to analyse the context of the problem a literature review is carried out. In this phase, a foundation for the project is created together with an introduction of the domain in which the research was carried out together with its corresponding boundaries. Various subjects occur within the domain of research such as the electricity assets present in the North Sea and the different forms of ownership allocation of these assets. In addition, various typologies were found on how to connect the assets with multiple countries. Last, different market designs were briefly investigated.

The second research questions focus on a specific asset, namely the offshore wind farm. In order to develop a conceptual model, a thorough understanding of the business case of an offshore wind farm is crucial. This extra research was carried out by additional desk research, and data was gathered regarding the costs that correspond when constructing a wind farm.

After this phase, identification of context will be provided, a foundation is created for the model and the background information is gathered for the development of the scenarios.

Phase 2: Modelling development

In the modelling development phase, the model of the business case of an OWF is developed. Additional desk research was carried out the collect market data. More specifically, the hourly spot price in the UK and NL was accumulated in order to set up a revenue stream. In addition, the main cost drivers are identified. After this phase, a model describing the business case of an OWF located at the Doggerbank will be realised. This will represent the base case on which simulations of the different scenarios will be carried out.

Phase 3: Scenario conceptualization and implementation

In order to measure external effects on the system, various scenarios impeding variables or constraints are developed. This is done by setting up two scenarios for the reference case in which the development of the wind farm is seen from a Dutch and British perspective. Furthermore, scenarios are created in which different market designs such as the offshore bidding zone influences the two reference cases. In addition, a similar approach will be carried out for the different connection schemes.

After this research phase, a set of different scenarios is developed. In addition, various new constraints and variables are identified.

Phase 4: Simulation

After the scenarios are developed, the effect of each scenario will be simulated. This research phase will provide intermediate results which act as a foundation for the next research phase. In addition, a first reflection on the obtained results will be carried out which could lead to changes in the scenarios.

Phase 5: Analysing mitigation options

This research phase addresses the fourth sub-research question and can be seen as an extra step that used the model developed in this research. In order to address the last sub-research question, an analysis is performed on the future proofness of the business cases of the offshore wind farms. In order to achieve this, further desk research will be carried out on some existing mitigation options. Through a policy analysis method, the advantages and disadvantages will be identified as well as the economic effectiveness and the feasibility of the options. In addition, possible new combinations will be tried to be developed. The outcome of this phase will in terms lay the foundation of the last phase.

Phase 6: Analysis of the results

Using the outcomes of phases 4 & 5 the selected mitigation options will be evaluated through simulations on the developed model. A conclusion will be formulated on the performance and feasibility of the selected options. In addition, further recommendations for future research will be discussed along with a reflection on the obtained results and research overall.

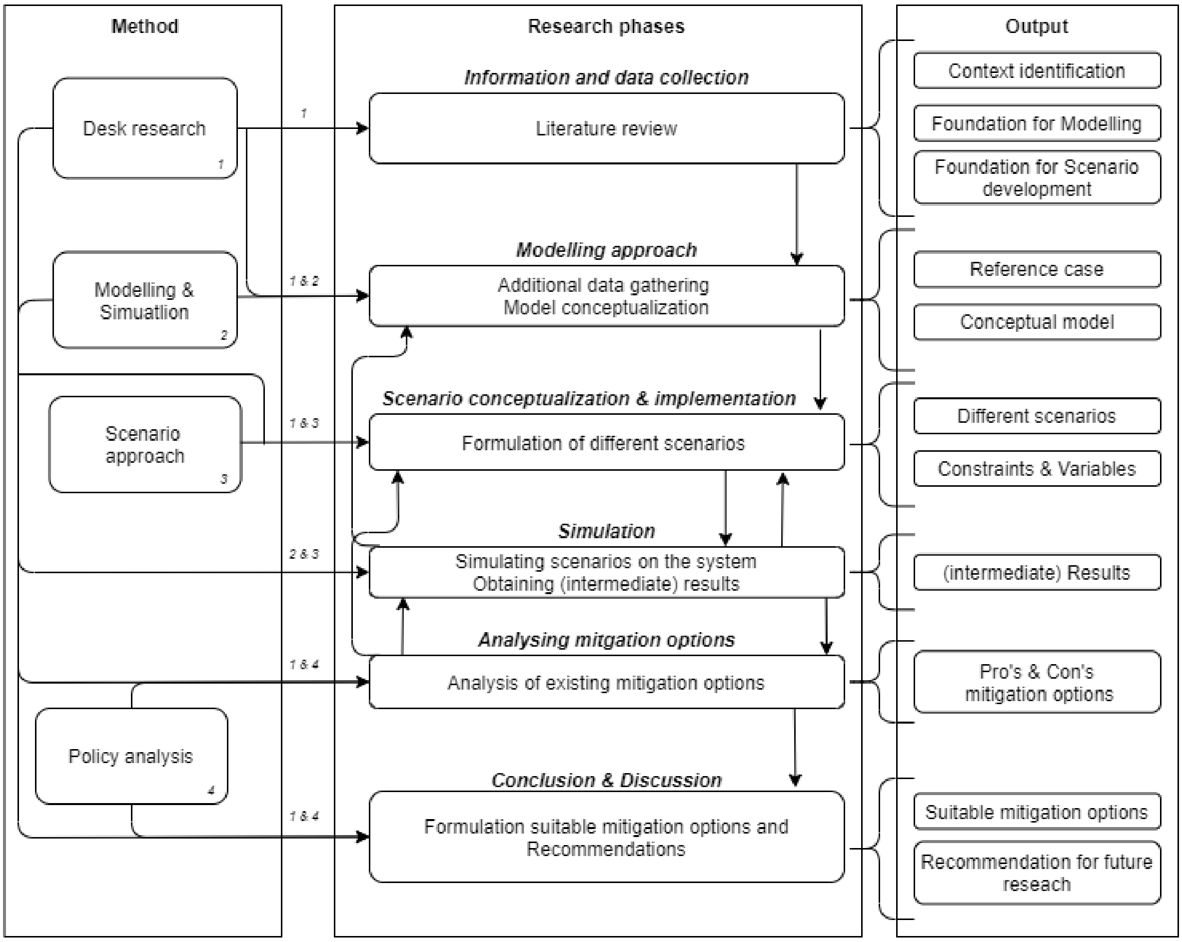


Figure 1-6: Research flow diagram.

Chapter 2

Literature review

A literature review was conducted in order to establish common ground regarding this topic, to explore the core concepts and to identify a possible knowledge gap. As the research question may suggest, the field of interest consists of multiple subjects. This section is divided into 5 subsections. The first subsection will provide an extensive background knowledge regarding offshore transmission infrastructure. Second, the characteristics of the assets connected to the offshore transmission grid will be investigated. Third, different options of market designs will be analysed. Fourth, different governance models regarding responsibilities will be investigated. This section concludes with the knowledge gap and the reasoning for the research question.

2-1 Offshore assets

In order to understand the complexity of meshing the NOSG, a background study is provided to gain an understanding of the associated benefits. As mentioned in the previous section, the current NSOG consists of different assets such as the OWFs (including its transmission infrastructure) and ICs.

2-1-1 Interconnector

Interconnectors are high-voltage cables that interconnect different Exclusive Economic Zones (EEZ) or bidding zones. Increasing the physical interconnection capacity between EUMBs is a top priority of the European community and is supported by both the European Commission and the European Council as more interconnections between neighbouring countries contributes to the integration of the European electricity system (Knops & De jong, 2005). One of the advantages of an IC is that it gives a market the ability to transport excess power caused by renewable energy sources, reducing the costs of the end users' electricity bill and making the electricity system more secure (National Grid, 2020). In addition, more competition can be introduced in markets that suffer from regulated price settings (Turvey, 2006). Currently, the United Kingdom has 4 operational interconnectors which supplied 8% (25 TWh) of the total electricity consumption in 2019. In addition, National Grid expects to construct two more ICs supplying 25% of the total electricity demand by 2024. One of the operational ICs is BritNed, an independent joint venture with TenneT, connecting the UK and the Netherlands since 2011.

The revenue streams of an IC consists almost fully through auctions of capacity, with revenues driven by the size of price differences between two markets. This is also known as congestion revenue. Two different types of interconnectors can be distinguished, a merchant interconnector and a regulated interconnector.

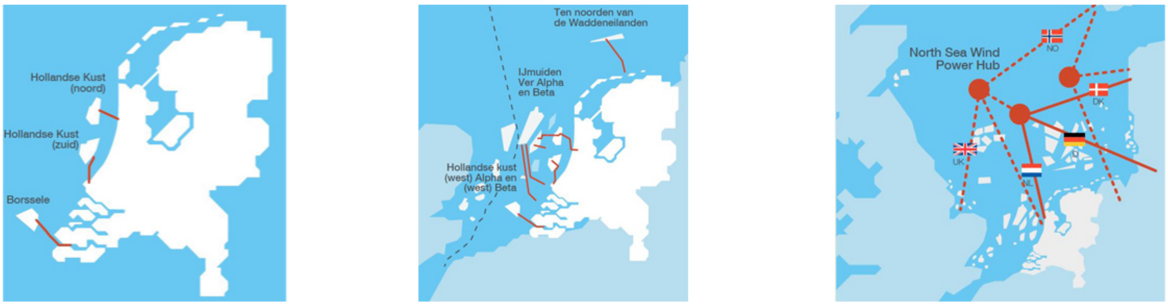
The first is the publicly funded merchant interconnector. This is a relatively new concept and much debate is going on about its responsibilities to network security. For instance, if an interconnector operator is not a TSO, it can pay its investors through its congestion revenues. The EU Commission is anxious to entrust the operation of critical energy infrastructure to profit-seeking businesses (Haverbeke, Blunsdoh, & Weber, 2019). The regulated ICs are operated by the TSOs on both ends of the IC. This is also the case with BritNed. In this case, the TSO is paid the difference between the two energy markets. In addition, TSOs are also compensated for system operating tasks such as liability management, organising third party access and setting regulated tariffs (Haverbeke et al., 2019).

The situation can become very complex when in an energy system multiple ICs provide multiple links to different bidding zones. In that case, the actual power flows in all of the ICs depend upon the configuration of all their transmission systems and upon the power injected and withdrawn within the system (Turvey, 2006). Furthermore, Turvey argues that physical flows and commercial exchanges are different phenomena and that the resulting pattern of physical flow across borders does not have to coincide with the cross-border commercial exchanges notified by the possessors of the transmission rights. This problem requires a market solution that might achieve coordination and enable more efficient and secure dispatch. This will be elaborated upon later.

2-1-2 Offshore wind farms

Naturally, ICs are not the only assets located in the NSOG. In between the UK and the Netherlands, numerous wind farms are located, and this is expected to increase rapidly. Figure 2-1 displays the vision of the Dutch TSO TenneT on the OWF expansion over the coming decades. This requires a cost-efficient manner since the development of OWFs are capital-intensive, upfront costs make up approximately 75% of the total lifetime costs. Furthermore, it is estimated that OWFs are 50% more expensive than onshore wind farms (Morthorst & Kitzing, 2016).

Naturally, all new generators will need a connection to the grid to shore, this is particularly challenging for OWFs as subsea cables are much more expensive than overhead transmission



Programme 2023 Programme 2030 Long term vision until 2050

Figure 2-1: Offshore grid development in steps (TenneT, 2019).

lines. Furthermore, because of the far distances OWFs are being built cables will have to travel long distances to a suitable point to be connected to the grid. In addition, a cable connecting a particular generator can only be used when the generator is producing electricity. Although the load factors of offshore wind are higher than onshore, it is still substantially lower than thermal power plants (Green & Vasilakos, 2011). Because of this, some OWF developers over design the capacity of the wind farm with respect to the cables as the wind farm will rarely generate full capacity. (Green & Vasilakos, 2011) argue that the optimal balance between reducing connection cost per generator and increasing the amount of electricity spilling lies around 112% of its connection capacity, and still with the relatively low load factor, the connection assets will be used at half of the available capacity.

The traditional topology of an OWF with components is shown in Figure 2-2. A distinction can be made in the grid connection types between OWFs close to shore and those further offshore. For OWFs close to shore (up to 120km) High Voltage Alternating Current (HVAC) is used to transport the electricity to shore. This electricity is first collected in the wind farm's own transformer station (Figure 2-2d) and subsequently it will be sent to the onshore stations (Figure 2-2-g).

Whenever an OWF is more than 120 km from shore, often the relatively new technology of High Voltage Direct Current (HVDC) is used to transport the electricity to shore. This is done because HVDC cables are cheaper for long distances (Gerdes, 2018). Again, the (AC) electricity is collected in the wind farm's own transformer and fed to the offshore converter, displayed in Figure 2-2e. This converter transforms the HVAC to HVDC and from the converter two DC-cables (one positive and one negative pole) feed the onshore stations. From there, the electricity is converted into AC again with the correct voltage and current and fed into the onshore transmission system (TenneT, 2018).

As a result of the increasing number of constructed wind farms in the North Sea, opportunities arise to construct new connections from existing OWFs from one EEZ to a different EEZ. In order to understand to what extent this would be possible, different offshore grid topologies need to be analysed.

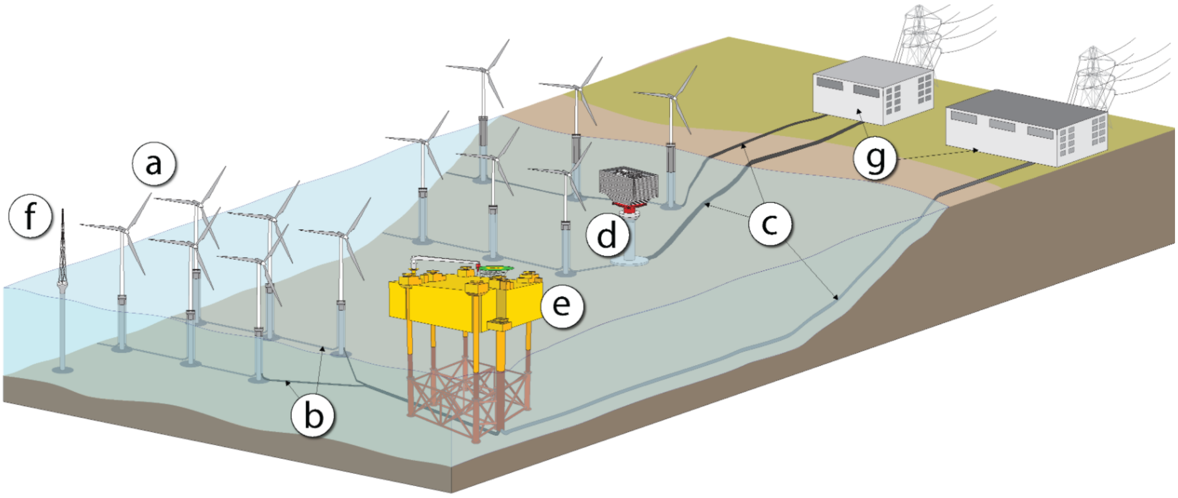


Figure 2-2: Main components of an OWF: (a) Wind turbines; (b) Collection cables; (c) Export cables; (d) Transformer station; (e) Converter station; (f) Meteorological mast; (g) Onshore stations. (Rodrigues et al., 2016a).

2-2 Offshore grid topology

As stated in the previous section, offshore wind energy is crucial to Europe's climate goals and as a result, an increase in the number of OWFs is observed. Because of this, the offshore power system as a whole needs to be investigated in order to ensure cost-efficient development. An example of the European Commission's support is the appointment of the North Sea Offshore Grid (NSOG) as a priority corridor in ENTSO-E's Ten Year Network Development Plan, meaning that it can be seen as a Project of Common Interest (PCI) (Klip, 2015). A PCI has some additional advantages such as funding, improved regulatory treatment and it benefits from more favourable permit granting procedures (ENTSO-E, 2016). This subsection investigates the possible integration scenarios of the offshore grid topology.

2-2-1 Radial connection

There are many ways to accommodate the integration of the NSOG, however to this date most wind farms in the North Sea are connected to shore by means of an individual power line. Figure 2-3a represents this so-called "Radial connection" in blue. The "regular" point-to-point connected ICs are depicted in red. As explained in subsection 2-1, these interconnectors are responsible for the connection of different EEZ. For this particular case, the IC can do so without any flow disturbance caused by the OWFs. The wind farms receive the price from their connected market and in general, the flow of the IC flows from the surplus zone to the deficit zone. One of the main advantages radial connections have over other types of connections types is the limited need for coordination.

2-2-2 Radial hub-to-shore connection

A slightly more complex infrastructure topology is the radial hub-to-shore option, displayed in Figure 7-8b. As the name states, this connection topology uses a "hub" which is an offshore substation that connects multiple wind farms in order to bring their combined energy to shore using a radial connection. As mentioned earlier, as OWFs are being built further offshore local coordination through the hubs becomes increasingly important (Daniel Adeuyi, Jenkins, & Wu, 2013). According to Klip, one of the advantages of this configuration is the opportunity to improve redundancy in case of cable failure by linking multiple hubs together, which is seen in Figure 7-8a. Although lacking in this Figure, there are also possibilities to connect a hub in one bidding zone to the shore of another bidding zone.

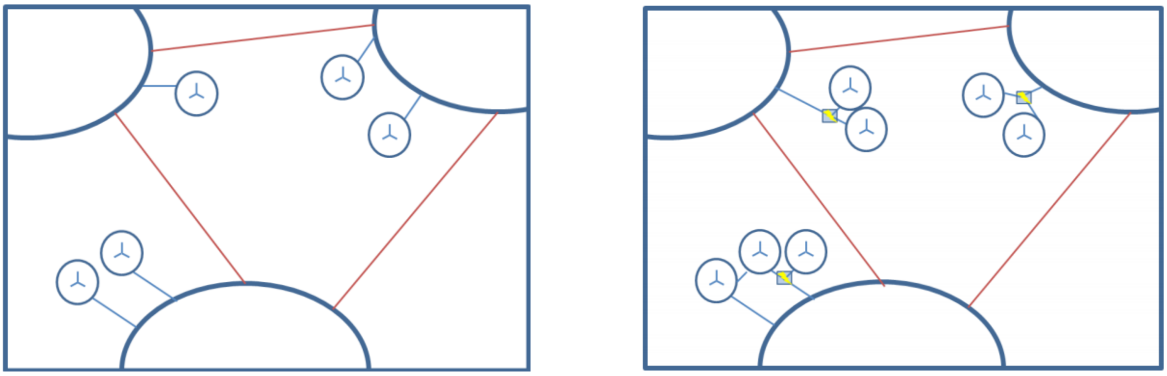

(a) Radial connection. **(b)** Radial hub-to-shore connection.

Figure 2-3: Current connection configurations by (Klip, 2015).

2-2-3 Combined grid solutions

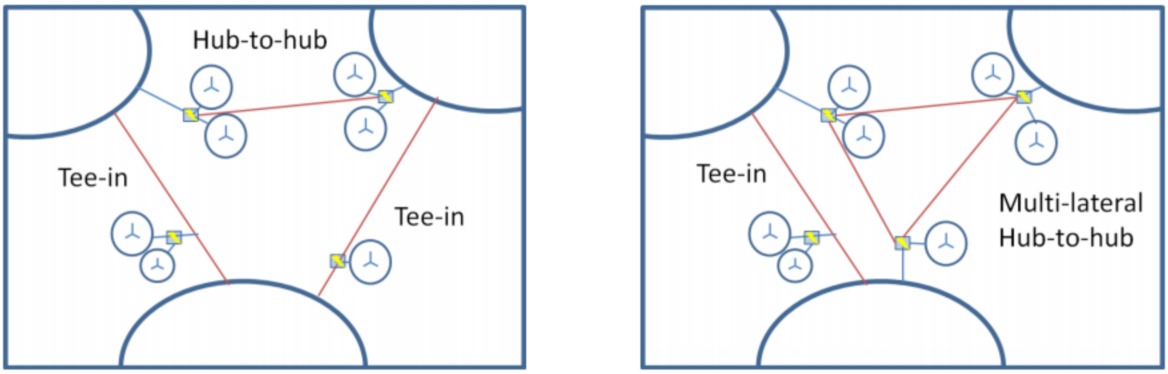
When gradually more and more OWFs are being built in the North Sea opportunities arise to interconnect the assets in the following configurations: First, depicted in Figure 7-8a existing interconnectors could be connected with the hubs of the OWFs, which is called a Tee-in solution. The entire asset being the OWFs and the IC is also referred as a hybrid solution, as the technical setup combines multiple configurations (ENTSO-E, 2020a). The difference with a radial hub-to-shore may seem relatively small, however, the tee-in or hub-to-hub connections differs significantly because it enables competition between the different bidding zones.

Unfortunately, to this day no examples exist (yet) of the topology represented in Figure 7-8b. Nevertheless, this theoretical representation has many advantages compared to the radial connections. According to a study conducted by Roland Berger, hybrid projects show significant economic savings which can be realised over the project lifetime of advanced hybrid projects with respect to the radial connected reference case (Weichenhain, Elsen, Zorn, & Kern, 2019). In addition, Ørsted (2020) concluded that hybrid projects enhance the robustness of both offshore wind and transmission projects as the generated wind energy could be dispatched to multiple markets, and at the same time, enable the possibility to trade

(Ørsted, 2020). According to PROMOTioN, Large scale build-out is driven by climate policy from which the pace and scale will be uncertain. Hybrids will allow a more efficient match of supply and demand, making them a "valve" for energy policy (Moore & P.Henneaux, 2020).

Although the meshed solutions sound extremely promising, many barriers have to be overcome in order to realise these projects in an efficient way. The biggest challenge for a meshed grid solution is its market design, this will be discussed later on. In addition, the current regulatory setup established to support existing projects is ill-suited for meshed solutions since there is no procedure for cost and revenue sharing that would incentivise all parties optimally (Ørsted, 2020). A lot of different subjects are still ambiguous such as sharing of responsibilities, cable classification, uncertainty about applicable subsidy schemes for renewable energy sources and allocation of green certificates and CO_2 credits (ENTSO-E, 2020a), (Klip, 2015), (Weichenhain et al., 2019), (Ørsted, 2020).

In order to gain a better understanding of the way in which the current NSOG is constructed, operated and maintained, a short analysis of the different governance models of the Uk and the Netherlands was conducted.



(a) Tee-in (hybrid) & hub-to-hub.

(b) Multi-lateral-hub-to-hub / meshed.

Figure 2-4: Integrated configurations by (Klip, 2015).

2-3 Offshore grid development models

In order to realise a possible meshed grid in the North Sea it is important to understand the way the current offshore transmission network was constructed. These days the deployment of offshore wind projects and grids are mainly national focused and are lacking a larger sea-basin perspective or coordination with neighbouring countries (Wind Europe, 2019).

While considering OWF development in general, 4 different stages can be distinguished: 1) Zone identification, 2) Site selection, 3) Permitting and 4) Construction (Wind Europe, 2019). Member states may choose different approaches when assigning responsibilities for grid development, connections and regulatory frameworks. Besides having different power markets, the United Kingdom and the Netherlands therefore also differ in the way offshore wind projects are realised.

2-3-1 Offshore grid development model: The United Kingdom

In the UK the regulatory framework is managed by the Office of Gas and Electricity Markets (OFGEM) in collaboration with the Department for Business, Energy and Industrial Strategy (BEIS). BEIS is the supervising government department whereas OFGEM is the economic regulator (Chan et al., 2019). Figure 2-5 displays the process which wind developers have to follow in order to construct an OWF.

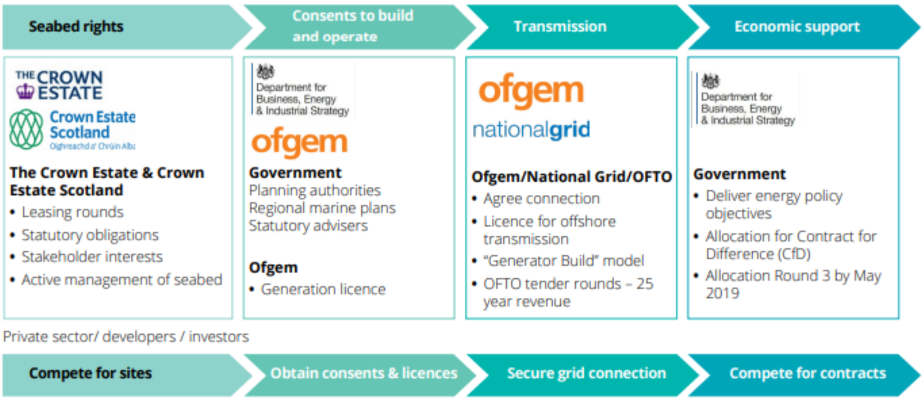


Figure 2-5: UK's high-level power market structure (Chan et al., 2019).

The first stage is the site competition. The Crown Estate (CTE) owns the seabed on which the OWF are to be realized. Leasing contracts are offered through competitive auctions. Each leasing round consists of 5 stages; First, a pre-qualification questionnaire is conducted to assess potential bidders, subsequently, stages of invitations are held, next, the fourth stage is about habitat regulations and finally, an Agreement for Lease is rewarded (Crown Estate, 2021). After obtaining the lease to develop an OWF, the developer has to obtain consent for construction by BEIS and a generation license from OFGEM. The third step is to construct the offshore transmission infrastructure. Previously, this was done under the Transition Regime where the transmission assets were constructed by the offshore developer and then transferred to the offshore transmission owner (OFTO). However, nowadays it is done under the Enduring Regime where offshore developers will have the flexibility to choose whether they or an OFTO is responsible for the offshore transmission infrastructure construction (OFGEM, 2021). Because of this, UK's offshore development model is often called an OFTO model or a "developer built" model, this is displayed in Figure 2-6. OFTOs also have to go through a competitive process to own and maintain the infrastructure which has to be agreed upon with the System Operator (SO). The last stage is about economic support through the so-called Contract for Difference (CfD) which is provided by BEIS. The CfD scheme is UKs main mechanism for supporting low-carbon electricity generation that pays the holder the difference between the strike price (a price for electricity reflecting the cost of investing in a particular low carbon technology) and the reference price (BEIS, 2020). The duration of the process starting from pre-tender engagement up to operation can be up to 12 years (Chan et al., 2019).

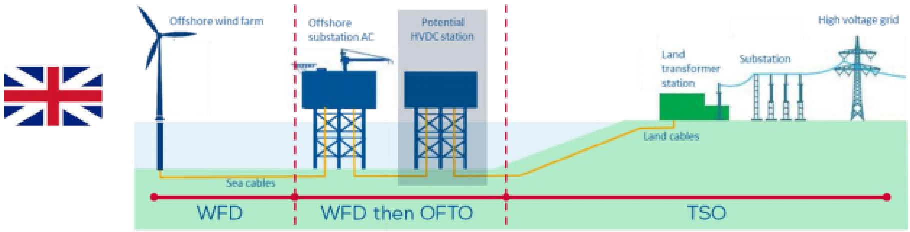


Figure 2-6: UK integrated competitive (OFTO) model (Wind Europe, 2019).

2-3-2 Offshore grid development model: The Netherlands

The Dutch grid development model differs from the UK's OFTO model in various ways. RVO or the Dutch Enterprise Agency is responsible for locating possible wind farm sites. The Ministries of Economic Affairs and of Infrastructure and the Environment will decide on the wind farm site location and specify the conditions under which it may be constructed and operated (RVO, 2015). After locating the wind farm site, commercial parties can participate in competitive tendering procedures. Whereas in the UK the wind developer was responsible for developing the offshore grid, in the Netherlands, this is the responsibility of TenneT (the Dutch TSO). After the tender process is complete, grants for wind farm sites will be awarded through a dedicated call for tender under the Stimulation of Sustainable Energy Production. This is similar to CfD scheme of the UK. However, under the scheme, producers receive financial compensation for the electricity generated over roughly 15 years. The lowest bidder will be awarded both the grant and the consent to build and operate a wind farm according to the conditions set by the RVO. This is displayed in Figure 2-7.

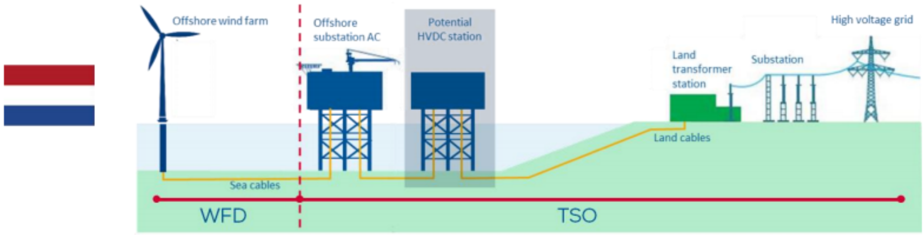


Figure 2-7: Dutch non-competitive segmented model (Wind Europe, 2019).

2-4 Market design for offshore meshed projects

When introducing a new generator, the point of connection determines into which bidding zone it will operate. If this new generator would introduce structural congestion in the power system it will trigger an incentive to create a new bidding zone or a redefinition of current bidding zones (Energinet, 2020). Energinet argues that it does not matter whether the generator is onshore or offshore. In addition, if the large scale of offshore wind integration in the North Sea causes structural congestion, bidding zones should be created or changed in a way that the bidding zone border reflects congestion. Much discussion is going on how to do this in an efficient way. The overall market income of a meshed project is made up of 2 revenue streams: the first being the revenues obtained by sold electricity by the OWF developers and the second is the congestion rent earned by the grid owner through the cross-border capacity exchange of electricity between two different priced areas (Ørsted, 2020). Primarily, the challenges in market design come down to two main problems; the first is the allocation of OWFs to the respected bidding zones and the second is how to allocate cross border dispatch between those zones (AFRY, 2020). This section will look into different market arrangements designed specifically for meshed grid solutions.

2-4-1 Dynamic flows to high- and low-price market concept

The Dynamic flow concept was originally identified by the North Sea Energy Cooperation (NSEC). When a Dynamic Bidding zone into High-prices zones is introduced, the offshore generators' bids are dynamically placed in the connected bidding zone that has the highest price. With the dynamic bidding into low-prices zones, it is the other way around, offshore generators' bids are dynamically placed in the connected bidding zone with the lowest price (THEMA, 2020). Multiple assessments of multiple organisations concluded that the dynamic option faced several crucial regulatory and operational challenges. THEMA argues that from a regulatory perspective the dynamically bidding zones would systematically discriminate in favour or against the offshore generators and consumers. In addition, the dynamic bidding zone concept would effectively imply changing zones ex-post, as a result of the market-clearing price, which is in conflict with the requirement of stability of bidding zones across market time frames.

Another conflict arises when looking at the operational perspective. The dynamic approach implicitly assumes that the merit order of the connected zones is unaffected by the offshore generation. As wind farm bids in on very low marginal prices, the high priced zone could be affected such that it would become the low priced zone. Furthermore, in the case of dynamic flows to high-priced markets, the OWFs and ICs are always in conflict since the commercial flow of both assets will be in the same direction. As for the low priced option, there are no conflicts since the commercial flows of the IC and OWFs will always be in the opposite direction (Weichenhain et al., 2019).

Because of the conflicts especially with EU regulations but also with operational challenges many studies concluded that the dynamic price zone concept should be eliminated from further studies (THEMA, 2020) (Weichenhain et al., 2019) (NSWPH, 2020).

2-4-2 Home market concept

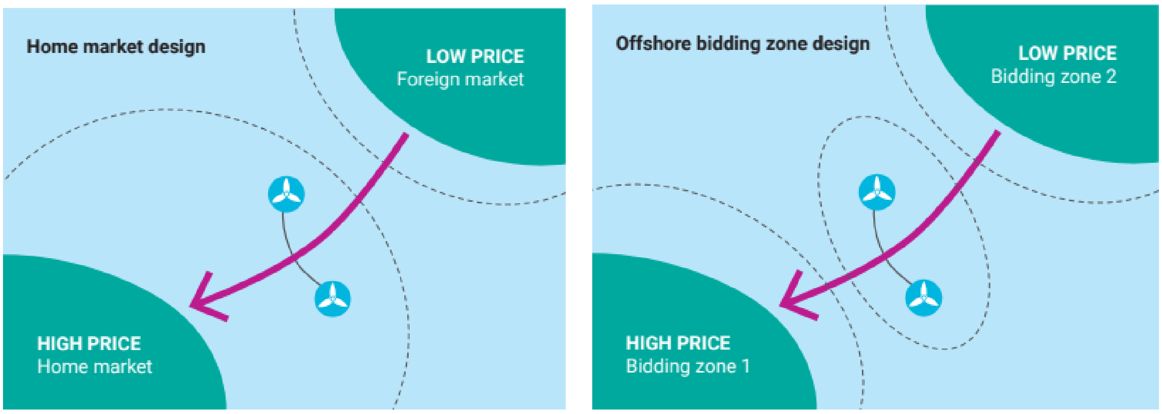
The Home Market concept, displayed in Figure 2-8a, is the commonly used concept for radial connections to OWFs or from the OWF hubs to shore. This concept makes no distinction between markets and whether the OWF is in the same pricing zone as the country in whose waters it was placed (ENTSO-E, 2020a). It is either a connection between the offshore power plant and the onshore grid, or an interconnection between the power plant and the foreign market. It participates in its own home bidding zone, and will always get that price, irrespective of the flow of electricity. Furthermore, because its part of its own home market zone, the OWF is exposed to the imbalance settlement price of that market. This market design was also chosen for Kriegers Flak. As seen in Figure 1-5, the OWFs Baltic 1 and Baltic 2 are part of Germany's bidding zone, and the connection to Denmark is classified as an interconnector. In this way, Kriegers Flak received subsidies and is contributing to meeting Denmarks 2020 RES target (Ørsted, 2020).

However, there are certain challenges using this market design. The first problem with this solution is that the OWF owner receives the home-market price for all power sold. Nevertheless, some power might be physically sold to another bidding zone that may have a higher price compared to the home market. This means that the physical flow would not be aligned with the commercial flow. In addition, Ørsted (2020) argues that for the grid operator this market solution would increase balancing risks since they are responsible for opening up capacity (through wind predictions) to the market. This market solution has little relation to the offshore physics and interconnection capacity. OWF potentials in EEZ with low onshore home-market electricity prices might be unused while incentives for the dimension of interconnectivity may not be fully aligned with a physical optimum.

An example sketched by Giesbertz is looking at a situation in which a Dutch wind farm is interconnected to the UK's electricity market, in which the Dutch electricity price is higher than the UK price by 10 euros. When the Dutch OWF is producing at maximum capacity and feeding the electricity into its home market, the interconnector will be unused despite a 10 Euro in price difference. This is in conflict with a statement from the Energy Package stating that to increase the capacity offered for cross-zonal trade, in particular, TSOs are required to ensure that a minimum of 70% of the transmission capacity is available for cross-zonal trade (Giesbertz, 2021), (ACER, 2020). Even if the OWF are not producing at full capacity, but 50% of its transmission line capacity, these problems still exist because the OWF has full unconstrained access to its home market.

2-4-3 The offshore bidding zone concept

Because of the previously mentioned 70% rule, the concept of separate offshore bidding zones has been proposed. With an Offshore Bidding Zone concept (OBZ), the OWFs are not part of their home market but create their own bidding zone, displayed in Figure 2-8b. The OWFs submit bids in the OBZ and are dispatched via market coupling to the onshore demand (Weichenhain et al., 2019). The price of the offshore bidding zones and the dispatch of OWFs depends on the neighbouring onshore bidding zones. The offshore price will in general be that of the zone where there is no congestion (the surplus zone that is exporting). In the Day-a-head market, the algorithm will match offshore generation with onshore demand, meaning the OWF will get the lowest price in a bidding zone. The utilisation of the grid connections will be a result of the day-ahead market coupling optimisation. The OWFs will be exposed



(a) Home Market design. **(b)** Offshore Bidding Zone design.

Figure 2-8: different market designs by (ENTSO-E, 2020a).

to their own imbalance price (ENTSO-E, 2020a).

This solution created no additional balancing risks when releasing capacity for trade. It also creates the possibility to link lumpy consumption, onshore, but in the offshore bidding zone, and thereby saving large onshore transmission investments (Ørsted, 2020). Furthermore, in a regulatory context, the application of offshore bidding zones ensures full compliance with some of the crucial rules for the functioning of the internal market (Energinet, 2020). The bidding zone concepts ensures that each offshore market player, being an OWF or interconnector is treated equally in the market. In addition, with small offshore zones, there are no internal constraints or possible loop flows, thus the full capacity of the interconnector can be allocated to the markets.

The revenues of OWFs under an OBZ are different from the HM setup. With the application of a bidding zone, OWF owners will either gain less revenue than in cases where they are radially connected to higher-priced zones or gain more if the radial connected market price is lower than the OBZ (Energinet, 2020). The income they potentially receive will result in additional congestion revenue for the TSOs. This is partly contradicted by Giesbertz (2011), since the offshore bidding zone is coupled with neighbouring markets, the price in the offshore zone will always converge to the market with the lowest price (Giesbertz, 2021).

2-5 Problem statement and knowledge gap

Based on this review of the existing literature included in this research proposal and the current status of offshore development and market design present, both an academic and a practical knowledge gap emerges.

Deriving from the literature, it is clear that the European Commission is pushing towards a fully integrated European electricity market in order to decarbonise its economy. As a result, the number of offshore wind farms has exploded in the past decades, increasing the need for more investments in the development of the North Sea offshore grid. With the increasing number of wind farms in the North Sea region, an opportunity arises to interconnect the offshore assets to different markets in a hybrid or meshed solution. Multiple typologies have been reviewed and existing analysis finds that continuing with an OWF infrastructure based on radial connections is likely to fall short of delivering the generation and transmission capacity needed, and may undermine efforts to attract the scale of investment required (Ørsted, 2020).

The question that is particularly relevant for offshore wind is not whether international interconnections are a good thing, but whether they should be made via wind farms. The downside for the OWF developer is the much-reduced revenues obtained as congestion rents take up more of the total revenues. It seems that these meshed solutions are more beneficial from the perspective of the TSOs. Nevertheless, it could lack incentives from the perspective of wind farm developers to participate. Without additional revenue allocation mechanisms, OWF developers would likely continue to prefer radially connected projects over the proposed hybrid or meshed models, which in turn undermines the European strategy to reach its climate goals (a cost-efficient manner).

Thus, in order to address this problem and to address this knowledge gap, the main research question emerges:

How does the North Sea transmission infrastructure integration impact the business cases of offshore wind farms under different market designs and how can these be protected for future grid development?

Chapter 3

The business case of an offshore wind farm

In the previous chapter, the most important components of an OWF were discussed. Furthermore, the British and Dutch governance models regarding the construction process were analysed. In this chapter, the business case of an OWF is investigated to get a better understanding of to what extent wind farm developers make certain decisions. The components are analysed further and the main cost drivers and the different streams of income are identified. In addition, the risks wind farm developers face when building a wind farm are analysed. This chapter provides the information on which a fictional wind farm is constructed as a reference case for the rest of this research. This chapter will provide an answer to the first sub-question: "What is the business case of an offshore wind farm from a Dutch and British perspective?". In addition, this chapter tries to show what it takes to make an OWF profitable from a Dutch and British perspective.

3-1 Cost components

In this section, the main cost drivers for offshore wind developers are identified. OWFs and other businesses have a variety of expenses. Desk research was carried out to identify the cost components of an offshore wind farm project. Various approaches were found to quantify different cost components in a wind farm. Sources such as cost estimates from wind developers, technical reports, white papers and consultancy reports all used different methods to categorize wind farms in terms of cost categories. Because of this, a basic representation is made that uses only the common distinction between Capital Expenditures (CAPEX) and Operational Expenditures (OPEX). The CAPEX category will be split into six basic representations of the components of a wind farm whereas the CAPEX is often a collection of multiple cost components and will be treated as a single entity.

3-1-1 CAPEX

Large scale renewable energy projects are known for requiring large initial investments, especially when it comes to offshore projects. According to the literature, about 70% - 80% of the total costs of OWFs are determined by the upfront investments (Junginger, Faaij, & Turkenburg, 2004a; Ioannou, Angus, & Brennan, 2018; BVG Associates, 2021; Morthorst & Kitzing, 2016). Many in-depth literature studies can be found regarding the costs of each of the components present, but for this research, the CAPEX is divided into six cost categories:

1. Turbines
2. Foundations
3. Inter array cables
4. Substations (offshore & onshore)
5. Export cables
6. Decommissioning

Turbines

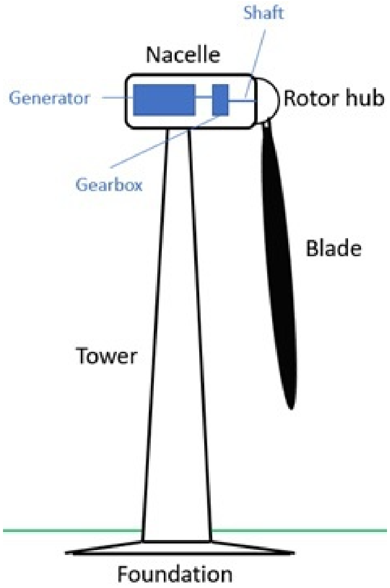


Figure 3-1: Basic components of a wind turbine (SpinningWing, 2021)

The first and biggest cost component of an OWF is the wind turbines. According to the guide made by BVG Associates (2021), the construction and installation of turbines account for approximately 30% of the total investment costs for an OWF. A wind turbine consists of many components, each in term crucial for operation. But to economically quantify each of these components is outside the scope of this research. Instead, the overall costs of wind turbines are determined by means of extensive literature research.

There are many ways to estimate or calculate the overall costs of wind turbines. For instance, BVG Associates (2021) divides the cost components into the cost for the physical components such as the cost of nacelles, rotors, towers and other costs. Such a basic formulation of the components of a wind turbine is seen in Figure 3-1. Additionally, IRENA's working paper uses a more comprehensive calculation in which the components such as the gearbox, control mechanisms, generators and transformer are added as variables to the total cost of a turbine (IRENA, 2012). On the other hand, a different way to express the costs of wind turbines is done by Gonzalez-Rodriguez (2017). In this paper, the overall costs of wind turbines are expressed by transactional costs such as acquisition, shipping & assembling and the costs of electrical installation.

An overview of the literature and corresponding methodology is presented in table 3-1. This table displays the author along with the corresponding methodology used and cost estimation in million euros per MW (mln€/MW) is made. The methodologies are categorized into three categories. First, a physical (P) approach can be taken. With this approach, the author identifies the important components of a wind turbine and sums up the costs of each component. Second, the transactional (T) approach can be used, which as mentioned earlier, looks into the transactional costs such as acquisition costs and installation costs. Last, the estimates of the manufacturer (M) can be taken into account by either finding an expression or converting the price of a turbine to a financial unit per wind turbine capacity.

In order to explain how an estimation was carried out, the article by Gonzalez-Rodriguez (2017) will be briefly discussed. Here the authors carried out an extensive review of cost data of multiple OWFs to find the main cost drivers affecting the capital and operational expenditures. For wind turbines, the accumulated data was gathered from 15 different sources. These sources could be real-life projects, estimates from companies and case studies. After the data has been gathered a regression was carried out to find an expression for the overall costs of wind turbines in terms of their capacity. The article concludes with an expression seen in equation 3-1, where the exponent lower than the unity reflects the presence of economies of scale for this category.

$$Cost = 1374.Cap^{0.87} \tag{3-1}$$

When comparing this expression with the costs of the two biggest turbines on the market today; the Hallade-X (13MW and 14MW) by General Electrics and the Siemens SG14-222 DD made by Siemens Gamesa (14MW). These turbines are estimated to have an overall cost of 13 to 14 million euros (OE, 2020) and 12 to 14 million euros (Foxwell, 2020) respectively (including installation). The expression from equation 3-1 would give an estimate in the range of 13 to 14 million euros. This would result in an overall cost of 0.97 million euros per MW. Differences in the estimates can be partially explained by the reduction in construction and installation costs over the past few years and due to the economies of scale, making turbines less expensive. In addition, the costs of turbines are highly dependent on environmental factors such as the sea depth and the distance from shore. The found estimations are seen in table 3-1

Table 3-1: Turbine cost: an overview of the literature with corresponding methodology and estimation

Author	Methodology	Estimaition (mln €/MW)
(BVG Associates, 2021)	P	0.86
(IRENA, 2012)	P	1.83
(Junginger, Faaij, & Turkenburg, 2004b)	T	0.86 - 1.43
(Gonzalez-Rodriguez, 2017)	T	0.97
(Foxwell, 2020)	M	1.00
(OE, 2020)	M	0.93

Foundations

Next to the cost of turbines, an additional costly part of the construction of OWFs results from the fact that the turbines will need a safe and stable base that is able to absorb all forces and loads during their lifetime. This is especially crucial in dynamic and, sometimes hostile environments, such as the ocean. The turbine must be able to withstand extreme weather conditions such as high waves and storms. Naturally, a lot of focus is spent on these supportive structures, or often mentioned as foundations and in general, takes about 14 to 30 % of the total cost of a wind farm offshore (Stehly & Beiter, 2020; Lacal-Arántegui, Yusta, & Domínguez-Navarro, 2018; Green & Vasilakos, 2011).

Currently there are several types of turbine foundations. The choice of a specific foundation typology is based on geographical variables such as sea depth, distance from shore, type of seabed and the size of the wind turbines. As seen in Figure 3-2, two main categories can be distinguished. The first category is the grounded foundations. These types of foundations are, as the name states, embedded in the seabed. These foundations are generally used in areas with a relatively shallow sea depth. Gravity-based foundations are often concrete-based structures in which the base width can be adjusted to suit the actual soil conditions. The concrete structure includes a shaft for the transition of the wind turbine. This typology, together with the bucket typology is often used at shallow waters (0 - 20 meters) and distances close to shore (Sánchez, López-Gutiérrez, Vicente, Esteban, & Dolores, 2019). The monopile structure is a simple design of a tower that consists of cylindrical steel tubes which are embedded in the soil. This foundation type is often used at sea depths ranging from 0 - 30 meters. Currently, this is the most common foundation type used and About 81% of today's foundations are monopiles (Ørsted, 2021). One of the main advantages of monopiles over other types of foundations is that with today's installation vessels the foundation can be relatively easily installed, also further from shore. At locations with a sea depth ranging from 5 - 50 jackets and tripods are used because at this point the monopile structures are vulnerable to buckling (IRENA, 2016).

As more OWFs are being built, they will gradually move away further from shore. At a certain point, it might become inevitable to develop wind farms at greater depths in which the embedded foundations may be unsuitable. This is where the second category of foundations comes into play. Although the technique is relatively new for wind farm developers

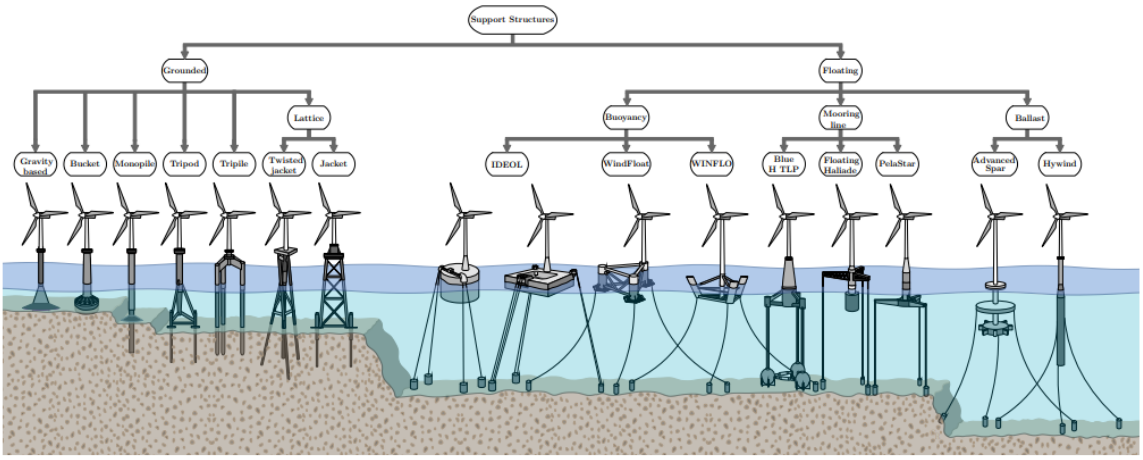


Figure 3-2: Overview of different foundation typologies (Rodrigues et al., 2016b)

it has been used for a long time by the oil and gas industry (Soler, Wiegand, & Iles, 2021). Currently, there are only a few wind farms developers that have made use of this floating structure technique. This is because it is a costly technique that could be easily avoided when constructing wind farms in shallow waters. Hywind Scotland is the first floating wind farm, operating at a sea depth of 90 to 120 meters and 25 km from shore. It was constructed by Equinor that used a spar floating typology (Power Technology, 2018).

