CfD designs for offshore wind farms in the offshore bidding zone approach

What are the advantages and disadvantages of different CfD designs for offshore wind farms in the North Sea?

CoSEM Master thesis

Timo van Delzen

Delft University of Technology

CfD designs for offshore wind farms in the offshore bidding zone approach

What are the advantages and disadvantages of different CfD designs for offshore wind farms in the North Sea?

by

Timo van Delzen 4485734

Chair:	Prof.dr.ir. L.J. de Vries
Supervisor 1:	Dr.ir. K. Bruninx
Supervisor 2:	Dr. A.F. Correljé
Project Duration:	March, 2023 - October, 2023
Faculty:	Faculty of Technology Policy & Management, Delft
Company:	ACER, European Union Agency for the Cooperation of Energy Regulators

TU Delft

Preface

I am thrilled to share this thesis with you. It has been an incredible journey that began with my relocation from the Netherlands to Ljubljana, Slovenia's capital.

During my time as a student in Delft, I developed a keen interest in the world of energy, particularly the energy transition. Therefore, when I was presented with the opportunity to write my thesis at ACER, a European institution that represents the "Agency of the Cooperation of Energy Regulators", I knew that this was the perfect place for me considering my interests.

My time at ACER provided me with a thorough understanding of the European energy sector, particularly the electricity markets, and heightened my interest in this field. Additionally, I view my experience at ACER as an important milestone in my professional growth, as I acquired knowledge about energy-related topics and worked with fascinating individuals from various parts of Europe in this international agency.

I hope you enjoy reading this thesis and that it gives you valuable insights into the complexities of creating a functional and cost-effective offshore grid. It also highlights one of the major challenges that we will face in the coming decades.

I didn't write this thesis alone. Firstly, I would like to express my gratitude to my first supervisor, Kenneth Bruninx, for his guidance and for steering me in the right direction. I would also like to thank my other supervisors, Laurens de Vries, Aad Correlje, and Mathieu Fransen.

Kind regards,

Timo van Delzen
Ljubljana, October 2023

Summary

The number of offshore wind farms in the North Sea seems to increase in the coming decades to achieve climate neutrality in the EU by 2050. Rational grid planning and deployment seem necessary to implement this offshore renewable energy deployment in a cost-efficient and sustainable way.

A method discussed in this thesis combines offshore energy production with a cross-border interconnector to optimise the use of the grid, eventually creating hybrid projects. The offshore bidding zone approach will integrate these hybrid projects into the internal energy market. The offshore bidding zone approach establishes a separate bidding zone for offshore electricity generators. This offshore zone has its wholesale electricity price and is connected to markets through interconnectors, resulting in cross-zonal flows. Denmark is already introducing such an offshore price zone (WindEurope, 2021).

These offshore bidding zones will eventually result in lower revenues for offshore wind farm owners due to a lower electricity volume and price risk, especially when flow-based market coupling and advanced hybrid coupling are implemented in the electricity system. This results in a demand to improve the investment climate for offshore wind farm owners. One measure that can be taken to improve this climate can be by introducing CfD schemes.

Because of the number of different design elements, designing a CfD for a specific situation can be seen as a complex process that considers many factors tailored to offshore bidding zones. This research will give an overview of some CfD design choices that need to be taken with their consequences and will help to answer the following research question:

”What are the advantages and disadvantages of different CfD designs for offshore wind farms considering the offshore bidding zone approach in the North Sea?”

By answering this research question, this thesis elaborates further on the existing literature around offshore bidding zones and CfDs with a comprehensive overview of different CfD schemes.

For the CfD design schemes, it can be recognised that these schemes around offshore bidding zones need to involve the following design elements:

- The strike price needs to be determined by an auction.
- The duration of a CfD scheme needs to be long, around 20 years.
- The price must be inflation-adjusted to reduce the risk for offshore wind farms.
- The CfD payment needs to be two-sided.