In order to estimate the cost of foundations for an OWF the same approach was adopted as was done for the wind turbines. Similarly, research was carried out to find that the costs of foundation strongly depend on variables such as the typology, transport, installation and price of commodities such as steel. In more general terms, it is seen that the overall costs strongly depend on the depth of the sea (typology), the distance from shore (installation) and the size of the turbine (bigger foundations thus higher commodity price). Although the turbine size matters, it is only to a minor extend with respect to the distance from shore and sea depth (Gonzalez-Rodriguez, 2017).

Table 3-2 shows an overview of the accumulated cost estimates of several foundation types. Some literature reviews accumulated data from real projects (R), other estimates were based on a certain percentage of the total costs of an OWF (p). In addition, these rough estimates were converted to the costs of the reference wind farm and then converted to a cost per MW with respect to the biggest turbines of Siemens and General Electric. It must be noted that these are rough estimates of what the actual costs are of certain foundations and are therefore only as an indication of what the actual cost could represent. In addition, since the use of monopile foundations is so common, the identified estimates correspond to that type of foundation. This will also be the foundation type used in the reference case.

Inter array cables

In order for the turbines to transport the generated electricity, subsea cabling is needed. These inter-array cables together with the wind turbines are often referred to as the collector

Table 3-2: Foundation cost: an overview of the literature with corresponding methodologies and estimations

Author	Methodology	Estimaition (mln €/MW)
(BVG Associates, 2021)	R	0.25 - 0.31
(Junginger et al., 2004b)	R	0.32 - 0.54
(Stehly & Beiter, 2020)	R	0.29 - 0.50
(Gonzalez-Rodriguez, 2017)	R	0.46 - 0.54
(Albani, Ibrahim, & Yong, 2014)	p	0.43 - 0.54
(Gomez Tuya & Lowen, 2019)	p	0.43 - 0.77
(Morthorst & Kitzing, 2016)	p	0.50 - 0.58

system (Moon et al., 2014). Depending on the rated power and the distance between each turbine a selection can be made. Most of the inter-array cabling is generally at high voltage (HV) levels of 33 - 36 kV. Depending on the layout and design of the wind farm the amount of inter-array cables can vary between 50 km for relatively small wind farms such as Egmond aan Zee (4C Offshore, 2021) and 350 km such as is going to be used for the wind farm Sofia (RWE, 2021).

The white paper of DNV-GL explains that the rated capacity of the turbines will gradually increase over the years. the choice for 66 kV cabling might reduce the initial cable investment up to 15 % (Lesser, 2015). The cable length will decrease and more power can be transmitted in a higher voltage cable. For wind farms such as Sofia wind farm, 66kV are chosen as inter-array cables.

The cost quantifying literature on array cabling is scarce, this is most likely due to its relatively low contribution to the overall costs of OWFs (around 5 to 10 %). It is often part of a bigger group called the Balance of System which consist of every component in an OWF except for the turbines, foundations and capital costs. The price of inter-array cables is often expressed as a certain price per kilometre cable (€/km) or as a certain price per wind farm capacity (€/MW). Nieradzinska et al. (2016a) compares the electrical setup of two (fictional) wind farms of 2.4 GW located at the Dogger Bank. Its conclusion is that the inter-array cables take up around 9.5 % of the total construction cost of the wind farm or about 1M£/km (1.16M€/km) for 66 kV cables. Lerch on the other hand estimates 210 k€/km - 354 k€/km array cabling for 33kV (Lerch, De-Prada-Gil, & Molins, 2021). Stehly and Beiter use an expression that roughly estimates 320 k€/MW for fixed bottom wind farms and 370 k€/MW for floating wind farms (Stehly & Beiter, 2020). In Addition, Gonzalez-Rodriguez (2017) estimates are ranging between 146 k€/km to 331 k€/km. An overview of the costs (expressed in euros) is seen in table 3-4.

Substations (offshore & onshore)

The following two categories, the on- and offshore substations together with the export cables are often referred to as a single cost category called "grid connection". In the following two paragraphs these categories are analysed independently.

Table 3-3: Cost overview of inter-array cables with the corresponding author

Author	Estimation (million €/MWh)
(BVG Associates, 2021)	0.35
(Stehly & Beiter, 2020)	0.32 - 0.37
Author	**Estimation (million €/MWh)**
(Nieradzinska et al., 2016a)	1 - 1.2
(Lerch et al., 2021)	0.21 - 0.32

As is seen in Figure 2-2d and 2-2e, the inter-array cables are collected in an offshore substation. Depending on certain characteristics of the wind farm such as its rated capacity, different decisions can be made regarding the design of the substations. Currently, there are two types of offshore substations. First, the offshore transformer stations are stations where the array cables are gathered and where the voltage is boosted in order for transmission over relatively short distances to shore. This is often the case for HVAC. On the other hand, when wind farms are further offshore it is economically more beneficial to use the HVDC technology for transmission. When using this technology a converter platform could be added to the substation or in some cases replace the transformer station. This can be seen in Figure 2-2e.

According to Dicorato, Forte, Pisani, and Trovato (2011), the main cost drivers for substations are the Medium Voltage/High Voltage (MH/HV) transformer, the number of switch gears, the type of foundation and the presence of additional services such as living quarters, a heliport and fuel. A resulting estimation of 15.8 million €for a 150 MW substation was derived.

A converter platform is generally used for bigger wind farms and needs a considerably higher initial investment compared to the earlier mentioned transformer stations. Härtel et al. (2017) developed a linear cost model based on branch length, power rating of the cable and converter stations. This was done through comprehensive cost reference data that was accumulated through realised and contracted VSC HVDC projects. When looking at 2000MW converter platforms such as IJmuiden Ver Alpha, P Hartel et all estimate a cost ranging from 300 M€to 600M€including foundation costs. The desk research resulted in cost estimation for offshore and onshore substations as follows:

Table 3-4: Substation cost: an overview of substations with corresponding author and estimate.

Author	Technology	Estimation (million €/MW)
(Dicorato et al., 2011)	HVAC	0,11
(BVG Associates, 2021)	HVAC	0.10
(Härtel et al., 2017)	HVDC	0.24 - 0.65
(Nieradzinska et al., 2016b)	HVDC	0.40

Export cables

Export cables connect the offshore transformer or converter station to the substation onshore. As was briefly explained in the previous chapter, the choice of using HVAC or HVDC is mostly depending on the size of the farm its distance to shore. Moon et al. (2014) argues that HVAC export cables can take up to 9.5% of the total cost for a wind farm using 5MW turbines. In addition, when looking at a big wind farm of roughly 2.5GW on the Doggerbank the grid connection which consists of the offshore substation, the export cable and the onshore substation represent 31% of the total costs. When looking into the cost of cables Moon et al. (2014) estimates are displayed in Figure 3-5.

Table 3-5: Export cable cost breakdown in million €/km by (Moon et al., 2014).

Cables	Price (million €/km)
VSC-HVDC Offshore Cable ± 320 kV	1.25
HVAC Offshore cable 33kV Inter-array to transformer	1.14
HVAC Offshore cable 275kV collector to converter	2.85
HVAC Onshore cable 275 kV to transformer and 400 kV to grid	2.85

Decommissioning

Currently, wind farm developers are responsible for the decommissioning costs at the end of the lifetime of a wind farm. This is often part of the permit received after the developer placed the winning bid in a tender (Klijn, Heijnsbroek, & Dieperink, 2015a). The estimation of the decommissioning of an OWF is similar to its construction in terms of determination of cost categories. an overview of the found estimates is seen in table 3-6.

The main cost drivers are dependent on geographical characteristics such as sea depth, distance from shore but also wind turbine size. The latter also depends on how much of the commodities like steel could be sold.

Table 3-6: Decommissioning cost: an overview of authors with corresponding estimates.

Author	Estimation (million €/MW)
(Kaiser & Snyder, 2010)	0.09 - 0.15
(Kaiser & Snyder, 2012)	0.09 - 0.12
(Adedipe & Shafiee, 2021)	1.60
(Henriksen, Osnes, & Eiane, 2019)	0.25 - 0.43

3-1-2 OPEX

The marginal costs of offshore wind is almost zero, but the annual costs to keep the farms running can be considerably high. According to Morthorst and Kitzing (2016) and Röckmann, Lagerveld, and Stavenuiter (2017) the OPEX may easily take up to 25 - 30 % of the total LCOE produced over the asset's lifetime. OPEX can be divided into various operational costs. Some examples are the cost of insurance, regular maintenance, repair, spare parts, access to platforms & turbines and administration costs. In addition, for OWFs in the UK seabed lease and transmission costs can also be included. An example of how OPEX can be categorized as seen in Figure 3-3. Where WTG are the wind turbines and BoP is the balance of the plant (rest of the assets except the turbines). It is seen that everything that involves the maintenance of turbines makes up a substantial part of the OPEX.

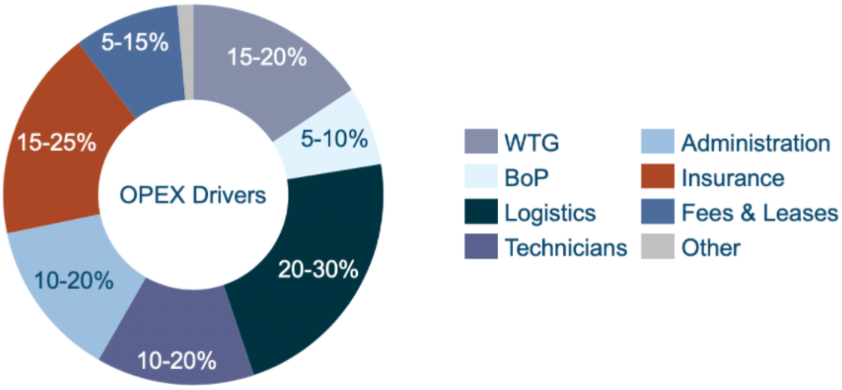


Figure 3-3: An illustration of OPEX components (Scheu, 2019).

When looking at the costs that correspond to this category, various estimates were accumulated from the literature. Morthorst and Kitzing (2016) discuss 4 estimations ranging between 19 k€/MW to 49 k€/MW accumulated from different sources such as companies and other literature. In addition Junginger et al. (2004b) Assumes an annual O&M cost in the range of 2 to 4.4 %. Stehly and Beiter (2020) estimates that the OPEX for monopile and floating wind farms are on average between $ 84k/MW/year and $ 144/MW/year. Peak Wind carried out an empirical study on 47 operational wind farms in Europe and found that on average the annual cost for OPEX is 118€/kW/year (Scheu & Stegelmann, 2020). All costs are converted to k€/MW as was done in the previous categories, the results are seen in table 3-7.

Table 3-7: OPEX cost: an overview of authors with corresponding prices.

Author	Estimation (1000 €/MW/Year
(Morthorst & Kitzing, 2016)	19 - 49
(Scheu & Stegelmann, 2020)	118
(Stehly & Beiter, 2020)	84 - 144

3-2 Revenue Streams

As offshore wind is still a maturing technology, there are various ways to receive income and support. This section will briefly discuss the different options of the streams of income for the wind farm developer. As is explained previously, a two-way approach is taken. This implies an analysis is carried out from the point of view of a Dutch wind farm developer and a second analysis from a British wind farm developer's view.

3-2-1 Commodity

The most straightforward way to secure income is of course to sell the electricity on the market. The electricity yield of an OWF depends on the capacity of the wind turbine, the number of wind turbines, the layout of the farm and the location-specific wind conditions (Morthorst & Kitzing, 2016; Green & Vasilakos, 2011). The capacity factor: the actual annual yield divided by the theoretical maximum annual yield is a factor that indicates the operational time of a wind farm. In the North Sea, generally, a capacity factor between 0.4 - 0.6 can be assumed.

3-2-2 Power Purchase Agreement

Because of the high investment in the construction phase, wind farms tend to secure long term contracts with energy providers or large (corporate) customers. These so-called Power Purchase Agreements (PPAs) are contracts that secure a steady revenue stream in which both the volume and price are defined. This paragraph briefly explains the types of PPAs and tries to give an idea of the prices associated with such contracts. It is noted that these prices will not be used directly into the model since these prices are project-specific and can be very inconsistent. However, the information is important in order to perform a robustness check on certain parameters of the reference case. Because of this, this chapter has only an explanatory function and together with getting insights into potential revenue streams that can be captured by wind farm developers.

According to Kruijsse (2019), there are three types of PPAs: Sleeved, Virtual and Direct PPAs. For the first type of PPA two contracts exists. In some high wind scenarios, the corporate receives too much energy from the wind farm, and therefore it also has a contract with the utility provider. In this contract, all energy is sold to the utility and the corporate buys the volume corresponding to its demand. This structure is done to balance the grid. The structure of a sleeved PPA is seen in Figure 3-4.

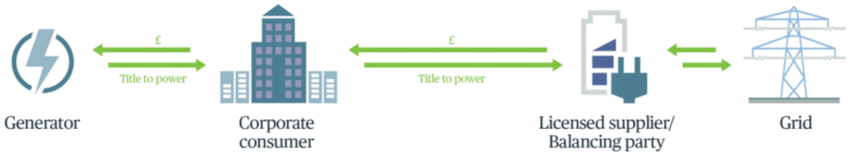


Figure 3-4: Structure of a sleeved PPA (Bird&Bird, 2018).

The Direct PPA is similar to the sleeved PPA in terms of structure. For this case, the wind farm has a direct contract with the corporate consumer and bears the risks of volatility in generation. The corporate consumer has a separate contract for balancing demand and supply with an Energy provider.

The second type of PPA is referred to as "synthetic" or "virtual" corporate PPA (Bird&Bird, 2018; Kruijsse, 2019). Traditionally, the generator sells its electricity to the utility company and the corporate consumer buys the volumes on the wholesale market. But in this case, a virtual contract is closed between the corporate consumer and generator where the price difference between market price and PPA price is settled. The corporate still received the Renewable Energy Certificates (RECs) from the wind farm, this structure is seen in Figure 3-5.

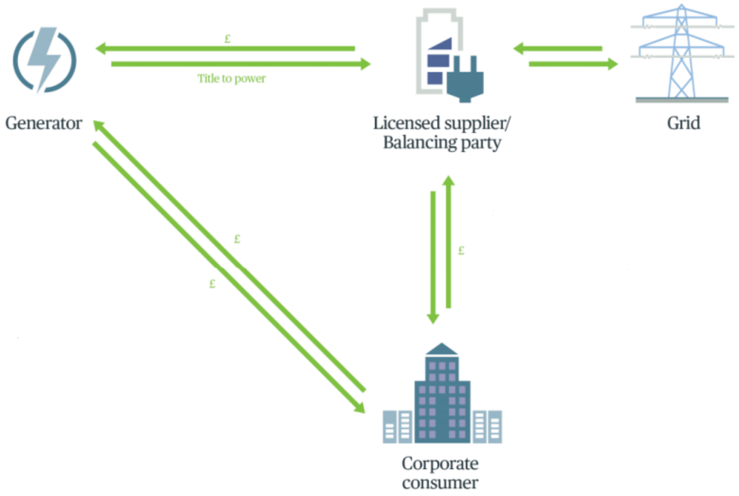


Figure 3-5: Structure of a virtual PPA (Bird&Bird, 2018).

Although long term contracts like PPAs are crucial to the construction of any wind farm, few to no publicly available data is accessible. This can be partially explained by the competitive nature of the market in which the generators operate. One source of PPA data was retrieved from the LevelTen Energy PPA price index. This index reports prices that wind and solar developers have offered PPAs for. The data was gathered from the LevelTen's own marketplace spanning 21 countries in North America and Europe (LevelTen-Energy, 2020). An overview of some relevant countries with corresponding PPA prices is seen in table 3-8. In addition, Lesser (2020) and Miller and Hamer (2020) analyses the cost of PPAs for offshore wind farms ranging from 300 to 1100 MW across the eastern coast of the united states. The offer prices are seen in table 3-9.

Table 3-8: Wind PPA Prices by Country (LevelTen-Energy, 2020).

Country	P25th Percentile Offer Prices (€/MWh)
Germany	52
France	91
United Kingdom	53
Spain	36

3-2-3 Support

Support schemes are often regarded as a form of long term contracts with the government. Similar to the previous paragraph about PPAs, the data gathered will only be used as a set

Table 3-9: PPA prices: an overview of PPA prices with corresponding authors.

Author	PPA prices (€/MWh)
(Lesser, 2020)	60.03
-	68.12
-	86.89
-	140.32
-	214.87
(Miller & Hamer, 2020)	85.95

of data to perform a robustness check. This may seem appropriate because of its nature and it may give an indication for LCOE for which the wind farm is constructed.

Because offshore wind technology is maturing, support schemes are still in most cases necessary to make the project financially feasible. On the other hand, the first few wind farms are tendered subsidy-free in the Netherlands (Goverment of the Netherlands, 2020). There are multiple support schemes that often differ per country. In this subsection, the SDE and SDE+ subsidy in the Netherlands is briefly explained together with the subsidy called Net op Zee. In addition, the Contact for Difference subsidy scheme will be explained for the United Kingdom.

Subsidy schemes in the Netherlands

The Stimulating Sustainable Energy Production, previously called the SDE+ and now the SDE++, is a feed-in-tariff scheme. Renewable Energy producers receive a guaranteed payment for the electricity they produce. In the Netherlands, this subsidy scheme is awarded in a package that includes the construction permit. Naturally, this subsidy is granted through a competitive tender or auction for offshore wind developers (Klijn, Heijnsbroek, & Dieperink, 2015b). The process starts with the minister of economic affairs announcing a location to be tendered. Additionally, all the necessary information about the specific location is reported such as wind speed, sea conditions but also environmental impacts, type of seabed and so on. The participants place a bid in €/MWh which represents the total construction costs of the project. The lowest bid and best project plan is awarded the subsidy and receives all the necessary information for construction. However, the initial investment is not supported through the subsidy since the SDE+ scheme is an operational subsidy, meaning that only support is granted for the generated electricity. Acquiring the initial investment for the wind farm is therefore the responsibility of the developer.

An aspect worth mentioning is the responsibility of connecting the wind farm to the onshore electricity network. In the Netherlands, TenneT is assigned as the offshore TSO. This means that the construction cost of the export cables and the substations along with the ownership allocation lies with TenneT. This is financed through the subsidy called Net op Zee. In addition, because of the support of this subsidy TenneT is not allowed to charge transport tariffs, as is the case in the UK.

The working of the subsidy scheme is presented in Figure 3-6. For this explanation, the

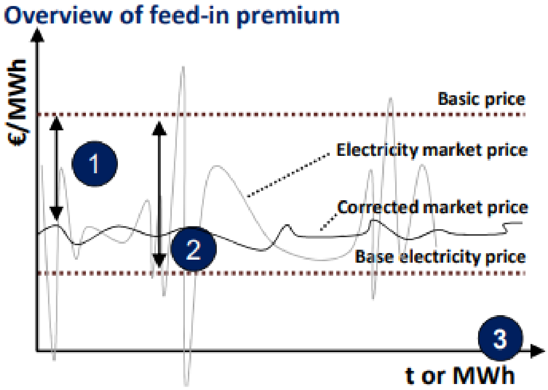


Figure 3-6: Working of the feed-in premium SDE+ (TKI Wind op zee, 2015).

assumption is made that wind farms sell electricity directly to the market at market price. According to TKI Wind op zee (2015), the amount of the subsidy received by the wind farm developers is determined by the difference between the strike price or basic price and the corrected price. The strike price is determined in a competitive auction and the corrected price is determined annually and expressed as the average electricity price for one year. The support received by the wind farm developer is displayed in 3-6 (1). When the market price falls below the base electricity price, no extra support will be granted. The only subsidy will be granted up to the base electricity price threshold. The difference between the strike price and the base price determines the maximum support a wind farm developer can receive and is set by the Dutch government. This can be seen as (2) in the Figure. In addition, the subsidy scheme is also capped in terms of load hours (operating time of the wind farm). Every month 80% of the subsidy is granted, based on the estimated corrected market price. At the end of the year, the final payments are calculated and granted.

Subsidy schemes in the United Kingdom

In the United Kingdom a different subsidy scheme is used. Up until 2017, the Renewables Obligation RO was used (OFGEM, 2015). This scheme places an obligation on the electricity suppliers in the UK to take a proportion of the supply from renewable resources. Similar to the ETS, renewable energy generators receive Renewable Obligation Certificates (ROCs). When suppliers do not have sufficient ROCs a payment must be made to a fund from which the cost of this scheme was paid.

Currently the Contract for Difference (CfD) scheme is used in the united kingdom. A basic representation of its working is seen in Figure 3-7. Similar to the Netherlands, CfD is awarded through competitive tenders held by the crown estate. Although, the winner of this auction only receives the subsidy scheme. It has to attend a different auction in which the location is auctioned. The price granted in the CfD is calculated as the difference between the guaranteed price (strike price in the auction) and the hourly electricity market price. In addition, balancing prices are not compensated (TKI Wind op zee, 2015). At times in which the market price is higher than the strike price, the developer has to pay back the difference through low carbon contracts companies (LCCCs). On the other hand, when the market price is lower than the strike price the OWF receives the strike price. But only for the output that is delivered to the grid.

Table 3-10 and 3-11 presents the awarded subsidy schemes for the Netherlands and for some OWFs in the United Kingdom respectively. As stated previously, these prices will not be used as input for the model but rather as a robustness check on certain parameters of the reference case. In addition, the first subsidy-free wind farms in the Netherlands can be explained due to the fact that wind farm developers are not responsible for the grid connection and therefore bear no extra costs or risks for the project.

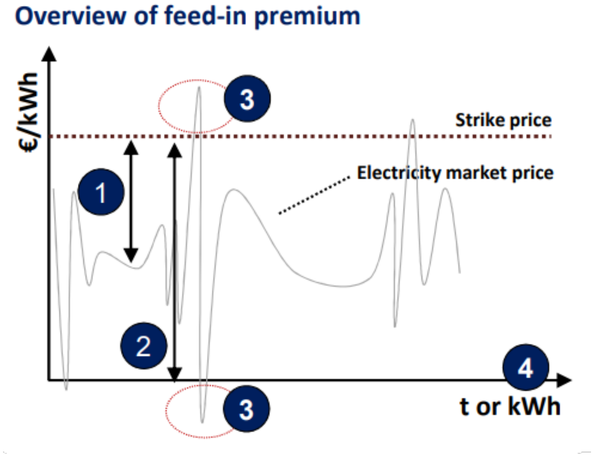


Figure 3-7: Working of the CfD (TKI Wind op zee, 2015).

Table 3-10: SDE+ auction prices: an overview of awarded SDE+ prices with corresponding wind farms in the Netherlands (Rekenkamer, 2018).

Wind farm	Auction prices (€/MWh)
Egmond aan Zee	158
Princess Amalia	163
Gemini	169
Luchterduinen	181
Borssele 1 & 2	88
Borssele 3 & 4	70
Hollandse kust (zuid) 1 & 2	*Subsidy free*
Hollandse kust (zuid) 3 & 4	*Subsidy free*

Table 3-11: CfD auction prices: an overview of recently awarded CfD prices with corresponding wind farms in the UK (Virley et al., 2019).

Wind farm	**Auction prices (€/MWh)**
Doggerbank A- Creyke Beck	45.32
Doggerbank A - teeside	47.56
Doggerbank B	47.56
Sofia	45.32
Doggerbank C	47.56

3-3 Literature findings

Previous in this section, extensive desk research was carried out to identify the characteristics of a business case an OWF. The main cost drivers were identified, briefly explained and data was gathered for the defined cost components. This has also been done for PPAs and subsidy schemes in terms of possible revenue streams. The resulting data is displayed in table A-1 and table A-2 in appendix A.

It was found that all cost components strongly depend on four main cost drivers. Water depth, Distance from shore, Turbine size and the number of turbines. The first two cost drivers are bound to the location of the wind farm. The water depth and distance from or to shore both have a big impact on all cost categories. Projects further from shore require longer instalment times, meaning longer operating hours for the installation vessels. In addition, the length of export cabling increases. Projects at greater water depth are exceedingly complex and require specialized equipment. In addition, the water depth has a big impact on the costs of foundation typology. The number of turbines and turbine size mainly influences the costs of connecting the wind farm to the grid. Larger turbines operate at greater power ratings which in terms influences the rated capacity of the substations, the export cables and inter-array cables.

Currently big offshore wind farms far away from shore still depend on subsidy schemes to make the project economically feasible for developers. Wind farm developers bear high risks to secure initial investments for a project since most subsidy schemes are so-called operation subsidies or feed-in-tariffs. In the Netherlands, the government takes responsibility for a large part of the initial investment through the subsidy scheme called Net op Zee. No transmission tariffs are paid by the wind farm and because of this, the first offshore wind farms are being built without any subsidy. Other options to secure a steady and long term cash flow is through corporate PPAs.

The finding presents the foundation on which the business model of a wind farm can be developed. Additionally, most decisions a wind farm developer makes is based on the LCOE, this will be further discussed in the next chapter. An overview of interactions and how the findings present a foundation for the model is seen in Figure 3-8.

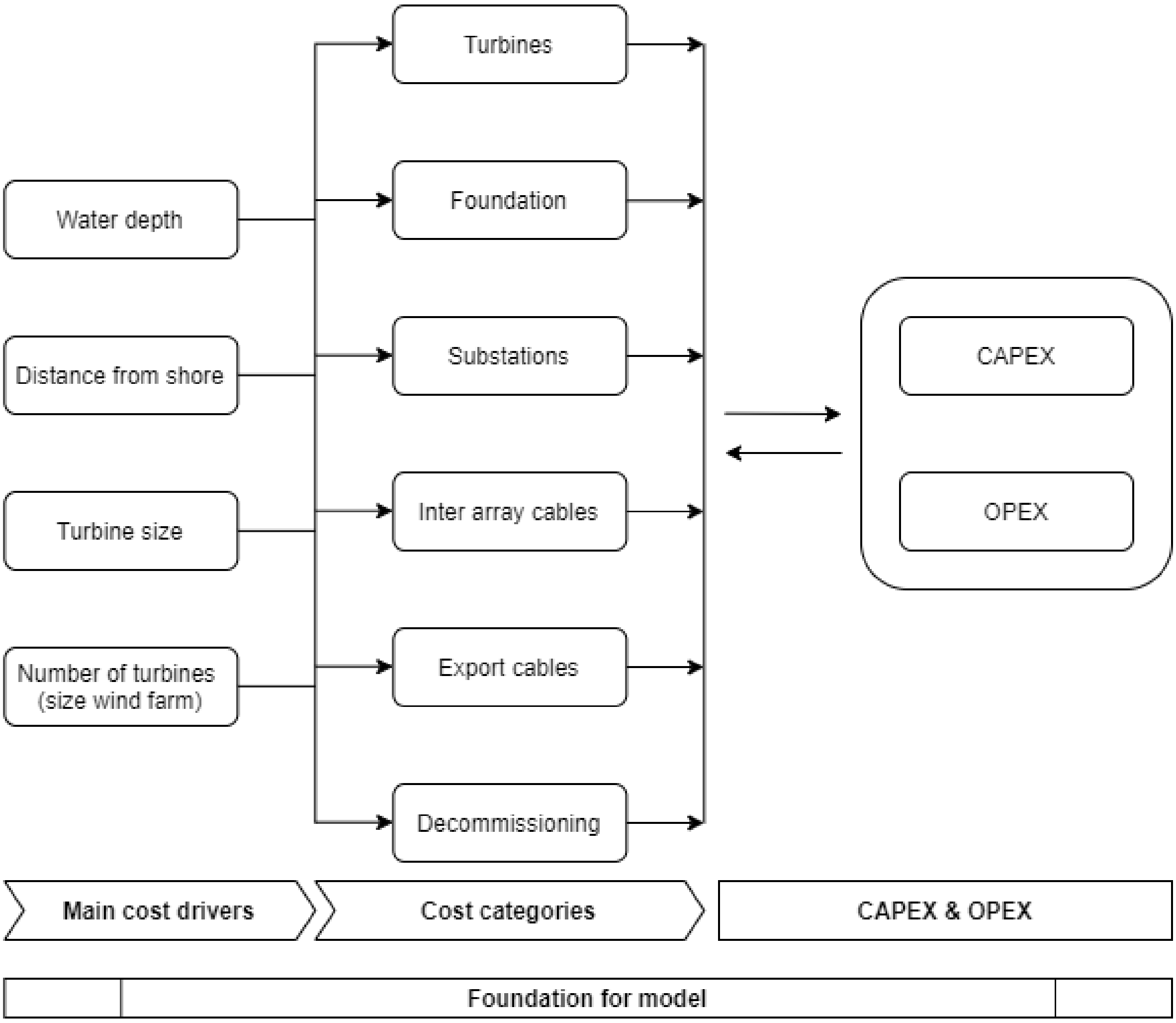


Figure 3-8: Overview of interactions and findings of this chapter.

Chapter 4

Modelling approach

This chapter discusses an approach towards a working model that will be used to gather insights into the effects of the different scenarios of the North Sea transmission network integration on the business cases of offshore wind farms. As mentioned in the introduction, a scenario-based simulation and modelling approach was chosen. First, the situation will be formulated along with the system boundaries. Then the scope of the model will be determined in which constraints and objectives are identified. Consequently, the conceptual model is developed with a brief discussion on the system inputs and outputs. Last, simplifications and assumptions made of the system are discussed. This chapter creates a base case that will act as the concept design of the model on which the simulations of the different scenarios will be carried out.

According to Lehtonen and Marttila (2013) the steps of a Scenario-based modelling and simulation approach can be identified as follows:

1. Analysis of the existing system
2. Identification of possible improvements
3. Define model scope and creation of a conceptual model
4. Create the computer simulation model
5. Compare the results to the existing system
6. implement changes or different scenarios to the base case model
7. Assess the effects of the scenarios by comparing the present and scenario model results

This chapter encompasses a step-by-step discussion of the scope of the model. In addition, the following sections of this chapter will elaborate on how the conceptual model and base case was created for this research. This is a crucial part of the research since the subsequent chapters will build on this conceptual model. Chapter 5, will analyse the conceptualisation of the scenarios.

The first two steps of a scenario-based modelling and simulation approach were performed to understand the situation along with its problems or opportunities. This has already been discussed throughout section 1 and 2. As these sections concluded, this is a complex situation in which multiple problems arise. The main problem found was formulated in the main research question and concerns the effect of different future scenarios of offshore grid development on the business cases of the offshore wind farms located in the North Sea. The overall problem reflected in this question is the knowledge gap of what certain future offshore policies will have on the current situation. This lack of knowledge will be further investigated by means of a set of sub-questions. These questions were formulated in section 1-5. This chapter, however, provides the approach to obtain a model needed to perform simulations of different scenarios in order to formulate an answer to sub-questions 2 and 3 and eventually 4:

- *How do different grid connection scenarios impact the business case of offshore wind farms?*
- *How does the offshore grid market design impact the business case of offshore wind farms?*
- *If a scenario yields a negative impact on the business case of a wind farm, what are possible mitigation options?*

As is mentioned earlier, in order to start with the development of a conceptual model, the problem this specific model will try to solve must be identified.

4-1 Problem situation

In order to define this problem, the existing system must be understood. According to TU Delft wiki (2010a) modelling refers to obtaining or developing a simplified representation of reality. This reality, or rather the existing system, can be formulated as follows: the existing system to be modelled is the current situation of the Dutch and British coast. More specifically, the situation describes its offshore assets such as offshore transmission cables, wind farms and/or interconnectors.

The physical boundaries of this system will be limited to just this offshore region between the two countries and its offshore assets. This means that the onshore grid is not included in the system boundaries and is always assumed to be able to balance the onshore grid despite the offshore generation. This will be elaborated upon later on. A representation of the location is displayed in Figure 4-1 where the upper orange Figure is part of the Doggerbank area in the national waters of the United Kingdom.

As is explained in section 1-2, the new wind farm will gradually move further from shore due to the lack of space close to the shore. As these wind farms move further from shore, the

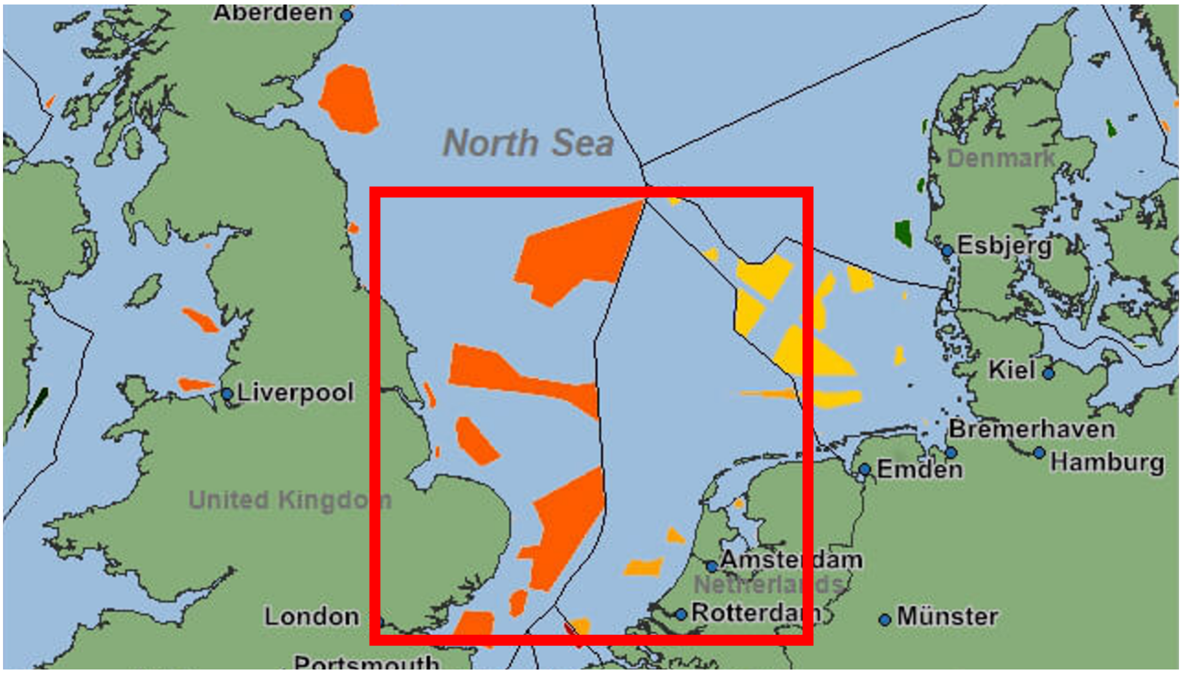


Figure 4-1: Representation of the location of the existing system (IWR, 2016).

already high initial investment costs increase. This calls for an economic efficient way to work towards an integrated European transmission system, one of the goals set by the European Commission. A solution to this problem might be to make use of the connection between the wind farms far offshore in order to create relatively low-cost cross-border connections. However, there is a lack of knowledge about the magnitude of the effects the integration of the offshore transmission system will have on the business case of offshore wind farms. This knowledge gap is the foundation for this research.

The situation between the Netherlands and the United Kingdom was chosen particularly because of the relatively short distances between the future-constructed wind farms of the United Kingdom and the Netherlands. In addition, TenneT is already investigating if a scenario with a low-cost interconnector between a Dutch and UK wind farm can be realised.

This implies that in the current situation, there is no cross-border connection constructed yet between the wind farms. In order to give a more focused representation of the situation, an illustration is made of a possible scenario. This is displayed in Figure 4-2, in which certain wind farms are presented with corresponding export cables (yellow). The white cable is an example of a low-cost interconnector cable. Similar situations will be used in order to create the conceptual model.

Now that the situation has been determined and the identification of possible improvements, or rather, the problem within the system has been identified, the next step is to set the scope for the conceptual model. An important note is that this process is subjected to the researcher's personal bias and to the available resources in which the research is conducted. This could have a potential effect during the modelling phase. However, the problem that

Figure 4-2: Representation of a possible physical representation of the system (Durakovic, 2018).

this research tries to address is well known both in literature and in practice.

4-2 Modelling scope

In order to formulate the conceptual model, a more detailed elaboration on the nature of the system is necessary. Most electricity systems consist of multiple voltage levels. Households and other low-level consumers are connected to the distribution grid, which, in the Netherlands, operates at low voltage levels. The electricity companies that generate the electricity use the transmission system in order to transport the electricity to the distribution grid in order to meet the demand of the domestic consumers. As explained in chapter 1, this system operates at high voltage levels and is operated by the TSO. This so-called high voltage level of the electricity system must always be in balance, meaning that demand must always meet supply meaning that his balance must always be in equilibrium. When looking at offshore appliances, only the transmission system is present to transport the supply to the demand onshore.

The nature of the situation can thus be described as more than just a physical system of transport cables with limited capacity. It also is as a market or even an international market where supply must always meet demand. This is why the electricity system is often regarded as a complex system. With the increase of volatile renewable generation capacity such as offshore wind, maintaining the balance on the transmission system becomes more complex. Increasing cross-border capacity could become more important for the reliability of the transmission system and energy supply for all EU member states.

4-2-1 Objectives

Now that the nature of the system is known, an approach to a conceptual model can be taken. Since a model or conceptual model is a simplified version of reality, clear boundaries and objectives have to be set in order to obtain meaningful results. Because of the dynamic nature of the environment (generation and demand changes all the time), a time period must be selected. In addition, because of the type of generation, which in this case is strongly dependent on seasonal and time-dependent factors, the modelling should be performed over at least one full year. Shorter time periods may not represent the true behaviour of the system and could cause the output of the model to be insignificant. The objective of the model can be interpreted as what the model should be able to do. The design objectives are listed below, and further elaboration on each objective will be elaborated upon. The objectives set for the conceptual model are scenario dependent and are listed below:

1. To determine the costs corresponding to the construction of a wind farm located in the North Sea
2. To determine the annual electricity yield of a wind farm located in the North Sea region on an hourly basis
3. To determine the revenue stream of a wind farm on an hourly basis
4. To calculate the profits or losses of a wind farm located in the North Sea
5. To calculate the net cross border transmission exchange on an hourly basis (if applicable)
6. To calculate the congestion income on an hourly basis (if applicable)
7. To calculate the costs of subsidy schemes on an hourly basis (if applicable)
8. To determine the magnitude of certain existing mitigation options (if applicable)

As is stated in chapter 1, in order to assess the effects on a business case of an offshore wind farm, first, the business case itself must be understood. The conceptual model should be able to give insights into the flexibility of an offshore wind farm to keep its business case profitable. This corresponds with minimizing the investment costs, which in terms will depend on geographical parameters such as sea depth, distance from shore, turbine size and wind farm size.

Furthermore, to establish a realistic reference case or base case, the costs of a wind farm can never outweigh the benefits or otherwise, there will not be a business case in the first place. In order to obtain more insights into this part of the business case, the model should be to formulate or determine generation profiles for a minimum of a full calendar year. In addition, this model should be able to perform this for wind farms using different types of turbines and locations in the North Sea.

If a generation profile is determined, the model should be able to convert this profile into a revenue stream for the wind farm developers. When a revenue stream is determined, a calculation can be performed to obtain the profits or losses for a wind farm. This, in essence, will give insights into the effects of certain scenarios on the business cases of wind farms.

When scenarios are introduced into the model, new objectives come can be identified. For instance, when a cross-border connection is introduced, congestion income is generated by the TSOs. The model should also be able to calculate these revenues. This is likely to be used in the assessments of the effects. In addition, depending on the connection scenario, wind farms can earn extra revenues by means of subsidies. These subsidies will also be implemented, and the model should be able to determine this effect on the revenue stream of wind farm developers.

Last, when scenarios are conceptualized, and the base case is established, the model should be able to determine the effect of certain mitigation options.

4-2-2 Constraints

The previous sections identified both the objectives and the goal of the model. The next step is to establish the constraints. Constraints are used to keep the simulation within certain regulatory or physical boundaries. The constraints for the conceptual model are listed below:

1. The model must run over a time period of a full year
2. The wind pattern or generation pattern must be based on actual values such as historical data
3. The electricity prices must be based on actual values such as historical data
4. Transmission capacity of export cables may never be exceeded
5. Transmission losses must be taken into account
6. No regulatory obligations can be broken

The constraints can be categorized as external, internal and physical or regulatory. First, an example of an external and physical constraint is the first constraint which states that the model must be able to simulate time periods of full years. This seems understandable since wind generation is strongly dependent on seasons. According to Gandy (2012), spring, for example, is the windiest time of the year. Winds in March and April tend to be 3 to 5 times stronger than in July or August. In order to represent the situation as accurately as possible, time periods should therefore be formed over full years.

The second and third constraints describe that the input data of the conceptual model should represent actual values. Historical data is used in order to come as close to the real-life behaviour of the system as possible. This is a post-process method to obtain insights into the behaviour of the system.

Constraints 4 and 5 represent the physical boundaries of the system. In reality, the electricity generated by a wind farm is exported to the market using export cables. These export cables have a certain capacity that cannot be exceeded. As a consequence, cable has a chance to break down, and the wind farm will be left with electricity which it cannot transport. In addition, transporting electricity always includes losses due to skin effects. According to Adewumi, Bamigbola, Ali, and Awodele (2014), power losses on transmission lines are the result of resistive and conductive forces. To cope with the maximal transmission capacity, these power flow losses have to be taken into account as well.

Last, not only the physical boundaries but also the regulatory boundaries of the system have to be taken into account. An example is the collection of congestion income by the TSOs. This is a revenue stream that occurs when two countries are trading and can only be collected by the TSOs and not the wind farm developers. In addition, certain cross border exchange policies cannot be neglected unless the scenario is designed to do that. This is all done again to come as close to a real-life representation of the system.

4-3 Conceptual model

The previous section discussed both the model objectives and constraints. The next step is to design the conceptual model. Displayed in Figure 4-3, a visual representation of the conceptual model is seen. The inputs are separated into 3 categorisations. The first category describes the characteristics of the wind farm, including its geographical parameters such as the distance from shore and water depth. These will be explained more thoroughly in the next section, as well as the outputs of the conceptual model. The second category describes the data sets used and will also be explained in the coming sections. Last, physical boundaries are included, which were described in the previous section.

The model objectives and constraints were developed in order to be able to answer the main research question: " How does the North Sea transmission infrastructure integration impact the business cases of offshore wind farms under different market designs, and how can these be protected for future grid development?". The operating boundaries in which the models tries to answer this question is also explained in the previous section. Not previously mentioned is the block encompassing the scenarios. This block will act as an extra input imposing new objectives or new constraints to the model. Chapter 5 will discuss this thoroughly.

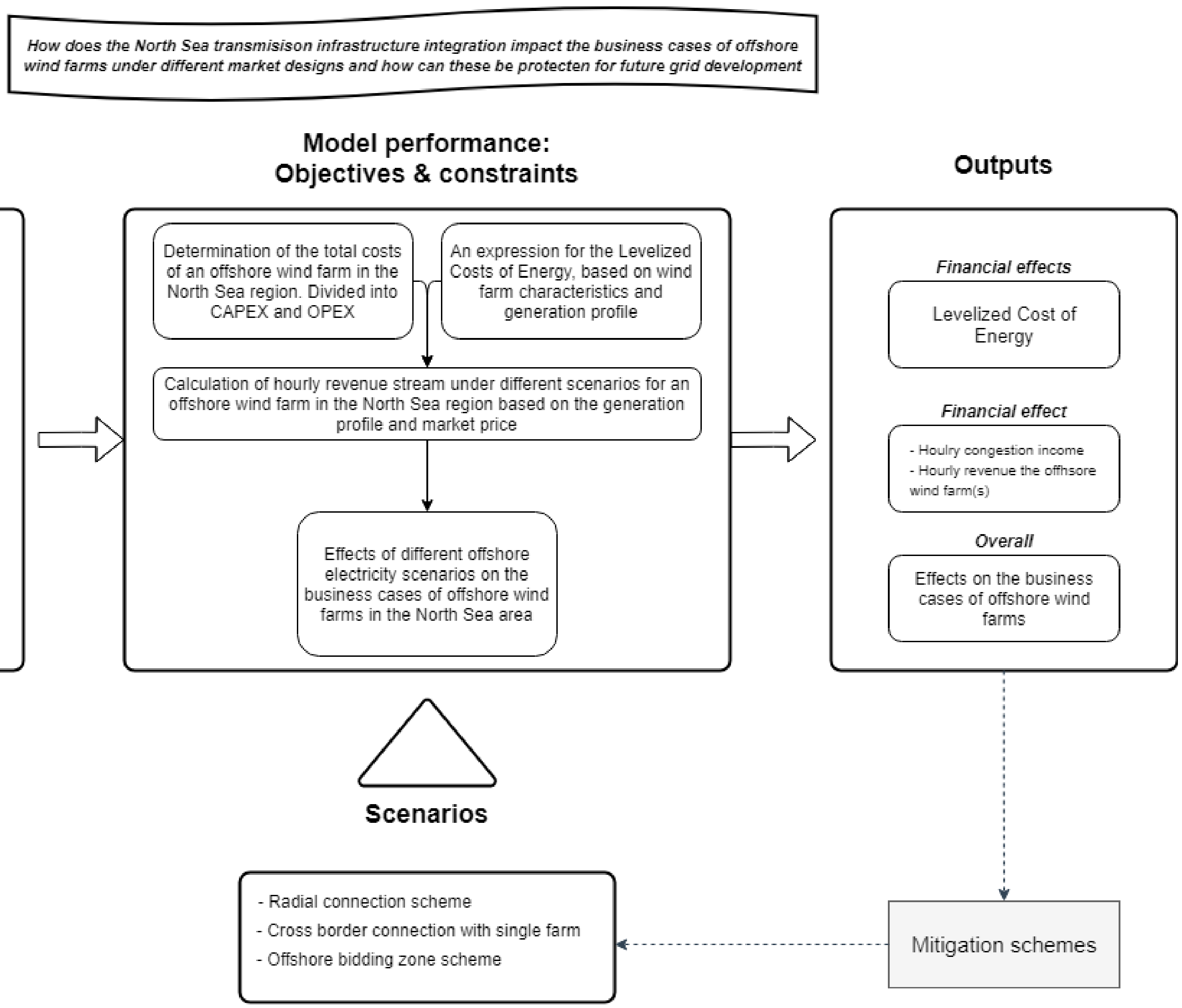


Figure 4-3: A visual representation of the conceptual model.

4-4 Inputs and outputs

This section will discuss the details of the inputs and outputs of the conceptual model. First, the desired outputs will be discussed to be able to understand the necessity of the inputs. Despite the fact that not all data is the same, the time period on which the model should operate is still a minimum of a full year in order to include the seasonal changes.

4-4-1 Outputs

As is represented in Figure 4-3, the total output of the conceptual model can be separated into two different outcomes. First of all, in order to assess certain effects on the business case of an offshore wind farm, the business case itself must be understood properly. The output of the conceptual model regarding this subject must be able to give insights into the costs and the benefits of an offshore wind farm. Costs outputs will be provided in two sets, one containing the hourly generated revenue under different scenarios and specified for a certain location within the system boundaries. In addition, other parameters affecting the operational expenses, such as transport tariffs for British wind farms, must be set as well. The other set of cost outputs corresponding with the business case of a wind farm will contain an expression for the LCOE, which can be seen as a point of reference to assess the expenses that need to be covered in order the keep a wind farm profitable.

Focusing on the income of a wind farm, the model should be able to calculate a set of hourly revenues generated by the wind farm developers. Different outcomes will be given for different scenarios imposing changes to the system in terms of physical or regulatory constraints. The revenues will be calculated using historical market- and generation data. In addition, physical constraints such as export capacity and transmission losses will also be included to determine the generation profile. Furthermore, different scenarios will be implemented, imposing new physical and regulatory constraints on the system, causing effects to be seen on the outputs.

After the outputs regarding the effect of different scenarios on the business case of an offshore wind farm are collected and assessed. When a scenario yields negative effects on the business case by, for example, reducing the original revenue received by a wind farm developer, schemes to mitigate this effect can be added to the situation. The scenario will be alternated to see what the impact is of certain mitigation schemes. This is depicted as a new block outside but still somehow connected to the output. In addition, because mitigation schemes often include extra financial support new constraint are set for the scenarios. As a consequence also a connection from the mitigation schemes block to the scenario input block is seen. New scenarios can be implemented on the system to assess possible mitigation options. This process will again result in the financial outputs for the business case of an offshore wind farm. The resulting impact of a mitigation schemes can be analysed.

4-4-2 Inputs

Now that the output is determined and explained, the necessary input will be discussed in detail. It must be noted that not all input data is similar, and some of the input data had to be converted to a suitable form. Some input data was found in literature, whereas other input data was gathered from different databases and had to be converted to a usable format. This section will elaborate on the input data used in this research and what role they play in the conceptual model. The transformation of large data sets such as the historical market data, generation profiles and CAPEX data will be discussed in the last section of this chapter.

Wind farm characteristics

The first type of input parameters are the ones on the characterisation of the offshore wind farm. The construction costs of an offshore wind farm highly depend on the type and number of turbines and their location. The location is associated with a variety of parameters such as the water depth and distance from shore. These parameters can significantly increase the cost of construction. In addition, a wind farm consisting of a larger number of turbines with a large rated capacity means it also has an increasing effect on the construction costs of an offshore wind farm. In chapter 3, a literature study was performed to obtain insights into the cost components of offshore wind farms. The chapter concluded with a list of costs and income streams that is presented in Table A-2 and Table A-1 in appendix A. In addition, a cost-increase factor dependent on the water depth and distance from shore is displayed in Table A-3 in appendix A.

Data sets

The second category of input data are data sets. As the name states, these inputs consist of large sets of data. These sets act as the backbone of the model in order to achieve its objectives. In addition, this category of inputs will be subjected to the constraints of the system and the changing scenarios. The first input of this category is one of a historical nature, namely the market prices. For this research, the "Time Series" data package was chosen from the Open Power System Data platform. This is a data package that contains different kinds of time series data relevant for power system modelling such as electricity prices, electricity consumption and renewable generation (solar and wind) along with its capacities (Nordpool group, 2021). The Open Power System Data platform aggregates the data by country, bidding zone or control area. The specific version used for this research only contained data provided by the TSOs and power exchanges via the ENTSO-E transparency platform. From this data package, the hourly market price for the UK was retrieved for the time period of 2015-2020. However, the spot market price data set for the Netherlands was not complete and had to be retrieved using a second source. The missing data was provided by the Nordpool group, a European power exchange trader owned by the Euronext and Nordic and Baltic countries' TSOs (Nordpool group, 2021). In the end, a data set containing the hourly spot market prices for the UK over the period of Jan-2015 until Sept-2020 was obtained. However, for the Netherlands, a substantial smaller data set was accumulated over the period of Jul-2019 until Sept-2020.

Besides the hourly spot market prices of the countries of interest, also the generation was retrieved from the Open Power System Data data package. In the set, a distinction was made between the actual load and the fore casted load for the demand of a country. In addition, multiple categories were identified in the generation data. The exact data for the offshore generation could not be used since the system of interest was appointed to be in the Doggerbank area. Because of this, some modifications had to be carried out in order to come up with a generation profile. This process will be described in detail in chapter 6.

A second data package was used in order to verify the modifications of the generation for a country to a specific location. This data package was retrieved from the Renewables ninja website. This website allows a visitor to run simulations of the hourly power output from (offshore) wind plants. These plants can be located anywhere in the world. The makers of this tool had the goal to help make scientific-quality weather and energy data available to a wider community (Pfenninger & Staffell, 2021). A data set containing the hourly wind speeds at the Doggerbank area is obtained in order to be able to calculate the generation of the wind farm over a larger period of time.

Physical boundaries

The last category describes the input regarding the size of the transmission cables and, more specifically, the export cables. This input specifies the constraint about physical boundaries. Although this is not a large data set containing a lot of information, the size of the transmission cables will have a big impact on the output of the model. In order to come up with accurate values for the cabling size, real-life situations of constructed wind farms were investigated. These are depicted in Table 4-1. This Table is only to give the modeller insights on the cable sizing used in real-life situations in order to come up with realistic values.

Table 4-1: An overview of export cable sizes of various projects.

Wind farm	**Export cable size (MW)**
Triton Knoll	400
Borssele Alpha	700
Borssele Beta	700
Hollandse Kust (zuid) Alpha	700
Hollandse Kust (zuid) Beta	700
Hollandse Kust (noord)	700
Hollandse Kust (west) Alpha	700
Hollandse Kust (west) Beta	700
Ten Noorden van de Waddeneilanden	700
Sofia wind farm	1000
Doggerbank wind farm	1000
IJmuiden Ver Alpha	2000
IJmuiden Ver Beta	2000

4-5 Simplifications and assumptions

Now that the input data used in the conceptual model is briefly discussed. Some simplifications and assumptions regarding the situation will be discussed. As is stated earlier in this chapter, the power system can be regarded as a highly complex system and therefore, it is almost impossible to simulate the system as a whole. Therefore it would not come as close to the real-life situation as possible. However, for this research, the purpose of the model is to highlight the effects the offshore transmission infrastructure has on the business cases of the wind farms. This is also the reason why the system boundaries were set. However, it is important to identify and explain these simplifications because they will have an impact on simulations and thus the results. In addition, it is deemed necessary to identify the simplifications and assumptions since the system is subjected to the modeller's own interpretation.

The first simplification is about the business case of a wind farm or rather an offshore wind farm. In the earlier chapters, the costs of a wind farm developer were divided into 2 categories, namely CAPEX and OPEX. However, these are not the only costs that are imposed on the wind farm developers. Most wind farm developers do not have the liquidity or equity to construct an offshore wind farm themselves. The initial investments a wind farm developer needs in order to be able to start a project simply is too high. Most wind farm developers find equity from various sources such as investors, bank loans, or they form a consortium to come up with the equity needed. Naturally, when equity is found in external sources, it is regarded as a debt, and interest rates have to be paid. However, the magnitude of this third costs category is difficult to quantify because of the relatively new market and its competitive nature. For this research and the corresponding time limit, this cost category is left out of scope. Because of this, the LCOE calculated are slightly lower than would have been when the cost of capital was included in the calculations.

The second simplification applied in this research is about the onshore electricity systems of the Netherlands and the United Kingdom. When countries are interconnected by means of large interconnections, pressure is put on its transmission system. In certain situations, countries even limit the cross-border capacity to solve congestion problems elsewhere in the system. This is partly the reason why the EC records the 70 per cent rule in The European Climate Pact specifically to prevent this from happening. Taking into account the congestion management of the onshore grids would be of no use since the 70 per cent rule is in place for home market scenarios. This will be further analysed in 6. Because of this, the onshore electricity system is deemed as a grid that is always able to accept the generated electricity by the wind farm. In other words, the capacity of onshore grids are assumed to be large enough to accept all electricity generated by the offshore wind farm, and therefore, the only limits on capacity are determined by the offshore transmission cables. This simplification is not expected to have a large effect on most of the scenarios which are to be simulated because the size of the export cables is build to be able to export 97% of the time the electricity generated by the wind farm. However, there are a few occasions in which this assumption could have a negative effect. Nevertheless, these scenarios are left out of the scope of this research.

The third simplification concerns the electricity price formation. As was mentioned in chapters

1 and 2, no extra expenses such as fuel costs are necessary when a wind farm is operational. This suggests that only operational expenses such as maintenance costs are imposed on a wind farm or any other renewable energy system for that matter. Because of this, wind farms are able to offer their generated capacity on the wholesale market for a price close to 0. Because of the nature of the market-clearing mechanism, capacity offered at lower prices will be selected to dispatch over higher-priced generators. The increase in wind energy will tend to have a decreasing effect on the wholesale electricity price. However, to have such an effect, an enormous increase in wind generation should be achieved. Nevertheless, it should be mentioned that in this conceptual model, the electricity market prices are not affected by the increase in offered capacity of low priced (renewable) generation.

The fourth simplification is similar to the above-mentioned simplification. As low priced electricity generators can lower the overall market price for electricity, so can a large share of interconnectors. As defined in subsection 2-1, interconnectors are, in general, transmission lines between 2 countries with a large capacity and high voltage. The direction of power flow on an interconnector is determined by the difference in market prices between the two connected countries. In the case of BritNed, also mentioned in subsection 2-1, the power flow goes to the country with the highest price for electricity. The difference in price is then earned as congestion income for the TSO in the respective country. In this way, the incentive for a TSO is always to maximise the utilisation of an interconnector. However, when the interconnection capacity becomes substantial large, the prices between the two zones will tend to converge. According to (Brabben, 2020), in the case of the UK, a cross border capacity of 6 GW will decrease the wholesale prices for electricity substantially. This phenomenon, however, is deemed too complex to simulate in the amount of time and with the available resources for this research and therefore is left out of the scope of this research.

The last simplification worth mentioning is specified on the system boundaries. As was stated throughout this research, the system of interest is chosen to be the North Sea region between the Netherlands and the United Kingdom. The onshore grids are left out of scope together with the effects of large injections of low priced wind energy and interconnection capacity affecting the electricity price. Furthermore, this research is limited to specific scenarios between 2 countries. If a third country would be introduced, for example, Belgium or Germany, the situation becomes much more complex. Limiting interconnection flows in Belgium, for example, could create more economic welfare in Germany since the electricity systems are connected through the Netherlands. Since the simplification is made that the congestion management is left out of scope for the onshore grid, it is also necessary to specify that this research will be limited to a situation in which no more than 2 countries are connected by means of offshore wind farms.

An overview of all simplifications or assumptions that have been made throughout this research are listed below:

- The onshore grid capacity is large enough to accept all generated electricity from OWFs
- The increase of offshore wind generation does not affect the electricity price

- The increase in interconnection capacity does not affect the electricity price
- The situation is limited to the connection between two countries
- Offshore wind developers intend to partake in a hybrid connections
- There are no technical difficulties regarding the connection of extra HVDC cables to the wind farms
- TSOs never fully utilise an interconnection cable because of internal congestion
- For the offshore bidding zone scenario the internal physical flows and connections are left out of scope

Chapter 5

Scenario conceptualization

In this chapter the scenarios are developed according to the scenario and modelling method discussed in chapter 4. This chapter also explained that the system of interest in the conceptual model undergoes changes due to the implementation of different scenarios. A visual representation of the scenario implementation within the conceptual model is displayed in Figure 4-3.

First, in order to develop the scenarios, a method is selected. Second, after the adoption of a method, six steps are introduced to develop the various scenarios from which four are performed in this chapter. Consequently, if additional simplifications and assumptions will be identified, these will be presented and discussed. Last, the scenario development and an overview of the changes imposed per scenario onto the system will be presented.

5-1 Method

As is briefly discussed in subsection 1-4-2, many ways of developing or using the scenario-based approach can be found throughout the literature. However, in this research, a combination of simulation & modelling and the scenario approach is taken. This section will dive deeper into the scenario approach itself and determine a method for how to set up a scenario.

According to Quade and Carter (1989): "A scenario can be seen as stories of possible futures. These stories are based upon logical consistent sets of assumptions, and fleshed out in sufficient detail to provide a useful context for engaging planners and stakeholders." Particularly for policy assessments, scenario-based approaches include assumptions about developments that will act as external effects on the system of interest. For this research, however, the scenarios have an explanatory function and therefore will not need probabilities as the scenarios will not have predictive functions.

According to Börjeson et al. (2006), people tend to think about the future in three ways, therefore, scenario development can be distinguished into three categories with six different types in total. The first category is described as scenarios that have a predictive function, these scenarios will try to answer questions such as: *"What will happen..."*. This category consists of two types depending on the constraints they pose on the system. First, the so-called forecasts scenarios respond to the question earlier mentioned. The second type of scenario tries to answer the what-if questions. As a consequence, additional conditions of some specified event are necessary. This results in the following question: *"What will happen if..."*.

The second category describes scenarios that have an explorative function. These are often used for strategic questions and have a goal to be able to plan and adapt to situations that are expected to occur in the future. The third category describes scenarios with a normative function. These scenarios try to answer the question of how a specific target can be reached. This could either be done using so-called preserving scenarios that respond to the question of how the target can be reached by adjustments to the current situation. In addition, transforming scenarios could also be used that respond to the question of how the target can be reached when the system prevents the necessary changes. An overview is presented in Figure 5-1.

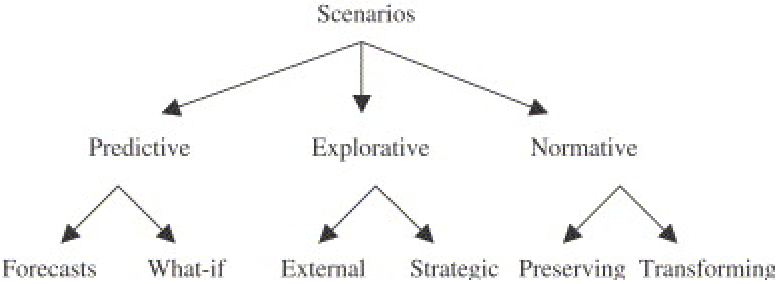


Figure 5-1: Scenario typology with three categories and six types (Börjeson et al., 2006).

It is clear that for this research, explorative scenarios are sufficient. External types of explorative scenarios respond to the user's question about what can happen to the system with the development of external factors. This aligns with the role the scenarios fulfil within the conceptual model, however, the strategic scenarios seem to fit better. Strategic scenarios respond to the question of what can happen if certain decisions are made within the system. The decisions can be made by the TSO and NRAs or ministries to develop certain types of connection scenarios. In a way, the wind farm developer can also make the decision to participate in the connection scenario but for this research purpose, the wind farm is expected to be willing to analyse all scenarios developed.

Now that the nature of the scenarios in this research has been identified, the next step is to identify the steps in order to create an explorative scenario. Various different methods to develop scenarios exist. However, for this research, it is important that the scenarios are compatible with the model. Therefore a quantitative or traditional method was found. According to TU Delft wiki (2010b) a quantitative method consists of seven individual steps. Since this research is combining the method of simulation & modelling with the scenario approach a slightly altered version is used that is developed. The method is displayed in

Figure 5-2, whereas the selected steps for this research are listed as follows:

1. Identification of the system boundaries
2. Identification of forces driving structural changes
3. Identification of system changes
4. Identification of uncertain forces and system changes
5. Development of the scenarios
6. Quantification of the scenarios

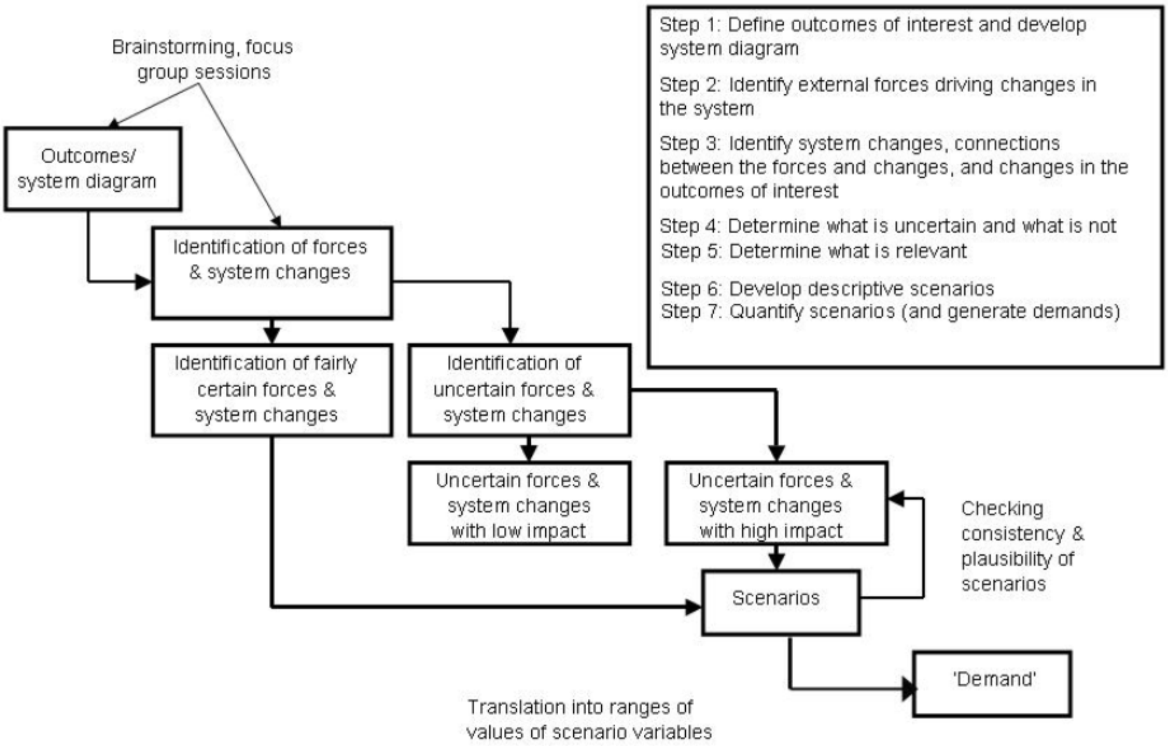


Figure 5-2: The scenario development process (Europe, 1997).

Identification of system boundaries

Step 1 has already been performed throughout chapter 4. In section 4-1, the system of interest was identified to be the wind farm located in the North Sea region between the United Kingdom and the Netherlands. The situation was simplified by not including more than two countries and to not include the characteristics of the onshore grid. The elaboration on the system of interest and its boundaries can be found in the earlier mentioned subsection.

Identification of forces driving structural changes

In the conceptual model, the scenarios are supposed to impose forces that drive structural changes to the system. Aside from the mitigation options that will be discussed later on, the only changes that are relevant in this research are physical changes. More specifically, changes in connection schemes. Section 2-2, describes some of the possible connection schemes. The way a wind farm is connected to a foreign shore, other offshore assets or its home shore drive the effects on the business case that is analysed in this research. In order to cope with the complexity of the issue and the assumptions and simplifications imposed on the model a few connection schemes were deemed acceptable for scenario development, this will be further explained in section 5-2. Besides the various connection schemes, the market setup is also a force that drives structural change onto the system of interest.

Identification of system changes

The identification of the changes within the system will be performed using a modelling and simulation approach. This step has for a large part been worked out in chapter 4. The revenue of a wind farm is dependent on the amount of electricity generated and in what market a wind farm can dispatch its generated electricity. In addition, these two components depend on the capacity of export cable and the market set up in which the wind farm is located in. The type of connection schemes that should be preferred in order to protect the future business cases of offshore wind farms is the desired outcome of the model. In addition, insights into the effects of the North Sea grid integration onto the business case of the wind farms. Chapter 7, will further discuss the regulatory changes in order to protect the business cases of OWF under future grid connections.

Identification of uncertain forces and system changes

This category describes the forces imposed onto the system that can be regarded as uncertain. Europe (1997) gives an example about hub-and-spoke systems for aviation airlines which are regarded as a structural change for the future. In this example, Europe (1997) argues that for a structural change, various underlying assumptions have been made. These assumptions must be tested invalidity which is often uncertain. For the hub-and-spoke concept of the aviation airlines, the assumption was made that European airlines are able to successfully restructure their route networks. In order to achieve that airports that will be marked as hubs should have enough capacity for peak hours of traffic.

For this research, the technical difficulties have already been proven to work in different projects such as BritNed for long HVDC cables and Kriegersflak which shows that it is possible to integrate ICs with existing wind farms. An uncertainty is that these connections are economically feasible. In addition, all parties have to be on board if such a connection scenario is to be adopted. In addition, section 4-5, describes the simplifications and assumptions that have been made for this research. In this process, most of the uncertainties have already been identified and taken into account. In addition, when underlying assumptions are identified during the simulations these will be added to ensure that as much of the uncertainties are dealt with.

The next section describes the development of each scenario used in this research. In addition, the last step describing the quantification of the scenarios will be performed through various simulations of the scenarios onto the conceptual model. The results of the system changes imposed by each scenario will be presented in chapter 6.

5-2 Scenario development

This section continues with the development of the scenarios assigned as step five in the previous section. Per scenario, a short description will be given. In addition, an overview of the new constraints imposed on the system will be presented. The resulting system changes will be discussed in chapter 6.

5-2-1 Reference case

The first connection scheme is the reference case. This is a wind farm located in its own home market with no cross-national connections. The system boundaries imposed in this scenario are mainly determined by the export cable size, the generation of the wind farm, the electricity prices and the presence of subsidy schemes. A physical representation of this scenario is displayed in Figure 5-3 as the bottom scenario.

An overview of the new constraints imposed onto the model are displayed in Table 5-1 and 5-2 for a Dutch and British wind farm respectively. To start with the market setup, the reference case is in a home market. This implies that no matter where the electricity is transported to, the wind farm will always receive the electricity market price from the (national) market in which it is located. The reference cases represent the current situation in real life, meaning without a cross-border connection.

One of the big effects on the system is the setup of the export cables and their size. The size of the export cables is set to be 1000 MW but this can be adjusted to analyse different situations. As is discussed in chapter 3, the cable sizing is determined depending on the total rated capacity of the wind farm. For this research, a wind farm of 1400 MW was selected with corresponding export cables of 1000MW with an according 3% of losses due to transportation. Furthermore, an option to include subsidies is also part of the scenario. Depending on the country of origin either the CfD or the SDE++ scheme is used. Last, because of the offshore grid developing model used in the United Kingdom, transport tariffs have to be paid to the OFTO. This is also included in the scenario and the amount of the tariff can be selected accordingly. A representation of the reference case is depicted as the first case (at the bottom) in Figure 5-3.

Table 5-1: Overview of possible constraints of the reference scenario affecting the system from a Dutch wind developer perspective.

Variable	Value
Market setup	Home Market
Cross-border connections	False
Nationality	Dutch
Export cable size	1000 MW
Export cable losses	3 %
Subsidy scheme 1	SDE++
Subsidy scheme 2	CfD

Table 5-2: Overview of possible constraints of the reference scenario affecting the system from a British wind developer perspective.

Variable	**Value**
Market setup	Home Market
Cross-border connections	False
Nationality	British
Export cable size	1000 MW
Export cable losses	3 %
Subsidy scheme 1	SDE++
Subsidy scheme 2	CfD
Transport tariffs	11.91 €/MWh

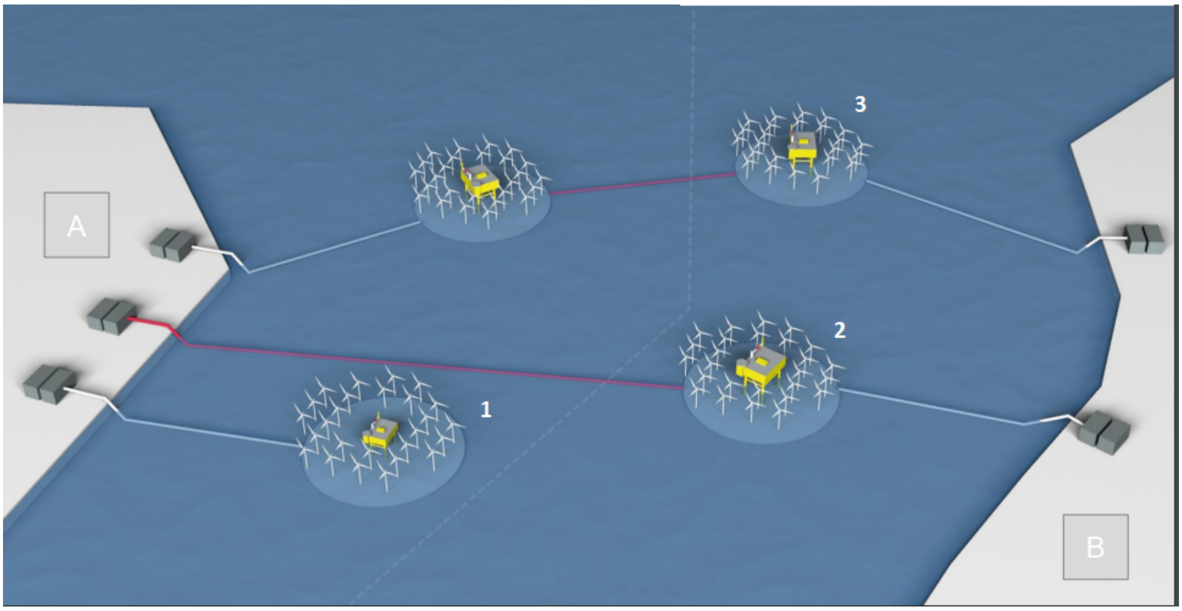


Figure 5-3: Different connection scenarios in a home market setup (van der Hage, 2019).

5-2-2 Radially connected wind farm including a cross-border connection

The first future scenario for the North Sea region is to develop a hybrid connection. This scenario is an addition to the reference case in which an existing radial connected wind farm has an additional connection to a foreign country. This can be seen second situation (middle) in Figure 5-3. This may seem like a small addition in comparison to the reference case. However, by the introduction of this additional export cable and consequently an addition of a second electricity market, substantial effects are imposed onto the system.

Next to the psychical system changes, also regulatory changes have to be adopted in this scenario because of the availability of cross-border capacity exchange. In the scenario in which a wind farm is part of a setup including a cross-border connection or rather an interconnector, a priority conflict of export cable utilisation between the TSOs and wind farm developers occur. The current regulation states that cross-border capacity has priority over the generated wind farm capacity. To cope with the effect this regulatory constraint is adopted in the scenario.

In addition, an additional regulatory constraint has to be adopted. This constraint is part of the CEP that states that at least 70% of the interconnector cable must be reserved for cross-border capacity exchange. This rule was adopted to increase the investments and utilisation of cross-border interconnections. Depending on whether the wind farm is seen from a Dutch or UK perspective the transport tariffs can also be added. An overview of the changes imposed onto the system of a Dutch and British wind farm is presented in table 5-3 and 5-4 respectively.

Table 5-3: Overview of possible constraints of the cross-border connection scenario affecting the system from a Dutch wind developer perspective.

Variable	Value
Market setup	Home Market
Cross-border connections	True
Nationality	Dutch
National Export cable size	1000 MW
Foreign Export cable size	1000 MW
Export cable losses	3 %
Subsidy scheme 1	SDE++
Subsidy scheme 2	CfD

5-2-3 Offshore bidding zone

The last scenario is the implementation of an offshore bidding zone. The concept of an offshore bidding zone has been discussed in subsection 2-4-3. It can be argued that an offshore bidding zone can be defined as a mitigation option to comply with the 70% rule. However, in this research, the introduction of an offshore bidding zone is considered to be a different scenario besides the connection schemes rather than a mitigation scheme. As is stated in chapter 2, in an OBZ, the wind farm developer is not part of its original home market anymore. Instead,

Table 5-4: Overview of possible constraints of the cross-border connection scenario affecting the system from a British wind developer perspective.

Variable	Value
Market setup	Home Market
Cross-border connections	True
Nationality	British
National Export cable size	1000 MW
Foreign Export cable size	1000 MW
Export cable losses	3 %
Subsidy scheme 1	SDE++
Subsidy scheme 2	CfD
Transport tariffs	11.91 €/MWh

the market setup is that of a new bidding zone located offshore between the United Kingdom and the Netherlands. A schematic representation of what an offshore bidding zone could be is displayed in Figure 5-4.

Within this bidding zone, the wind farms can be connected in various ways. In addition, it must be noted that an OBZ would most likely not represent a circle but rather a zone spanning the whole sea representing the structural congested region. The difference between an OBZ and the previously mentioned HM, however, is the unique characteristic of an OBZ, being the lack of electricity demand of users (load) present within the zone. This implies that the price of the bidding zone in which the wind farms are located is completely determined by the adjacent (and physical connected) markets. The reason why is because of the bidding prices renewable energy technologies bid into the market which is close to 0, representing the marginal costs to operate the renewable generator. The only demand coming in the zone is that of the national electricity markets of the Netherlands and the United Kingdom which in terms are the price setters. In addition, an important note is that in an OBZ, demand is completely determined by the capacity of export cables and ICs, just as the transmission system onshore.

Before the scenario of an OBZ can be developed, a simplification has to be introduced. In order to be able to obtain insights into the effects of the scenario it is assumed that, in terms of the limited capacity, the bidding zone acts as a black box where electricity will and can always be dispatched. Meaning that, in the model, only the export cables connecting the zone to shore are taken into account. Within the zone, the electricity will flow and will not be limited due to different connection schemes. The constraints implied by an OBZ on the system are presented in table 5-5

Table 5-5: Overview of possible constraints of the offshore bidding zone scenario affecting the system from.

Variable	Value
Market setup	Offshore Bidding Zone
Cross-border connections	True
Nationality	British and/or Dutch
National Export cable size	1000 MW
Foreign Export cable size	1000 MW
Export cable losses	3 %
Subsidy scheme 1	SDE++
Subsidy scheme 2	CfD
Extra regulation	70% rule

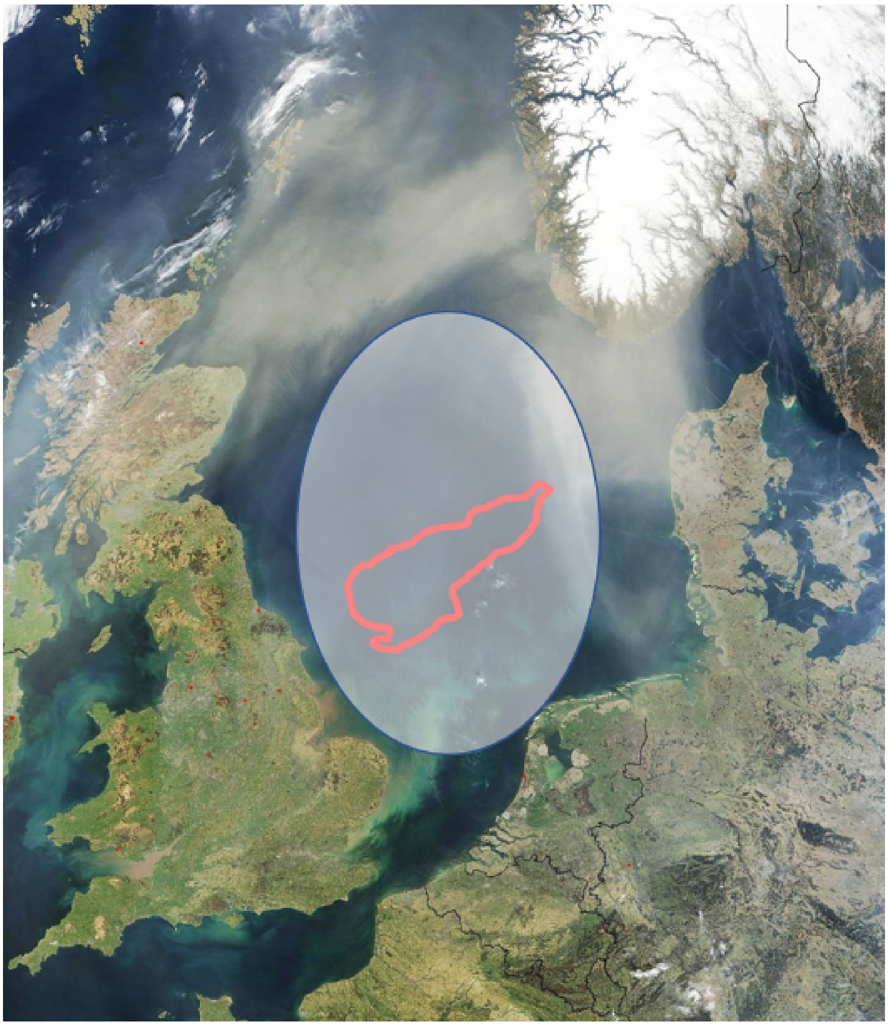


Figure 5-4: Visual of what an offshore bid zone can look like.

Chapter 6

Simulation and Results

This chapter presents and discusses the simulations steps and the corresponding output of each scenario according to the approach discussed in the conceptual model (chapter 4). In order to be able to use the conceptual model, scenarios were created in chapter 5. These scenarios are then used in the conceptual model to simulate the effects of each scenario on the business case of an offshore wind farm. Because of the relatively small size of the input data sets, these simulations were carried out in Microsoft Excel. First, a so-called base modelling step will be carried out. This is done in order to realise a basic case that can be transformed using minor alterations to replicate a scenario. This is done in order to illustrate the effects of each scenario more clearly.

After the base case has been developed, the simulation of the selected scenarios will be carried out by first simulating the reference case scenario. In essential, this is the current situation of a radial connected wind farm. Next, the second scenario describing a cross-border connection using a single wind farm in a home market situation (either Dutch or British) will be simulated. Then, the third scenario is simulated that describes the market setup of an offshore bidding zone scenario. After each simulation step, the results will be presented and discussed.

The goal of this chapter is to obtain insights and to present the effects of various connection scenarios on the current connection scenario in real life, and essentially, on the business case of an offshore wind farm located in the North Sea region. In addition, in the case that this chapter provides scenarios that will affect the business case negatively, the output will be used in chapter 7 for further investigation.

6-1 Base modelling

This section discusses the base modelling step. In this modelling step, the input data described in section 4-4, will be used to create a first starting point on which the simulations of the scenarios are carried out. In addition, the used values of input variables will be determined. First, the geographical and design parameters of the wind farm will be determined. After the wind farm characteristics are set, it is possible to calculate the electricity yield of the wind farm based on the historical input data sets. Next, an expression of the LCOE is calculated. Last, by introducing the historical input data set containing the electricity prices into the base model, the theoretical revenue can be obtained for the wind farm. The output of this section describes the situation for an offshore wind farm in terms of theoretical generation and revenues and acts as a starting point on which the scenarios will be simulated. A schematic overview of this process is presented in a conceptual diagram in Figure 6-1.

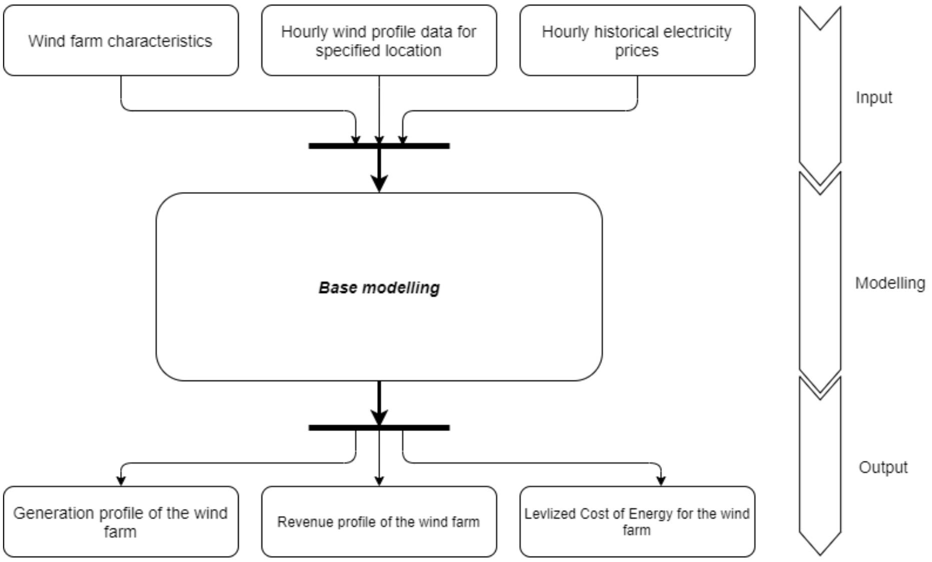


Figure 6-1: Schematic representation of the base modelling with according inputs and outputs.

Wind farm characteristics

Before any of the modelling can be performed, the characteristics must be set for the wind farm. As is described in chapter 4, in this research the system of interest is that of a wind farm located in the North Sea region. More specifically, the objective is to obtain insights into the effects of the transmission infrastructure integration on the business cases of the existing wind farms. In order to start with the development of the base model, the geographical characteristics such as the sea depth and distance from shore have to be determined. In addition, the size of the wind farm, depending on the number and size of the turbines have to be determined. Based on the wind farm characteristics the input data can be used to calculate the wind generation profile, the Levelized Cost of Energy LCOE and revenue stream. These are then analysed in order to obtain insights in the business case of an offshore wind farm.

As was explained in chapter 3, the LCOE, is a factor describing the costs of the generated electricity over the assets lifetime. Basically, this is the minimum price a wind farm owner has to receive for its commodity in order to reach break-even on its investment. However, before the calculation can be carried out various economic factors such as the lifetime of the wind farm and the interest rates have to be determined. An overview of the chosen wind characteristics is displayed in table 6-1. The reasoning for these parameters was discussed in chapter 5.

Table 6-1: Setup of the wind farm characteristics.

Factor	Value
Water depth	23 m
Distance from shore	145 km
Turbine size	14 MW
Number of turbines	100
Life-time wind farm	25 years
Interest rate	6 - 8%

Hourly wind profile data for specified location

Based on the characteristics of the wind farm, the hourly electricity yield can be calculated. This can be computed in various ways. In the period in which this research has been performed two ways were found. The first method makes use of the generation data available on the Transparency platform of the ENTSO-E (ENTSO-E, 2021). However, as the data set required preferably as much data as possible, this method was later found to be insufficient for this research. Because of the relatively little data the data set contained, an alternative method (solution) was found.

The alternative approach that was adopted, makes use of the database of Renewables.Ninja (Pfenninger & Staffell, 2021). This is an online database that allows the user to simulate the power output of a renewable energy system located anywhere in the world. The objective of this tool is mainly to support researchers to make scientific-quality weather data available. From this database, a set of hourly wind conditions specified for the location near the Doggerbank was obtained spanning almost 30 years from 1980 to 2019. However, because of the size of the data set for the electricity prices only a time window of 5 years could effectively be used, namely from 2015 to 2019. Table B-1 shows the input used for the online tool. The output of the online tool gives a data set containing historical wind speeds per hour over the time period previously mentioned.

Generation profile of the wind farm

Now that a wind profile and the wind farm characteristics are determined, the theoretical generation of the wind farm can be calculated. Normally this could be easily performed using a so-called turbine-specific power curve graph. According to DWIA (2003), a power curve is a graph that indicates how much electricity can be generated at certain wind speeds and is dependent on various wind turbine characteristics. The Renewables.ninja website makes use of such a power curve of various specific types of turbines in combination with the wind profile and wind farm size in order to generate the total hourly electricity output of the wind farm. However, in this research the choice has been made to use of the Haliade-X, a 14 MW turbine, as these types of turbines will be used for larger projects such as the Doggerbank wind farms and wind farm Sofia (RWE, 2021). The increasing size of the turbines can be partially explained by higher generation efficiencies, economies of scale and less transport losses (Doolan, 2019). However, these 14 MW turbines are still in the developing phase and because of this, no power curve is publicly available yet.

Nevertheless an approximation of the power curve was obtained by means of linear regression. According to Campbell et al. (2020) the output of a turbine is depending on a few characteristics such as hub height, blade diameter and wind speed. These characteristics are publicly available for the Haliade-14MW turbine of GE. The actual electricity yield of the wind farm with a size of 1.4 GW was calculated by performing a linear regression on the nine largest turbines available on the renewables.ninja database. Appendix B-1 further elaborates on the estimation in order to determine the generation profile used throughout this research. The resulting wind profile and corresponding electricity yield profile are seen in Figure 6-2 and Figure 6-3 respectively. The seasonal dependence of wind generation can be clearly seen. The wind generation is about two times lower around June and July in comparison to December and January. In addition, it can be seen that the wind generation over this time period is quite consistent. The wind profile with the greatest energy-generating potential is that of the year 2015 and 2017 in wchich it generated around 7.55 and 7.09 TWh respectively. Furthermore, it can be observed that the average wind speed lies between the interval of 7 m/s and 14 m/s, except in December 2015 where it slightly exceeds 14 m/s. A turbine produces its maximum electricity yield at the rated wind speed (NWW, 2021). For the Haliade-14 this maximum is achieved for wind speeds about 13.5 m/s. If a different turbine would have been chosen, for example one with a rated wind speed of around 10 m/s, then the generation profile would have its maximums in the warmer period of May and June.

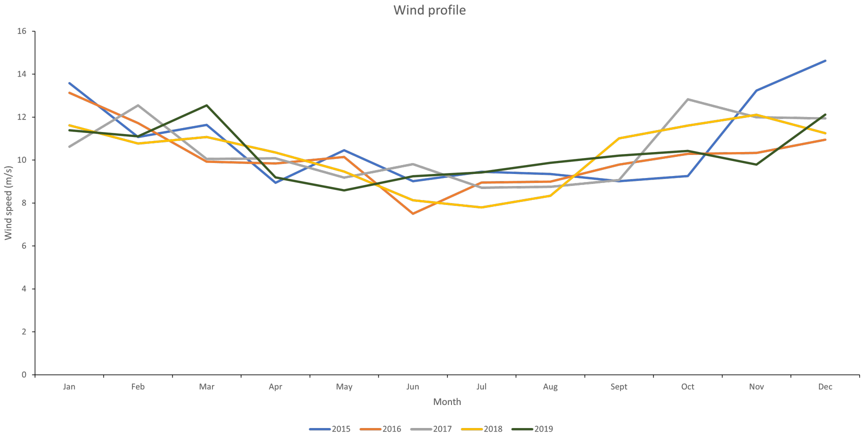


Figure 6-2: Monthly average wind speed profile of the selected location over the period 2015-2019.

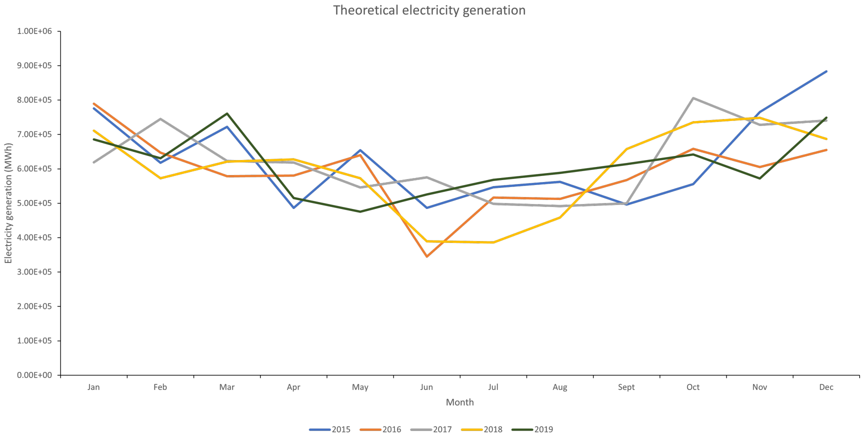


Figure 6-3: Monthly aggregated (theoretical) electricity yield of the selected wind farm over the period 2015-2019.

Hourly historical electricity prices

Now that the generation profile has been determined the last step of the base modelling is to introduce the last input, namely the electricity prices. As was stated in section 4-4-2, the electricity prices were accumulated from the database: "Open Power System Data" (OPSD, 2021). It must be noted that this is the limiting data set regarding the time period on which the simulations are able to be performed. As is stated before, the historical wind pattern data set spans a time period of 30 years whereas the historical electricity prices only start from the year 2015 and end in 2019, both for the Dutch and British electricity prices. To convert the Great British Pounds (GBP) to euros the average conversion factors of each year was used. These yearly average exchange rates were retrieved from Exchange Rates UK (rates UK, 2015-2019). This is presented in the appendix, more specifically, in table B-5.

Revenue profile of the wind farm

Now that the generation profile and corresponding electricity prices are determined, the theoretical revenue of the OWF can be calculated according to equation 6-1. The term "theoretical revenue" implicates the revenue that can be earned in a situation in which all generated electricity is sold. This, of course, is an ideal case that never occurs in reality. In reality, the revenue earned by an offshore wind farm developer is limited by the capacity of the export cables connecting the wind farm to shore and the internal congestion of the onshore transmission network. In addition, because of the volatile nature of wind energy, this upper limit of electricity transport is seldomly reached. However, for simplicity it is assumed that the market is able to sell all the electricity. Figures 6-4 and 6-5 illustrate the theoretical generation of the wind farm when it is able to sell all its electricity for its national market price respectively. In addition tables 6-2 and 6-3 show an expression of the revenue that is earned per unit of generated electricity. This is done in order to compare this with the LCOE.

$$\begin{gathered} TR = P \times Q \\ \text{total revenue} \;=\; \text{price} \;\times\; \text{quantity} \end{gathered} \tag{6-1}$$

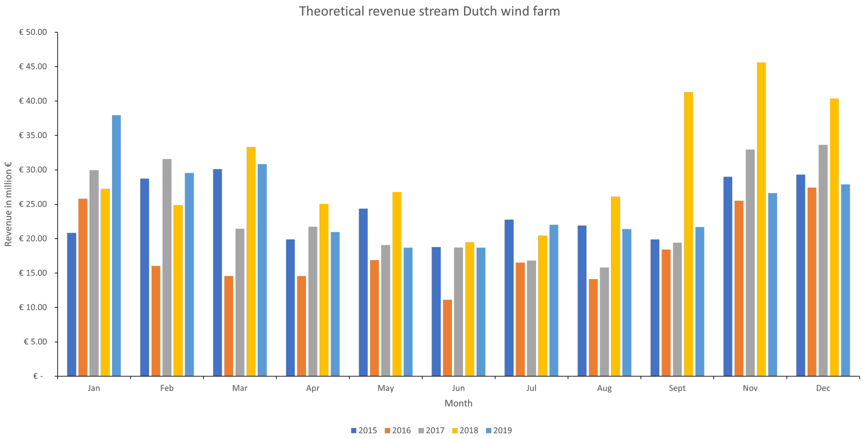


Figure 6-4: The theoretical revenue stream of a Dutch wind farm selling into its home market.

Table 6-2: Theoretical revenue per MWh that would be earned by a Dutch wind farm over a time period from 2015 until 2019.

Year	2015	2016	2017	2018	2019
Revenue (€/MWh)	38.17	31.81	39.03	52.21	40.91

Some first observations can already be obtained from these graphs and tables. When looking at the overall generated revenue, it can be seen that the monthly revenue of a British wind farm is on average around 9 million euros higher than the revenues of a Dutch wind farm. Naturally, this results from the higher electricity prices in the UK. In addition, it can be observed that the wind generation and electricity prices for the time period 2015 - 2019 are quite steady, with the exception of the year 2018.

Levelized Cost of Energy

As was stated before, depending on these wind farm characteristics, the Levelized Cost of Energy or LCOE can be calculated. A more in-depth explanation of the initial investments such as the assets or capital expenditures (CAPEX) and operational expenditures (OPEX) that in term determine, amongst other parameters, the LCOE was given in chapter 3. As was explained, this is an expressions that indicates the cost of per generated unit of electricity. In terms, this is the minimum price the wind farm developer should receive in order to break-even on its investment. Generally speaking, the LCOE can be calculated summing the total costs of the project and divide it by the total generation a wind farm can generate throughout its life time. In addition, a discount factor is introduced to take into account the changing value of future cash flows. More background information and an in depth calculation of the LCOE is presented in Appendix B-2. In addition, the resulting LCOE using a discount rate of 6.5% and an annual increasing OPEX is presented in table 6-4.

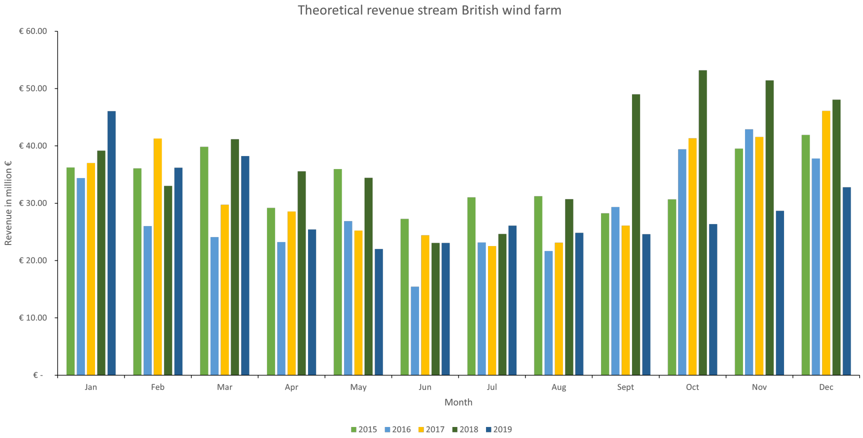


Figure 6-5: The theoretical revenue stream of a British wind farm selling into its home market.

Table 6-3: Theoretical revenue per MWh that would be earned by a British wind farm over a time period from 2015 until 2019.

Year	**2015**	**2016**	**2017**	**2018**	**2019**
Revenue (€/MWh)	53.91	48.53	51.66	64.70	48.38

Table 6-4: Levelized Cost of Energy (LCOE) of a wind farm constructed from a Dutch and British perspective.

Nationality	**Netherlands**	**United Kingdom**
LCOE (€/MWh)	43.24	52.92

6-2 Scenario 1: Reference case

As was stated earlier on, the simulations of the scenarios are performed on the resulting base model. In addition, each simulation process of a scenario is performed in a similar way. First, the physical constraints such as the cable capacity and transport losses are introduced on the base model that was previously described. This implication on the system will result in some first minor effects. For this first simulation, no regulatory constraints are added in order to create a robust situation on which the effects of the other constraints can be identified. When such a base case is determined, the next step is to add the first regulatory constraint and to analyse its effects. Then, after these effects have been analysed, the next regulatory constraint will be added, this approach continues until all constraints on the system that represent the real situation have been met. The number of constraints imposed on the system depend on the specific scenario. A schematic representation of this approach specified for this scenario is seen in Figure 6-6.

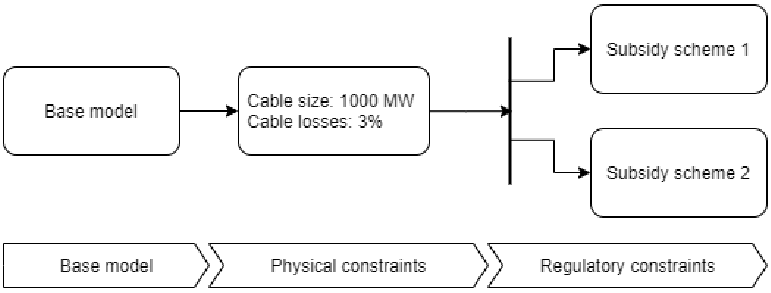


Figure 6-6: Simulation steps taken for scenario 1: Reference case.

The first scenario that will be simulated is that of the current situation, namely the radial connections. The radial connections have briefly been discussed in chapter 2 and a physical representation can be seen in Figure 2-3a and in Figure 5-3 (connection scheme 1). The constraints imposed on the system have been presented in chapter 5 and are presented in table 5-1 and 5-2.

This situation is regarded as the first scenario that will be simulated. In addition, this scenario will act as the reference case in which the effects of the other scenarios are being analysed. Currently, in the United Kingdom and the Netherlands, only radial connections exist for offshore wind farms. Naturally, this is the situation that has the potential to evolve into a hybrid configuration including an interconnector, but before that will take place, the effects of such a new configuration must be analysed.

As is seen in, for example, table 5-1, the psychical constraints imposed on the system represent the export cables that transport the generated electricity of the wind farm to shore. Naturally, the amount that can be transported is limited by the capacity of the cable and the transport losses. In addition, the amount of electricity that is transported to shore is limited by internal congestion within the onshore transmission or distribution networks. Nevertheless, for simplicity, it is assumed that no offshore wind capacity is being limited due to internal congestion management. The results of the first constraint with respect to the theoretical case is presented in Figure 6-7. It can be observed that, on average, for this particular connection scenario, about 15% (about 1 TWh) of the electricity generation is lost due to a combination of overproduction that exceeds the transport capabilities and transport losses. Naturally, this holds for both the Dutch and British perspectives.

Now that the effects of the transport constraints are known, the revenues earned in the reference case can be simulated. Since in this scenario both the wind farms would have a single radial connection to their home market, the Dutch wind farm can only receive the Dutch electricity prices whereas the British wind farm can only receive the British prices for the generated electricity. The results are displayed in Figure 6-8. The revenues are expressed in a similar way as the LCOE, this is done in order to obtain insights into the business case of the wind farm during this time period. When this expression for revenues exceeds the LCOE, naturally the wind farm developer makes a profit. Immediately the price difference of the two bidding zones can be seen. On average the electricity prices in the United Kingdom are substantially higher than the electricity prices in the Netherlands. The average annual

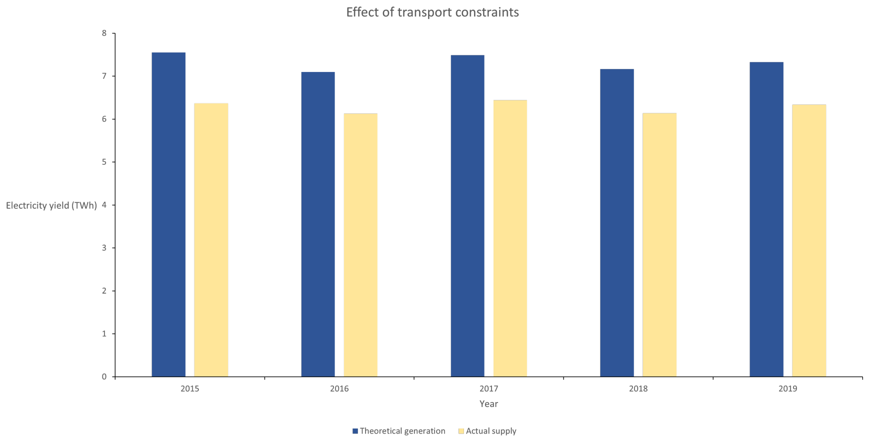


Figure 6-7: Theoretical generation and actual supply of a the specified wind farm under export capacity constraints.

electricity price in the United Kingdom in 2016 was about 49.49 €/MWh whereas the Dutch average electricity price for 2016 was just 32.35 €/MWh.

When looking at the profitability for the wind farm developer an example is taken. In the year of 2016, the theoretical energy production was 7.09 TWh. In addition, the losses due to the transport constraints result in an actual supply of about 6.13 TWh corresponding to a total revenue of almost 300 million euros for a Dutch wind farm. When dividing the revenue by the total generation in 2016, an expression is obtained that is comparable with the expression of the LCOE. This results in 31.89 €/MWh for a Dutch wind farm in a radial connection. In addition, the resulting Levelized Cost of Energy for a Dutch wind farm was estimated to be 43.24 €/MWh. The calculation approach taken for the LCOE has been carried out in appendix B-2. For this year it can be clearly stated that without any type of support this wind farm, which is constructed under a Dutch governance model, will most likely not be able make a profit. The other factors are represented in table 6-5, only in 2018 will the wind farm generator will earn a profit.

Table 6-5: Revenue earned per MWh by a Dutch and British wind farm over a time period from 2015 until 2019.

	2015	**2016**	**2017**	**2018**	**2019**
Dutch Revenues (€/MWh)	38.46	31.89	39.05	52.31	40.98
British Revenues (€/MWh)	54.33	48.78	51.55	64.78	48.40

Now that the first simulation part of this scenario has been carried out, the regulatory constraints can be implemented. It must be noted that for this particular scenario no cross-border connections are present. This also implies that the scenario is relatively straightforward regarding regulatory constraints. The only constraints that can be introduced are in fact the financial support schemes such as the SDE++ and the CfD schemes.

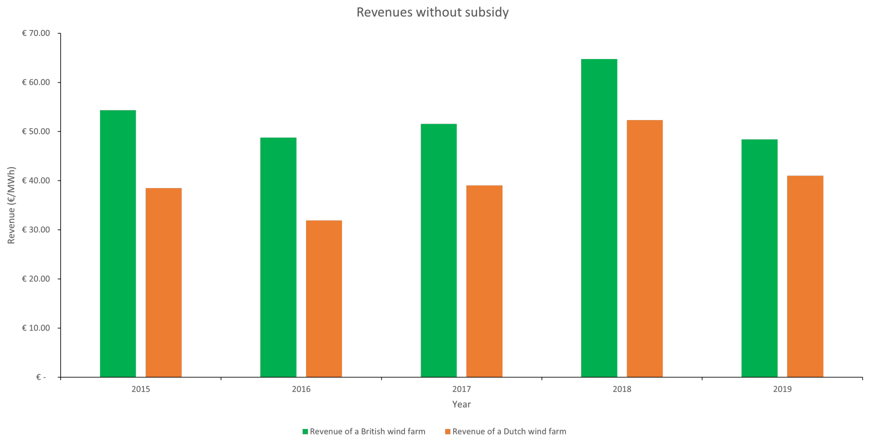


Figure 6-8: Actual revenues of a Dutch and British wind farm in the reference case scenario.

Currently in the Netherlands, no feed-in-tariff (FIT) schemes are granted anymore. The last subsidy scheme that has was granted was the SDE+ (now SDE++) for the Borssele 3 & 4 tenders in 2016. These tenders were won by a consortium of Shell through a competitive auction for at a price of 54.5 €/MWh. An overview of other historical winning bids for various tenders is presented in table A-2. In addition, the British support scheme, the CfD scheme, is still active. For example, for Wind farm Sofia, which is to be constructed on the Doggerbank, a subsidy of 45.32 €/MWh was won by RWE. Both subsidy schemes are FIT that grant support through the operation of the wind farm and are therefore often referred to as operational subsidy schemes. The framework to determine the height of the support has been explained in subsection 3-2-3.

In order to obtain insights into the effects of these subsidy schemes a height of the granted support was calculated. As was explained in subsection 3-2-3, the SDE++ scheme works with a correction price that is equal to the average electricity price of that particular year. Whereas the CfD scheme works with a double capped price in which the height of the upper limit is set in a competitive auction. Using the historical electricity market data the amounts of support was calculated. This process is explained thoroughly in appendix B-3. The resulting height of the subsidies in €/MWh are depicted in table 6-6. Immediately the year of 2015 and 2019 stand out since, in the British electricity market, no subsidy is granted when using the SDE++. This can be explained due to the strike price that has been adopted in the calculation and the relatively high market prices in the UK.

It can be observed that, the amount of subsidy received by the British wind farm is substantially lower in the situation when using the previous mentioned historical strike prices. More specifically, the price of the Borselle tender for the SDE++ subsidy and the winning bid of wind farm Sofia for the CfD scheme for both the Dutch and British wind farms. This can be explained beause of the higher electricity prices in the UK. However, comparing these values is somewhat incorrect, since the British wind farm will most likely adopt a different biding strategy in a SDE++ tender. In addition, this holds for the CfD scheme. The determination of the height of the CfD schemes has been elaborated upon in appendix B-3. In table B-3, the annual maximum heights of the CfD are depicted. As a reference point the strike price has been taken from a wind farm in a similar region and similar size, namely Sofia wind farm, in order to reflect the real-life situation.

Table 6-6: Resulting heights of the SDE++ scheme in €/MWh for the Dutch and British electricity markets.

	2015	**2016**	**2017**	**2018**	**2019**
NL market (€/MWh)	15.50	22.25	15.19	1.96	12.95
UK market (€/MWh)	0	5.01	2.77	0	12.95

In Figure 6-9, the resulting revenues are shown for a Dutch wind farm under a SDE++ scheme and a CfD scheme. In addition, a horizontal line representing the height of the LCOE is displayed. Only when the bars exceed this threshold, a profit is made by the wind farm developer. Similar, in Figure 6-10 the revenue earned of a British wind farm in the reference case scenario are depicted. In addition, the annual heights of the subsidies are shown in table B-13 and B-14. In addition, in appendix B-4 the height of the collected revenues (in euros) by the wind farm developers form both perspective and under various subsidy schemes are shown in Figure B-4 and B-5.

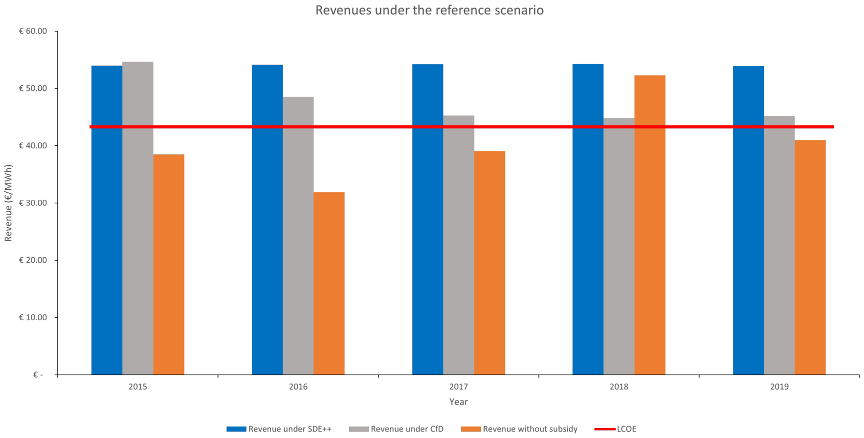


Figure 6-9: Revenues of a Dutch wind farm with and without subsidy schemes.

Naturally, the increased revenue for the wind farm is eventually paid by society through the subsidy. The costs imposed on society are often larger than just the financial compensation for the wind farms. Additional employees are necessary to carry out the policy, among others, in terms of administrative work. However, since the details regarding policy and regulations is left out of the scope of this research, the costs of the subsidy schemes are assumed to simply equal the difference in the extra revenue collected by the wind and the reference case. The resulting costs of the subsidy schemes are displayed in Figure B-6 and B-7. A notable remark is that it is theoretically possible for a government to earn money on the CfD scheme. For this scenario to occur, it implies that the strike price was relatively low in comparison to the actual market prices. Nevertheless, this does not imply that a wind farm developer is making a loss on its investment. The CfD schemes are meant to take away the volatile risk in electricity prices. As a consequence, a wind farm developer will never submit a bid that makes it impossible to earn a profit in the end of a projects life time.

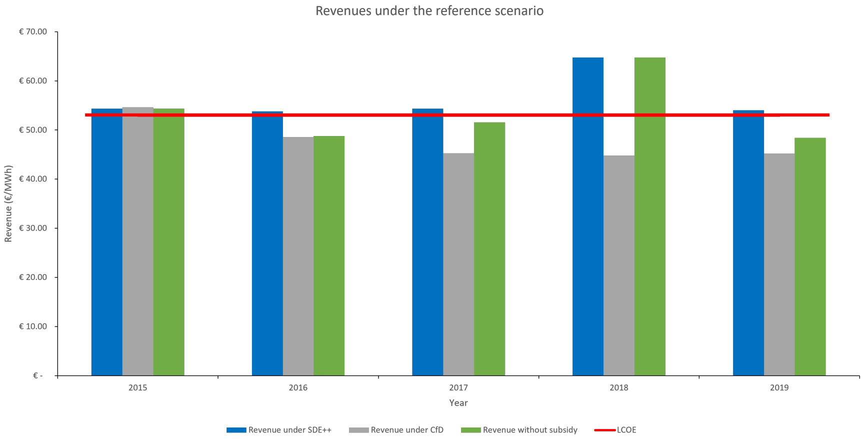


Figure 6-10: Revenue of a British wind farm with and without subsidy schemes.

6-3 Scenario 2: Cross-border connection

Now that the base case has been established and the reference case has been simulated, the second scenario can be implemented in the conceptual model. As stated before, this is a cross-border connection with a single wind farm that is operating in its home market. This situation is often mentioned as a hybrid connection which implies that an interconnection is established using, in this case, an offshore wind farm. This section simulates the effects of the introduction of an additional connection to a second market. Nevertheless, before insights of these effects on the business case of the wind farm can be obtained, the first step is to introduce a set of new physical constraints. The schematic representation of the simulations steps taken can be seen in Figure 6-11.

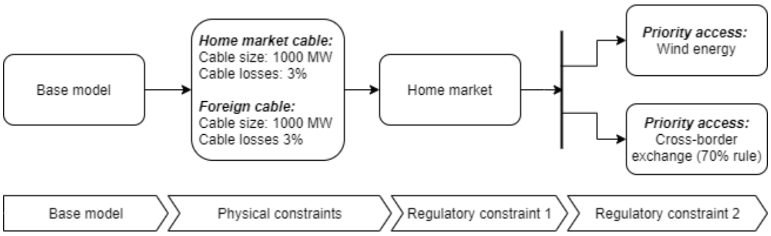


Figure 6-11: Simulation steps taken for scenario 2: Cross-border connection.

A physical representation of the cross-border connection scenario is illustrated as the second connection scheme in Figure 5-3. This seems like a relatively simple scenario, but as this section will illustrate, the addition of a second market in the system calls for regulations to clarify certain conflicts. Because of the OFTO governance model used in the United Kingdom transport tariffs are introduced by the OFTO, as was explained in chapter 5. However, this is only the case for transmission cables, more specifically, internal transmission cables. Currently, there are no transport tariffs imposed by the British ESO National Grid cables that classify as interconnector cables.

6-3-1 Free situation

In order to be able to solely simulate the effect is of the new connection scenario a set of additional parameters is added to the system, namely the set of cable capacity and losses. The characteristics of this cable is set to be identical to the home market connection cable. This has been presented in chapter 5. Furthermore, with the new cable connection, the data set of the British electricity prices will become available to the Dutch wind farm developer and vice versa. Because of this, there is no right way of simulating just the effects of the extra foreign connection, without any regulations. The scenario will be explained using Figure 6-12 and table 6-7, where Q_{max} is the maximum capacity of the export cables in MW. Every hour the situation changes according to the electricity output of the wind farm and the price developments in both bidding zones. Either the output of the wind farm is less than the available export capacity (situation 1 and 2) or it exceeds the available transport capacity (situation 3 and 4). In addition, the changing electricity prices determine the direction of the power flow.

Figure 6-12: Schematic representation of a connection scenario including a Dutch wind farm with a cross-border connection.

Table 6-7: Different situations in terms of wind farm generation, and price difference in adjacent bidding zones.

Situation	Generation farm	Prices bidding zones
1	$<Q_{max}$	NL >UK
2	$<Q_{max}$	UK >NL
3	$>Q_{max}$	NL >UK
4	$>Q_{max}$	UK >NL

In order to simulate the effects of a cross-border connection it is first assumed that there are no regulations at all. This implies that the wind farm developer can make its own decisions about selling its electricity to the bidding zone with the highest price, only limited by the amount of transport capacity available. This is carried out in order to set up a case to see what a wind farm theoretically should be able to earn by just the implementation of this cross-border connection. Nevertheless, it is important to comprehend that this situation does not represent reality. This would be impossible because of the balancing responsibilities of both the connected TSOs. In addition, it is also impossible because of the unbundling rules stating that generators may not take ownership in transmission assets what basically happens in case. However, this step is solely performed in order to obtain insights into what extent the wind farm developer could earn its maximum (theoretically) revenue.

The resulting effect on the generation for a wind farm in this particular connection scenario is depicted in Figure 6-13. It is seen that the actual generation is close to the theoretical generation calculated in the base model. This can be explained due to the large capacity of transport made available in this situation. Generally speaking, the wind farm has two ways of both 1000MW to export its generated capacity. Due to the volatile nature wind generation the wind farm becomes quite over-designed.

When looking at the revenues in terms of export capacity, one situation out of the four described in table 6-7 occurs every hour based on the generation and market price of the wind farm and bidding zone respectively. It is assumed that in situations 3 and 4 (table 6-7) in which the wind farm has a surplus of energy, meaning that it generates more than the capacity of one export cable, the electricity is sold first to the higher priced bidding zone until that particular export cable becomes congested. Next, if there is still a surplus capacity left, the electricity is sold in the lower-priced bidding zone. In addition in the situation 1 and 2, no congestion occurs and the generated wind capacity is sold in the bidding zone with the highest price. An accumulation is shown in Figure 6-14, the revenue earned per unit generated electricity over the specified time period for the free cross-border scenario and both the reference cases for Dutch and British wind farms is. In addition, the absolute revenues in euros under this first simulation step can be seen in Figure B-8. Furthermore, a graph presenting the levels of both the LCOE for a Dutch and British wind farm with respect to the revenues earned can be seen in Figure B-9.

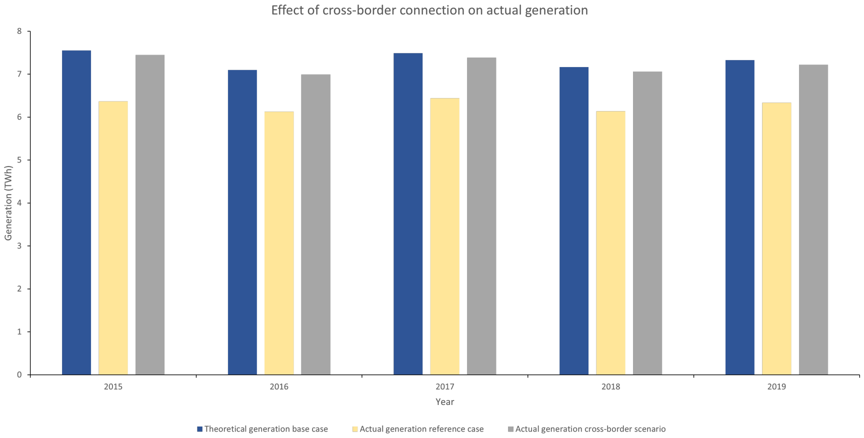


Figure 6-13: Comparison of the actual electricity generation of a wind farm in a cross-border scenario (free situation) with respect to the reference case and the base case.

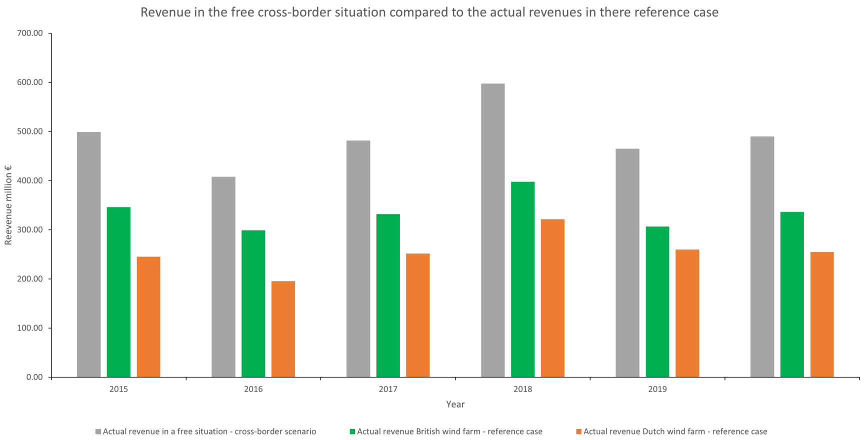


Figure 6-14: Comparison actual revenue per unit of electricity generation of a wind farm in a free cross-border scenario with respect to the reference scenarios.

6-3-2 Effect of the home market

As was stated in the previous paragraph, this scenario does not represent reality. In order to represent the situation more realistically, the regulatory constraint of the home market is introduced in the next simulation step. As stated earlier throughout this research, the home market situation makes it impossible for the offshore wind farm developer to receive a foreign electricity price for its generated capacity. It can only sell its electricity within the borders of the market in which the wind farm is located. Currently, as the offshore wind sector is relatively new, the wind farms are still seen as part of the onshore electricity grid. When building on the free situation that was previously described, two situations occur when implementing a home market. First the effect of an home market set up will be analysed in which a wind farm developer has priority access on the export cables over cross-border capacity exchange. The second situation follows the current regulation and will focus on the priority for cross-border capacity exchange on the export cables. The resulting effects of each situation will be presented.

Priority access: wind energy

The first situation that will be discussed, is similar to the free situation. When situation 3 or 4 from table 6-7 would occur. Thus, when the wind farm has generated more than the transport limit on one of the export cables, the wind farm developer would in a free situation try to export this surplus capacity to the adjacent bidding zone in order to maximize its profits. As was discussed in the previous section, this is not possible in a real-life situation because a numerous reasons. As the wind farm has priority access over the cross-border capacity exchange, it becomes difficult to calculate the congestion income. For example when situation 3 or 4 occurs from table 6-7 in which the wind farm produces a surplus of electricity. The direction of the power flow is of no interest for the wind farm developer since it will always receive the electricity price from its home market. An assumption has to be made that clarifies the direction of the generated wind capacity in certain price-related situations. When the price of the home market of the wind farm exceeds the price of the foreign market the generated capacity will flow to the home market. Nevertheless, following this theoretical situation in which the wind farm is able to do this an underlying assumptions is automatically made, namely that generated wind electricity has priority access on the cables. However, as multiple actors are present on the exporting cable such as the TSOs, conflicts may occur as to whom has priority access on the cable.

Building on the free situation previously described, the first simulation takes into account that the capacity generated by the connected wind farm has priority access on the cable over everything else. As a consequence of the home market setup, the wind farm developer will receive the market price of its national (home) market no matter the direction of the physical power flow. The offshore wind farm could be seen as any other onshore generator, and is subjected to the dispatch order that follows after market clearing. In addition, cross-border exchange is calculated and dispatched through market coupling mechanisms that make no distinction between generators and follows from the electricity prices and transport limits between the zones. However, as priority access for wind generation in hybrid setups is becoming more debatable, simulating a situation in which wind has priority access may give new insights for discussion. The effect of the home market set-up including wind priority on the export cables with respect to the free situation is illustrated in Figure 6-15 and corresponding values are depicted in table 6-8 for a Dutch and British wind farm respectively. In addition, Figure B-10 shows the absolute revenues in million euros that the wind farms are able to collect under this situation.

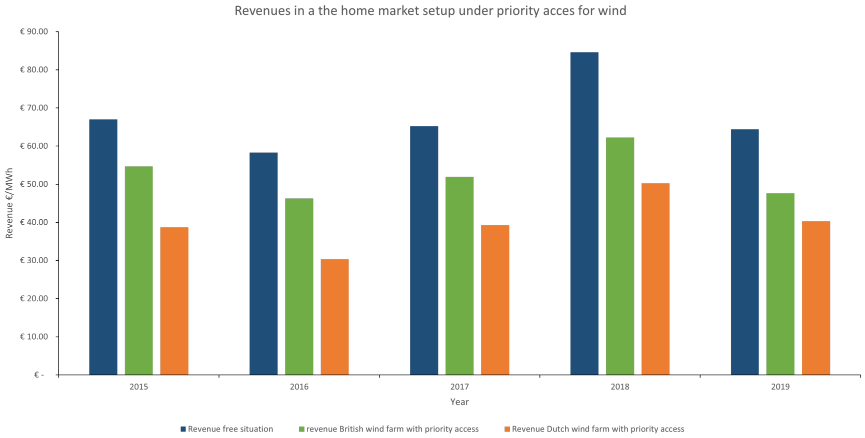


Figure 6-15: Revenue collected by a Dutch and British wind farm in a cross-border scenario under the home market setup in which wind generation has priority access.

Table 6-8: Revenue collected by a Dutch and British wind farm in a cross-border scenario under the home market setup in which wind generation has priority access.

	2015	**2016**	**2017**	**2018**	**2019**
Revenue under in the free situation (€/MWh)	66.96	58.31	65.21	84.59	64.39
Dutch revenues (€/MWh)	38.70	30.30	39.25	50.22	40.24
British revenues (€/MWh)	54.66	46.23	51.95	62.23	47.59

As the wind farm has priority access over the cross-border capacity exchange, it becomes difficult to calculate the congestion income. For example, when situation 3 or 4 occurs from table 6-7 in which the wind farm produces a surplus of electricity, the direction of the power flow is of no interest for the wind farm developer since it will always receive the electricity price form its home market. An assumption has to be made that clarifies the direction of the generated wind capacity in certain price-related situations. When the price of the home market of the wind farm exceeds the foreign price, the generated wind capacity will be dispatched over the export cable connecting the wind farm to its home market. This is done in order to clearly show the different effects of the distinct priority access situations. In addition, when the foreign price exceeds the home market price the wind farm will be dispatched over the interconnection cable and if there is still a surplus of electricity left it will be dispatched over the export cable in the direction of the home market. In addition, the TSOs are not incentivized to 100% utilize an interconnector for cross-border exchange because of its internal congestion management. Because of this, the assumption was made that no additional cross-border exchange between the countries in this situation occurs. An example of the situations that could occur is displayed in Figure 6-16.

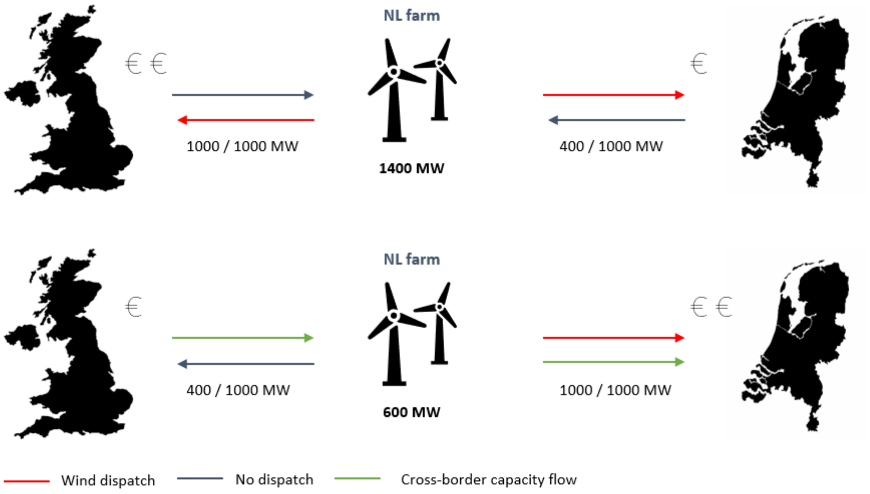


Figure 6-16: Direction of dispatched capacity when wind generation has priority access on the export cables over the cross-border capacity exchange.

Because of the cross-border connection an additional monetary flow occurs, namely the congestion income. This has been mentioned a few times throughout this research, such as in chapter 2. Congestion income can be best explained as the difference in price between two separate bidding zones connected by means of an interconnector. This amount is received by the TSOs of the connected bidding zones. This financial flow however, is regulated. This implies that the NRA determines how much of the collected CI can be spend on which projects. If for some reason, it becomes inefficient to spend the congestion income on existing projects resulting in a surplus of CI, the income can be used to lower the transport tariffs. The amount of CI received by a TSO depends, aside from the difference in price, on the stake of ownership in the interconnection asset. However, in this research the simplification has been made that the congestion income is evenly distributed over both TSOs. When looking at the earlier described situation without restrictions or rather free situation, a first insight in the collected CI can be obtained for a Dutch and British perspective respectively. Al-though the CI is evenly distributed among the TSOs, it is still important to take both perspectives into account since much less congestion income is generated when looking from a British wind farm selling most of its electricity in its home market.

From Figure 6-16 it can be seen that only in two situations congestion income can be collected by the TSOs if, and only if, the wind energy has priority access over the cross-border exchange. When looking at the situation in which a Dutch wind farm is used, congestion income can only be collected when the British electricity prices exceed the prices of in the Dutch home market. This would be the same in the situation of British wind farm. The power flows are exactly the same in the wind priority situation as for the the free situation, except for cash flow for the offshore wind farm. The congestion income which is applicable for both the wind priority and free situations can be seen in Figure 6-17. The next situation however, will affect the balance of revenue and congestion income with respect to the situation in which wind generation is priority access over cross-border capacity exchange. This will be discussed in the next paragraphs.

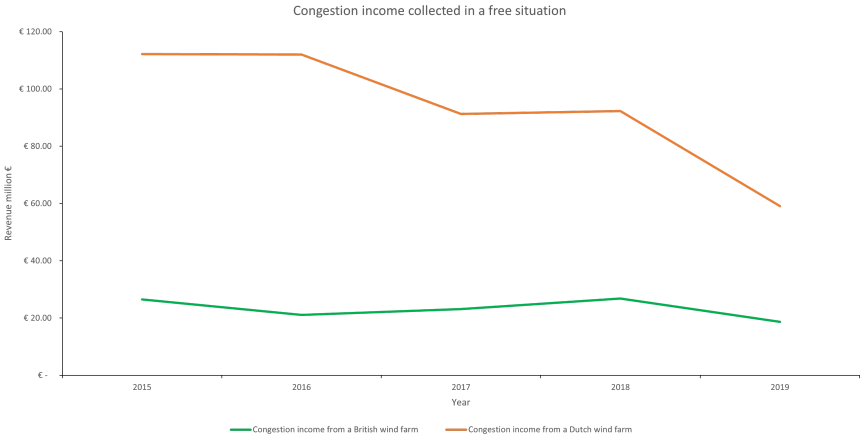


Figure 6-17: Total accumulated congestion income in the case of a Dutch wind farm and a British wind farm per year.

Priority access: cross-border exchange

The second situation displays the current case in real life. In this situation, the cross-border capacity flow between the connected bidding zones has priority access over the wind capacity generated by the wind farm that are part of this hybrid setup. According to a staff document written by the EC, for hybrid projects, priority dispatch of large renewable energy generators is no justification for reductions in cross-border capacity made available for trade (European Commission, 2020b). With the introduction of offshore hybrid connections, this is a topic that is heavily debated in the discussion on hybrid asset regulation. Especially by offshore wind developers that are looking into the option to participate in a hybrid connection. However, as of today, no regulatory-related changes have been introduced to this situation. As a consequence, the priority access on the cable is appointed to the availability of cross-border capacity exchange between bidding zones. This, of course, will in some cases impose a negative effect on the usable capacity on the export cables for the wind farm developers.

It is important to understand that a TSO is not always incentivized to fully utilise a cross-border connection, especially when the cross-border capacity is relatively large in terms of capacity. A fully utilisation of the interconnection cable implies a constant power flow of 1000 MW each hour going in or out the asset. Ideally, a TSO makes use of the interconnection cable in order to solve its internal congestion, increasing or decreasing cross-border capacity dependent on the onshore grid situation. In order to obtain some insights into what order TSOs are actually utilising interconnector cables, the power flow from the BritNed and COBRA interconnector cables over a period of 2016 until 2020 was analysed. This data was received from the Open power system database (OPSD, 2021). Over this period both cables possessed an average utilisation of a little more than 70%. However, this was not the case when looking at an hourly time window, which were much more spread out. Furthermore, the infrastructure further onshore, connecting these ICs was designed and adjusted according to the projects whereas an additional cross-border connection to an existing wind farm may not and as a consequence may cause congestion when utilized fully. In addition, both the Cobra cable and NorNed cable have targets regarding the utilisation of the cable whereas the BritNed cable is a merchant interconnector which follows different rules. When the target is met or even exceeded, a bonus is granted. On the contrary, if the targets were not met a fine was impeded on the owners.

As is described in the problem statement, in order for Europe to cope with the dealing issues of the energy transition one of the goals set by the EC is to work towards a fully integrated European electricity network. In order to establish, or rather, accelerate this goal, the EC has adopted a somehow controversial rule. This legislation is described in the Clean Energy Package (CEP) and it states that each member state has to reserve at least 70% of its interconnectors for cross-border capacity trade. Naturally, a lot of discussion is subjected to this rule. It can be easily assumed that without any form of exemption of the 70% rule, wind farms will only be able to use a maximum of 30% of the export capacity of the cables. This implies that almost all wind energy production of offshore wind farms in hybrid connections will be curtailed due to the limited capacity available. Curtailment is the process of reducing or even shutting down the output of generators, often to solve congestion. However, the curtailment of wind and the 70% rule have in term a positive effect on the collected congestion income by the TSOs. This is shown in Figure 6-18. The increase in congestion income can be explained due to the fact that if cross-border capacity exchange has priority access on the cable, a minimum 70% of the cable is used for this exchange. Naturally, this has an positive effect on the congestion income collected over the cross-border capacity echanges by the TSOs.

In order to comprehend the effects of this priority access rule for cross-border capacity trade on the business cases of wind farm it is crucial to know how much wind energy is being curtailed in this scenario. This is displayed in Figure 6-19. In addition, this implode of generated capacity by the wind farms do not necessarily mean that the wind farm developers receive less income. According to AFRY (2020), Dutch wind farms for example are being compensated 100% for curtailment. This implies that the wind farm receives the market price that it would have gotten when offered to the market (including its FIT premium). For the UK however, bilateral contracts have been setup for each specific wind farm 6-9 and 6-10

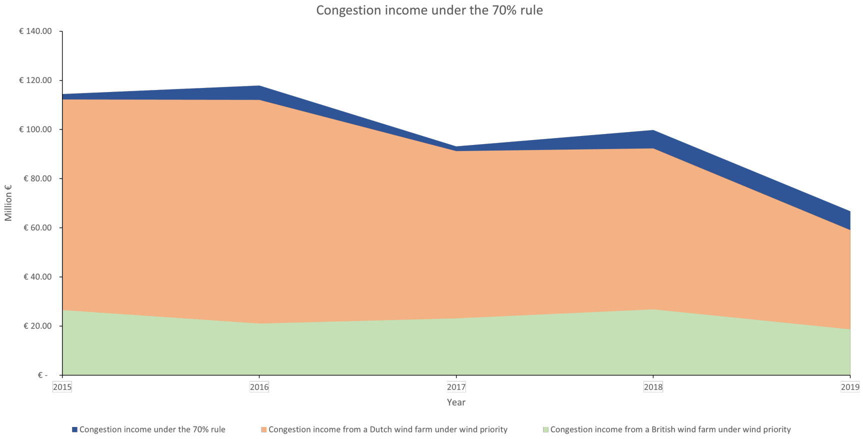


Figure 6-18: Collected congestion income in a home market setup including the 70% rule compared to the wind priority situations.

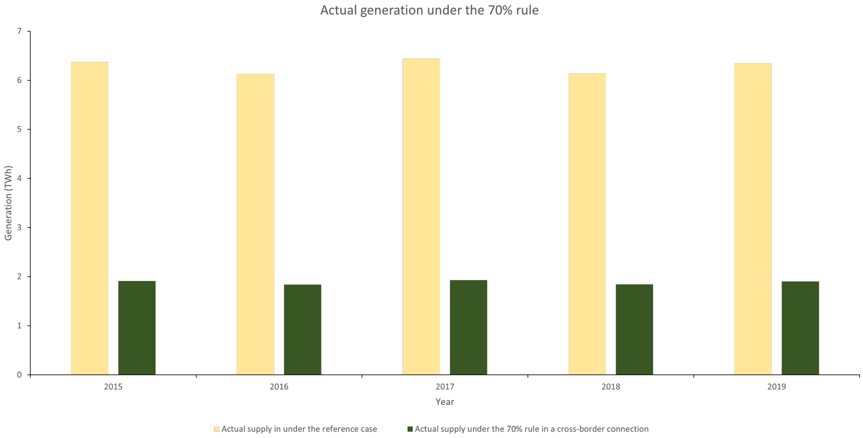


Figure 6-19: Wind farm supply in the reference case compared to the home market setup including the 70% rule.

From this simulation arises a discussion because the rule does not state clearly to what part of the cable the 70% rule applies to. If in a home market set up a cross-border connection via an offshore wind farm is realised as is illustrated in Figure 6-12. Technically, in a home market setup, only the interconnection connecting the Dutch wind farm to the British shore and vice versa is defined as an interconnector. Unfortunately for the wind farm developer, this would not matter as long as the cross-border capacity is prioritized over the wind generation in the transmission cables. If 70% is obligated at the interconnection cable, the TSO will make sure that when it is importing electricity from the UK, to curtail the surplus energy of the wind farm. This would be the case even if wind generation has priority over cross-border capacity trade. For example, in the situations in which the Dutch TSO is importing electricity, the wind farm has to be curtailed to a maximum of 30% of the cable in order to be compliant with the 70% capacity coming in via the interconnection cable.

In addition, another difficulty arises. There is the question of how to grant support schemes for future hybrid connections. This is especially important for the British wind farms since currently no British wind farms have been constructed without the support of the CfD scheme. In addition, at this point, it is safe to conclude that without the introduction of any type of support, no hybrid connections by means of an OWF will be established in the current home market setup. Furthermore, the SDE++ scheme seems to be unequipped for the job since there is the interaction of two electricity markets, which may be conflicting in determining the annual correction price.

The resulting effects are displayed in Figure 6-20. There is no addition for the 70% rule because the Dutch government compensates the wind farm fully with respect to its radial connected situation. Therefore, the revenues including the subsidy premiums are equal to that when implementing the 70% rule. In addition, the resulting effects on a British wind farm are displayed in figure 6-21.

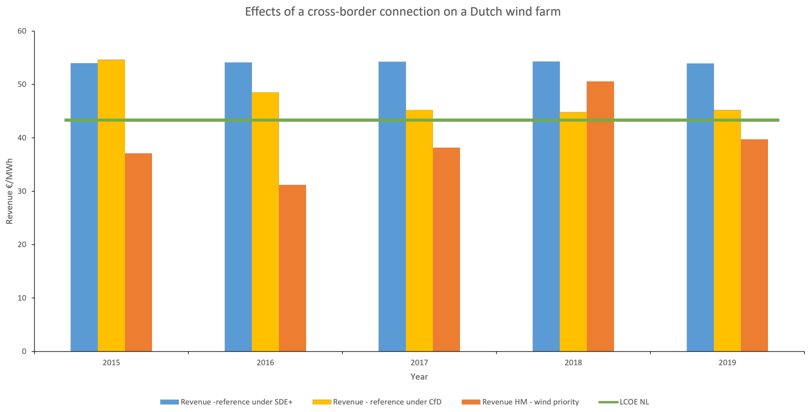


Figure 6-20: Overview of the introduced effects on the revenue stream of the Dutch wind farm in a cross-border connection scenario.

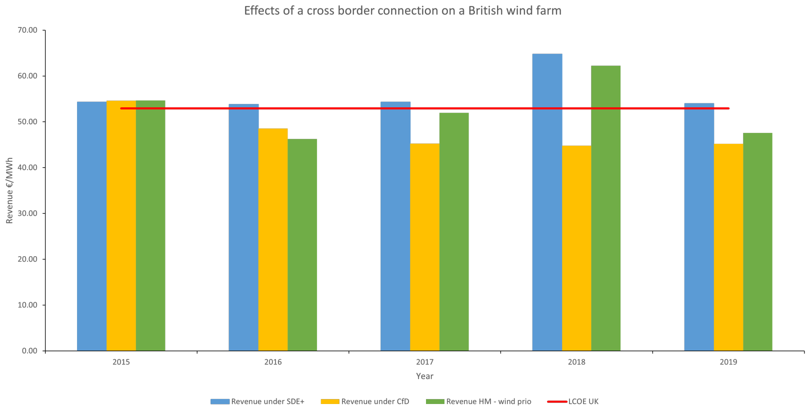


Figure 6-21: Overview of the introduced effects on the revenue stream of the British wind farm in a cross-border connection scenario.

6-4 Scenario 3: Offshore Bidding Zone

The method used for simulating the cross-border scenarios is not fully applicable to the offshore bidding zone scenario. As is explained in chapter 5, the offshore bidding zone could be seen as rather a market change than an actual change in connection typologies. In order to address the effects of this scenario on the business case of a wind farm, a situation in which a wind farm with a single cross-border connection is present within the offshore bidding zone. A schematic representation of the simulations steps are displayed in Figure 6-22.

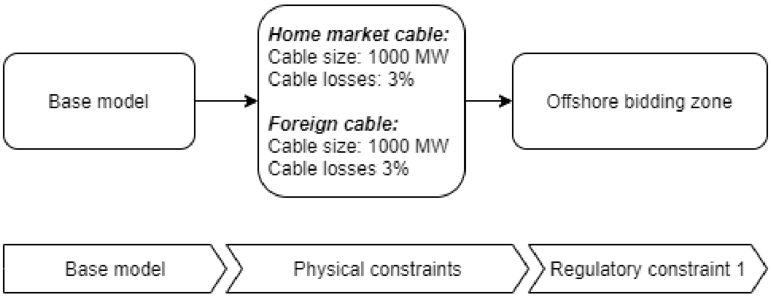


Figure 6-22: Simulation steps taken for scenario 3: Offshore Bidding Zone.

For this research solely the situation of a single wind farm with a cross-border connection is simulated under an offshore bidding zone market setup. This is done because the time period in which this research was performed was too limited to consider additional conneciton scenarios. For example, a cross-border connection between an British and Dutch wind farm could be simulated, or even a more complex situation such as the hub-and-spoke system. In these scenarios still every wind farm would operate in its own biding zone.

However, to clarify this simplification, an example will be demonstrated. If a combination of multiple radial connected British and Dutch wind farms were to exist in an OBZ (see figure 5-4), it would not matter how or if these farms are connected to one another. The net capacity going in and out of the zone is fully determined by the export cables reaching the shore since these cables set the demand. A schematic representation is seen in Figure 6-23.

As is stated earlier, the price within an offshore bidding zone is fully dependent on the adjacent bidding zones. The reason why is because only generators are present within the bidding zone and as a consequence there is no demand in an OBZ. This may however change in the future when storage is included. Nevertheless, currently this is not the case since at the moment no offshore biding zone exists in real-life. With the lack of a demand within the bidding zone the wind farms often will get a converged price of the two bidding zones which it is connected to. In most cases, this results in an electricity price which is equal to the lower market price of the connected bidding zones. When the offshore bidding zone is implemented in the model, an hourly merit order is created such as displayed in Figure 6-26. The advantage for an offshore bidding zone with respect to the home market is that the offshore bidding zone is compliant to the 70% rule.

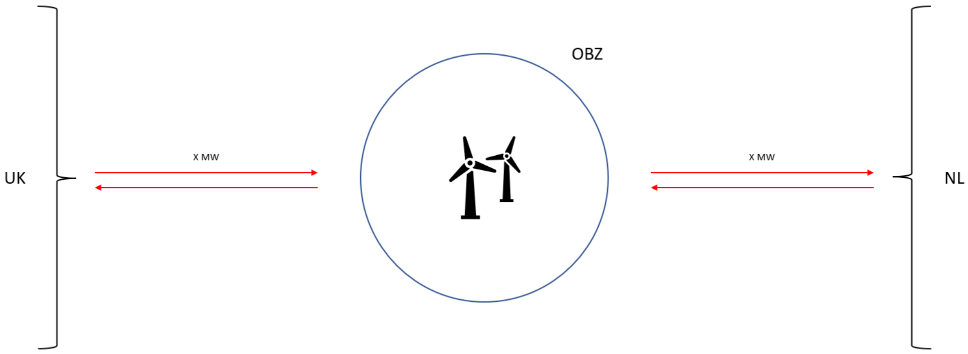


Figure 6-23: A schematic representation of a simplified offshore bidding zone scenario.

The effects resulting from the simulations are displayed in Figure 6-24 and Figure 6-25. In these graphs the revenue of a Dutch and British wind farm under an offshore bidding zone with respect to the cross-border connection scenario in which wind- and cross-border capacity have priority on the transmission cables are displayed. It can be seen that the revenues collected by the wind farms in an offshore bidding zone are similar to revenues that can be collected when the wind farms is in a cross-border connection where wind has priority access onto the transmission cables. This can be explained due to the fact that no curtailment occurs because the offshore bidding zone is compliant to the 70% rule. The dispatch is always a cross-border capacity exchange between the bidding zones. In addition, similarity is also observed with cross-border scenario including the 70% rule. Nevertheless, it must be noted that all compensation to the wind farm is imposed as costs onto society because this is paid by the TSO through higher transmission tariffs.

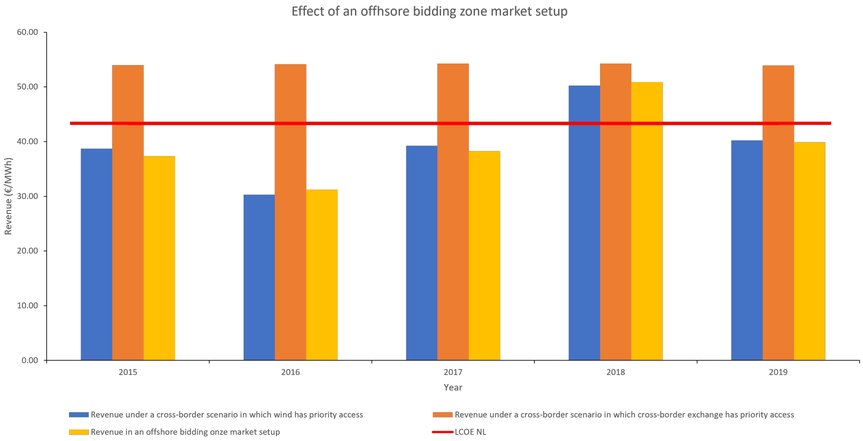


Figure 6-24: Revenue earned by a wind farm in an offshore bidding zone with respect to cross-border scenario for a Dutch wind farm with wind priority access and priority access for cross-border capacity exchange.

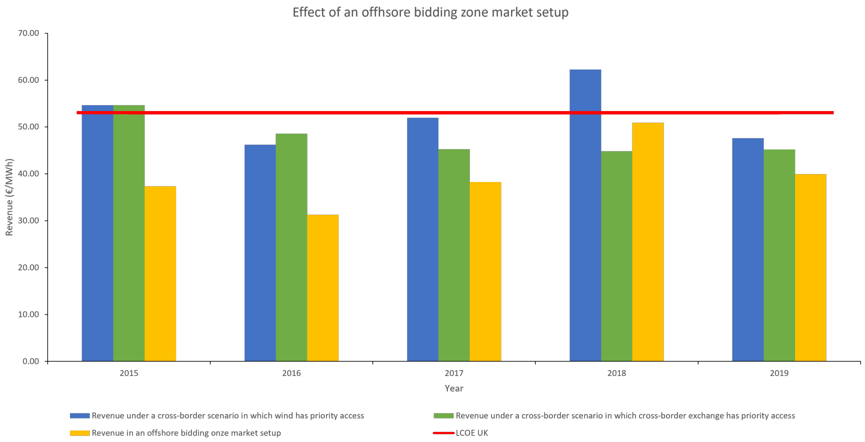


Figure 6-25: Revenue earned by a wind farm in an offshore bidding zone with respect to cross-border scenario for a British wind farm with wind priority access and priority access for cross-border capacity exchange.

Table 6-9: Revenue earned per MWh by a single cross-border wind farm under an OBZ over a time period from 2015 until 2019.

	2015	**2016**	**2017**	**2018**	**2019**
Revenue under OBZ mln €/MWh	37.37	31.25	39.05	52.31	40.98

Focusing on the revenues of the wind farm, it can be observed that the revenues are slightly lower compared to the reference case. As was mentioned earlier in this section, this can be explained due to the market-clearing mechanism in the OBZ. Because the zone has no market players that demand electricity and since the zone contains a set of critical interconnectors, determining the amount of capacity that can be transported between the zones, these transmission cables act as the demand. This implies that the demand can not exceed the capacity of the interconnector cables. In addition, since wind farms have almost no marginal costs, the wind farms present in the zone offer their capacity to the market for a price close to zero. Assuming that the connection cable to the higher-priced zone will be the first to be congested and that there is still supply for the demand in the lower-priced bidding zone, the offshore bidding zone settlement price will almost always be equal to the lower price. This is depicted in 6-26. In this figure, it is assumed that the British electricity price is lower than the electricity price in the Netherlands. In addition, it is important to note that the wind farm will not offer its capacity for marginal price for this scenario. Nevertheless, the figure clearly shows that wind farms have little to no influence on the price.

Besides the revenues collected by the wind farm, the TSO can collect Congestion Income. This is displayed in Figure 6-27. It is seen that the CI collected by the TSOs exceeds that of the cross-border scenario for a British wind farm in which wind has priority. Naturally, this can be explained due to the fact that the previous radial connections now act as interconnectors to the offshore bidding zone. This implies that all exchange between the wind farm and the onshore grid can be seen as a cross-border capacity exchange on which congestion income is collected. Figure B-13 and table B-17 displays all the congestion income collected

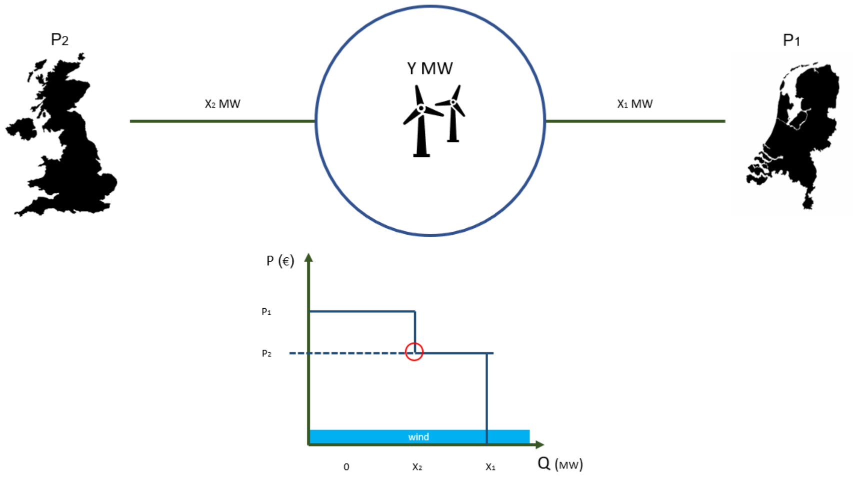


Figure 6-26: Schematic representation of the price settlement in an offshore bidding zone setup.

under the different scenarios. In addition, all revenues that has been simulated per scenario is displayed in appendix B-4 in table B-16 and table B-15.

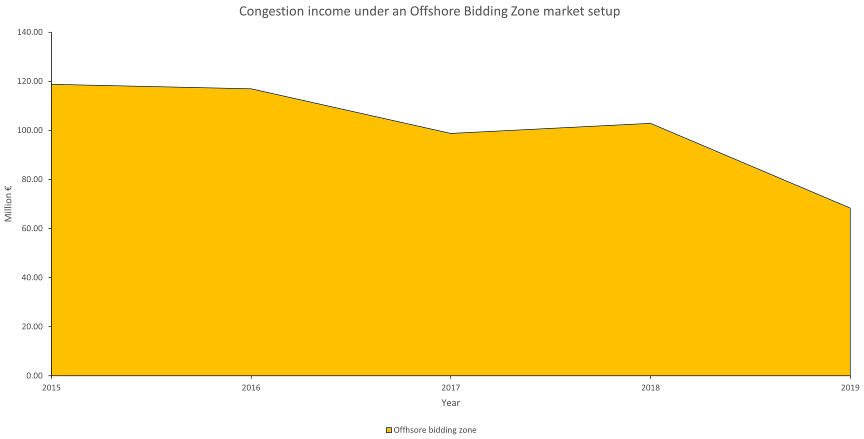


Figure 6-27: Congestion income earned under an offshore bidding zone setup.

6-5 Simulation findings

Th next section serves the purpose to summarize the results found during the simulations of each scenario. In addition, intermediate conclusions and insights will be presented.

This chapter started with the simulation of a base model that was used a starting point for the simulation of the various scenarios. A theoretical generation profile was introduced, meaning the total generation of the wind farm at a specified location without transmission limits. The average theoretical yield over the five-year period was about 7.3 TWh. Introducing capacity limits based on existing or future build wind farms, the actual yield of the wind farm was found to be 6.28 TWh.

The first scenario described a case of a radial connection to the national (home) market of the wind Dutch and British farms respectively. This case the currently present in the energy system and will be used as the reference case to compare the simulation output from different scenarios. It was found that for these specific wind farms, under the historical data such as wind generation and electricity prices the annual average revenue were about 336 and 254 million euros for a British and Dutch wind farm respectively. In addition, it was found that both Dutch and British wind farms are in need of support as the total income received per unit electricity did not exceed the LCOE. However, it is difficult to predict the dependency on subsidy schemes in the long term. Al tough the trend in LCOE tend to be decreasing, as the wind farms are being further constructed off shore, the prices tend to increase for grid connections. In addition, because of the expansion of the electricity system, it is relatively unknown what future electricity prices will be.

The effects of the introduction of a cross-border connection, as was simulated as the second scenario, had minor to no effects on the revenue obtained by the wind farms. This can be explained due to the fact that when a wind farm, or any type generator for that instance, is curtailed, the TSO is obligated to compensate the generator for its lost revenues. The height of the compensation is based on the amount the wind farm would have dispatched according to the market clearing mechanism. It can therefore be concluded that, the effects of a cross-border scenario have no negative impacts on the business case of a wind farm, or at least to a minor extend. However, this connection scenario imposed an additional financial burden on society as the compensation received by a wind farm developer are paid through collective institutions. Nevertheless, this does not imply that the net impact on society is negative. In addition, current regulation makes it nearly impossible for all actors besides a wind farm developer to construct these type of hybrid connections.

The offshore bidding zone market setup can have negative impacts on the revenues obtained by a wind farm, depending on the prices of its home market. In this simulation, the Dutch electricity market was the lower priced zone most of the time. Because of this, the impact of an offshore bidding zone from the perspective of a British wind farm are larger than for a Dutch wind farm. The British wind farm experiences a decline in revenue whereas the Dutch wind farm has an increased revenue under the offshore bidding zone market setup, for the specified location and time period. This can be explained by the fact that the cross-border connections adds additional transport capacity. Because of this, the wind farm can always be dispatched in its own bidding zone because its rated capacity, for this simulation, was less than the available interconnection capacity.

The simulations output of the second scenario describing the cross-border connection of a single wind farm clearly shows minor to no impacts on the business case of offshore wind farm developers. However, it shows an important regulatory conflict of priority access on the transmission cables. As a consequence, the wind farm will be curtailed most of the times and additional expenses are imposed on society. Because of the insights and simulation results, an offshore bidding zone seems to be a better a more suitable market setup for the cross-border connection scheme, at least for the early stages of unlocking the North Sea wind potential. The offshore bidding zone is complaint with the 70% rule, and no priority access conflicts are present. In addition, more wind capacity can be transported. However, from a wind farm perspective this is not a preferred options because of the loss of a part of its revenues. In order to mitigate this effect, additional support schemes will be investigated in chapter 7. By default, the analysis will mainly focus on the offshore bidding zone market setup.

Chapter 7

Mitigation options

The previous chapter described the effects of various scenarios on the business cases of offshore wind farms. In addition, various negative effects were found regarding the wind farm developers revenue and the costs imposed on society. In addition, it was shown that without the use of a support scheme such as the currently used SDE++ and CfD schemes, the business case of both the Dutch and the British wind farms are not profitable (in the short term).

This chapter focuses on how the business cases of wind farms can be protected. This implies identifying instruments that can offer financial compensation for the lost revenues of the wind farms that partake in a hybrid asset, as was described in the various scenarios in chapters 5 and 6. These instruments are policy schemes and will be regarded as "mitigation options" or "mitigation schemes" since these instruments adopt the goal to mitigate the loss in revenue for wind farm developers. In addition, the scope of this research is limited the the assessments that can be carried out based on the output of the model.

To summarize, first, the selection of an academic method for assessing the mitigation schemes will be discussed. Second, an overview of today's proposed mitigation schemes is identified. In addition, each mitigation scheme needs an additional explanation that will be presented. Third, the identified method will be used in order to compare the mitigation schemes on certain criteria that have been identified in the subsections elaborating on the method. Last, the method is carried out by assessing the criteria for each scheme in one of the scenarios presented in the previous chapters. The financial criteria will be analysed using the developed model, by adding additional constraints in the existing scenarios in order to see the effects on the business case of the wind farm developers. Last, the qualitative criteria are analysed using the information found in the literature throughout this research.

It is important to take into account that currently the EC and its subordinate organisations such as ACER and ENTSO-E are still discussing this topic with the national TSOs and NRAs of the member states and some of the involved offshore wind developers. This implies that, to this day, there is no preferred mitigation scheme selected and various position papers are still being produced on the topic. This chapter will elaborate on some mitigation proposals found in the current literature. In addition, the author of this research paper proposes an additional solution by combining some of the proposed mitigation schemes.

This chapter has various goals. Its main goal is to assess various mitigation schemes proposed in the literature by means of quantifying the economic impact on the business cases of offshore wind farms using the developed model. In this way, new insights may be obtained into the effectiveness of the proposed mitigation options. In addition, this chapter introduces an academic approach to assess the currently proposed mitigation options by means of scoring various criteria. As a consequence, this chapter also served to goal to start the discussion on what the important criteria are, how to score them, and what actors should be involved in the discussion.

7-1 Method

In order to assess policy schemes, various methods or approaches can be adopted. According to the TU Delft-Wiki Index of methods, three methods seem applicable to this particular situation, namely the policy analysis framework, the policy hexagon model and the policy scorecard method. Each of these three methods will be briefly discussed and a selection will be made on which approach is adopted in this research.

Policy Analysis Framework

The first method, the Policy Analysis Framework, is a framework that is both used in governments and in consultancy firms. It can be seen as a general way for problem-solving rather than for specific problem-solving. This method sets up a similar system just like the modelling and simulations approach mentioned in chapter 1, but then specified to policy-making situations. System boundaries are introduced and external effect labelled as "policy changes" are being implemented that causes the system to change. A visual representation of the method can be seen in Figure 7-1. Here it is observed that the system of interest is limited to a set of boundaries which represent the external forces. In addition, policy scenarios are implemented into the model and the outcomes are evaluated according to the goals and objectives the policy has. In addition, the steps in order to perform this approach are listed to the right in the Figure.

Policy Analysis using the Hexagon Model

The second method, Policy Analysis using the hexagon Model, adopts a model that attempts to restructure the discipline of policy analysis into a single conceptual model. van Daalen et al. (2010) identifies six activities which are then translated into various underlying policy analytic styles. The conceptual model is displayed in Figure 7-2. All corners of the hexagon indicate the different policy analysis styles that can be carried out by the researcher adopting this method. Then, criteria for the success of policy analysis are shown inside the corners of the hexagon. The method is widely applicable to various situations. The objective of

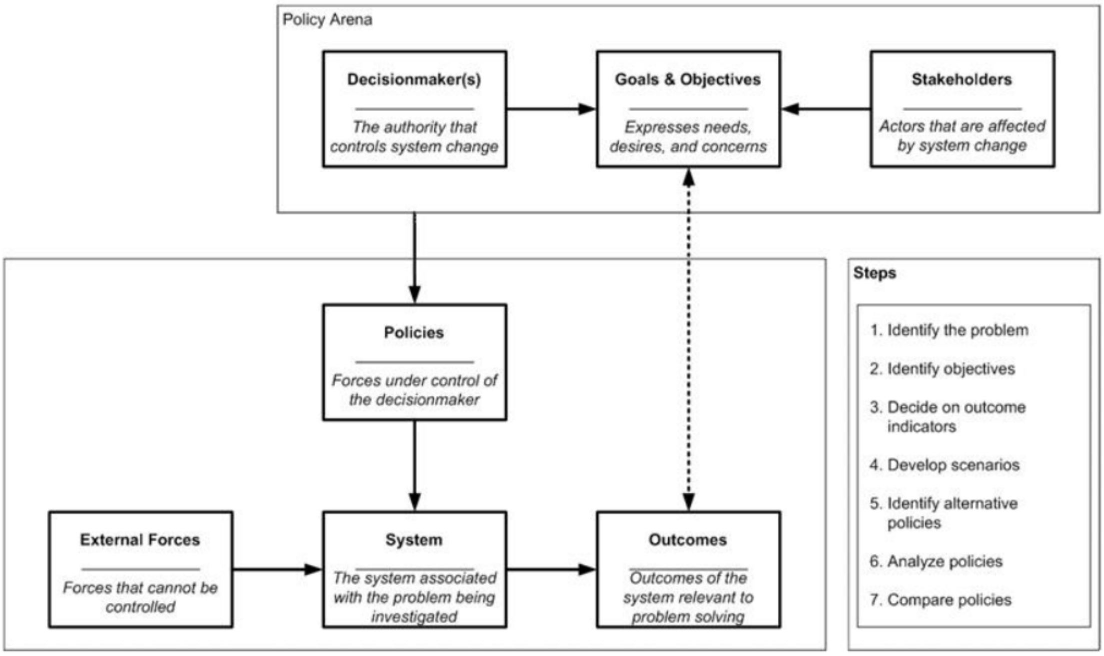


Figure 7-1: The policy analysis framework and steps (Walker, 2010a).

this method ultimately is to inform and improve policymakers or policy-making processes. This method serves three purposes, namely understanding the policy analysis as a discipline, contribution to newly developed policy methods and approaches and serves as guidance to evaluate methods and projects (van Daalen et al., 2010). Especially, the third purpose may seem applicable the problem that is analysed in this research.

Although both methods might be applicable to these policy-related issues, it seems that these methods adopt a policymaker perspective. This is often regarded as the traditional way to assess policies. However, for this research, actors of interest are the wind farm developers. As has been mentioned throughout this research, this was chosen this way because insights into the wind farm developers is crucial as they could act both as barriers and as gateways in the realisation of these hybrid offshore connections. Therefore, a more suitable method might be to include their perspective on mitigation schemes besides the conventional actors such as the TSO and NRAs or Ministries.

Policy scorecard

The third method called the "Policy Scorecard" may seem to be a better fit for assessing the mitigation schemes. This method is often used in the final stage of policy analysis and focuses on choosing the right strategy or policy out of a set of possible options or scenarios. In addition, the policy scorecard approach is often associated with a multi-stakeholder analysis in which each impact is weighted by its relative importance and combined into some single unit such as money, worth or utility (Walker, 2010b). The method uses multiple techniques to help an individual decision-maker choose a preferred strategy. One of the advantages of this method is that the Policy Scorecard makes it available to include both quantitative criteria

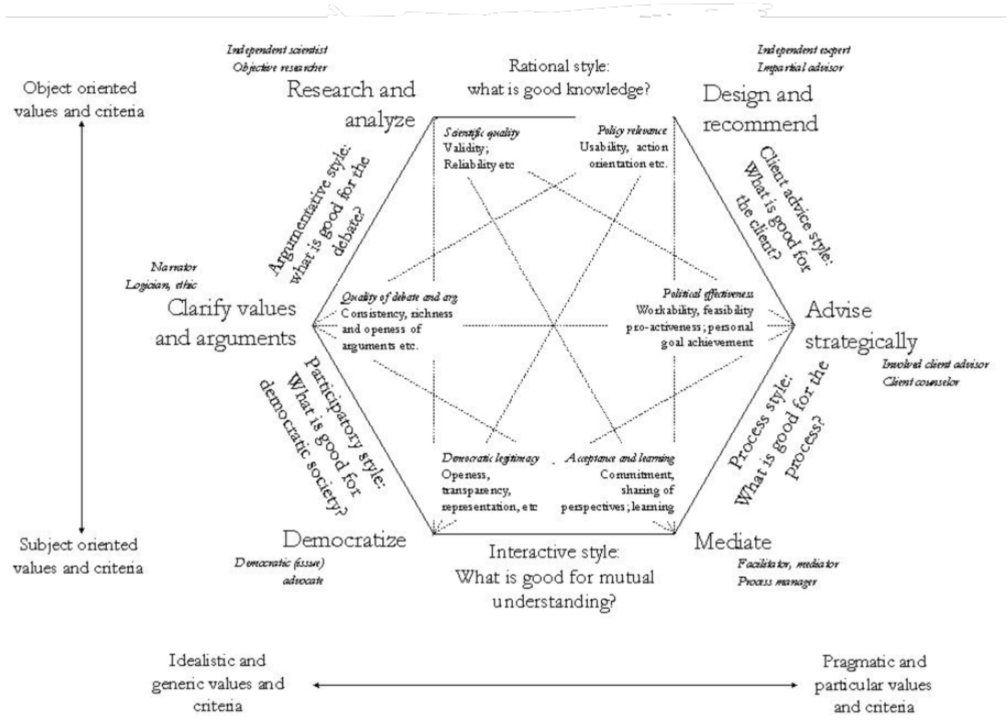
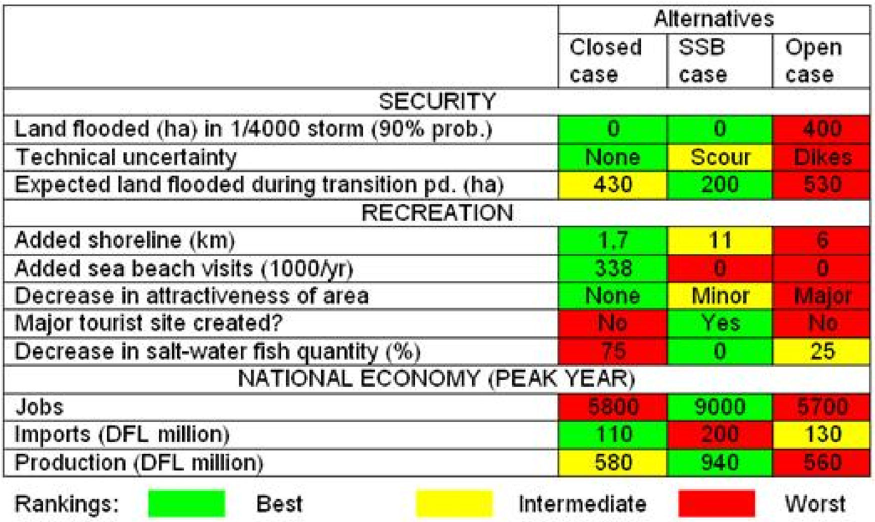


Figure 7-2: The hexagon model of policy analysis (van Daalen et al., 2010).

as well as qualitative criteria.

The disadvantage of this method, however, is that it is subjected to the weights assigned by the individual carrying out this method. Nevertheless, according to Walker (2010b) the policy scorecard method avoids a type of problem, namely practical problems that include the need to answer the issue of interpersonal comparison of values. Within the scorecard, each row represents specific criteria and each column represents a policy option. In this way, the scorecard evaluates the impact of various policy schemes based on the specific scenario and according to the specified criteria. The rows show each assigned weight for a single impact. Each stakeholder can score the card to its own weight. In addition, some effects can be described in a quantitative way and other effects might be described in qualitative ways. An example is seen in Figure 7-3. It can be observed that both qualitative and quantitative criteria are used to score three distinct alternative (policy) scenarios. In addition, as there are many ways to assign scores, two additional examples are presented in Figure C-1 and C-2. The first example showing solely a qualitative scorecard on which policies are scored regarding the shortage of female nurses in Jordan. In addition, the second scorecard was used to evaluate the EU Safety & Health at Work legislation. In this policy scorecard, the columns and criteria were alternated, meaning that the columns are the criteria and the rows are the different policies. In addition, a range from zero to five was used to evaluate the distinct policies for each criterion, zero being the worst and five being the best score.

Considering these three methods, it can be concluded that the first two methods have the ability to describe process of policymaking more accurately. However, the third method



	Alternatives		
	Closed case	SSB case	Open case
SECURITY			
Land flooded (ha) in 1/4000 storm (90% prob.)	0	0	400
Technical uncertainty	None	Scour	Dikes
Expected land flooded during transition pd. (ha)	430	200	530
RECREATION			
Added shoreline (km)	1.7	11	6
Added sea beach visits (1000/yr)	338	0	0
Decrease in attractiveness of area	None	Minor	Major
Major tourist site created?	No	Yes	No
Decrease in salt-water fish quantity (%)	75	0	25
NATIONAL ECONOMY (PEAK YEAR)			
Jobs	5800	9000	5700
Imports (DFL million)	110	200	130
Production (DFL million)	580	940	560

Rankings: 🟩 Best 🟨 Intermediate 🟥 Worst

Figure 7-3: Sample scorecard (from the Policy Analysis of the Oosterschelde (POLANO) project) (Walker, 2010b).

"The Policy Scorecard" includes a neutral point of view of the system in which scores can be appraised by various perspectives. This characteristic of the method is more important to address the problem of this research. Furthermore, this research does not go into the details of policymaking. Therefore, this third method seems to be a better fit compared to the other methods. As seen in Figure 7-3, a scorecard consists of two major elements, namely the alternative policies indicated in the columns and the scoring criteria indicated by the rows. In the following sections, the first element will be determined by identifying an overview of distinct mitigation options. After this overview has been identified, the second element of a scorecard, namely the criteria, will be determined.

7-2 Mitigation schemes

In this section, an overview of mitigation schemes that will be used in the policy scorecard will be determined. This research uses the terms mitigation schemes and support schemes alike. It is important to comprehend the difference between support- and mitigation schemes. This will be explained first by presenting a definition of both schemes. In addition, the various ways or categories of granting financial support, in general, will be identified. Second, according to each category, current proposals for mitigation schemes found in the literature will be presented and discussed. In addition, this section ends with an additional proposal for a new mitigation option.

7-2-1 Definition of mitigation schemes

As was stated at the beginning of this section, this research makes a distinction between support- and mitigation schemes. The term support schemes implies the way of granting financial aid to, for example, renewable energy technologies in the form of subsidies or other benefits. However, giving financial support to renewable technologies in order to create a mature and robust new market can be done in various ways. The term mitigation scheme, on the other hand, implies the additional financial support the offshore wind farm developers require when being part of an offshore hybrid asset. Mitigation schemes can thus be regarded as additional support schemes for the specific scenario of hybrid offshore assets specified to mitigate the decline in revenues by the wind farm developers. First, an example will be presented as to how offshore wind developers look at possible mitigation options.

As was briefly shown in chapter 6, the impact the offshore transmission grid integration has on the revenue streams was in most cases harmful to the overall business cases of offshore wind farms for that particular scenario. Naturally, offshore wind developers have already anticipated this effect themselves. One of the few position papers written these days was written by the offshore wind farm developer Ørsted. This paper makes a few suggestions as to how the wind farm developers could be compensated for the decline in revenue caused by various scenarios. An important note to this revenue loss is that no economic welfare is being lost but rather the balance is shifted from the revenue collected by the wind farms to CI for TSOs. The position paper of Ørsted recognises this problem and states that a way must be found in order to redistribute or rather re-allocate this welfare to compensate the lost revenue for the offshore wind farm developers.

The first suggestion made by Ørsted (2020), is to design and implement an ex-post revenue distribution mechanism for offshore bidding zones. The generated electricity from the offshore generators flows to the adjacent zone with the highest price. After market clearing, redistribution of revenues should be done according to a framework including contracting between the involved parties. Such an example of the paper of Ørsted is scarce, few position papers exist that describes various support schemes for offshore wind farms in hybrid connections (a combination of an offshore wind farm connected to an IC). In addition, a working paper published by the EC, also discusses some mitigation schemes.

In order to be able to understand how these mitigation schemes came to be, it is important to comprehend what type of support is granted today in general. An approach is adopted in which an overview of existing support schemes is created in order to specify the types of support. These types or categories of support could then be used to identify or create new mitigation options for the wind farm developers in hybrid connection assets.

7-2-2 Types of support schemes

According to Abolhosseini and Heshmati (2014), EU member states or in general, nations, can use three different types or categories of support schemes for renewable energy technologies. The first category mentioned is to grant benefits through operations, specifically by means of feed-in-tariffs (FIT). Some examples, such as the SDE++ for the Netherlands and the CfD in the United Kingdom, were discussed in subsection 3-2-3. In general, feed-in-tariffs are often regarded as operational support schemes since the benefits are only granted for the electricity infeed into the grid. Thus, the support is only be granted during the operations of the generator. These types of support schemes try to boost the development of renewable energy technologies. In addition, by financially supporting the technology in this way, the creation of a market where the technology can mature can be established. Depending on the situation, operational support for offshore wind farms often expires after 15 years, depending on the tender specifics. In addition, the support scheme ends entirely when the market for the technologies is matured and a profitable business case can be established without the need for support.

The second category of support schemes mentioned by Abolhosseini and Heshmati (2014) describe instrumental tools to grant benefits or support in the financial domain. Tax schemes, for instance, are often looked upon as a negative mechanism because it increases costs for non-renewable generators. However, in some cases, it can serve as a strong tool to boost the incentives to adopt renewable technologies over other forms when, for example, it is used to reduce the taxes that have to be paid. In addition, benefits to create a reduction in initial investments can be established to further strengthen the business case of renewable energy technologies. These so-called tax credits could also be used to lower costs during operation (€/MWh). In addition, certain benefits to attract relatively cheap loans for wind farm developers could also provide an increase in the attractiveness for making a business case for offshore wind.

The last support scheme mentioned, describes tradable green certificates or also known as guarantees of origin certificates. These certificates are part of the Emission Trading System adopted by the European Commission to lower the overall carbon emissions and to increase the share of renewable energy (Comission, 2021). For each unit (often in MWh) of generated green electricity, a certificate is granted to the generator. These certificates can be sold to electricity providers or companies that try to compensate for a part of their carbon emissions. The revenue collected from trading these certificates is an addition to the revenue collected by offering electricity into the market (Commission, 2018). In other words, the green certificates can be sold independently from the generated electricity. However, it can be argued whether this support scheme is categorized as an operating support scheme or rather as a regulatory support scheme. Nevertheless, for the sake of the purpose of this subsection, a third category will be assigned to this support scheme, namely, support through regulatory changes.

Summarizing the types of support schemes that are currently granted to renewable energy technologies, three distinct categories can be identified. These are listed below.

1. Support through operations
2. Support by means of financial benefits
3. Support by means of changes in regulations or policies

However, the second category describing benefits through the financial domain, mainly focuses on tax benefits. This financial domain about the wind farms was left outside the scope of this research. As a consequence, this research focuses on mitigation options through wind farm operations or by means of regulatory changes.

7-2-3 Current proposals for mitigation schemes

As is stated throughout this research, currently only a few proposals for mitigation options that give additional support to offshore wind farms in hybrid setups can be found in the literature. Solely one mitigation option is currently used in real life. This is the case for the combined meshed grid solution of Kriegers Flak that has gotten a derogation the 70% rule. A description of the situation of Kriegers Flak was briefly presented in subsection 1-2. This example will be discussed later on in this section.

In order to create an overview of mitigation options for the policy scorecard, the three categories on how to grant support, in general, will be used. As was mentioned in subsection 7-2-2, because the scope of this research does not focus on the support through tax benefits of an offshore wind farm, these type of support schemes will not be included. An earlier assumption was made in this research, simplifying the LCOE calculation by not looking into debt, taxes or other forms of financial costs. Because of this, it is not possible to eventually assess mitigation options in this domain. As a consequence two out of the earlier mentioned categories will be used to identify mitigation options. First, three distinct type of mitigation options that grant (monetary) benefits through operational support are discussed. Second, mitigation options that provide exemptions or benefits through regulatory changes are presented. Last, an additional mitigation options is proposed by the author of this research.

Operational mitigation schemes

The first category includes the support that can be granted during- or post-operation. The earlier mentioned example in the position paper of Ørsted which described the post-redistribution of revenues is an example of this category. Operational support, in the context of this research, implies the support that can be received when looking at the operations of the generator. However, this does not necessarily imply that post-operational options are excluded from this category. Every form of benefit or support that is granted based on the operational time of the generator is being included. The following paragraphs will discuss the mechanisms of some existing proposals for mitigation schemes within this domain. In addition, the advantages and disadvantages of each option will be analysed.

Post operation compensation

The first and simplest form of the mitigation schemes is to support the wind farm developers through financial compensation coming from the national ministries. This is a slightly altered version of the ex-post value redistribution mentioned by Ørsted (2020). In order to calculate the amount of financial compensation, an example is taken. Figure 7-4, shows the hourly cash flow for a British wind farm under a HM and OBZ setup for the date: 12-01-2016. The amount of financial compensation a wind farm developer requires can be calculated by comparing the difference in revenues between the scenario in an offshore bidding zone, or any other setup for that matter, and for the scenario in which the wind farm would have been in a radial connection. As concluded in chapter 6, a price difference was observed, this is presented in Figure 7-4 by the red arrows. The compensation can be calculated by summing up the hourly price difference between the two different market setup scenarios, as is shown in equation 7-1. Where S is the amount of subsidy received in €. P_1 and P_2 are the hourly market prices in €/MWh under a HM and OBZ market setup respectively. Whereas Q_h is the amount of capacity that has been sold to the market in MWh. The time period over which the financial compensation can be granted could be specified in the contract between the actors.

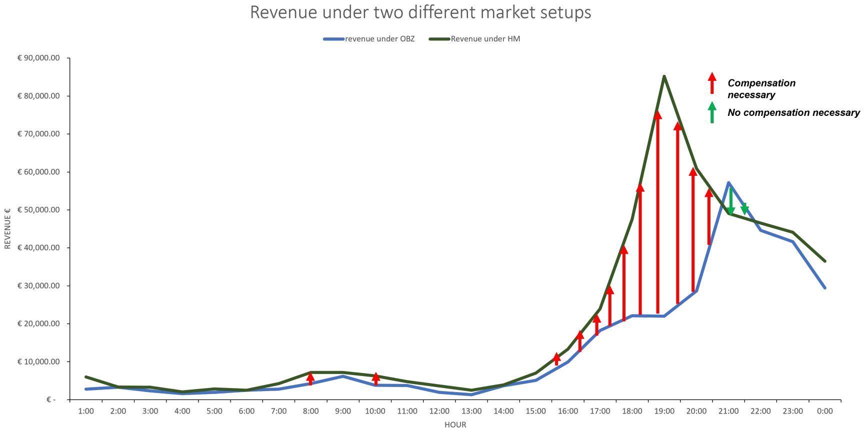


Figure 7-4: Revenue earned by a British wind farm under the home market setup and the offshore bidding zone setup (timestamp: 12-01-2016).

$$S = \sum_{h=0}^{N} ((P_1)_h - (P_2)_h) \times Q_h \tag{7-1}$$

The main advantage for this scheme is that, when taking a wind farm developer perspective, this mitigation option increases the revenues when the wind farm is under an OBZ market setup to the levels of the reference case. It is important to comprehend that the business cases of the existing wind farms are based on radial connection scenarios which is a home market setup by default. As a consequence, from a wind farm developers perspective, in order to preserve its original business case proposal, this would be an effective mitigation scheme since it restores the cash flow to the old situation of a radial connection. In addition, this scheme is able to adapt relatively quickly to the evolvement of the connections as more offshore wind capacity is being installed in the future. When the actor that is responsible for granting the compensation is included in the early stages of feasibility processes the mitigation scheme can be changed accordingly.

Nevertheless, this mitigation option also has some disadvantages. The first disadvantage is the possible value lost to society. Compensating wind farm developers in this way implies costs for the institution that is responsible for the compensation. If this responsibility is appointed to the national ministries, this of course implicates possible costs for society through taxes. In addition, financial compensation may be better used in different ways, for example, to increase the incentive for hybrid connections in the long term. The profit collected by the wind farm developers using this mitigation scheme arguably goes to the shareholders in the form of dividends. As a consequence, a regular financial compensation, as is proposed in this section, may not be an effective scheme looking from a societal perspective. Abolhosseini and Heshmati (2014) states that: "Direct financial transfer may lead to the enhancement of renewable energy consumption, but the main target (i.e., market creation) is not achieved. Because of this, it can be disputed whether this is an efficient mitigation option or not.

Additional support through (additional) feed-in-tariffs

A similar mitigation option might be to introduce (additional) FIT premiums. The advantage of FIT schemes is that, compared to most schemes, it is relatively simple to implement and can be effective if the price is right (Erwin, 2011). In addition, depending on the objective of the situation, additional design parameters can be added to the scheme. One of the main disadvantages, however, is that FIT schemes respond relatively slow to large changes in electricity prices. The effect of the large investments that are required in the coming decade regarding the energy transition on the electricity prices are still relatively undetermined. In addition, for offshore wind, the large quantities of additional installed capacity and thus large integration schemes of the North Sea transmission infrastructure may cause the initial price settings to be calculated incorrectly. If this is the case, the wind farm developer may receive subsidies based on old situations that do not reflect the dispatch accordingly.

In this section, three distinct types of FIT will be discussed. The constant priced FIT, the SDE++ and CfD. Focusing on the first FIT scheme, the working is relatively simple. An additional price is granted for every unit of electricity capacity that is fed into the transmission lines. The effects of the resulting electricity price within the offshore bidding zone are displayed in Figure 7-5. In addition, the effect on the revenue in the same period is displayed in Figure C-3. It can be seen that the price received in the offshore bidding zone increases according to the set price of the FIT. The working of this mitigation options might seem relatively simple, the price determination however is not. Because of the static determination of the price, no alterations are performed due to high- or low priced periods. As is stated earlier, a more flexible determination of the subsidy grants may be preferred in a situation which is expected to go through many changes. Nevertheless, the CfD and SDE++ schemes, take this into account.

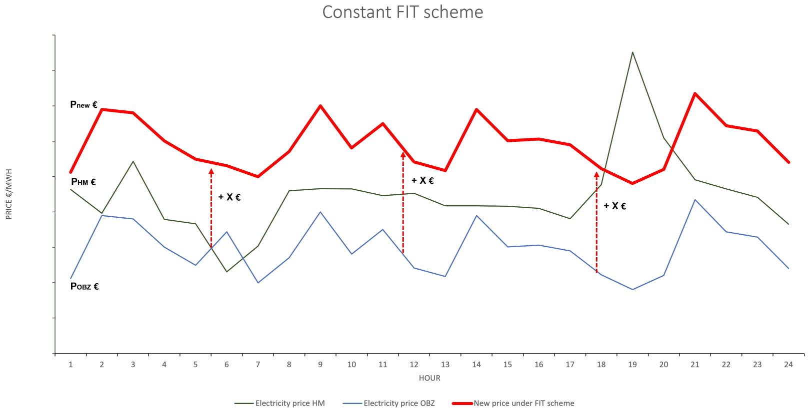
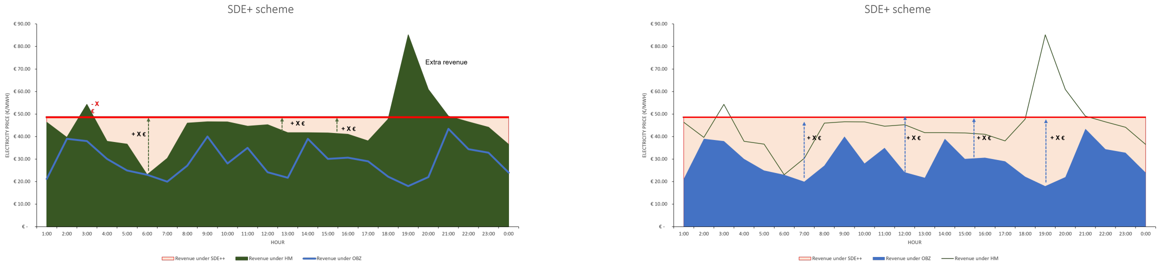


Figure 7-5: Effect of the constant feed-in-tariff scheme on the electricity prices (€/MWh) in an OBZ compared to a home market setup for a British wind farm (timestamp: 12-01-2016).

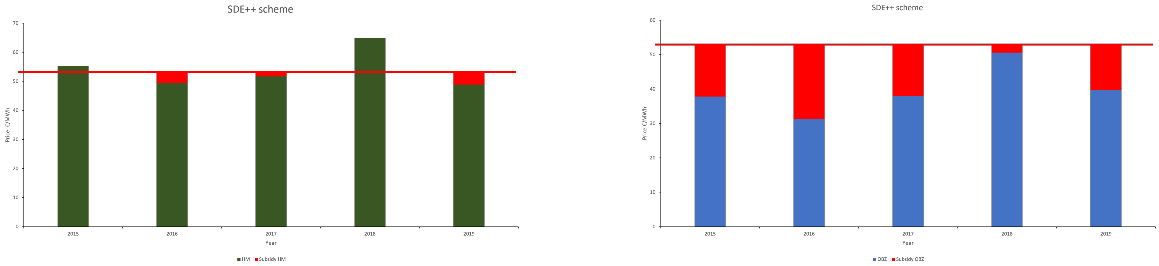
When focusing on the SDE++ scheme as a possible mitigation option, a slightly different resulting revenue can be observed as was shown in Figure 6-9 and 6-10. As has been explained thoroughly in appendix B-3, the SDE++ is often regarded as a sliding FIT scheme because it grants the amount of subsidy according to a correction price. The SDE++ scheme has been used in the Netherlands to grant subsidies to the Borssele wind farm tenders for a striking price of 88 and 54.5 €/ MWh as is displayed in table A-2. The working of the scheme also has been explained thoroughly throughout chapter B-3. To summarize; the amount of the SDE++ scheme is determined by the difference between the average annual electricity price and the strike price. In addition, when electricity prices exceed the strike price, no additional support is granted. However, in this situation, the wind farms do not have to pay back any income. The effects of the SDE++ scheme is on the prices received for the generated electricity is shown in Figure 7-6 during the day and in Figure 7-7 over the years. In addition, the effect of the prices changes on the revenue is shown in Figure C-4. For the setting of the amount of compensation, a similar approach was taken as explained in appendix B-3, however only with the correction price based on the 2016 OBZ prices. This graph may seem similar to the constant FIT scheme. This can be explained due to the fact that the time period of just one day is too small to show the real differences between the constant and SDE++ FIT schemes. If the time window would be applied over a few year, the sliding effect would have been observed.



(a) Effect of the SDE++ feed-in-tariff scheme on the electricity prices (€/MWh) in a home market.

(b) Effect of the SDE++ feed-in-tariff scheme on the electricity prices (€/MWh) in an OBZ.

Figure 7-6: Effect of the SDE++ feed-in-tariff scheme on the electricity prices (€/MWh) in an OBZ compared to a home market setup for a British wind farm (timestamp: 12-01-2016).

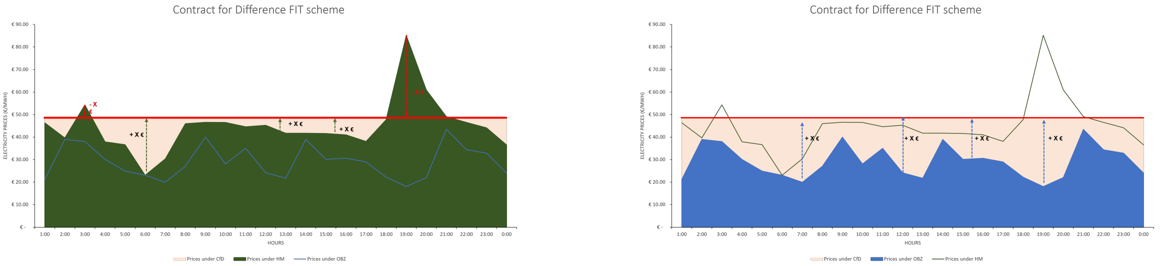


(a) Effect of the SDE++ feed-in-tariff scheme on the electricity prices (€/MWh) in a home market.

(b) Effect of the SDE++ feed-in-tariff scheme on the electricity prices (€/MWh) in an OBZ.

Figure 7-7: Effect of the SDE++ feed-in-tariff scheme on the electricity prices (€/MWh) in an OBZ compared to a home market setup for a British wind farm.

As was seen in chapter 6, the SDE++ scheme results in different revenues for wind farms compared to the CfD scheme. The effect of the CfD scheme on the price setting is shown in Figure 7-8, similarly to the SDE++ the cash flow graph is shown in Figure C-5. It can be observed that, when the price is set well, the CfD scheme is the most cost-efficient from a societal perspective. In addition, this scheme supports the business case of an offshore wind farm the most in terms of stability income.



(a) Effect of the CfD feed-in-tariff scheme on the electricity prices (€/MWh) in a home market.

(b) Effect of the CfD feed-in-tariff scheme on the electricity prices (€/MWh) in an OBZ.

Figure 7-8: Effect of the CfD feed-in-tariff scheme on the electricity prices (€/MWh) in an OBZ compared to a home market setup for a British wind farm (timestamp: 12-01-2016) .

In addition, replacing the various FIT schemes with a standardized FIT scheme in future connections may result in a more flexible business case for offshore wind farms. The disadvantage for the standardized subsidy scheme is, however, that individual wind farms may receive different levels of benefit since the LCOE (project costs) may differ per wind farm. In addition, subsidy schemes are paid by the ministries, the question arises to what extend the costs of standardized subsidy schemes are allocated between the different countries. Nevertheless, when looking from a wind farm developer perspective to mitigation options that grant additional FIT premiums that eventually compensate the difference of the future revenues with respect to the initial situations, may seem like a favourable option.

Redistribution of congestion income

One of the main (mitigation) solutions according to the earlier mentioned literature, to the revenues in an OBZ is to re-allocate the congestion income earned by the TSOs. Chapter 2 briefly touched on this topic explaining that congestion income is the revenue earned by TSOs when facilitating cross-border electricity exchange. The price per MWh the TSO receives is determined by the difference in price between the bidding zones in which the exchange is made as is seen in equation 7-2. The total congestion income collected over a certain period of time is the sum of the hourly price difference times the transported capacity. In addition, the amount received of congestion income is often divided between the two TSOs according to the stakes of ownership of the interconnection asset.

$$CI = \sum_{h=1}^{N} |(P_1)_h - (P_2)_h| \times Q_h \tag{7-2}$$

The redistribution of congestion income is a popular topic of discussion these days. An important note is that with the introduction of the Clean Energy Package of the EC, TSOs cannot spend this income freely. In addition, it can even be argued whether congestion can be called an actual income since the NRAs decide what happens with the income collected. Thus, the amount of financial investments into what projects is completely determined by the NRA, and not the TSO. To this day it is being debated whether it should be used for market player compensation at all. Nevertheless, the explanatory document by the ENTSO-E clearly states that, according to the Clean Energy Package, congestion income can be spend on two major fields. In addition, an extra field can be used when there is a surplus of income (ENTSO-E, 2020b):

1. Guaranteeing the actual availability of the allocated capacity
2. Maintaining or increasing cross-zonal capacities through optimisation of the usage of existing interconnectors by means of coordinated remedial actions, where applicable, or covering costs resulting from network investments that are relevant to reduce interconnector congestion
3. If there is a surplus of congestion income, this can be used to lower the transport tariffs

If an exception of these obligations regarding the CI can be made particularly for hybrid interconnection projects including offshore wind, a mitigation scheme can be identified. If this income should be allowed to be spend on support for the offshore wind developers it can be argued that it would still fulfil the same purpose as the obligatory investments in cross-border connections. Wind developers will act as barriers against the North Sea grid integration as long as there is no incentive to participate in these hybrid cross-border connections. Therefore, to be able to support wind developers by means of congestion income, this mitigation option may serve as a short-term solution to boost offshore transmission integration.

The amount of Congestion Income over on the 12th of January 2016 is shown in Figure C-6. In addition, the effect the redistribution of congestion income has on the revenue for the wind farm is shown in Figure 7-9. In this Figure, the congestion income was fully redistributed to the offshore wind farm developer in order to increase its cash flow.

Although all of the above-mentioned mitigation options provide an answer to the problem from a wind developer perspective in an offshore bidding zone market setup, it is questionable when looking from a societal perspective. Nevertheless, there are different ways of supporting wind farm developers.

When looking at the next category of support schemes, it is about making changes in regulatory compliance. In general, all mitigation schemes demand certain changes in regulations and are therefore policies. However, according to papers such as the ENTSO-E position paper (ENTSO-E, 2020a), the AFRY report for the Dutch ministry of economic affairs (Stead, Tarasewicz, & Husband, 2020), the final report of Guidehouse and Sweco for the EC on hybrid connections (Boeve et al., 2020), among others, mention a new and robust setup of a regulatory framework, especially for hybrid connections. In this research, the details of the regulations are mostly left out of scope since it will increase the complexity of the situation.

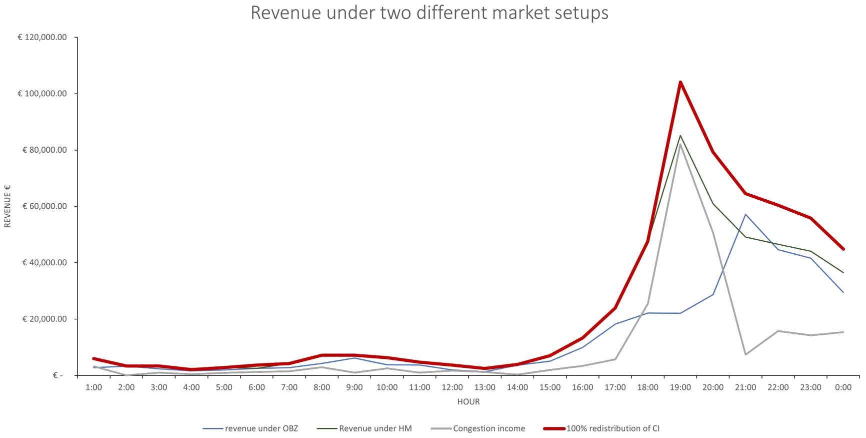


Figure 7-9: Revenue of a British wind farm under a HM, an OBZ and if the congestion income would be fully redistributed to the OWF under an OBZ.

In addition, it is the nature of the system and the effects of changes on this system what this research tries to obtain insights into and not the details of the current regulation.

Mitigation options trough changes in regulations or policies

Exemption of 70% rule

The 70% rule has been mentioned a few times already in this research. This rule states that 70% of the capacity available on an IC must be made available for cross-border capacity exchange (ACER, 2020). It is important to comprehend that this specific form of a mitigation option will only be used in situations in which a home market setup is to be realised. The offshore bidding zone is fully compliant with this rule since all capacity exchanged can be regarded as cross-border capacity exchange.

The impact of the 70% rule has been demonstrated in subsection 6-3-2. It was seen that the revenues did not change with respect to the reference case mentioned in subsection 6-2. This can be explained, for example for the Netherlands, due to the fact that the national TSO is obligated, to compensate the losses that follow from lost income due to TSO related activities such as curtailment (Elektriciteitswet, 1998, H3 §2 Artikel 16f). As a consequence, the cash flow of the wind farms is not being reduced. However, as these compensations are being paid by the TSO, the extra costs are eventually imposed on society. Naturally, when this rule is removed, this extra cost category dissolves.

An example of where a derogation for the 70% has already been granted is for the first hybrid connection in the world: "Kriegers Flak". As is briefly discussed in chapter 1, Kriegers Flak is an example of a simple meshed offshore grid (MOG) configuration better known as a hybrid connection. A physical representation of the project can be seen in Figure 1-5. In order for this project to be realised, the EC has given a temporary derogation for the project regarding the 70% rule (Durakovic, 2020). However, this project is an experimental project. The derogation is applied for the first 10 years. If after these 10 years, the business case still depends on the derogation it can be extended for another 15 years to cover the life time of the wind farm.

Now that less than 70% of the transmission cable can be reserved for cross border capacity exchange, more capacity generated by a wind farm can be dispatched to shore. However, for this case, still, the issue of conflicting priority access occurs as the cross-border capacity exchange has priority access over wind capacity. Therefore, wind farms may still be curtailed, only less than in the case in which the 70% rule is active. Thus, the disadvantage when exempting projects of the 70% rule is that these projects possibly do not maximise the utilisation of the IC cable. This naturally implies higher costs of the cable which are imposed on society in terms of transport tariffs. In addition, Witkop (2020) argues that the 70% rule may become costly in some scenarios as it imposes countries to introduce new bidding zones corresponding to the systems physical limits instead of country borders. On the other hand, Witkop argues that it also might be the only way to move towards an integrated European electricity system.

Another highly debatable subject of the 70% rule is the question of where the rule applies to. Take the situation of a Dutch radial connected wind farm with a cross-border connection to the UK for example. The 70% rule is applicable only for IC and not for regular transmission assets, as was the initial radial connection to the Netherlands. Should the rule apply to the whole asset, acting as a large IC? Or does it apply to the part of the hybrid connection which serves as the cross-border connection, which technically is the only interconnector cable?

TSO certificate for wind farms

A different way to generate extra income for the wind farm developers is to assign them with a so-called TSO-light certificate. In this way, the wind farm developers can partake in the ownership of the IC asset. This scheme makes it possible to co-finance the IC, decreasing social costs, but also it enables offshore wind developers to take a share of the generated CI. In general, this is a slightly different method than the redistribution of CI mitigation scheme.

However, this particular mitigation option would need a change in the core foundation on which the electricity system is built. According to Rossetto (2020) the unbundling rules state clearly that separation must be achieved in activities that are potentially subject to competition from those where competition is not possible or allowed. An example is a separation between electricity generation and the transmission and distribution of electricity. So in general, generators cannot own transmission assets to ensure fair competition and third party access. In order for these mitigation options to take place, a potentially long trajectory of regulatory change must be carried out. Nevertheless, for special cases such as the hybrid interconnections, the wind farm developer should be allowed to partake in the ownership in order to collect some support. Therefore, to ensure fair competition and third party access, this certificate should limit the role of the wind farm developer purely to just the collection of CI. In addition, the amount of extra income received depends on the stake of ownership the wind farm developers has in the transmission asset.

7-2-4 Proposal for a combined mitigation option

Regulated post operation compensation

All of the previously mentioned mitigation schemes are a much-debated topic. However, an alternative to the existing mitigation options in the operating domain can be identified. More specifically, the support structure of the financial compensation combined with the regulatory constraints of the redistribution of CI scheme. In order for this particular policy to be as efficient as possible, it should adopt a centralized goal that tries to align the goals of all involved actors, in this case, the European member states, the TSOs and the wind farm developers. As is stated for the redistribution of CI, the goal is, among other things, the reinforcement of the cross-border capacity between European Member states. In addition, the clean energy package also states goals in order to increase renewable energy generation in Europe.

Therefore, a regulated financial compensation for the wind developer could be adopted. In this combined solution, the wind farm is financially compensated for the lost revenues with respect to the original scenario on which the business case was proposed. However, for this extra granted income a similar obligatory scheme applies as for the spending of the CI. The amount of support received by the wind farm developer should only be allowed to spend on further investments in the offshore renewable energy sector, creating an increase in offshore wind which will create new possible projects for hybrid connections. However, if this would be enough for the wind farm is yet to be seen.

Summary

Summarising this section, the approach to identify the existing mitigation options was carried out. This was done by first analysing the general method on how (financial) support is currently granted by the corresponding authorities. It was seen that there are three ways to grant support, namely the traditional way of granting financial support through the operations of a generator, granting financial support in terms of cost reduction schemes and changing regulations in favour of the wind farm developer. For each of the identified categories, existing proposals for mitigation options were identified. In addition, an extra mitigation option was proposed. This mitigation option proposes a regulated version of the normally financial support scheme through operations. A resulting overview of the mitigation options that have been identified for further analyses are listed below:

1. Post operation compensation
2. Additional support through (additional) feed-in-tariffs
    a) Constant FIT scheme
    b) SDE++ FIT scheme
    c) CfD FIT scheme
3. Redistribution of congestion income
4. Exemption of the 70% rule (for home market setups)
5. Granting the wind farm developer a TSO-licence
6. Regulated post operation compensation (idea of the author)

7-3 Criteria

Now that the first element of the policy scorecard method regarding the alternatives mitigation options has been identified, the criteria on which the policies are going to be evaluated have to be determined. As stated in section 7-1, the main advantage of the policy scorecard method over other methods is that it enables the possibility of including multiple perspectives of the various actors involved. In addition, the method uses an aggregation of quantitative and qualitative effects. This aggregated approach enables the user to include all types of criteria. However, this also implies that this method is strongly subjected to the user's choice of criteria. In other studies, these selected criteria can seem insufficient depending on the situation in which the method is used. The definition of criteria for policy assessment is that it measures the dimension of an objective. In addition, criteria are used to compare the effects of alternative policies on reaching the same goal (University, 2021).

in order to select relevant criteria, the scope of this research has to be understood properly. the criteria should describe an effect or objective that meets the interest of all involved actors. This is process could become difficult if there are conflicting goals between the actors. If this is the case, the criteria could become vague or fuzzy. As there can be many criteria covering many fields of research, a limitation should be included for the approach. With the information and insights gathered throughout this research, an assessment can be made from a more neutral perspective. In addition, the quantification of the mitigation options can be achieved using the model. In addition, based on these quantitative criteria also an analysis on the feasibility of the proposed mitigation options can be carried out.

As discussed thoroughly in the chapters 1 and 4 the problem at hand is that offshore wind farms do not have any incentive to participate in hybrid connections. As a consequence, the wind farms act as barriers rather than gateways to a cost-efficient North Sea grid integration. The goal, therefore, should provide an answer to this problem. In addition, the criteria should be set up in a way that tries to minimize potential conflicting goals between the actors.

Therefore, in order to develop a scorecard that includes all important criteria, the behaviour of the involved actors must be understood properly. The first actor involved is the offshore wind farm developer. It can be assumed that offshore wind developers can be regarded as traditional companies that try to maximize profit and growth and minimize costs. Therefore, the goal of an offshore wind developer could be expected to increase their market share of offshore wind in order to maximize growth and profits. A distinction is made for wind farm developers originating from the UK and from the Netherlands. This is necessary because the regulatory system such as choice of subsidy differs per country.

The second actors involved are the TSOs, more specifically, TenneT and National Grid (which is officially not a TSO but a NETSO). The assumption made is that TSOs will prioritize system reliability, security of supply and balance of the system over for example minimizing costs as these are the main tasks of a TSO. Therefore the goal of the second actor is to be able to fulfil its regulatory tasks as best as possible. The last actor is the national ministries and/or regulatory authorities in the country. They will always try to act to the importance of the project in terms of social welfare and look at the long term strategy such as the Clean Energy Package of the EC and the compliance with it.

Now that the actors are identified along with some general goals, the criteria can be determined. In general, for basic criteria, economical, equity, technical and political domains are used. In some cases, even the administrative domain is included (University, 2021). For this research the policy scorecard will include the following criteria domains:

1. The financial domain
2. The feasibility domain

7-3-1 Financial domain

As was mentioned previously, the criteria should be able to assess the policy options on certain goals or objectives. Naturally, all mitigation options share the same objective, namely to support the wind farm developer for the revenue losses. As a consequence, compensating the wind farms often imposes costs on society via the TSOs or governments either in terms of higher transmission tariffs or increased taxes. In order to assess the effectiveness of the mitigation schemes, criteria concerning these financial effects are necessary.

More specifically, the financial effects of the various mitigation options may have large impacts on all actors. It may have an impact on the wind farm developers in terms of CAPEX, OPEX and revenues as was discussed thoroughly throughout chapter 3. For TSOs, the impact may have effects regarding investments in new assets, which in term has an effect socially through the transport tariffs. Last, for ministries when extra financial benefits in the form of subsidies are being paid, or the new asset of the TSO is inefficient, the ministry has to support the project financially which in term have a similar cost-increasing effect on society.

As a consequence, financial effects imposed on all involved actors should be included into the policy scorecard. Thus, criteria that evaluate the alternative mitigation schemes in terms of income and costs are included in the policy scorecard. More specifically the following financial criteria will be used:

1. *Revenue collected by the wind farm developer*
2. *Congestion income collected by the TSOs*
3. *Cost implied on the TSOs*
4. *Cost implied on the national ministries*

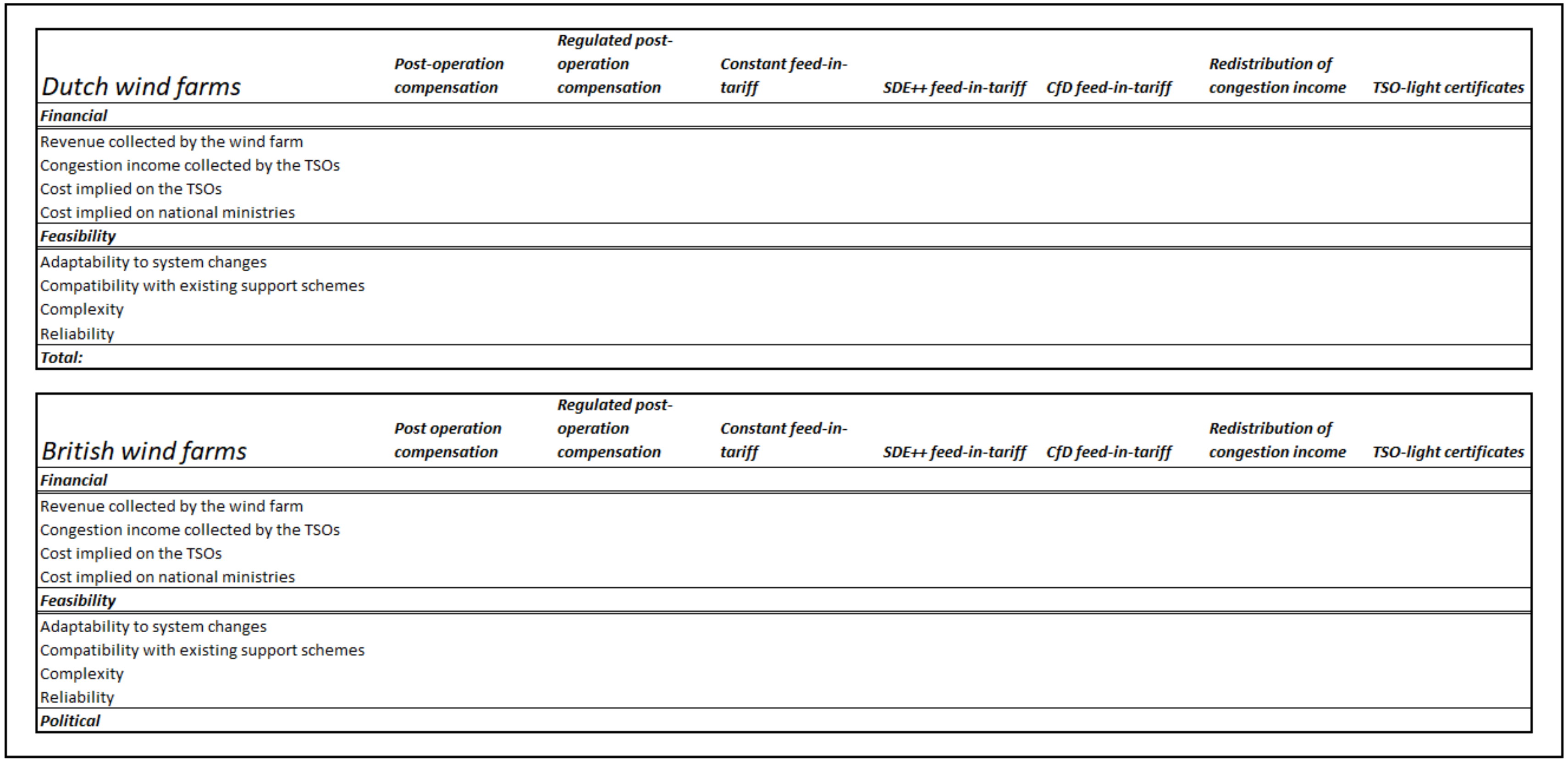
It is important to comprehend that all financial effects are calculated with respect to the reference case. For example, the exemption of the 70% rule may have an impact on the societal costs, however it is expected to have minor effects on the resulting revenue of a wind farm compared to the radially connected reference case. Furthermore, additional FIT schemes may have an substantial effect.

7-3-2 Feasibility domain

The second criteria domain describes the feasibility of the existing mitigation schemes. An example of a situation in which the feasibility of a mitigation scheme could be questioned is when the implementation time of a certain policy is so long that it conflicts with the window of opportunity of a project to start. In addition, future-proofness is becoming more important as new wind farm projects may open up new connections options. Therefore, the adaptability of the proposed mitigation options will be assessed. If a mitigation scheme is relatively easy altered according system changes, the mitigation scheme is regarded as flexible. In addition, the existing wind farms may have different support schemes installed already, therefore the mitigation schemes should be assessed on their compatibility with existing support schemes. The reliability criteria tries to address the robustness of a mitigation option. Having some flexibility might be preferred however, the mitigation scheme cannot stray too much from the initial objective. An example could be the FIT schemes that can be affected by rapid changing electricity prices. The following criteria have been adopted in the policy scorecard and assess the mitigation options:

1. *Adaptability to system changes*
2. *Compatibility with existing support schemes*
3. *Complexity*
4. *Reliability*
5. *Regulatory fit*

Now that both the elements of the policy scorecard are determined, the development of the policy scorecard can be carried out. A schematic design is displayed in Figure 7-10. The next section will discuss how the weights were set up and determined in order to score the policy scorecard.



Dutch wind farms	Post-operation compensation	Regulated post-operation compensation	Constant feed-in-tariff	SDE++ feed-in-tariff	CfD feed-in-tariff	Redistribution of congestion income	TSO-light certificates
Financial							
Revenue collected by the wind farm							
Congestion income collected by the TSOs							
Cost implied on the TSOs							
Cost implied on national ministries							
Feasibility							
Adaptability to system changes							
Compatibility with existing support schemes							
Complexity							
Reliability							
Total:							

British wind farms	Post operation compensation	Regulated post-operation compensation	Constant feed-in-tariff	SDE++ feed-in-tariff	CfD feed-in-tariff	Redistribution of congestion income	TSO-light certificates
Financial							
Revenue collected by the wind farm							
Congestion income collected by the TSOs							
Cost implied on the TSOs							
Cost implied on national ministries							
Feasibility							
Adaptability to system changes							
Compatibility with existing support schemes							
Complexity							
Reliability							
Political							

Figure 7-10: Schematic design of the policy scorecard including the determined criteria and alternative mitigation schemes.

7-4 Scoring

Before the scorecard can be filled in, it is necessary to discuss the weights assigned to the criteria. As is stated in the previous sections two types of criteria are used in this policy scorecard, namely quantitative- and qualitative criteria. First, the approach of scoring the quantitative criteria using the model will be discussed. Additional constraints are added in the existing scenarios and will be presented. The approach taken to score the qualitative or criteria is discussed subsequently. Naturally, in order to score the qualitative criteria, the model cannot be used and thus, a different method should be adopted. A small literature review was performed to identify the different ways to score qualitative criteria according to the policy scorecard method. An overview with additional explanation will be presented first. In addition, the approach will be determined how to score the qualitative criteria in this research.

7-4-1 Quantitative criteria

In order to be able to score the quantitative or rather financial criteria, first, additional scenario specification is needed. As is seen in the conceptual model in Figure 4-3, the effects of the mitigation options are added as additional constraints to the developed scenarios. However, as was stated in section 6-5, for this research, it is important to analyse the effects of the mitigation options when a wind farm is under an offshore bidding zone compared to its radially connected reference case (under a home market).

In chapter 5, the scenarios were developed in order to be able to simulate the effects. The height of the subsidy was initially based on historical data, namely the Borssele tender of roughly 54.5 €/MWh and the wind tender for Sofia which was about 45.43 €/MWh. In addition, as was concluded in chapter 6, the wind farms will not have a positive business case without any form of support. As a consequence, when different FIT schemes are compared to one another, it necessary to formulate the reference case scenario in which the wind farms do have a positive business case. In order to do this, the height of the subsidy has to be calculated based on the calculated LCOE of the specified Dutch and British wind farms.

Chapter 6 and appendix B-2 elaborated upon the calculation of the height of the subsidies based on historical data such as electricituy prices and winning tender bids. A similar approach to calculate the height of the subsidy has been carried out, except for the fact that the strike price was set equal to the Dutch and British LCOE that has been calculated in appendix B-2. The resulting heights can be seen in table 7-1 for the SDE++. For the CfD the strike price is set equal to the LCOE, meaning that the grant received for the subsidy is calculated as the difference between the electricity price and the LCOE for a Dutch and British wind farm respectively.

The annual revenue collected under this slightly altered scenario is presented in Figure C-7. Table C-1 presents a both the revenue expressed in €/MWh and the absolute revenues in million euro for the new SDE++ scheme. In addition, the new revenues under an CfD subsidy scheme are presented in table C-2.

	2015	***2016***	***2017***	***2018***	***2019***
Strike price NL	**43.24 €/MWh**				
Height SDE++	€ 4.24	€ 10.99	€ 3.93	€ -	€ 1.69
Strike price UK	**52.92 €/MWh**				
Height SDE++	€ -	€ 5.79	€ -	€ -	€ 16.02

Table 7-1: New subsidy heights for the reference case, based on the calculated LCOE.

Now that the reference case has been adjusted accordingly, the effects of the mitigation schemes are able to be analysed. For the first mitigation option, the so-called post operation compensation, a conflict was identified. As wind farms are currently being constructed using subsidy schemes, a decline in revenue will result in a rise in subsidy received by the wind farm developers. As wind farms bid marginally low with respect to their break-even points (or LCOE), the height between the strike prices of the current subsidy schemes will automatically adopt to the changed electricity prices and subsequently grant more subsidy. This would imply that the adoption of a post operation compensation would be meaningless. However, financially, the post compensation option can still be calculated as the difference in revenues between the resulting revenue collected annually for the reference case without subsidy and under the offshore bidding zone *with* subsidy. The reason why a situation with- and without subsidy is taken is because the wind farm should obtain a positive business case. The calculation serves the purpose to obtain insights into the amount that would have to be compensated. Naturally this is similar to the case of redistribution of congestion income. The only difference is that the compensation comes from a different institution.

For the first feed-in-tariff as a mitigation scheme, the constant FIT scheme, the height of the compensation per MWh of electricity in-feed has to be determined. As was stated in section 7-2-3, the determination of an effective price is complex. The approach was adopted to calculate the average electricity price of the total period of 2015 until 2019. In addition the height that can be set for the FIT scheme is the difference between the Dutch and British LCOE and the average electricity prices. Using equation 7-1, the total required compensation can be calculated. The average in the OBZ over the period of 2015 until 2019 was found to be 39.49 €/MWh. This implies a height of 3.75 and 13.43 €/MWh for the Dutch and British in-feed respectively.

When looking at the SDE++ and CfD schemes as mitigation options, a distinction between two possible scenarios is introduced. First scenario are the wind farm that in an originally radial connection were granted subsidy. Since the wind farms that originally receive financial benefits through these forms, the question arises if the support scheme is still efficient rather than the question whether *additional* support is needed. It is assumed that wind farm developers would bid as low as the LCOE, to obtain subsidy schemes in the wind tenders. If the strike prices are close to the LCOE, then from the perspective of a wind farm developer, it does not matter if the prices decrease as long as they stay above the lower threshold in the subsidy scheme. This would only result in more subsidy. Both the SDE++ and the CfD schemes will adjust automatically to these decrease in prices.

As a consequence it might be relevant to look at the second scenario in which the wind farm originally did not receive any financial support. The winning bids of the initial wind farm tenders should be used to give an indication of the wind farms LCOE. Then accordingly, a subsidy could be introduced.

When looking at the regulatory mitigation option that allows wind farm developers to take part in a so-called TSO-light configuration it is important to understand how much stake the wind farm developer has in the project. The amount of ownership over the interconnection cable determines the height of the income distribution. For this research it is assumed that both TSOs will not allow the wind farm to have more ownership of the cable. As a consequence, 33% ownership devided over TenneT, National Grid and the wind farm developer is assumed. Therefore, the wind farm developer should be able to collect at least a third of the congestion income over the cable. Nevertheless, this also implies that the wind farm developer should pay for a third of the cable, meaning an increase in CAPEX. However, as the price difference between the Dutch and British electricity markets are relatively large, this could be enough to create a profitable business case.

7-4-2 Qualitative criteria

Various scoring approaches can be found in literature, for example, Trevisan (2021) discusses a qualitative scorecard for startups. Using a pool of random participants scoring the scorecard an accumulation of the answers were found and expressed in weighted averages and percentages. One of the advantages of this approach is that a diverse input is obtained which may lead to an effective outcome. The second approach that was identified four symbols were used. Upturn (2017) describes a policy scorecard for the evaluation of policies about body cameras worn by police officers. Using this method, the best policy that fully satisfies the criteria received a green check. In addition, a policy that did not address the issue, or the policy was against principles received a red cross. Furthermore, a yellow circle was assigned to policies partially meeting the criteria. Last, a neutral score was given to policies that were not ranked because it was not applicable to the other departments. Similar to the case of the body-worn cameras for the police is the article by Höhne, Burck, Eisbrenner, Vieweg, and haber (2009). In this research, an assessment was done on scorecards on the best and worst policies for a green new deal. Best-case scenarios were ranked on a scale from 3 (best case) to -3 (worst case). Per categories, a maximum score could be attained and the policy was graded based on the total points received. The policy scorecard presented in Figure C-1 uses symbols to assign positive effects (+) and negative effects (-). Subsequently all weights are evenly distributed and the total positive- and negative effects are summed up. Then the negative effects are subtracted from the positive effects and a resulting score is obtained. Last, a policy scorecard to assess the effectiveness of different policies was found using a five level range in which zero is the worst case scenario and 5 the best case scenario. In addition, the total weighted average was expressed using symbols, this can be seen in Figure C-2.

Aproach	Author
- Weighted average - Percentages	(Trevisan, 2021)
- Four level evaluation - Symbols	(Upturn, 2017)
- Six level evaluation - Numbers - Summation of scores form a final overall score	(Höhne et al., 2009)
- Postive or negative effects - Symbols	(Nashwan, 2015)
- Five level evaluation - Symbols	(Leka et al., 2014)

Table 7-2: Overview of approaches to scoring qualitative criteria with the corresponding sources.

In order to form a decision on how to score the qualitative criteria, a combination of methods seems to be the best fit. Since the scorecard is meant for multiple actors who can score criteria based on their own views, there is no one solution that fits all. However, in a scorecard where quantitative criteria are included, it seems that this could come into conflict if the average weights or grading schemes are used for the qualitative scenarios. However, this can be done using a colour scheme that determines whether a criterion is scored high, medium or low in its own range. Thus a combination of particular scores will be used.

7-5 Results

This section will discuss the results from the policy scorecard. First, a reflection of the selection of criteria will be discussed. Because the identified mitigation options were based on literature review no reflection was deemed necessary on the selection of mitigation options. Subsequently, the quantitative results will be presented and elaborated upon. Last, the results following from the quantitative criteria will be discussed. At the end of this section a brief summary will be presented.

7-5-1 Criteria validation

Before the results are discussed, it is important to comprehend how the scores can be interpreted. One of the disadvantages of the policy scorecard that was mentioned in the beginning of this chapter, was that the scorecard is largely subjected to decision making and preferences of the person carrying out the scoring. However, as this approach has not been adopted before for this specific problem situation, also the selection of criteria domains are subjected to the decisions made by its developer. As a result, a reflection is necessary on the selected criteria domains.

The first domain, describes the monetary effects of the mitigation options on the actors involved. These actors were identified as the wind farm developer, the TSOs and the governments. Part of the problem that this research tries to solve is how the business cases of offshore wind can be protected if negative effects occur with the addition cross-border connections. Chapter 6, clearly shows than for some cases a decline in revenue was seen for the wind farm developers under the offshore bidding zone market setup. In order to assess schemes that mitigate this effect, the objective can thus be identified as to increase the revenues for the offshore wind farm developers. As a result, no comparison between various mitigation options can be performed without having insights into the financial effects. However, the manner in which costs are imposed on society or on the TSOs are largely not investigated and can thus be regarded as relatively shallow.

The second domain about the feasibility of the proposed mitigation options is also important. Especially when the environment is changing fast, as is the case of the offshore transmission infrastructure. In order for Europe to be able to unlock the large offshore wind goals set by the EC, mitigation options should be robust but also be flexible to adapt to the according system changes. Therefore the question is rather if the selected criteria within the domain are sufficient than if the domain itself is necessary. However, as the financial criteria were simulated, insights were obtained that allowed for a reasonable selection of feasibility criteria. Nevertheless, the criteria that are introduced will still have to be evaluated by experts in policy making. That will be discussed later in this research.

7-5-2 Results criteria

Quantitative criteria

As was explained in subsection 7-4-1, a new subsidy scheme was implemented. This was done in order to be able to assess the minimal support the wind farm needs under the given farm characteristics, geographical location and time period. The resulting revenue for a Dutch and British wind farms were presented in appendix C-3-1. When taking the average revenue collected over the given time period for a Dutch wind farm, a resulting 284.02 million euro or 45.26 €/MWh was found when implementing the SDE++ scheme. In addition for the CfD scheme this resulted in a slightly lower amount of 274.68 million euro or 43.72 €/MWh. Similarry, for a British wind farms this resulted in 368.09 million euro or 58.64 €/MWh under a SDE++ scheme and 336.17 million euro or 53.51 €/MWh under a CfD scheme.

The evaluation of the effects of the mitigation options were compared with the previously mentioned reference case. It is important to understand that for this research, wind farms will need additional support even in the reference case. This means that when comparing the cash flow of a wind farm in different market setups, the additional costs imposed by the subsidy schemes will be calculated. When for example the wind farm from the reference case under an SDE++ scheme is placed in an offshore bidding zone market setup, the revenue or cash flow of the wind farm will not change due to the subsidy scheme. However, as the prices are lower in an offshore bidding zone setup, the amount of subsidy received by the wind farm developer increases. This difference is the resulting additional costs or support a wind farm needs to create a positive business case. Similarly, for a CfD scheme, the change in market setup results in the extra amount of subsidy granted to the wind farm developer. This results are displayed in tables C-9 and C-10 for the SDE++ scheme, and in tables C-11 and C-12 for the CfD scheme.

For the other mitigation options, a slightly different approach can be adopted. For the post operation compensation for example, two situation can be adopted. The first in which the wind farm already has the benefit of a subsidy scheme, basically making this mitigation option redundant. For this example, the post operational compensation is calculated by comparing the most cost-efficient subsidy scheme in the reference case to which a wind farm has a positive business case. Thus, in this research the CfD scheme. The amount of compensation received from the post operational compensation is thus equal to the difference in costs for the CfD schemes under the different market setups. Second, a situation can be adopted in which the wind farm has no subsidy, however in that case, the amount of compensation just equals the total costs for a CfD scheme under the OBZ market setup. This of course, also hold for the regulated version of the post operation compensation.

For the constant feed-in-tariff, first a price was determined. This was done according equation C-1. Where the amount of compensation per MWh was calculated by subtracting the average price in an OBZ from the LCOE for a Dutch and British wind farm respectively. This calculation only only serves an indicative purpose of the effects of the constant FIT scheme, as a consequence, it may not represent such a scheme in reality. The resulting subsidy prices for a Dutch wind farm was estimated to be 3.75 €/MWh and 13.43 €/MWh for a Dutch and British wind farm respectively. In addition, the resulting revenues are displayed in table C-7. The corresponding were found to be 42.74 and 50.36 million euro on average every year for a Dutch wind British wind farm respectively. The results are displayed in table C-8.

The redistribution mitigation option, discussed in subsection 7-2-3 was simulated using a similar approach as discussed in the previous paragraph. The reference case was taken to be the CfD scheme, as that is the most cost-efficient scheme in the home market to grant support to the wind farms. In addition, under an OBZ market setup naturally, congestion income is collected. The average amount of the total accumulated annual congestion income was found, in section 6-4, to be 101.13 million euro. If congestion income is to be redistributed, the question arises to what extent. This research, redistributes the revenue up until the revenues are equal to the revenue that would have been collected in the reference case under an CfD scheme. As a consequence, on average, there would be around 100 million euros to redistribute every year. The results in this case are equal to that of difference in costs for the CfD scheme under a home market and offshore bidding zone. The results are displayed in the policy scorecard presented in Figure 7-11.

The last mitigation options that will be discussed, describes the partially ownership of an offshore wind developer of the transmission asset. Similarly to the redistribution of congestion income, the question arises how much of the congestion income can actually be compensated to the offshore wind farm. It is unlikely that the wind farm developer would have a higher stake of ownership than one of the two involved TSOs. As a consequence, it is assumed that a wind farm developer is able to own a maximum of 33% of the cable. This means that only a third of the collected congestion income can be collected by the wind farm developer. Again the results are shown in the policy scorecards.

Qualitative criteria

The first qualitative criteria that will be discussed is about the feasibility domain. As was stated in section 7-4, a specific scoring approach will be adopted for the qualitative criteria. The resulting scores per domain will be explained for each mitigation option.

The first qualitative criteria describes the criteria regarding the feasibility of a mitigation option. In subsection 7-3-2, the selection of each individual criteria was discussed. For the scoring of this criteria domain an approach was selected that adopts a three-level scale using symbols. When a mitigation option has a positive effect a "+" was assigned. If the mitigation options had a neutral effect to the according criteria a "o" was assigned. Last, if a negative effect was seen, a "-" was rewarded to the mitigation option. After the criteria were scored, the "+" and "-" were summed up and the difference was determined. This resulted in the final score. In addition, the neutral score ("o") received no weight. from The criteria were listed as the adaptability of a mitigation option to system changes, compatibility with existing subsidy schemes, the complexity of the mitigation option and its reliability.

Starting with the post-operation compensation scheme, it is seen that a total score of 1 out of 4 was assigned to its feasibility. As was stated earlier in this research, the post operation compensation is basically redundant when a wind farm receives grants from a FIT scheme. As is mentioned earlier in this research, British wind farms are still being constructed while receiving the CfD scheme. As a result, the compatibility was scored with a "-" rather than a "o" whereas the reliability was scored with a "o". In addition, this mitigation options is relatively easy compared to some of the other proposed mitigation options. In addition, No conflicts with regulations were identified and it is possible to calculate the revenue difference using a model as is shown in this research. This all contribute to the decision to score "+" for complexity. The strongest feature of this mitigation options is that adapts easily to system changes, because only the resulting revenue differences are being compensated post operation, resulting in a "+" for adaptability.

The regulated version of the post-operation compensation is very similar to the previously mentioned mitigation option. However, as this scheme implies additional regulation it seems much more complex than the un-regulated version. In addition, the reliability of this scheme is uncertain. An annual compensation of about 20 to 30 million euro for a British wind farm may be much too low. As a consequence, the objective of the mitigation option, namely to increase investments in the offshore wind sector may not be achieved. Because of this, the mitigation options was scored with a "-" in compatibility, complexity. In addition a "o" was awarded to its reliability. In addition, a "+" was appraised to the adaptability resulting in a total score of -1 for its feasibility.

The constant feed-in-tariff, was from the perspective of the offshore wind farm developers the most attractive scheme as the highest revenues were collected using this option. However, this is the least attractive options from a societal perspective as it imposes the highest cost of all mitigation options. This can be the result of a poor approach for the price setting. However, the constant feed-in-tariffs are also not flexible in terms of adaptation to new situations. In addition, they are also not easily compatible with other type of subsidies and too much compensation may be given during high wind periods. As a consequence the adaptability, the compatibility and reliability were scored with a "-". Nevertheless, the constant feed-in-tariff is relatively easy to implement and thus, assigned with a "+" for complexity. The resulting score of the constant feed-in-tariff is a - 2.

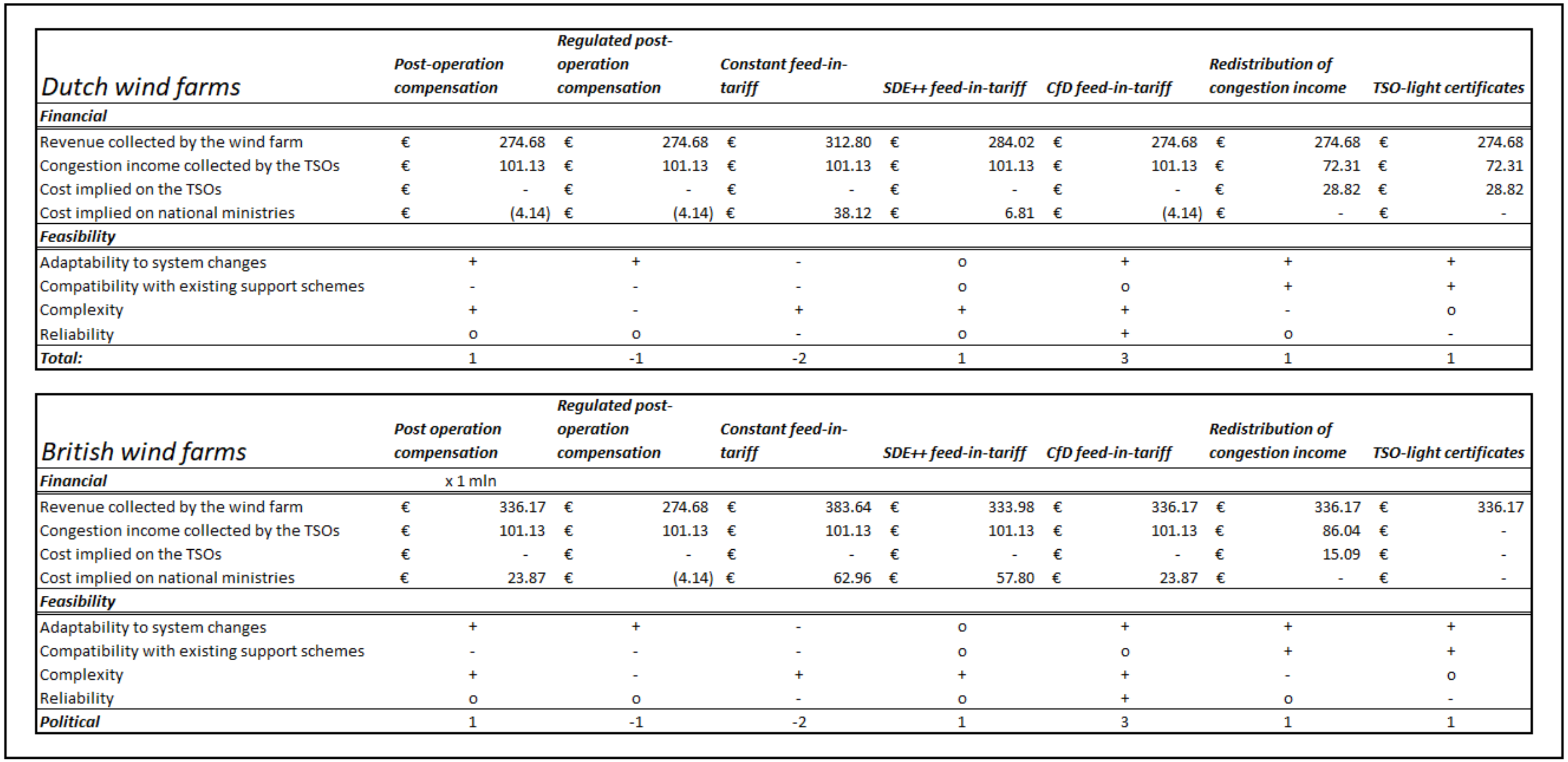
The SDE++ scheme, also results in higher revenues for the wind farm developers compared to the other mitigation options (except for the constant FIT). This can be explained by the fact that electricity prices exceeding the strike price for the subsidy scheme do not have to be refunded by the wind farm developers. However, similar to the constant FIT scheme the SDE++ imposes relatively high cost on society. In addition, because of the non-refunding part, this mitigation scheme is not very flexible to large changes in electricity prices. As a consequence, its adaptability was scored with a "-". Furthermore, its reliability is scored with a "o" since it can cause a surplus in compensation, however, this will not happen too often in an offshore bidding zone. Likewise, the compatibility and adaptability were scored with a "o" because the compatibility is not really applicable to this subsidy scheme and the adaptability because the SDE++ still realizes a positive business case under a market setup change.

The CfD scheme is the most cost-efficient scheme and also the leas compensation is granted to the offshore wind developer. For Dutch wind farms no additional costs are made with respect to the reference case, since the sold capacity actually tends to increase under an offshore bidding zone setup. However, some costs were imposed when applied to a British wind farm. In addition, this scheme was awarded with a "+" for the adaptability, complexity and reliability. Similar to the SDE++ scheme the subsidy scheme responses well to the change in market setup, still ensuring a positive business case for the wind farm developer while imposing few costs on society. In addition, the scheme may have been complex in the beginning, the scheme is a well known and applied subsidy scheme in the United Kingdom resulting in a positive score. Last, the compatibility with other subsidy schemes may be positive or negative, depending on the existing or proposed subsidy scheme. As a consequence, it was scored with a "o". The resulting score on feasibility is a 3 out of 4.

The redistribution of congestion income scored a positive for the compatibility and adaptability criteria. As the monetary flow comes from the TSO instead of the government, the extra income stream may not be redundant when the strike price of a current subsidy scheme is lowered accordingly. In addition, it is somehow difficult to comprehend how the collection of congestion income can be affected under new connection scenarios, however under an OBZ all transported electricity generated congestion income. Therefore, as long as the wind farm is under an offshore bidding zone, the congestion income is fairly adaptable to system changes. However, congestion income is spend by the NRA. This organisation should have a neutral perspective in the energy sector. Changing national and international regulations may become very complex and as a consequence the complexity was scored with a "-". In addition, the congestion income is meant to be spent on additional cross-border connections or lowering transmission tariffs. Its reliability is difficult to assume, as the congestion income is used and may result in some (minor) effects. As a consequence, the criteria was scored with a "o". The resulting score of the redistribution of congestion income is 1.

When wind farms are partially owners of the connection cables, a part of the congestion distribution of the congestion income may become simpler. The main difference with this mitigation option with respect to the previously mentioned options is that its reliability may be less. Because of the shared ownership the wind farm has to co-finance the cable, resulting in an increase in CAPEX which in term may result in a share of congestion income that may not enough to reach a positive business case for the offshore wind farm developer. As a consequence the a "-" was assigned to the reliability criteria and a "o" to the complexity.

During the policy scorecard it was concluded that with all the information gathered throughout this research, not enough knowledge was adopted in order to establish a robust and sound scoring approach for the political and system domain. These domains require additional evaluation from field experts that are able to evaluate the criteria. As was stated earlier in this chapter, the qualitative criteria were mainly adopted to indicate how a policy scorecard could be developed for this specific situation. This is critical as the developments in the offshore transmission integration will continue to achieve the goal of reaching 300 GW by the end of 2050. Furthermore, other important criteria may be missing.



Dutch wind farms	Post-operation compensation	Regulated post-operation compensation	Constant feed-in-tariff	SDE++ feed-in-tariff	CfD feed-in-tariff	Redistribution of congestion income	TSO-light certificates
Financial							
Revenue collected by the wind farm	€ 274.68	€ 274.68	€ 312.80	€ 284.02	€ 274.68	€ 274.68	€ 274.68
Congestion income collected by the TSOs	€ 101.13	€ 101.13	€ 101.13	€ 101.13	€ 101.13	€ 72.31	€ 72.31
Cost implied on the TSOs	€ -	€ -	€ -	€ -	€ -	€ 28.82	€ 28.82
Cost implied on national ministries	€ (4.14)	€ (4.14)	€ 38.12	€ 6.81	€ (4.14)	€ -	€ -
Feasibility							
Adaptability to system changes	+	+	-	o	+	+	+
Compatibility with existing support schemes	-	-	-	o	o	+	+
Complexity	+	-	+	+	+	-	o
Reliability	o	o	-	o	+	o	-
Total:	1	-1	-2	1	3	1	1

British wind farms	Post operation compensation	Regulated post-operation compensation	Constant feed-in-tariff	SDE++ feed-in-tariff	CfD feed-in-tariff	Redistribution of congestion income	TSO-light certificates
Financial	x 1 mln						
Revenue collected by the wind farm	€ 336.17	€ 274.68	€ 383.64	€ 333.98	€ 336.17	€ 336.17	€ 336.17
Congestion income collected by the TSOs	€ 101.13	€ 101.13	€ 101.13	€ 101.13	€ 101.13	€ 86.04	€ -
Cost implied on the TSOs	€ -	€ -	€ -	€ -	€ -	€ 15.09	€ -
Cost implied on national ministries	€ 23.87	€ (4.14)	€ 62.96	€ 57.80	€ 23.87	€ -	€ -
Feasibility							
Adaptability to system changes	+	+	-	o	+	+	+
Compatibility with existing support schemes	-	-	-	o	o	+	+
Complexity	+	-	+	+	+	-	o
Reliability	o	o	-	o	+	o	-
Political	1	-1	-2	1	3	1	1

Figure 7-11: Resulting scores of the policy scorecard from a Dutch and British perspective respectively.

Chapter 8

Discussion

This chapter presents the findings of this research. The findings are categorized as insights or results obtained from the literature study, the scenario-based modelling & simulation approach and the policy analysis on the mitigation schemes. Afterwards, the limitations and possible effects on the outcomes of this research will be discussed.

8-1 Findings

Throughout this research various steps were performed in order to answer the main research question. First, the findings that were obtained through extensive literature research on the theoretical background of the system of interests will be discussed. These will be regarded to as the general findings. Second, by means of additional desk research the background on the business case of an offshore wind farm has been investigated. Next, a combined scenario-based modelling & simulation approach was performed to obtain insights into the effects of various future scenarios. These findings will be presented. Moreover, various policy schemes were identified and analysed how the business cases of offshore wind farm developers can be protected for future connection scenarios. This was carried out through a policy analysis to assess and compare various mitigation schemes.

8-1-1 Literature study findings

General findings

The problem that this thesis tries to solve is a current and growing problem for all actors in the energy system around the world. The particular problem that this research tries to address, however, is relatively new territory. As was explained in the introduction, the EC adopted two goals that are important for this research regarding the climate transition. First, in order to reach the European climate goals an offshore energy strategy was adopted by the EC. This strategy aims to install at least 60 GW of offshore wind by 2030, and up to 300 GW in 2050 (European Commission, 2020a). Second, in order to accelerate the energy transition, the EC strives to work towards an integrated European electricity system. In order to achieve this in a cost-efficient way, hybrid connections by means of the current radially connected offshore wind farms are seen as a potential gateway.

Europe seems to be well progressing well, because it was found that the overall capacity of offshore wind in the northern part of Europe is booming. For example, the Netherlands plan to build 11 GW of offshore wind before 2030. In addition, it is not just the number of offshore wind farms that is increasing, but also its size in terms of turbine capacity and the number of turbines used. The next decade the United Kingdom plans to construct three wind farms with a combined capacity of 3.6 GW using 14 MW turbines, these will be the largest in the world (RWE, 2021). Furthermore, as more and more wind farms are being built, close-to-shore regions become occupied. As a consequence, offshore wind farms are built further away from shore. Turning in potential hybrid connections in which a much shorter, and as a consequence, a much cheaper cross-border interconnection may possibly be established. Various scenarios were identified how such connections could be made, which would be later used in the scenario development.

As these wind farms gradually move further away from shore, the required initial investment also increases to a point that only a few market players are able to create a profitable business case of such large projects. Because of this phenomenon, the North Sea region is an ideal situation to this research because of the favourable geographical conditions. In addition, This location is in particular interesting as the future wind farms will enter a distance from the foreign shore or a foreign offshore wind farm in which a possible interconnection may be feasible.

Findings on the business case of offshore wind farms

In chapter 3, the components of the business case of an offshore wind farm were discussed and identified. Figure 3-8 represents all cost components associated with the first step in determining the business case of an offshore wind farm, namely the expression of the LCOE. Accordingly, it was found that the connection to the grid, which consists of the export cables and the on- and offshore substations demanded the highest investments of all cost categories of an offshore wind farm. This, in some cases, could take up to a third of the total project costs. Furthermore, the sea depth and distance from shore are the two main geographical factors that have an accelerating effect on the project costs. It was found that most offshore wind farms adopt strategies to collect a more reliable way of income in order to secure a profitable business case. This is done by means of long-term PPAs or through support schemes such as the CfD in the UK. In addition, a British wind farm needs higher revenues to secure its business case than for the Dutch wind farms. This is because the United Kingdom possesses a framework in which the wind farm developers are obliged to pay for the grid connection whereas the Dutch wind farm developers are not.

However, it is important to note that a LCOE calculation, especially for energy systems in a rapidly growing market, is extremely difficult as it consists of many uncertainties. Especially in this research, in which many sources were used to come up with an expression for the CAPEX, these uncertainties could be quite high. The offshore wind market is a competitive market in which almost no relevant data is publicly available. Therefore, the literature often works with estimates. Nevertheless, a validation point was used in this research, and as a consequence the uncertainties of the LCOE calculation were be limited. Nevertheless, various LCOE were calculated under different economic parameters such as the discount rate and increasing OPEX were performed in the appendix B-2. A resulting LCOE of 52.92 and 43.24 €/MWh under a 6.5% discount rate and 2% annually increasing OPEX was chosen for this research. These numbers seemed rather high when comparing the British LCOE to the recently granted CfD schemes. A reason that may explain this is mentioned by the OWPBoard (2016). In this technical report, it is argued that offshore wind farm developers will do anything to lower the LCOE in order to be more competitive in the CfD auctions. This implies that the real LCOE is estimated to be higher, and thus not directly equivalent to the granted CfD price. In addition, to acquire a larger market share, wind farms may be willing to receive less income over the period in which the CfD is granted (15 years) which is less than the entire project lifetime.

8-1-2 Model and Simulation findings

The findings on the modelling and simulation part of this project are based on the results of the simulations that were performed on the constructed scenarios. The development of the scenarios were presented in chapter 5. In addition, the outputs of the performed simulation steps have been presented in chapter 6. The output of the results can be distinguished into two categories. First, the effects on the revenue of the wind farm due to physical system changes, for example by introducing an cross-border connection. Second, the effects when introducing market changes on the revenue collected by the wind farms. In addition, when a cross-border connection is established, effects are also observed on the collected congestion income per scenario by the TSOs. Depending on the scenario, different simulation steps were performed to obtain insights into different effects of physical or regulatory system changes on the model output. It is important to note that all of the findings were based on the same wind farm characteristics and geographical location.

Base model

A first insight into the cash flow and energy yield of a wind farm was obtained by simulating a base model. This model presents a scenario in which no regulations or physical constraints were introduced onto the system. It was seen that the selected wind farm has a capacity factor of almost 60% when using the data retrieved from the Open Power System Database. In addition, an annual average electricity yield of almost 7.0 TWh was achieved using 100, Haliade-X turbines of 14 MW. In theory, it can be observed that, should all generated electricity be sold into the market a wind farm is be able to collect an average income of 296 million euro over a time period of 2015 until 2019 for a Dutch wind farm. In addition, for a British wind farm the annual revenues were found to be substantially larger, resulting in roughly 391 million euro on average. Although these effects do not give insights into the system of interest, it presents insights in the operations and the overall potential of an offshore wind farm regarding collecting revenue to cover costs.

Reference case scenario

In the reference case it was seen that a decrease in the annual generation of about 14% is observed when a radial connection is imposed onto the system. Although this has no effect on the LCOE, the maximum revenue that is limited by its transmission capacity was obtained. In addition, the difference between a constructed British wind farm and a Dutch wind farm are substantial. The initial investment costs of a British wind farm are almost 30% higher because of the different governance models regarding the construction and ownership of the grid connection costs. In addition, the OPEX costs are much higher for a British wind farm than a Dutch wind farm because of the transmission costs that are imposed on the British wind farm. However, the revenue collected by a radial connected wind farm to the United Kingdom is much higher in comparison to a Dutch wind farm. The average electricity price in the United Kingdom is about 54.06 €/MWh over the specified time window whereas the average Dutch electricity price was 40.92 €/MWh. The simulations for the reference case showed an average annual revenue of 40.54 and 45.14 expressed in €/MWh for a Dutch and British wind farm respectively. This implies that no profit was made since the LCOE of both farms exceed the collected revenues. Thus, financial support still seems necessary for these large offshore wind projects.

As a result of the previous findings additional simulations introducing the SDE++ and CfD subsidy schemes, based on historical tender prices were performed. These additional simulations resulted in an average annual revenue of 54.11 and 56.25 €/MWh for a Dutch and British wind farm respectively for the SDE++ scheme. In addition, lower values of 47.69 €/MWh were found for both wind farms under the CfD scheme. These simulations were based on the latest strike price of the SDE++ subsdiy scheme for the Borssele 3 & 4 tender in the Netherlands. In addition, the CfD was based on the winning tender bids of farm Sofia in the UK.

Cross-border scenario

The system effects that provide answers to the objective of this research were found in the last scenarios. To start with the cross-border connection using a single radial connected wind farm, it was seen that just the addition of a cross-border connection affects the system substantially with respect to the reference case. Three simulations were carried out for the Dutch and British wind farms respectively. First, a situation in which no regulatory constraints were imposed on the system was carried out. Meaning that the wind farm developer can decide how much electricity is sold in what market. This resulted in an average annual revenue of 490 million euros. However, in order to represent the real-life situation, the home market setup was introduced.

These simulations show no substantial effects on the revenue of the wind farm. However, a regulatory conflict was identified. The EC adopted a rule that states that at least 70% of the interconnection cable must be reserved for cross-border capacity exchange on interconnectors. This implies that wind farms, when part of a hybrid connection, are curtailed most of the times. When a wind farm is curtailed due to transmission bottlenecks, it is compensated by the TSO. Although this does not show large effects on the cash flow of a wind farm, it imposes additional costs on society by the TSOs, through higher transmission tariffs. Both the situations in which the wind generated capacity has priority access on the cables and cross-border exchange having priority access were simulated. It was found that the only substantial difference in revenue occurred in the congestion income collected by the TSOs. In the case of wind farm capacity having priority access the average annual accumulated congestion income was about 24 million euro when the setup was simulated using a British wind farm. In addition, using a Dutch wind farm resulted in a much higher average annual accumulated congestion income of about 93 million euro. Furthermore, when following the current regulation, namely when cross-border capacity exchange has priority access on the interconnection cables, the average annual congestion income was almost 100 million euro. These differences can be explained due to the home market setup. In addition, the average annual income collected for a Dutch wind farm under a home market setup is similar to that of the reference case.

Offshore bidding zone scenario

The last simulations were performed under the offshore bidding zone market setup and were represented in section 6-4. Different effects were seen on the revenues of offshore wind farms. First, for the Dutch wind farm, an increase in revenue of approximately 5 to 10 per cent was observed. In addition, a decrease of 10 to 15 per cent was seen for a British wind farm with respect to the home market. This is an interesting insight because the literature always assumed a negative impact for offshore wind farms under an OBZ. However, it was found that if a wind farm that is connected to the bidding zone with lower prices most of the time, the revenue actually tend to increase. This can be explained due to the fact that the wind farm is able to dispatch more capacity as there is more interconnection capacity. In addition, the wind farm that was originally connected to the higher priced bidding zone experience a lot more effects of the market change. In addition, the offshore bidding zone seems to fit under current regulation as there is no conflict with the 70% rule. However, additional support may be needed for wind farm developers in order to establish these hybrid connections.

Before discussing the findings from the policy scorecard, an additional simulation was performed. As was stated in the previous paragraph, the business case of a wind farm for the specified location and wind farm characteristics was found not to be positive over the specified period. An additional simulation was performed to find the minimum revenue or amount of support needed for both the British and Dutch wind farms in order to reach a break-even point in terms of the business case. This is used as a new reference point for the mitigation analysis. The amount of support under a SDE++ and CfD were calculated based on the calculated LCOE for both the Dutch and British wind farms. When applying these subsidy schemes with the correct strike price, the average annual revenues were found over the given time period. For a Dutch wind farm this resulted in an annual average revenue of 284 million euro, or 45.26 €/MWh under an SDE++ scheme. In addition, a slightly lower revenue was found under a CfD scheme, namely 274 million euro or 43.72 €/MWh. For a British wind farm under the SDE++ scheme, this resulted in 368 million euro or 58.64 €/MWh. In addition for the CfD scheme this resulted in 336 million euro or 53.51 €/MWh. Therefore in terms of making cost-efficient hybrid interconnections, first the wind farms that are connected to the lower priced bidding zones should be used, as it requires less compensation for the wind farm developer that is ultimately imposed as additional costs on society.

8-1-3 Policy scorecard findings

A third research phase was adopted in this research, in order to identify possible instruments to protect the future business cases of offshore wind farms under the changing connection scenarios. More specifically, this resulted in the analysis of additional support instruments to mitigate the possible decline in revenue for the wind farm developers. In addition, an analysis was performed in order to assess the effects of the mitigation options on all actors involved. These actors were identified as the wind farm developers, the TSOs and the governments. By means of additional desk research, the policy scorecard method seemed to be the best fit for the purposes of this research. Other policy analysis instruments were identified, but lacked the ability to take into account a neutral point of view that allows all actors to give an individual score. In addition, a total of six existing mitigation proposals were identified. Out of these six options, two were combined into a seventh (and thus a new) mitigation option. Next, a set of two criteria domains were adopted that fit in the scope of this research. These two domains take a neutral perspective on the situation and are based on the output of the modelling and simulation and by means of additional desk research.

The first insight that was obtained during this process, was that when a wind farm was constructed in a radially connected situation in which either an CfD or SDE++ subsidy scheme was granted, the post operation compensation would be redundant. This was explained thoroughly in chapter 7. As the CfD and SDE++ adjust automatically due to the change in prices, the post operation compensation would just be granted in the form of a higher amount of subsidy. If however, a wind farm would be built without subsidy, the post operation compensation option would have similar results as the CfD scheme and the regulated post operation compensation. One of the main advantages found when using a post-operation compensation scheme is that it rarely grants a surplus of compensation to the wind farm developers, making it a cost-efficient scheme.

As was stated earlier, both the Dutch and British wind farms need support in order to establish a positive business case. For a British wind farm it was found that more support is needed than in comparison with a Dutch wind farm. In addition, from a societal perspective, the least attractive mitigation options were identified to be the constant FIT, and the SDE++ scheme. These schemes imposed an additional average annual cost of roughly 62.96 and 57.80 million euros respectively over the given time period with respect to the same subsidy scheme in the reference case. As a consequence, the constant FIT scheme resulted highest annual average revenue for the wind farm developer of about 383 million euro over the given time period. However, from a societal perspective, the redistribution of congestion income would be the best option. This was found to be cost-free, as there was enough congestion income collected to support the wind farm developer over the given time period. In addition, about 15% of the accumulated annual average congestion income would be redistributed to the British wind farm developer. Last, would the wind farm developer be partly made the owner of the interconnector, the TSO-light certificate seems also as a feasible option based on the financial criteria.

For a Dutch wind farm, similar findings were observed. It was found that a CfD scheme is the most cost efficient scheme together with the (regulated) post operation compensation, requiring no additional costs with respect to the same subsidy in the reference case. Naturally this can be explained due to the fact, that the Dutch wind farms were generating more revenue instead of less revenue. Nevertheless, support was still necessary to achieve a positive business case. The least cost efficient mitigation scheme for mitigation of a Dutch wind farm was also found to be the constant FIT scheme, requiring average annually costs of about 38 million euro. In addition, a slightly higher redistribution of congestion income was found; about 30% resulting roughly 30 million euro on average every year within the given time period.

When looking at the feasibility of the proposed mitigation options, additional insights were obtained. It is important to comprehend that there is no substantial difference in the scoring of the feasibility looking from a Dutch or British perspective. The feasibility primarily focuses if the mitigation schemes are applicable to a wider situation, in terms of future proofness. It was found that the mitigation options with the worst score was the constant FIT scheme which obtained a score of -2. This mitigation option is not flexible for system changes, such as large fluctuations in electricity prices. In addition, the newly proposed regulated post-operation compensation was also found to have a relatively poor score in terms of feasibility, as was explained in section 7-5. In terms of this criteria the CfD scheme was found to be the best option with a corresponding final score of 3 out of 4. Followed by a group of the SDE++ scheme, the redistribution of CI and the TSO-light certificates with a resulting score of 1.

8-2 Limitations

The following section discusses the limitations of this research. This is carried out through a reflection on the important research phases that were presented in Figure 1-6. These limitations have an impact on the results and originate mainly from the scenario-based modelling & simulation approach. First, a general reflection will be carried out, discussing assumptions and simplifications that have been adopted in the beginning of this research. Second, simplifications regarding the modelling & simulations will be discussed, and their impact will be analysed. Third, limitations in the mitigation analysis will be discussed.

8-2-1 Reflection on general assumptions

One of the main simplifications adopted in this research is the decision to leave out the cost of finance such as taxes or costs of loans in the assessment of the business case of offshore wind farms. Naturally, as the initial investment costs are large, this simplification may possibly have an noticeable impact on the LCOE. This would imply that the calculated LCOE in this research are actually lower than they would be in reality. However, it becomes difficult to identify this impact on the LCOE, since investment data in offshore wind farms are not publicly available because of the competitive nature of the market. In addition, B-2 shows the effect of various financial parameters on the calculation of the LCOE.

The next general assumption is also about the costs related to the construction of offshore wind farms. For the upcoming decade, TenneT is appointed to be the offshore transmission system operator for the Netherlands, responsible for the grid connection of the offshore generator assets. Currently, the costs are paid through a subsidy named Net op Zee, resulting in a lower total CAPEX for Dutch offshore wind farm developers. As a consequence, it became possible to construct the first wind farms without additional support such as the SDE++. However, it is uncertain if TenneT will be responsible for future wind farms, especially when they will gradually move further offshore, and as a consequence will increase the costs of grid connections. The objective of this research was to find the effects of the grid integration on the (current) business cases of offshore wind farms. As a consequence, the assumption was adopted that Dutch developed wind farms will still receive a grid connection from the Dutch government via TenneT in order to assess the effects with the current situation.

The last general assumption that was adopted is that both a Dutch and British wind farm can be built under the specified geographical characteristics. In offshore wind tenders, also a feasibility study is carried out in order to assess the impact of the construction of a wind farm on the ecosystem. As a consequence, the Dutch part of the Doggerbank has already been appointed as a no-go zone because of the fragile ecosystem. This research therefore, assumes that similar geographical features can still be found in the Dutch waters near the Doggerbank. If this is not the case, it may have an increasing effect in the construction (CAPEX) of the offshore wind farms, increasing the LCOE.

8-2-2 Reflection on the modelling approach

This section discusses the main assumptions of the modelling & simulation approach adopted in this research. In chapter 4, the approach to develop a conceptual model was discussed. Accordingly, as a model is often described as a simple representation of the system of interest, some simplifications were introduced. An overview of these simplifications and the reasoning behind this was elaborated in section 4-5.

The first simplification that may have an impact on the system is the assumption that takes into account the extra capacity of cross-border exchange in the onshore grid. It assumes that the onshore grid is able to absorb a constant flow of 1000 MWh, or at least at times when it actually occurs in this research. Although the assumption has been made that TSOs have enough capacity to accept the generated electricity from a wind farm. To assume that the onshore grid is large enough to accept a constant import/export of a large interconnection cable is something entirely different. Offshore wind farms select the size for the export cables on a prediction of the electricity yield in that particular location. Often a smaller export cable is chosen with respect to the wind farms rated capacity in order to optimise the utilisation or rather to optimize the operational costs of the cable. As a consequence, the assumption is that the onshore grid can accept a constant stream of 1000 MWh. This may not be realistic. For radial connected wind farms this is not an issue because no cross-border connection that could add extra capacity is present. however, with the introduction of a hybrid connection setup, this becomes relevant. As is stated in chapter 6, the transmission infrastructure is designed on transporting the in-feed of a wind farm with a volatile generation which is about 40 - 60 % of the export cable's rated capacity. This simplification may affect the costs imposed on society as wind farms could be curtailed because of the priority access conflict that was discussed in chapter 6.

Next, simplifications were made regarding the electricity prices. In reality, electricity prices are elastic and are set on an hourly basis. Theoretically, when for example in the Netherlands a large wind farm is added with a rated capacity of 1.4 GW it could seriously have a decreasing effect on the Dutch electricity price since the generated capacity is offered at a price close to zero. The intersection where demand meets supply in the merit order would be shifted downwards because of the "cheap" capacity offered by the wind farm. However, in order to be able to quantify this phenomenon, the biddings into the wholesale markets should have to be known, in order to see the effect on the market clearing mechanism. However, this would unnecessarily increase the complexity of the system because the goal of this research is to see effects in the revenue by including the limitations of transport due to different connection schemes with corresponding regulations. In addition, this described phenomena may also be valid for interconnection cables. As the cables may at times cause for cheaper capacity to flow into the market.

The second limitation of the model is also regarding the electricity prices. As historical data is used, the baseline in revenues is subjected to the time period over which the simulations have been carried out. These prices are the result of external factors within that specified time window. For example, during the time that this thesis was written, the gas prices were extremely high. High gas prices may result in an increase in electricity prices when gas generators are utilized. This phenomena was not observed in the cash flow as the historical data was limited to a set period. As a consequence, it must be understood that the conclusions are based on the specified time period, and expanding this period may result in a different base revenue for the wind farm developers.

Next, the simplification that limits the system to the involvement of just two countries has been adopted in this research. The logic behind this is that with the involvement of an additional third country, the system becomes much more complex. As no connections are made yet, it seemed more appropriate to start with the analysis on the effects of just two countries. It is difficult to comprehend the exact effects of this simplification, as it is dependent on various parameters such as the relative height of electricity prices, governance models and national policies. However, this is an effect that should be introduced for future research as meshed offshore grids configurations will probably include multiple countries. This will be further explained in the next chapter.

8-2-3 Reflection on the mitigation analysis

Simplifications or assumptions made in this research phase are largely related to the uncertainties originating from the model. Nevertheless, some simplifications were made regarding the financial criteria. The first assumption describes the amount of additional support needed by the offshore wind farms under an OBZ. Because it was found that the wind farms need support even in the reference case, the calculation of the amount of additional support was based on the reference case already having a subsidy scheme. This was done in order to simulate reality as close as possible. In addition. the strike price, or winning tender price was set equal to the LCOE of the respectively wind farms. This implicates of course, that the wind farms are cost-efficient enough to be able to win a competitive auction for a wind tender. In addition, the uncertainties from the LCOE calculation and the simulation may affect the resulting costs imposed by the mitigation schemes.

Another limitation regarding the last research phase in introduced by the method that was adopted, namely, the policy scorecard. As was mentioned a few times in chapter 7, the development of the policy scorecard is subjected to the individual carrying out the approach. In this research this was performed solely by one individual. This may have additional effects especially on the feasibility criteria. The appropriateness of the scores is subjected to the expertness level of this individual and may misjudge the resulting scores.

In addition, it is crucial to understand that, when looking at a broader perspective of the problem situation more criteria are necessary in order to come up with a final decision about the proposed mitigation options. As was made clear in the introduction of the research, this problem has a broad nature in terms of different aspects. This research mainly focused on the modelling output and according insights that could be obtained through the outputs. However, the offshore infrastructure integration by means of hybrid assets, imposes effects on a much broader scale. Because of the broader political impact, in terms of financial budget requirements on a member state level, general public support for support schemes and overall effectiveness of support schemes in light broader policy objectives, the political domain requires more attention to obtain that broader perspective for political decision making. The impact on the operations of the onshore electricity system, in terms of impact on overall market efficiency, operational incentives and possible abuse of market power, is another example of yet another different field of research that has not been investigated in this research. Therefore, the deliverable of this research, namely the policy scorecard, should be further developed in different field of research in order to formulate a sound conclusion about the effects of the mitigation options from a broader perspective that enables political decision making on a national and European level.

Chapter 9

Conclusion

In this chapter conclusions will be drawn based on the outcomes of the performed research. This is done by first answering the main research question and subsequently the sub-research questions. Next, a section will be dedicated to a reflection in which the academic- and the practical & societal relevance is discussed. In addition, recommendations and future research on this topic will be identified and proposed. Last, a personal reflection is added, marking the end of this research.

9-1 Main research question

The objective of this research was to find a solution to the problem that currently takes place in the offshore renewable energy domain. As Europe tries to cope with the climate goals set up during the Paris Climate Agreement in 2015 and in the resulting Clean Energy Package, an enormous boost in offshore capacity is necessary. Two specific goals are of interest in this research. First, the goal defined in the European strategy for offshore wind, which is to install 60 GW of offshore wind by 2030 and up to 300 GW by 2050. Second, the goal describing the ambition to work towards an integrated European electricity system. In order to achieve these goals and especially to unlock the large amount of renewable energy, enormous investments in the expansion and reinforcement of the current off- and onshore transmission grid are necessary. To be able to unlock this increase in offshore wind capacity in a cost-efficient manner, so-called hybrid connections are seen as potential gateways. Hybrid offshore connections imply a scenario in which a cross-border connection is added in a configuration with a present radially connected offshore wind farm.

Accordingly, the main research question was constructed as follows:

How does the North Sea transmission infrastructure integration impact the business cases of the offshore wind farms under different market designs and how can these be protected for future grid development?

This question reflects the goal of this research, namely being able to develop a model which allows the user to simulate various future scenarios regarding the North Sea grid integration. In this research, this was performed by constructing a fictional wind farm from a Dutch and British perspective. In addition, to obtain insights into the effect that it imposes on the business cases of offshore wind farms. Last, to be able to analyse possible protection instruments if negative effects are observed.

It was seen that for the given time period, geographical- and wind farm characteristics additional support is needed for both the Dutch and British wind farms in the current radial connection. Second, The effects when wind farms were located in a hybrid setup including a single cross-border connection were analysed. In addition, when this scenario is also under current regulation, meaning that cross-border capacity exchange is prioritized over the wind-generated capacity on the transmission cables, both the British and Dutch business cases were not affected substantially. However, it imposes substantial costs on society. In addition, when the effects on the business cases were analysed for the offshore bidding zone setup, it was found that on average the more support was needed in order to maintain a positive business case for the offshore wind farms.

For the last part of the main research question, various ways to protect the business cases for future grid development were identified. It was found that there are three categories in which governments tend to support renewable energy technologies in general. In addition, eight mitigation options were identified specifically granting additional support to wind farms in hybrid setups. Only seven mitigation schemes were analysed in terms of effects on the cash flow of the wind farms and costs imposed on other actors. These seven mitigation schemes were selected due to the fact that they apply on the offshore bidding zone market setup whereas the eighth did not. In addition, the feasibility was analysed of each mitigation option. It was found that under the scope of this research, the CfD scheme seems to be the best choice in terms of financial effectiveness and feasibility. However, additional perspectives are required in order to actually make a decision on the selection of a mitigation option. The redistribution of congestion income or granting a TSO-light certificate can be seen as an acceptable alternative, once more within the scope of this research, if CfD might not be applicable for other reasons.

9-1-1 Sub-research questions

The main research question was subdivided into four sub-questions that represent the steps that were carried out in order to answer the main research question. These sub-research questions were answered throughout the research. In this subsection, a summary of the findings and corresponding conclusions will be presented for each sub-research question.

1. What is the business case of an offshore wind farm from a Dutch and British perspective?

This sub-research question was set up in order to provide background on the process of constructing a business case for offshore wind farms. The question ought to give insights into the decision-making processes of wind farms and try to identify the main cost drivers for a wind farm developer. In addition, it was explored how an offshore wind farm collects its income. The approach used has been elaborated throughout chapter 3. The business of an offshore wind farm seems to be a broad question. It was found that the business case of a wind farm can be best expressed in this research using the expression of the LCOE. The lower the LCOE, the more competitive a wind farm developer is. In addition, the LCOE is the minimum value of a bid that can be offered by wind farm developers in tenders that are sold in competitive auctions. However, in reality, the bids in competitive auctions tend to be lower than the LCOE. This was partially explained by the incentive of wind farms to obtain a higher market share.

The total sum of revenues that are collected by wind farms per unit generated electricity must always outweigh the value of the LCOE in order to be able to construct a profitable business case. It was seen that there are a few ways for offshore wind farms to generate income. The main focus in this research was limited to the income stream collected by offering their generated electricity into the wholesale market and receiving the electricity price and in some cases some extra revenue due to subsidy schemes. Another way to collect income for a wind farm is by long-term PPAs or through green certificates.

Within this sub-research question, a distinction is made between the business cases of a British and Dutch wind farm. Naturally, the market for offshore wind energy makes no distinction between nationalities, therefore no difference is seen in costs for the components of a wind farm. However, the biggest difference in a business case between a British and Dutch wind farm is the governance model used to construct the connection to the grid which consists of the on- and offshore substations along with the export cables. This increases the initial investment for British wind farms and in addition, the operational expenses because of the transmission tariffs. Dutch wind farms do not have to invest in the grid connections, this is done by its national TSO. More detail is found in chapter 3. Furthermore, different subsidy schemes are used. However, the height of the subsidy is predominantly determined by the LCOE of the wind farms.

The second and third sub-research questions are of a similar nature. The goal was to obtain insights into the effects imposed by connection scenarios and under different market designs. In order to answer these following two sub-research questions in a structured way, first a conclusion of a home market scenario will be discussed. For the second sub-research question the effects of market changes on the system the conclusions will be made of the effects of an offshore bidding scenario. Both questions were answered using a model on which various scenarios were simulated. This model development process has been discussed in chapter 4. In addition, the construction of the scenarios was discussed in chapter 5.

2. How do different grid connection scenarios impact the business case of offshore wind farms?

First of all, It was found that for home market situations, which are the current radial connected wind farms, a small loss in electricity generation was observed as not all generated capacity can always be transported to shore. Naturally, this imposes also a minor decrease in revenue for the wind farm developer.

When a cross-border connection is added to a radial connected wind farm various effects were observed with respect to the reference case. First, if a wind farm were to be in a situation without any regulations, a so-called free situation, the extra connection imposes a positive effect on the business case of the wind farm since it can transport all its electricity. However, when the current regulatory effects are imposed on the system no substantial effects were observed in the revenue of the offshore wind farm developer. This is discussed in chapter 6. However, a substantial cost imposed on society was seen through TSO compensation for the wind curtailment.

Furthermore, with the implementation of a cross-border connection for a single wind farm, the process of implementing subsidy schemes has become much more complex with respect to the reference case. This further imposes a negative effect on the solidness of the business cases of offshore wind farms trying to partake in hybrid connections. This uncertainty has to be solved by the governments or offshore wind farm developers who may decide not to partake in hybrid connections.

The goal of this question was to obtain the first insights into the system of interest. More specifically, insights into the effect of various connection scenarios on the business case of an offshore wind farm. This is one out of the two main changes that were imposed onto the simulation model in this research. In addition, it is important to understand that the answer to this research question always acts in a certain market setup, which was the home market setup.

3. How does the offshore grid market design impact the business case of offshore wind farms?

With this sub-research question the second system change was investigated. This was done by analysing the implementation of an offshore bidding zone onto the model. The background information about the offshore bidding zone has been discussed in subsection 2-4-3. The offshore bidding zone imposes negative effects for the wind farm normally connected to the higher-priced zone. The effects were based on its current radially connected reference case. The results are discussed in section 6-4. However, for Dutch wind farms, which are originally connected to the lower-priced bidding zone the revenues tend to increase under an offshore bidding zone. As a consequence, when exploring these hybrid connections, this seems like a good fit for the Dutch wind farm developers. Nevertheless, this market design still imposes a negative effect in terms of revenue loss for specific situations. Again, especially the business cases of British wind farms are in danger, as the wind farm developers made their business case based upon the higher British electricity prices. Additional financial support is most likely needed. However, the process of designing a subsidy scheme specifically for the offshore bidding zone is simpler than compared to the wind farms with a cross-border connection under a home market setup. In addition, when an additional support scheme is implemented for an offshore wind farm in an offshore bidding zone, the business case is much more reliable than in a home market setup. Concluding, that the offshore bidding zone market setup, under current regulations and within the scope of this research seems to be the best choice of market setup.

4. How can the business cases of offshore wind farms be protected if a scenario yields negative effects?

The last sub-research question serves the purpose to propose a method to identify instruments to compensate the wind farm developers under an offshore bidding zone. This specific additional compensation for hybrid offshore wind projects is regarded to as mitigation options. A first assessment, using the policy scorecard method, was carried out to assess existing mitigation proposals within the scope of this research. The approach adopted in order to perform this step in the research is described in detail in chapter 7. Eight schemes were investigated, most of the schemes were categorized as operational mitigation schemes. As the scope of this research was limited, the assessment was mainly focused on the financial effects of the mitigation schemes and the feasibility of the proposed mitigation schemes.

When looking solely at these criteria, the CfD scheme may seem like an efficient choice of support. It was found to be the most cost-efficient from a societal perspective. In addition, the scheme ensures a stable income and prevents so-called windfall profits that could happen under a SDE++ scheme resulting in stronger business cases under efficient support. However, as the problem is much broader than just a financial- or feasibility domain no conclusion can be made in a broader perspective. This implies that although the protection instruments were found, and thus an answer is obtained for the sub-research question, no solution was found to solve the current problem.

9-2 Reflection

In this section, the whole process of conducting this research is being reflected. The relevance of this research will be discussed using two domains. The first domain describes the academic relevance of this research whereas the second domain discussed the practical & societal relevance. In addition recommendations for future work will be proposed in the last section.

9-2-1 Academic relevance

In this thesis the combined research method; the scenario-based modelling & simulations approach was used to model the effects of the North Sea grid integration on the business cases of the offshore wind farms. A literature review was conducted to identify the knowledge gap, which states that it is not known what the magnitude is of the effect of the North Sea grid integration on the business cases of offshore wind farms. More specifically, how these business cases are affected under different connection scenarios and market designs. In addition, no research has been performed yet that develops a model that allows the simulate revenues under different connections, market setups and subsidies for a wind farm anywhere in the North Sea region. The North Sea region has some unique characteristics such as the relatively shallow sea depth and the strong and consistent wind profiles which makes it ideal for offshore wind. It can be assumed that more studies in this specific location will be carried out in the coming decades. These findings in this research could be used for the coming research. The academic contribution can be argued to be of significance since two distinct sets of historical data were used.

The strength of this project can be found in the academic approach to develop the model that allows simulations based on scenarios. In addition, the assumptions and simplifications adopted in this research are clearly stated throughout the process making it, with some minor adjustments to the model, relatively easy to use for different locations and wind farm characteristics. Because of the usage of multiple scenarios, the effects of the various ways of integrating the North Sea grid can be clearly seen. All this makes the findings in this research user friendly for other researchers.

The findings of the beginning of the project may also be used for research into the construction of wind farms. An approach was proposed to identify the main cost drivers of the construction of an offshore wind farm. In addition, the LCOE was calculated for a particular case in the North Sea which may be beneficial to other studies that focus purely on wind farms.

In addition, very little to no research has been performed on these so-called hybrid connections from an academic point of view. As actors such as the national TSOs and different market players may be biased because this subject can have big impacts on their day-to-day tasks, a neutral perspective may be valuable to future research.

9-2-2 Practical & societal relevance

This project was carried out by means of an internship at the Dutch TSO TenneT. Additionally, the data sets were accumulated from the European network of TSOs or ENTSO-E that receive data from all European TSOs. Therefore, practical relevance is also important.

As was stated in the introduction of this research, the problem that was tried to solve is currently still under debate. Various studies for the EC were carried out, such as the two studies by Roland Berger: (Weichenhain et al., 2019) and (Kern, Zorn, Weichenhain, & Elsen, 2018) and the study of Sweco and Guidehouse (Boeve et al., 2020) that took a first glimpse in this subject. However, the solution has yet to be found. The modelling of the different scenarios may give insights for offshore wind farm developers that are constructing business cases for future (hybrid) offshore projects. For current wind farm developers, the effects may give insights into the discussion that eventually will occur about the manner of compensation when participating in the hybrid connections. In addition, the clear steps of simulation may give insights into the development of new support schemes for these particular situations. Last, it could also be used by the other actors such as the NRAs, TSOs or ministries to assess policies regarding cross-border capacity exchange.

The societal relevance of this research is that it presents findings that could accelerate the unlocking of the great wind energy potential in the North Sea region. As a consequence, the findings of this research can aid in the increase in renewable energy in Europe.

9-2-3 Recommendations for future work

Based on the insights obtained in this research and the relevance of the findings some recommendations can be proposed for future research. The recommendations should reflect and align with the findings of this research. The first recommendation, however, reflects on the simplifications made throughout the research. One major simplification was to exclude the congestion management of the onshore grid in this research. A recommendation would be to try to include this into the model. As the share of volatile renewable energy systems is increasing, the onshore grid will be put under pressure in windy and sunny times and may not have the capacity to adopt the large quantities of wind capacity generated by the wind farms, this will have an additional effect on the system.

A second recommendation would be to expand the system boundaries by including a third country. Currently, a consortium of TSOs is looking into the development of a North Sea Wind Powerhub, which is a hub-and-spoke concept that tries to connect German, British, Danish and Dutch wind farms to one big hub or several distributed hubs. The model may be of use for these types of projects and new insights may be adopted when including the third country. As a consequence, additional connection schemes could be analysed. For example what happens when an interconnector is placed between two wind farms. Or when multiple wind farms are being connected in a hub-and-spoke configuration.

Third, some further research can be performed on the cost of finance for the wind farms. In this research, this was left out of scope, but it is important to fully comprehend the business case of a wind farm as it may have a substantial impact on the LCOE. The closer a real-life situation can be simulated, the better a wind farm can be comprehended the decision making. This of course, contributes to the discussion of whether wind farms partake in hybrid offshore wind projects, or act as barriers to the North Sea transmission system integration.

However, the main recommendation for future research may involve the last research phase, namely to assess the mitigation schemes. As was discussed in chapter 7 and 8, the method that was adopted requires additional research in order to formulate a conclusion about the best choice of mitigation options within the broader perspective of the current situation. More specifically, the current criteria domains should be evaluated and additional criteria domains should be investigated. As the policy scorecard that was developed in this research is heavily subjected to the researchers own thinking, field experts should be brought in the evaluate the scorecard as it now is.

Furthermore, to address the problem in a way that reflects all incentives of the actors involved, a start to develop additional criteria may be to include domains from those perspectives. The actors identified were the wind farm developers with a commercially perspective, the TSOs having a perspective more related to the electricity system, the NRAs and governments that have a predominantly societal or political perspective. It is recommended to perform additional research in these sectors. The commercial perspective should be investigated by, for example, interviewing wind farm developers whereas the political domain could be analysed by looking at EU legislation, and climate-related goals of the member states. When a broad perspective is obtained, a better solution to the current problem may be found.

9-2-4 Personal reflection

The final part of this research is dedicated to the personal reflection of its researchers. This master thesis project is the last step in order to obtain the master degree in Sustainable Energy Technology (SET) from the faculty of Electrical Engineering, Mathematics and Computer Science at Delft, University of Technology. In this research, I was confronted with the complexity of the problem, as it touches upon various fields of expertise in which, for some fields, I had limited to no understanding. However, this has resulted in a much broader understanding of the current electricity system and what the future holds for possible developments. In addition, carrying out the research at the Dutch TSO TenneT, thought me much about how the electricity system is operated in real life. I think it is safe to say that as Europe will try to work towards an integrated offshore electricity transmissions system, hybrid offshore wind projects can indeed be seen as a cost-efficient gateway in order to achieve this goal.

Appendix A

Data collection on the business case

Table A-1: Total cost overview of corresponding to an offshore wind farm.

Author	Technology	Estimation	Unit
(BVG Associates, 2021)	Turbine	0.86	million €/MW
(IRENA, 2012)	Turbine	1.83	million €/MW
(Junginger et al., 2004b)	Turbine	0.86 - 1.43	million €/MW
(Gonzalez-Rodriguez, 2017)	Turbine	0.97	million €/MW
(Foxwell, 2020)	Turbine	1.00	million €/MW
(OE, 2020)	Turbine	0.93	million €/MW
(BVG Associates, 2021)	Foundation	0.25 - 0.31	million €/MW
(Junginger et al., 2004b)	Foundation	0.32 - 0.54	million €/MW
(Stehly & Beiter, 2020)	Foundation	0.29 - 0.5	million €/MW
(Gonzalez-Rodriguez, 2017)	Foundation	0.46 - 0.54	million €/MW
(Albani et al., 2014)	Foundation	0.43 - 0.54	million €/MW
(Gomez Tuya & Lowen, 2019)	Foundation	0.43 - 0.77	million €/MW
(Morthorst & Kitzing, 2016)	Foundation	0.5 - 0.58	million €/MW
(BVG Associates, 2021)	Inter array cables	0.35	million €/km
(Stehly & Beiter, 2020)	Inter array cables	0.32 - 0.37	million €/km
(Nieradzinska et al., 2016a)	Inter array cables	1 - 1.2	million €/km
(Lerch et al., 2021)	Inter array cables	0.21 - 0.32	million €/km
(Dicorato et al., 2011)	Substation - HVAC	0.11	million €/km
(BVG Associates, 2021)	Substation - HVAC	0.10	million €/km
(Härtel et al., 2017)	Substation - HVDC	0.24 - 0.65	million €/km
(Nieradzinska et al., 2016b)	Substation - HVDC	0.40	million €/km
(Moon et al., 2014)	Export Cable HVDC	1.25	million €/km
-	Export Cable HVAC	1.14	million €/km
-	Export Cable HVAC	2.85	million €/km
(Kaiser & Snyder, 2010)	Decommissioning	0.09 - 0.15	million €/MW
(Kaiser & Snyder, 2012)	Decommissioning	0.09 - 0.12	million €/MW
(Adedipe & Shafiee, 2021)	Decommissioning	1.6	million €/MW
(Henriksen et al., 2019)	Decommissioning	0.25 - 0.43	million €/MW
(Morthorst & Kitzing, 2016)	OPEX	19 - 49	€1000/MW/Year
(Scheu & Stegelmann, 2020)	OPEX	118	€1000/MW/Year
(Stehly & Beiter, 2020)	OPEX	84 - 144	€1000/MW/Year

Revenue streams

Table A-2: Overview of reviewed income streams for an offshore wind farm except the normal commodity price.

Author	**Type and specification**	**Price (€/MWh)**
(LevelTen-Energy, 2020)	PPA - United Kingdom	53
	PPA - Germany	53
	PPA - France	91
	PPA - Spain	36
	PPA	60.03
	PPA	68.12
	PPA	86.89
	PPA	140.32
	PPA	214.87
	PPA	85.95
(Rekenkamer, 2018)	SDE+ - Egmond aan Zee	158
	SDE+ - Princess Amalia	163
	SDE+ - Gemini	169
	SDE+ - Luchterduinen	181
	SDE+ - Borssele 1 & 2	88
	SDE+ - Borssele 3 & 4	54.5
	Hollandse kust (zuid) 1 & 2	*subsidy-free*
	Hollandse kust (zuid) 3 & 4	*subsidy-free*
(Virley et al., 2019)	CfD - Doggerbank A- Creyke Beck	45.32
	CfD - Doggerbank A - Teeside	47.56
	CfD - Doggerbank B	47.56
	CfD - Sofia	45.32
	CfD - Doggerbank C	47.56

Table A-3: The impact of depth and distance on costs (Green & Vasilakos, 2011).

Depth (m)	Distance (km)							
	10	***20***	***30***	***40***	***50***	***100***	***200***	***300***
20	1.00	1.02	1.04	1.07	1.09	1.18	1.41	1.6
30	1.07	1.09	1.11	1.14	1.16	1.26	1.5	1.71
40	1.24	1.26	1.29	1.32	1.34	1.46	1.74	1.98
50	1.40	1.43	1.46	0.15	1.52	1.65	1.97	2.23

Appendix B

Simulation

B-1 Wind- and generation profile

This section discusses the approach on how the accumulated data from Pfenninger and Staffell (2021) was used in order to define a generation profile of the Haliade-X wind turbines (14 MW). First the inputs used for the online tool of are displayed. Second, the estimation of the power curve for the Haliade-X wind turbine is elaborated.

Table B-1: Input values in the online tool of Renewables Ninja.

Input	**Value**
Point	Doggerbank
Latitude	54.8368
Longitude	3.2218
Data set	MERRA-2 (global)
Year	2015-2019
Capacity	1400 kW
Hub height	135 m
Turbine model	see table B-2
Include raw data	True

The output of the online tool using the data from table B-1 and B-2 is a dataset containing the hourly generation for the specified location and turbine. This means that nine slightly different data sets were retrieved. In order to come up with an estimation of the power output of the Haliade-X (14MW) turbine, a linear regression was performed on four wind turbine characteristics that are displayed in table B-3. It was found that the cut-in and cut-off wind speeds had no significant effect in the regression and therefore a second regression was carried out without these characteristics.The used wind farm characteristics and corresponding electricity output of the Haliade-X is seen in table B-4. An expression of the resulting formula used is seen in equation B-1.

Table B-2: Turbines from Renewables.Ninja used for the linear regression.

Turbine type
Vestas V164 9500
Vestas V164 8000
Vestas V150 4000
Vestas V136 4000
Enercon E126 7000
Enercon E126 7500
REpower 6M
Repower 5M
Gamesa G128 5000

Table B-3: Wind farm characteristics and power output used in regression.

Name:	**electricity generated [MWh]**	**hub height [m]**	**Rated wind speed [m/s]**	**Rotor Diameter [m]**	**Rated power [MW]**	**Cut-in wind speed [m/s]**	**Cut-off wind speed [m/s]**
Vestas V164 9500	34514775	135	14	164	9.5	3.5	25
Vestas V164 8000	37157477	135.5	13	164	8	3.5	25
Vestas V150 4000	44260331	135.5	9.9	150	4	3	22.5
Vestas V136 4000	36026705	157.5	13.5	136	4	3	25
Enercon E126 7500	30798982	135	17	127	7.5	2.5	25
Enercon E126 7000	32360426	135	16.5	127	7	3	34
REpower 6M	33487461	95	14	126	6	3	30
Repower 5M	36026705	90	14.5	126	5	3	30
Gamesa G128 5000	36967423	87	14.5	128	5	2	27

$$y = 40.15\times10^{6} - 22.95\times10^{6}h_{\text{hub}} - 80.97\times10^{6}v_{\text{wind}} + 12.23\times10^{6}r_{\text{rotor}} - 11.49\times10^{6}P_{\text{turbine}} \tag{B-1}$$

Table B-4: Resulting data used in regression and the output of the Haliade-X.

Turbine model	*Generation [MWh]*	*hub height [m]*	*Rated wind speed [m/s]*	*Rotor Diameter [m]*	*Rated power [MW]*
Vestas V164 9500	34514775.47	135	14	164	9.5
Vestas V164 8000	37157477.27	135.5	13	164	8
Vestas V150 4000	44260331.15	135.5	9.9	150	4
Vestas V136 4000	36026704.99	157.5	13.5	136	4
Enercon E126 7500	30798982.19	135	17	127	7.5
Enercon E126 7000	32360425.51	135	16.5	127	7
REpower 6M	33487460.98	95	14	126	6
Repower 5M	36026704.99	90	14.5	126	5
Gamesa G128 5000	36967422.78	87	14.5	128	5
Haliade - X	***36608428.23***	***150***	***13.5***	***220***	***14***

Table B-5: Yearly average exchange rates used to express British electricity prices in euros.

Year	**Conversion factor**
2015	1.3777
2016	1.2242
2017	1.1414
2018	1.1301
2019	1.1405

B-2 Calculation of the Levelized Cost of Energy (LCOE)

This section explains the approach on how the LCOE was calculated in this research. First the factors which determine the LCOE are elaborated upon and the resulting formula is presented. When the expression has been determined, a representation of how the input data was used in order to calculate the LCOE will be discussed. Then the CAPEX and OPEX are determined based on the literature study that has been performed in chapter 3. In addition, the Annual Energy Production (AEP) that has been determined in appendix B-1 will be introduced in order to calculate the LCOE for a Dutch an British wind farm respectively.

B-2-1 Identification of additional parameters in order to calculate the LCOE

In order to evaluate any type of wind farm, the Annual Energy Production (AEP) has to be calculated. This is the energy that a wind turbine at a specific location can generate, and it is a function of a time window (T) (often annually) in hours, the wind speed (U) in m/s at a certain location ($_i$). In addition, it is a function of the power curve of a specific type of turbine in MW ($P(U)$). The expression for the AEP is seen in equation B-2.

$$AEP = \sum_{i=1}^{I} T \cdot f_i \int_0^{\infty} p_i(U)P(U)\mathrm{d}U \tag{B-2}$$

Normally in order to express the operational performance of an OWF, the capacity factor is used. This is a factor of the actual generation divided by the theoretical maximum generation within a certain time period. It is an expression of how long the farm operates at maximum rated power in a year. The capacity factor for the North Sea is in the range of 0.3 to 0.5 and is calculated as is seen in equation B-3. Where P_n is the power output at a certain time stamp t.

$$CF = \frac{AEP}{P_N \times t} \tag{B-3}$$

However, for this research the actual generation ouput of a wind farm was calculated using an online tool. This has been discussed in appendix B-1. Nevertheless, it is important to understand the manner in which the AEP is calculated when no online tool can be used.

The Weighted Average Cost of Capital (WACC) is as the name states, the average cost a wind farm developer has to pay over its debt in which weighting is based on the share of funds provided from different sources (Hundleby, 2016). It is an important factor that has a strong correlation with the LCOE. According to Hundleby (2016), if typical offshore wind values are used for CAPEX, OPEX with a life time of 25 years a WACC of 10%, then almost 50% of the LCOE is from the cost of finance. The equation is displayed in equation B-4.

$$WACC = \frac{\sum_{i=1}^{N} r_i \cdot MV_i}{\sum_{i=1}^{N} MV_i} \tag{B-4}$$

$WACC$ = weighted average cost of capital
N = number of sources of capital (securities, types of liabilities)
r_i = required rate of return for security
i = security
MV_i = market value of all outstanding securities

The Levelized Cost Of Energy (LCOE) is a way to quantify the cost of a generating asset by looking at the total project cost and electricity production over its lifetime. It is seen as a metric that combines the costs and energy production rather than the conventional performance indices such as the net present value (NPV) and Rate of Returns (RoR). According to (BVG Associates, 2021) the LCOE is used to compare and evaluate the electricity production of different technologies at different locations. In addition, it is mostly used by technology players and industry enablers rather than investors. One benefit of using the LCOE rather than rate of returns or net present value is that it is compatible with the (operational) subsidies such as the CfD and SDE++ (€/MWh). The expression for the LCOE is shown in equation B-5.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{B-5}$$

Where n is the lifetime of the project in years, r is the weighted average cost of capital WACC, E_t is the AEP in year t, M_t is the operation & maintenance cost in year t and I_t is the CAPEX in year t. Most of these indices mainly rely on the main cost drivers defined in the previous chapter.

In order to develop the fist concept of the model, input variables were introduced. Input variables include the main cost drivers, the hourly spot price, the capacity factor and the discount rate. These are often specified and differ per location. Figure B-1 displays the diagram which presents the approach to calculate the LCOE

B-2-2 Input

In order to test this cost-model a real life project was chosen. As stated a few times earlier in this research, the location chosen for the model is around the Doggerbank region. This is a relatively shallow sand bank located in the North Sea relatively close to the Dutch and British shore. One of the main reasons for choosing this location is the available data of one three big wind farms being built in the future, namely Sofia, Doggerbank A, B and C wind farms. These wind farms can be used to validate the resulting expression of the LCOE for the specified wind farm. For example, Sofia was awarded with a CfD price of 45,43 €/MWh (Virley et al., 2019). Furthermore, according to Power Technology (2021) the 1.4 GW wind farm was constructed for roughly 4 billion pounds.

An assumption was made for each cost category within the ranges the literature study provided. For example, for the turbines the literature found a range of 0.86 to 1.83 Million euro per MW. Assuming a wind farm similar to Sofia with 100 x 14MW turbines results in

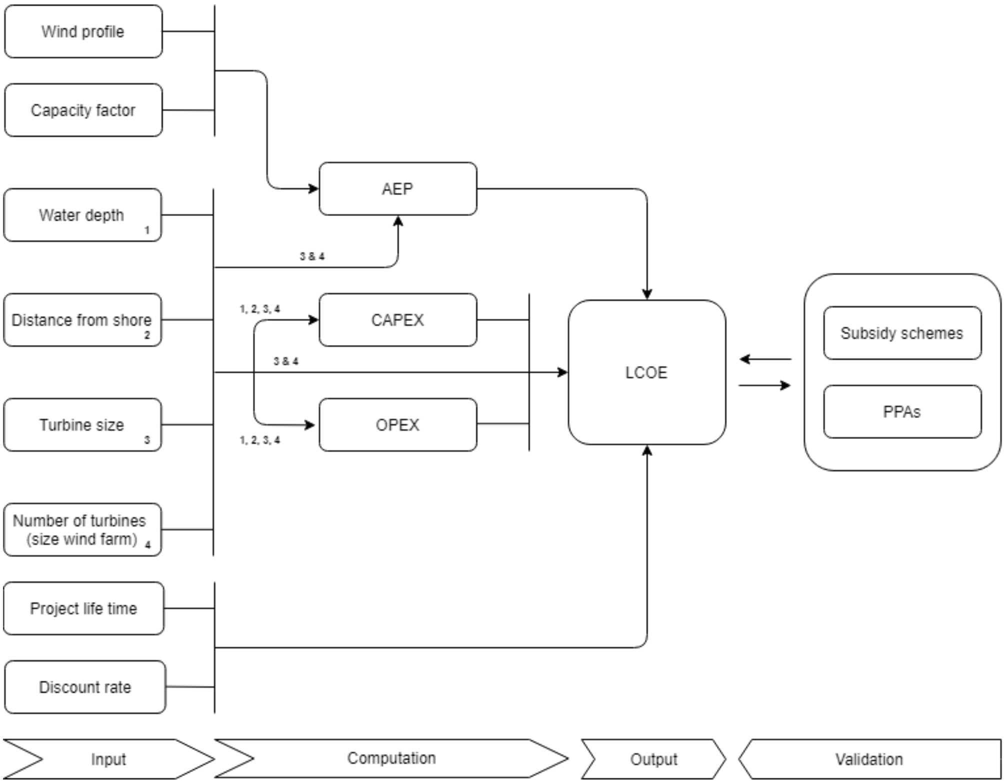


Figure B-1: Representation of a diagram of the approach to calculate the levelized cost of energy for an offshore wind farm.

a cost for turbines somewhere between 1.204 and 2.604 million euro. Furthermore, it is well known in literature that this particular cost category takes up about 20 to 30 % of the total investment costs of a wind farm. This approach was taken for every cost category and the resulting costs are seen in table B-6 and B-7 for a Dutch and British wind farm respectively.

It is important to note that , as is explained in section 2-3, the governance models for offshore grid construction differ somewhat between the Dutch and British approach. Normally this would not have a big impact, however, the Dutch TSO TenneT has been appointed as the offshore TSO for the Netherlands. This implies that TenneT is appointed to construct the offshore transmission (and collection) assets which are being paid by the "Net op Zee" subsidy. Because of this, TenneT may not impose transport tariffs onto offshore asset users such as wind farms. Nevertheless, this is not the case for the British side. Here the offshore cable will be sold through a competitive auction, and transport tariffs are imposed on the use of the cable. The determination of the height of The Transmission Network Use of System Charge (TNUoS) could be performed. However, for this research the simplification was made that when the grid connection costs are adopted in the CAPEX no extra OPEX (tariffs) would have to be calculated since the wind farm has to pay back the full grid connection price over the life time of the assets to the OFTO.

In addition, in order to validate the the values of the financial parameters such as the project life time and the discount the used literature review in chapter 3 could be used. In general, most papers estimate a project life time for offshore wind farms to be about 25 years

Table B-6: Outcome model: cost overview of construction of an offshore wind farm from a Dutch perspective.

Category	**Total cost estimation (million €)**	**Percentage of total cost**
Turbines	1680	55.89
Foundation	800	26.61
Inter-array cables	350	11.64
Export Cables (HVDC)	-	-
Substations	-	-
Decommissioning	126	4.19
OPEX	50	1.66
Total cost	**3006**	**100**

Table B-7: Outcome model: cost overview of construction of an offshore wind farm from a British perspective.

Category	**Total cost estimation (million €)**	**Percentage of total cost**
Turbines	1680	55.89
Foundation	800	26.61
Inter-array cables	350	11.64
Export Cables (HVDC)	950	17.7
Substations	1200	21.69
Decommissioning	126	4.19
OPEX	50	1.66
Total cost	**3006**	**100**

(Morthorst & Kitzing, 2016) (BVG Associates, 2021). In addition, no literature was found that contradicts this assumption. As a consequence a project life time was set for 25 years.

Martín, Coronas, Alonso, de la Hoz, and Matas (2020) performed a research in the viability of the LCOE used for bids in various tenders and subsidy actions for wind- and solar energy. In this research various case studies were analysed and a range of used discount rates in various calculations for the LCOE was mentioned. Martín et al. (2020) found that a range of 5 to 10 per cent depending on the way that capital was found. Therefore, it assumed that a value of 6% is a commonly used discount rate.

B-2-3 Output

Various calculations have been performed using different discount rates, and different generation profiles. In addition, in real-life situations the operational expenditures normally increase over the assets life time. An older wind farm generally requires more frequent maintenance as compared to a relatively new wind farm. In order to take this into account an options was added into the calculations in which the OPEX increases linearly per year. According to

(BVG Associates, 2021) this number can be assumed to be 2% of the OPEX.

Table B-8: Various LCOE under different discount rates an operational expenditures for a British wind farm.

Discount rate	**6.0%**	**6.5%**	**7.0%**	**7.5%**	**8.0%**
LCOE when Opex increases 2% anually	51.66	52.92	54.32	55.66	57.02
LCOE when Opex is constant	50.19	51.57	52.93	54.31	55.70

Table B-9: Various LCOE under different discount rates and operational expenditures for a Dutch wind farm.

Discount rate	**6.0%**	**6.5%**	**7.0%**	**7.5%**	**8.0%**
LCOE when Opex increases 2% anually	41.69	43.24	44.83	46.44	48.09
LCOE when Opex is constant	38.34	39.69	41.05	42.43	43.83

This approach was carried out numerous times until the LCOE came close to the identified awarded CfD schemes. As a consequence, a resulting LCOE of 43.24 €/MWh was found for a Dutch wind farm and 52.92 €/MWh for a British wind farm for a discount rate of 6.5%. This difference can be explained due to the distinct governance models used in the United Kingdom and the Netherlands. This has been explained in section 2-3.

B-3 Subsidy scheme calculations

This section will purely focus on the calculations of the used support schemes. More background information was presented in subsection 3-2-3. First, the SDE++ scheme calculation is presented. After, the amount of SDE++ support is determined, the CfD calculation is presented.

SDE++ scheme

As is displayed in Figure B-2 there are some parameters that need to be determined, before the amount of support can be calculated. As explained in subsection 3-2-3, the height of the support is determined as the difference between the basic price, which is set in auction, and the corrected price. The corrected price is expressed as the average price of that particular year, as it changes annually. An expression can be found in equation B-6, in which n is the number of hours in a particular year and Pn is the corresponding electricity price.

$$P_{\text{correction}} = \frac{\sum_{n=1}^{n} P_n}{\sum_{n=1}^{n} n} \tag{B-6}$$

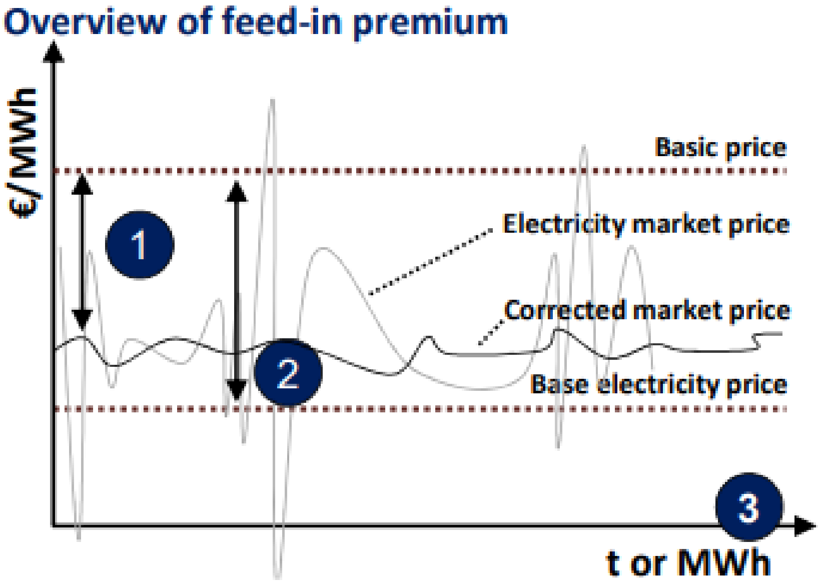


Figure B-2: Working of the feed-in premium SDE+ (TKI Wind op zee, 2015).

The second parameter needed to calculate the height of the SDE++ support is depicted as the base electricity price in figure B-2. This is a price which is set by the government responsible for the holding the auction. Unfortunately, this price is not always publicly available. Nevertheless, the impact of such a price is neglectable as long as the corrected market price is above the base electricity price. The base price is introduced if, somehow, the annual average electricity price is below this threshold. This has a protective function to the government which in this case only has to pay the difference between the base price and the price set in auction. For this research the base price is assumed the be 25% of the base price. The last parameter is the strike price or depicted as the basic price in the Figure. Since this price is set in auction, it is difficult to make a sound assumption of what the height would be for the selected wind farm in the Doggerbank area. Because of this, the last granted subsidy strike price is assumed to be given for the wind farm used in this research which is 54.5 €/MWh. If it is assumed that the SDE++ subsidy is granted in an hourly manner, the resulting support can be determined using equation B-7. Here the hourly SDE++ price is determined as the strike price minus the annual correction price.

$$P^{n}_{sde++} = P_{\text{strike}} - P_{\text{correction}} \tag{B-7}$$

The resulting annual correction prices and corresponding strike- and basic price are depicted in table B-10. It can be seen that no correction prices fall below the threshold set by the base price. As a consequence the granted subsidy is presented in table B-11. As is mentioned a few times throughout this research, the nature of this subsidy scheme is that of an operational one ans as a consequence, the granted support is depicted in €/MWh.

Table B-10: Resulting annual correction prices for the SDE++ subsidy scheme in a Dutch electricity market with corresponding strike- and basic price (€/MWh).

Base price	**17.50**
Strike Price	**54.50**
Corrected price 2015	39.00
Corrected price 2016	32.25
Corrected price 2017	39.31
Corrected price 2018	52.54
Corrected price 2019	41.55

Table B-11: Resulting annual height of the SDE++ subsidy scheme in a Dutch electricity market.

Height of support	**€/MWh**
2015	15.50
2016	22.25
2017	15.19
2018	1.96
2019	12.95

This ofcourse can also be done the same way for the British electricity market. This may give some insights later on, in the asssessments of the results. The resulting prices are depicted in table B-12 and B-13.

Table B-12: Resulting annual correction prices for the SDE++ subsidy scheme in a British electricity market with corresponding strike- and basic price.

Base price	**17.50**
Strike Price	**54.50**
Corrected price 2015	55.28
Corrected price 2016	49.49
Corrected price 2017	51.73
Corrected price 2018	64.91
Corrected price 2019	48.89

Table B-13: Resulting annual height of the SDE++ subsidy scheme in a British electricity market.

Height of support	**€/MWh**
2015	0
2016	5.01
2017	2.77
2018	0
2019	12.95

CfD scheme

In a similar way as the SDE++ scheme, the amount of support received by the offshore wind farm developers, using a CfD scheme can also be determined. This process, however is slightly different, as is explained in subsection 3-2-3. Seen in Figure B-3, the CfD is straight forward. A strike price is determined through a competitive auction where lowest bid of all the offshore wind farm developers win. This price is the treshold used for te determination of the height of the subsidy. In comparison to the SDE++ scheme, the CfD scheme does not work with an annual correction price, but instead uses the hourly electricty price. The amount of support granted is simpy the difference of the strike price and electricity price, depicted as number 1 in the Figure. In addition, whereas the SDE++ subsidy scheme allows the wind farms to keep the revenue earned for the situations in which the electricity price exceeds the strike price, the CfD scheme does not. When the electricity price exceeds the strike price the wind farm has to pay the difference back. In addition, when the electricity are negative the wind farm developer will not receive any subsidy. The maximum received support is basically the strike price.

To take an example, the strike price of wind farm Sofia is taken; which is 39.65 £/ MWh. Table B-14 shows the strike price converted to the right monetary term using the exchange factors depicted in table B-5.

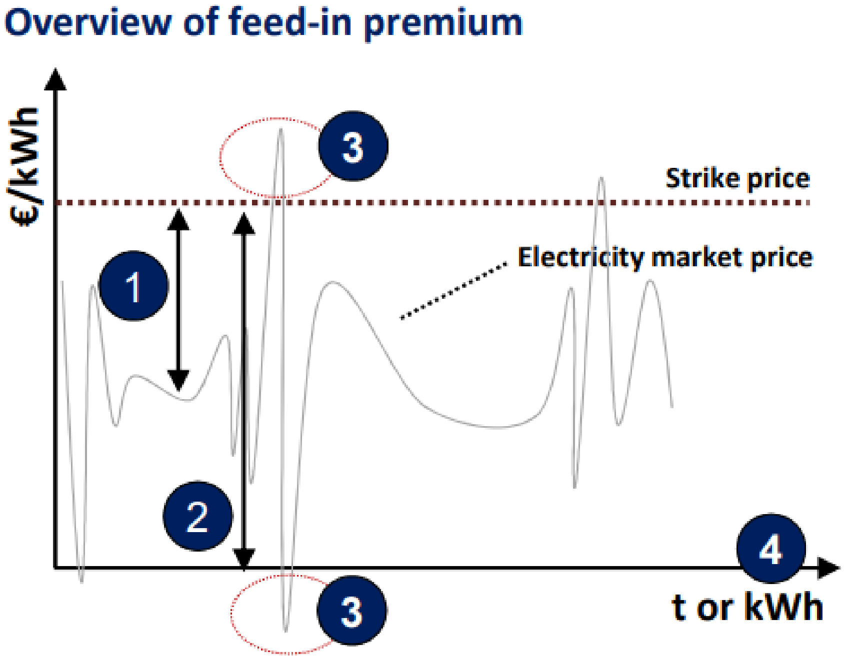


Figure B-3: Working of the CfD (TKI Wind op zee, 2015).

Table B-14: Maximum height of the support granted using the CfD scheme.

Strike price	**£ 39.65**
Granted 2015	€ 54.63
Granted 2016	€ 48.54
Granted 2017	€ 45.26
Granted 2018	€ 44.81
Granted 2019	€ 45.22

B-4 Cash flow graphs

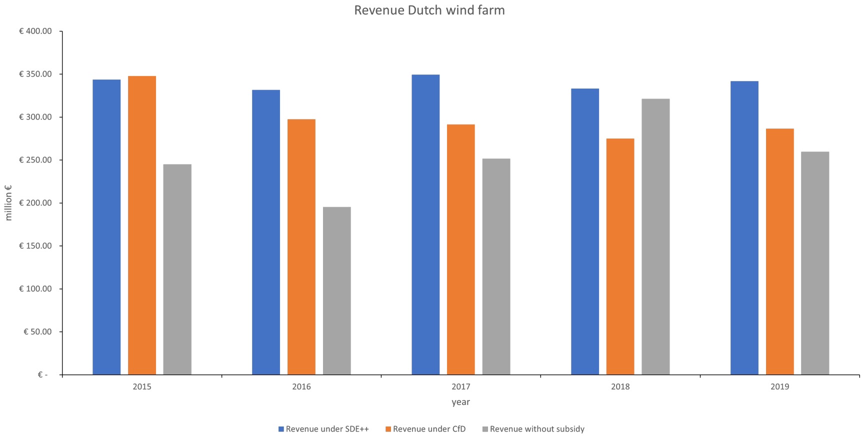


Figure B-4: Revenue collected under different subsidy schemes by the wind farm constructed from a Dutch perspective in the reference case scenario.

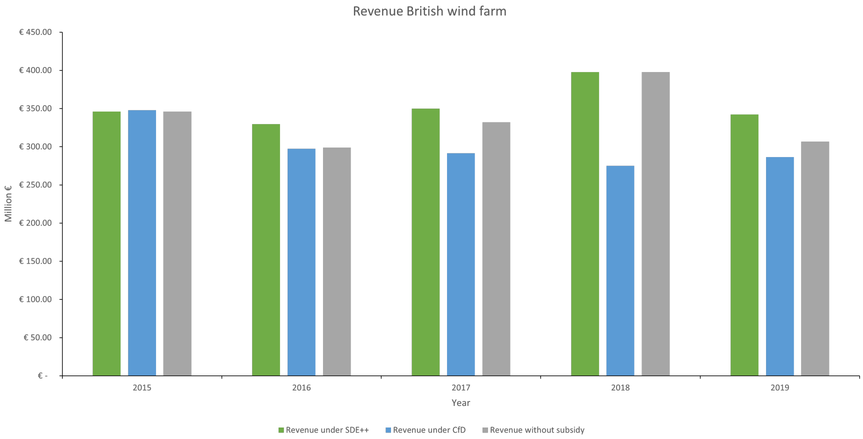


Figure B-5: Revenue collected under different subsidy schemes by the wind farm constructed from a British perspective in the reference case scenario.

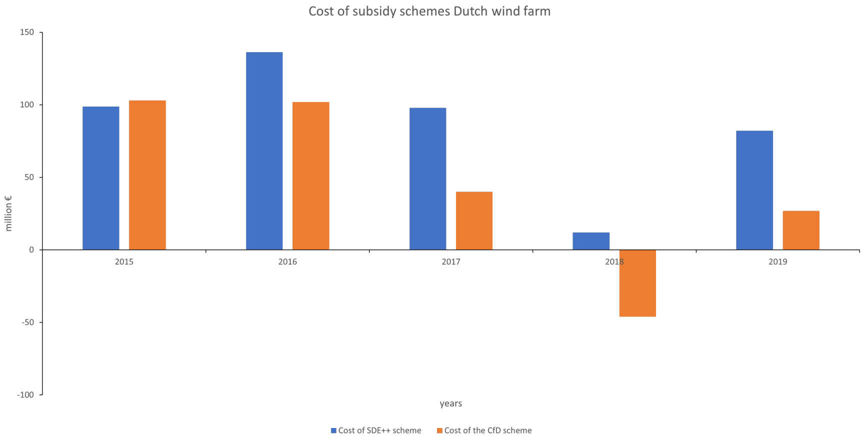


Figure B-6: Costs of the SDE++ and CfD subsidy schemes for a Dutch radial connected wind farm.

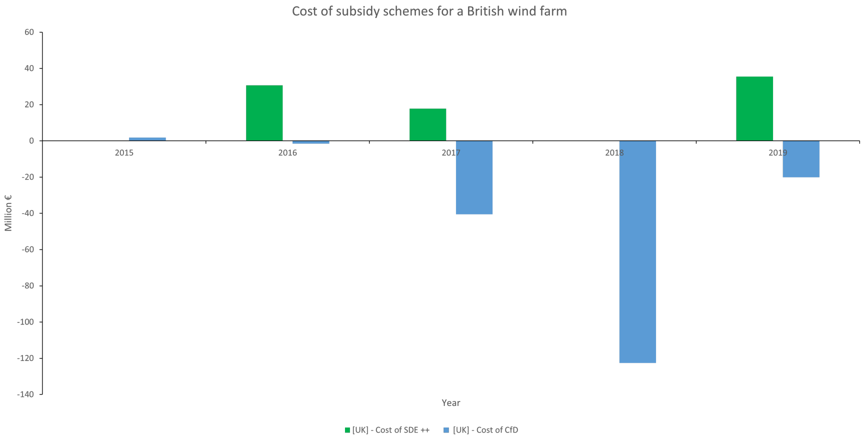


Figure B-7: Costs of the SDE++ and CfD subsidy schemes for a British radial connected wind farm.

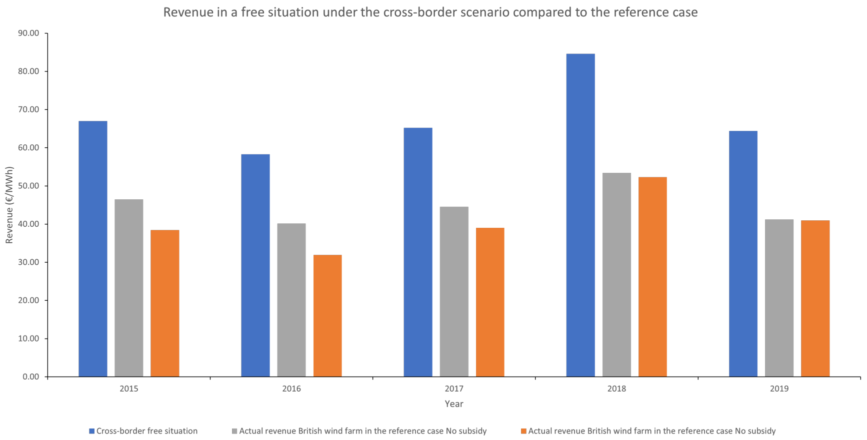


Figure B-8: Comparison actual revenue of a wind farm in a cross-border scenario (free situation) with respect to the reference case of both the Dutch and British wind farms.

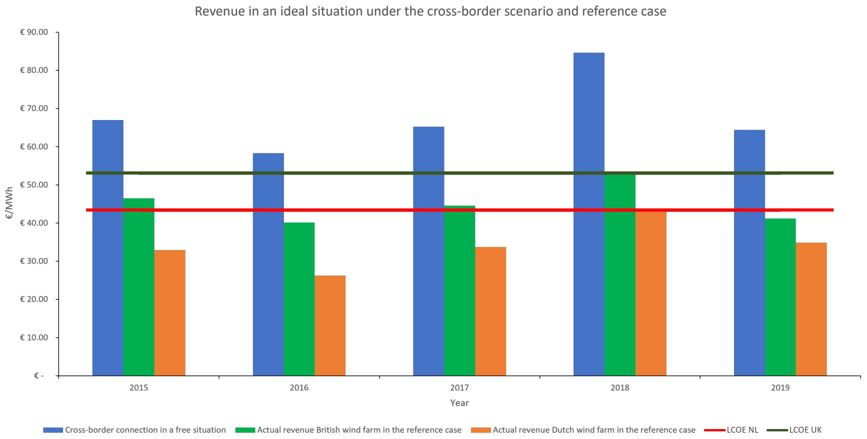


Figure B-9: Comparison actual revenue per unit of electricity generation of a wind farm in a cross-border scenario (free situation) with respect to the reference scenarios of both nationalities including both LCOE.

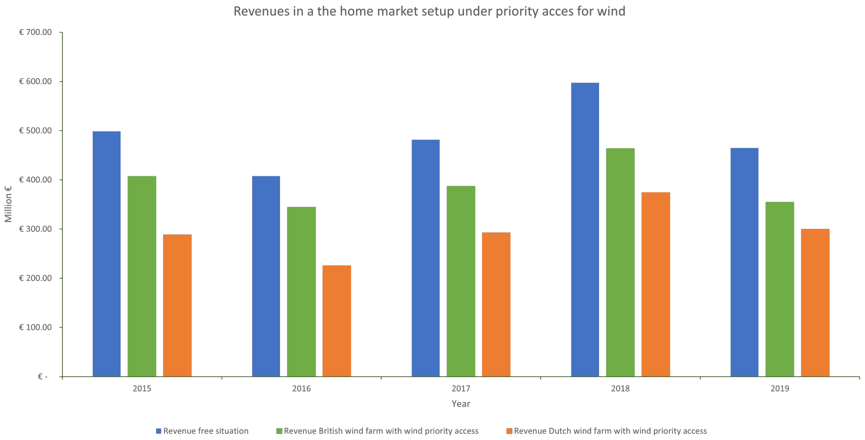


Figure B-10: Revenue collected by a Dutch and British wind farm in a home market setup in which wind generation has priority access over cross-border capacity exchange.

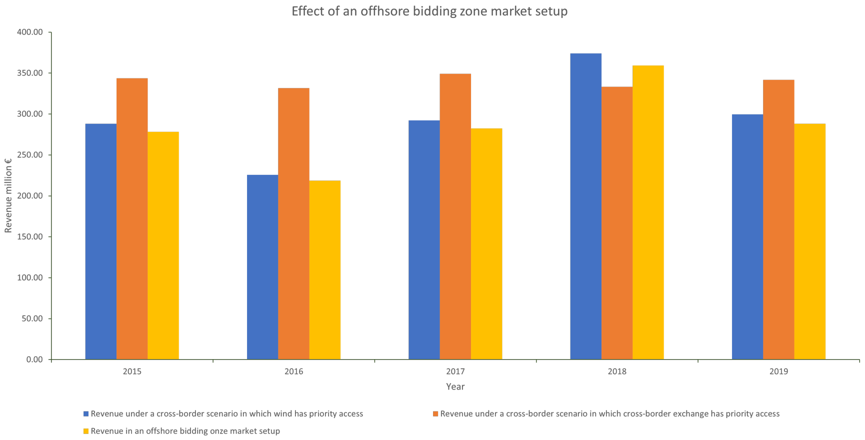


Figure B-11: Revenue collected by a Dutch wind farm in an OBZ with respect to the home market scenarios in millions euros.

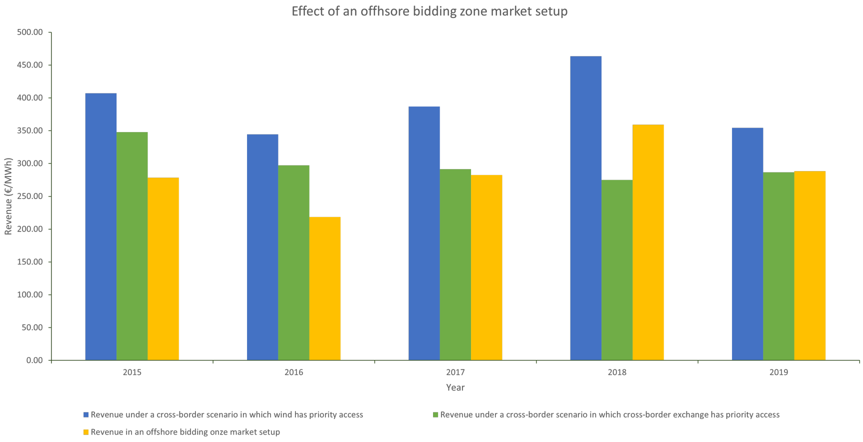


Figure B-12: Revenue collected by a British wind farm in an OBZ with respect to the home market scenarios in millions euros.

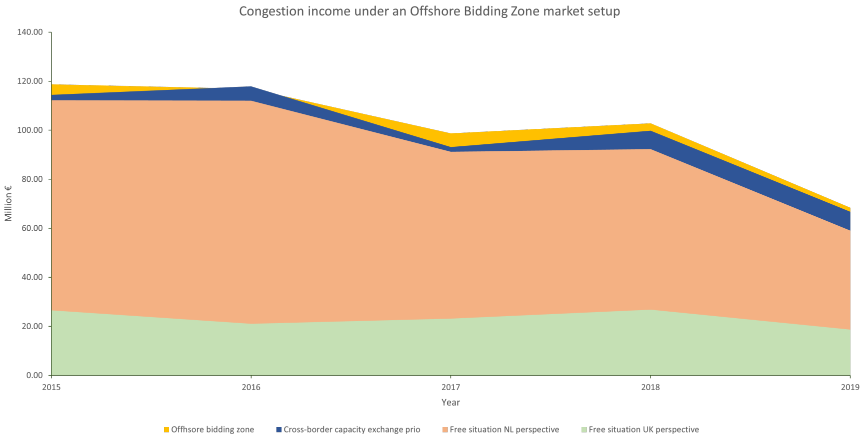


Figure B-13: Accumulation of total congestion income collected per year per scenario by the TSOs.

B-5 Overview of simulation results

Table B-15: Resulting annual revenues factors in €/MWh for all scenarios.

Scenario:	*2015*	*2016*	*2017*	*2018*	*2019*
Theoretical revenue in the base model Dutch wind farm	38.17	31.81	39.03	52.21	40.91
Theoretical revenue in the base model British wind farm	53.01	48.53	51.66	64.7	48.38
Revenue reference case NL (no subsidy)	32.89	26.23	33.76	43.11	34.87
Revenue reference case UK (no subsidy)	46.46	40.12	44.56	53.39	41.18
Revenue reference case NL (SDE++subsidy)	53.97	54.15	54.25	54.27	53.93
Revenue reference case UK (SDE++subsidy)	54.33	53.79	54.33	64.78	54.01
Revenue reference case NL (CfD subsidy)	54.63	48.54	45.26	44.81	45.22
Revenue reference case UK (CfD subsidy)	54.63	48.54	45.26	44.81	45.22
Cross-border free situation	66.96	58.31	65.21	84.59	64.39
Cross-border wind prio NL (HM)	38.70	30.30	39.25	50.22	40.24
Cross-border wind prio UK (HM)	54.66	46.23	51.95	62.23	47.59
Cross border X-border prio NL (HM)	53.97	54.15	54.25	54.27	53.93
Cross border X-border prio UK (HM)	54.63	48.54	45.26	44.81	45.22
OBZ	37.37	31.25	38.25	50.88	39.91

Table B-16: Resulting annual revenues for all scenarios (million €).

Scenario:	*2015*	*2016*	*2017*	*2018*	*2019*
Theoretical revenue in the base model Dutch wind farm	288.25	225.72	292.34	374.08	299.71
Theoretical revenue in the base model British wind farm	407.14	344.37	386.95	463.56	354.48
Revenue reference case NL (no subsidy)	244.97	195.38	251.45	321.13	259.72
Revenue reference case UK (no subsidy)	346.04	298.86	331.93	397.68	306.74
Revenue reference case NL (SDE++subsidy)	343.72	331.70	349.28	333.19	341.82
Revenue reference case UK (SDE++subsidy)	346.04	329.54	349.80	397.68	342.30
Revenue reference case NL (CfD subsidy)	347.90	297.36	291.40	275.08	286.61
Revenue reference case UK (CfD subsidy)	347.90	297.36	291.40	275.08	286.61
Cross-border free situation	498.75	407.74	481.59	597.26	464.91
Cross-border wind prio NL (HM)	288.25	225.72	292.34	374.08	299.71
Cross-border wind prio UK (HM)	407.14	344.37	386.95	463.56	354.48
Cross border X-border prio NL (HM)	343.72	331.70	349.28	333.19	341.82
Cross border X-border prio UK (HM)	347.90	297.36	291.40	275.08	286.61
OBZ	278.34	218.49	282.47	359.26	288.19

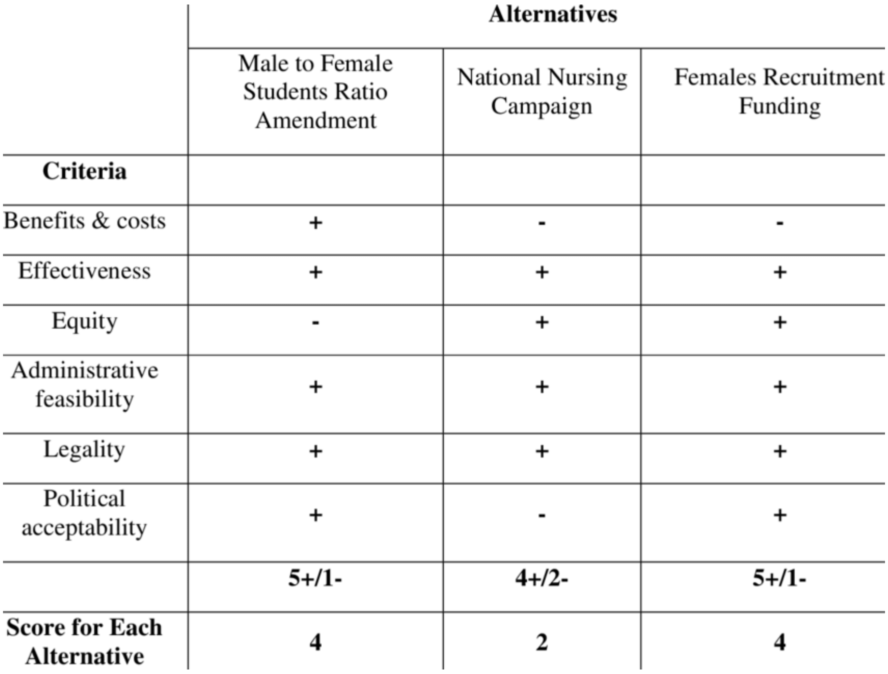
Table B-17: Accumulation of total congestion income collected per year per scenario by the TSOs (million €).

Scenario:	*2015*	*2016*	*2017*	*2018*	*2019*
Free situation NL perspective	112.21	112.04	91.24	92.28	59.10
Free situation UK perspective	26.50	21.07	23.12	26.84	18.71
Cross-border capacity exchange prio	114.47	117.93	93.15	99.84	66.76
Offhsore bidding zone	118.76	116.94	98.75	102.86	68.35

Appendix C

Mitigation options

C-1 Policy scorecard examples



	Alternatives		
	Male to Female Students Ratio Amendment	National Nursing Campaign	Females Recruitment Funding
Criteria			
Benefits & costs	+	-	-
Effectiveness	+	+	+
Equity	-	+	+
Administrative feasibility	+	+	+
Legality	+	+	+
Political acceptability	+	-	+
	5+/1-	**4+/2-**	**5+/1-**
Score for Each Alternative	**4**	**2**	**4**

Figure C-1: Policy analysis scorecard: Female Nurses and Midwives Shortage in Jordan (Nashwan, 2015).

Document	Mental health in the workplace referred to in the objectives and scope of the policy	Coverage of exposure factors in relation to mental health in the workplace	Coverage of mental health problems at work and related outcomes	Coverage of risk assessment aspects in relation to mental health in the workplace	Coverage of preventive actions in relation to mental health in the workplace	Overall
1. **Guidance: ILO, 1986** Psychosocial factors at work: Recognition and control	4	5	5	5	5	★★★ ★★
2. **Guidance: EC, 1999** Guidance on work-related stress – Spice of life or kiss of death?	4	5	5	5	5	★★★ ★★
3. **Guidance: EU-OSHA, 2002** How to Tackle Psychosocial Issues and Reduce Work-Related Stress	4	5	5	5	5	★★★ ★★
4. **Guidance: WHO, 2008** PRIMA-EF: Guidance on the European Framework for Psychosocial Risk Management: A Resource for Employers and Worker Representatives	4	5	5	5	5	★★★ ★★
5. **Guidance: WHO, 2003** Work Organization and Stress	4	5	5	4	5	★★★ ★⯪
6. **WHO Healthy Workplaces Framework, 2010** Healthy workplaces: a model for action: for employers, workers, policymakers and practitioners	4	5	4	4	5	★★★ ★⯪
7. **WHO Mental health declaration for Europe, 2005** and Mental Health Action Plan for Europe	5	4	4	4	4	★★ ★★

Figure C-2: Policy Scorecard – Non-binding/voluntary policy initiatives of relevance to mental health and psychosocial risks in the workplace (Leka et al., 2014).

C-2 Effects of mitigation options on cash flow of a British wind farm in an offshore bidding zone market setup

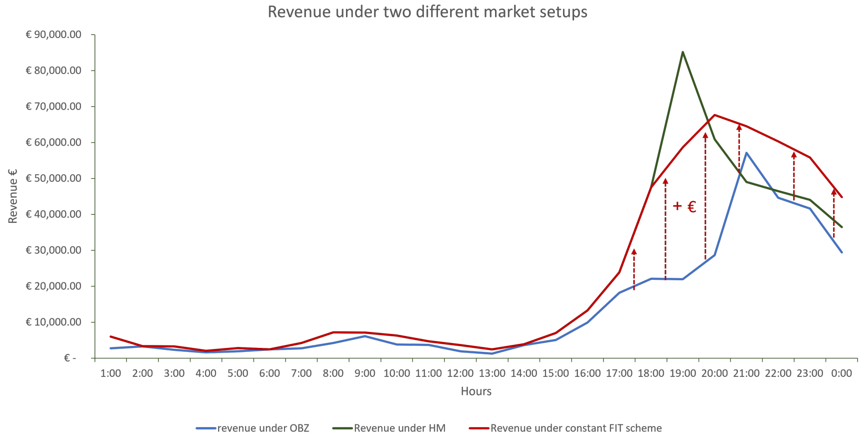


Figure C-3: Revenue earned by a British wind farm under the constant feed-in-tariff scheme (timestamp: 12-01-2016).

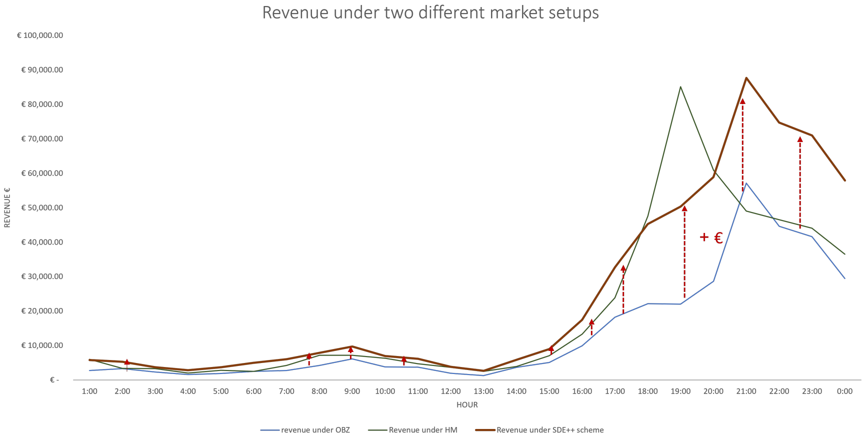


Figure C-4: Revenue earned by a British wind farm under the SDE++ feed-in-tariff scheme (timestamp: 12-01-2016).

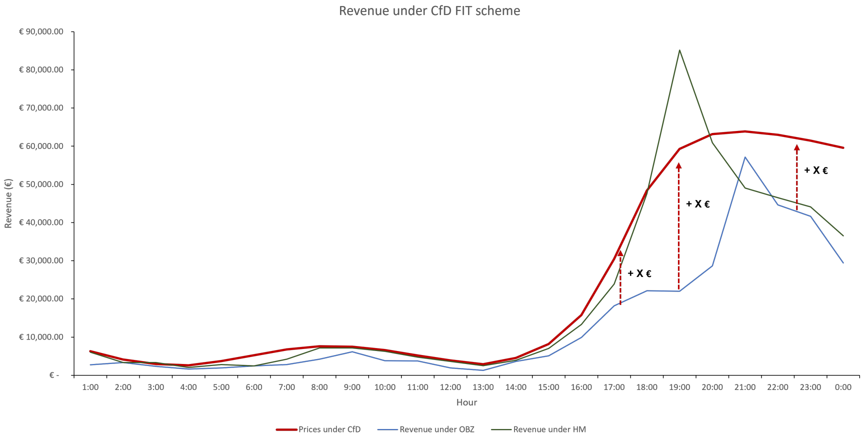


Figure C-5: Revenue earned by a British wind farm under the CfD feed-in-tariff scheme (timestamp: 12-01-2016).

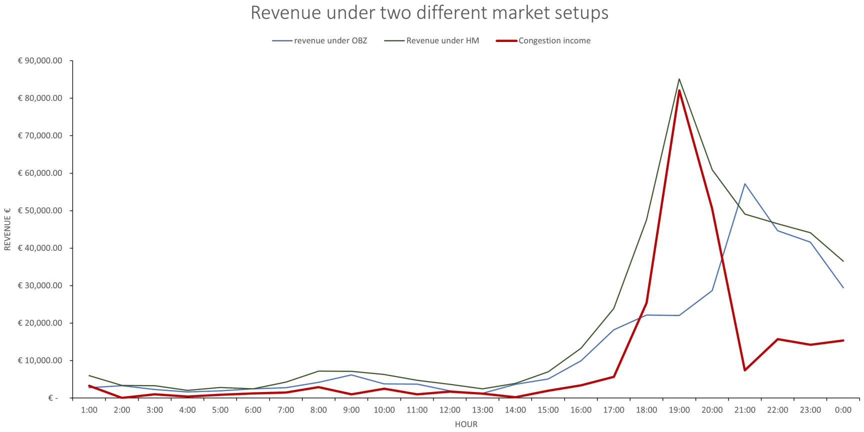


Figure C-6: Revenue of a British wind farm under a HM, an OBZ and with the collected congestion income (timestamp: 12-01-2016).

C-3 Resulting effects of mitigation options

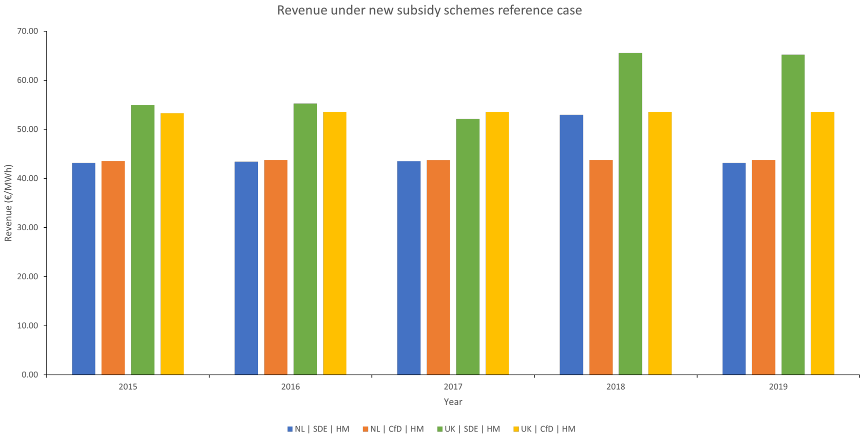


Figure C-7: Revenue of a Dutch an British wind farm respectively under the new subsidy heights.

Table C-1: Revenues of the reference case under the adjusted SDE++ subsidy scheme, expressed in €/MWh and million €respectively.

	2015	*2016*	*2017*	*2018*	*2019*
NL / SDE / HM	43.18	43.43	43.50	52.96	43.21
UK / SDE / HM	54.97	55.27	52.15	65.58	65.22

NL / SDE / HM	274.99	266.05	280.08	325.13	273.87
UK / SDE / HM	350.06	338.61	335.81	402.60	413.39

C-3-1 Reference case under new subsidy

Table C-2: Revenues of the reference case under the adjusted CfD subsidy scheme, expressed in €/MWh and million €respectively.

	2015	*2016*	*2017*	*2018*	*2019*
NL | CfD | HM	43.54	43.78	43.75	43.77	43.78
UK | CfD | HM	53.29	53.58	53.54	53.57	53.58

NL | CfD | HM	277.32	268.19	281.70	268.71	277.46
UK | CfD | HM	339.40	328.23	344.76	328.86	339.58

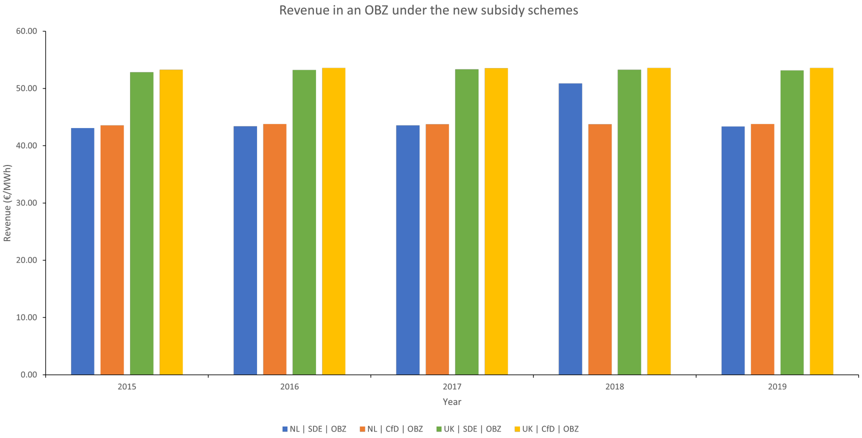


Figure C-8: Revenue under the adjusted subsidies in an offshore bidding zone setup.

C-3-2 Post operation value redistribution

Table C-5: Post operation compensation - financial scoring NL.

Financial criteria	**Effect (million €)**
Revenue collected by the wind farm	274.68
Congestion income collected by the TSOs	101.13
Cost implied on the TSOs	-
Cost implied on national ministries	-4.14

Table C-6: Post-operation compensation - financial scoring UK.

Financial criteria	**Effect (million €)**
Revenue collected by the wind farm	336.17
Congestion income collected by the TSOs	101.13
Cost implied on the TSOs	-
Cost implied on national ministries	23.87

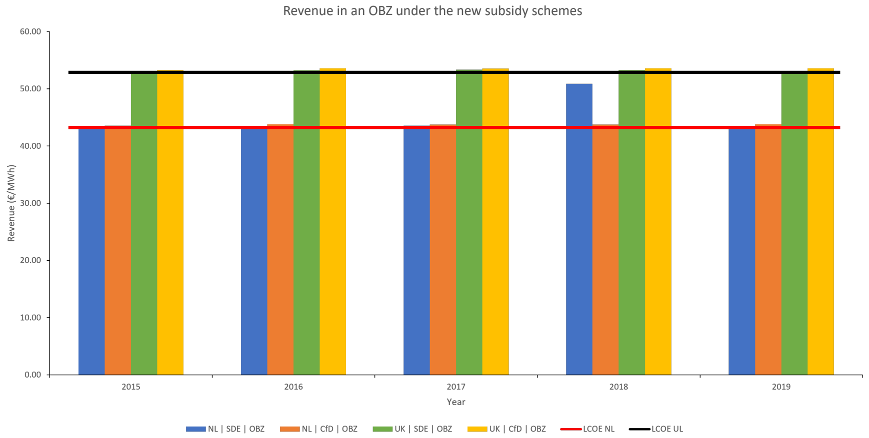


Figure C-9: Revenues under the adjusted subsidies in an offshore bidding zone setup including the LCOE.

Table C-3: Revenues in an offshore bidding zone for the adjusted SDE ++ subsidy scheme, expressed in €/MWh and million €respectively.

	2015	***2016***	***2017***	***2018***	***2019***
NL | SDE | OBZ	43.08	43.42	43.55	50.89	43.37
UK | SDE | OBZ	52.83	53.22	53.34	53.26	53.17

NL | SDE | OBZ	274.39	265.99	280.41	312.43	274.86
UK | SDE | OBZ	336.47	326.03	343.47	326.96	336.97

C-3-3 Constant feed-in-tariff

$$\text{Price}_{FIT} = LCOE - \frac{\sum_{i=1}^{N} p_{i,obz}}{\sum_{i=1}^{N} t_i} \tag{C-1}$$

$$S_{FIT} = \sum_{i=1}^{N} P_{FIT} \times Q_i \tag{C-2}$$

Table C-7: Revenue under a constant feed-in-tariff in €/MWh and million euro respectively.

	2015	***2016***	***2017***	***2018***	***2019***
NL	€ 48.13	€ 40.01	€ 48.23	€ 62.90	€ 49.81
UK	€ 59.56	€ 51.22	€ 59.49	€ 74.19	€ 61.00

NL	€ 306.53	€ 245.10	€ 310.55	€ 386.13	€ 315.67
UK	€ 379.29	€ 313.78	€ 383.06	€ 455.48	€ 386.59

Table C-4: Revenues in an offshore bidding zone for the adjusted CfD subsidy scheme, expressed in €/MWh and million €respectively.

	2015	*2016*	*2017*	*2018*	*2019*
NL | CfD | OBZ	43.54	43.78	43.75	43.77	43.78
UK | CfD | OBZ	53.29	53.58	53.54	53.57	53.58
NL | CfD | OBZ	277.32	268.19	281.70	268.71	277.46
UK | CfD | OBZ	339.40	328.23	344.76	328.86	339.58

Table C-8: Costs under a constant feed-in-tariff in million euro respectively.

	2015	*2016*	*2017*	*2018*	*2019*
NL	€ 29.22	€ - 23.09	€ 28.86	€ 117.42	€ 38.20
UK	€ 39.90	€ - 14.45	€ 38.30	€ 126.62	€ 47.01

C-3-4 SDE++ feed-in-tarrif

Table C-9: Additional costs of the SDE++ subsidy scheme of a Dutch wind farm under the different market setups in €/MWh and million euro respectively.

SDE++	*2015*	*2016*	*2017*	*2018*	*2019*
HM	€ 4.27	€ 11.13	€ 3.98	€ -	€ 1.71
OBZ	€ 5.47	€ 12.11	€ 5.38	€ -	€ 3.51
Total	€ 1.20	€ 0.98	€ 1.40	€ -	€ 1.79
HM	€ 27.22	€ 68.18	€ 25.63	€ -	€ 10.87
OBZ	€ 34.85	€ 74.18	€ 34.65	€ -	€ 22.24
Total	€ 7.63	€ 6.00	€ 9.03	€ -	€ 11.37

Table C-10: Costs of the SDE++ subsidy scheme of a British wind farm under different market setups expressed in €/MWh and million euro respectively.

SDE++	*2015*	*2016*	*2017*	*2018*	*2019*
HM	€ -	€ 5.86	€ -	€ -	€ 16.22
OBZ	€ 15.22	€ 21.91	€ 15.18	€ 2.37	€ 13.31
Total	€ 15.22	€ 16.05	€ 15.18	€ 2.37	€ - 2.91
HM	€ -	€ 35.92	€ -	€ -	€ 102.80
OBZ	€ 96.93	€ 134.22	€ 97.72	€ 14.53	€ 84.35
Total	€ 103.19	€ 139.00	€ 107.52	€ 65.75	€ 94.99

C-3-5 CfD feed-in-tarrif

Table C-11: Costs of the CfD subsidy scheme of a Dutch wind farm under different market setups expressed in €/MWh and million euro respectively.

CfD	*2015*	*2016*	*2017*	*2018*	*2019*
HM	€ 9.90	€ 14.20	€ 10.34	€ 13.66	€ 9.29
OBZ	€ 9.65	€ 14.10	€ 9.71	€ 11.76	€ 8.85
Total	€ - 0.25	€ - 0.10	€ - 0.63	€ - 1.90	€ - 0.44
HM	€ 63.06	€ 86.97	€ 66.58	€ 83.85	€ 58.90
OBZ	€ 61.47	€ 86.35	€ 62.52	€ 72.21	€ 56.10
Total	€ - 1.59	€ - 0.62	€ - 4.05	€ - 11.64	€ - 2.80

Table C-12: Costs of the CfD subsidy scheme of a British wind farm under different market setups expressed in /euro/MWh and million euro respectively.

SDE++	*2015*	*2016*	*2017*	*2018*	*2019*
HM	€ 10.24	€ 15.72	€ 10.88	€ 14.39	€ 11.23
OBZ	€ 16.20	€ 22.69	€ 16.70	€ 10.71	€ 14.99
Total	€ 5.96	€ 6.97	€ 5.82	€ - 3.68	€ 3.76
HM	€ 65.21	€ 96.32	€ 70.08	€ 88.34	€ 71.18
OBZ	€ 103.19	€ 139.00	€ 107.52	€ 65.75	€ 94.99
Total	€ 37.98	€ 42.69	€ 37.44	€ - 22.58	€ 23.81

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