On the contrary, there will also be design choices for CfDs around offshore bidding zones, which are less obvious. This thesis looks into the following designs:

- The conventional CfD design
- The advanced CfD design
- The capability-based CfD design with a fixed strike price
- The capability-based CfD design with a cap and floor strike price
- The financial CfD design with a reference generator
- The financial CfD with weather data as reference

It can be concluded that the conventional CfD and the advanced CfD design don't meet all the requirements necessary for a CfD in the offshore bidding zone context. For the conventional CfD, this is because farms are only incentivised to maximise their production and don't look at the value of their product. Therefore, when the electricity price in the offshore bidding zone becomes negative, offshore wind farms are still incentivised to produce as much as possible, which results in a large part of the CfD payout being lost due to an inefficient market design. Offshore wind farms face a constraint in advanced CfD due to the absence of protection against volume risk. This means that even if the electricity price is zero, it will still be reflected in the reference price, but the offshore wind farm cannot dispatch all its electricity, resulting in lower revenues for the owner of the offshore wind farm. This leads to the following CfD design that needs to be considered on a case-to-case basis:

- The capability-based CfD design with a fixed strike price
- The capability-based CfD design with a cap and floor strike price
- The financial CfD design with a reference generator
- The financial CfD with weather data as reference

When looking at the capability-based CfDs, several advantages and disadvantages can be identified. When implementing a cap and floor strike price, OWFs are encouraged to produce electricity when it is mostly needed in their CfD payout. However, this creates a double incentive, as the wholesale electricity market already incentivizes them to produce when electricity prices are highest. This double incentive increases the risk for investors. Because keeping this risk low is an important characteristic of the CfD design. A fixed strike price appears to be the preferred option to achieve this goal.
Furthermore, for the financial CfD, a physical reference generator will probably adjust its bidding strategy, like the actual asset, due to multiple factors, such as congestion or a safe margin, because of forecasting errors and balancing costs. On the other hand, a financial CfD with weather data as a reference or a capability-based CfD with a fixed strike price will not do this, which can be considered unfair and a disadvantage over a financial CfD with a physical reference generator.

Additionally, for different CfD schemes, because of the international aspect of offshore bidding zones, especially with flow-based market coupling and advanced hybrid coupling, developments in one bidding zone can impact the CfD payout done by the government of another bidding zone. This results in inequalities between stakeholders in different bidding zones, which are intensified by the uncertainties of future developments. It can be acknowledged that stakeholders have different preferences around offshore bidding zones and, in this case, the CfD scheme. When designing a CfD, stakeholders should be involved to ensure the eventual system works as intended. Furthermore, a market structure should be developed where all stakeholders, like governmental bodies, regulatory authorities and transmission system operators, on national and European scales, fulfil a certain role.

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

Abbreviation	Definition
AC	Alternating Current
ACER	European Union Agency for the Cooperation of Energy Regulators
ADMM	Alternating Direction Method of Multipliers
BZ	Bidding Zone
CEER	Council of European Energy Regulators
CfD	Contract for Difference
DAM	Day-ahead market
DC	Direct Current
EC	European Commission
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
GW	Giga Watt
HM	Home Market
MW	Mega Watt
NRA	National Regulatory Authorities
OBZ	Offshore Bidding Zone
OnBZ	Onshore Bidding Zone
OFW	Offshore Wind Farm
TAG	Transmission Access Guarantee
TSO	Transmission System Operator

1
Introduction

European industries are leading the way in developing innovative technologies to produce electricity on our seas. Offshore wind farms (OWFs) provide clean electricity that competes with and sometimes even is cheaper than current fossil-based generation alternatives (Kitzing & Weber, 2014). The European Commission (EC) has unveiled the EU Strategy on Offshore Renewable Energy with the aim of reaching climate neutrality in the EU by 2050. The strategy calls for raising Europe's offshore wind capacity to 60 GW by 2030 and 300 GW by 2050. Furthermore, it aims to incorporate 40 GW of ocean energy and floating wind and solar technologies by 2050 (European Commission, 2019).

A new approach and more explicit EU regulatory framework

To implement offshore renewable energy deployment in the European Union in a cost-efficient and sustainable way, rational grid planning and deployment seem necessary. To achieve this, the concept of so-called hybrid projects, including energy islands and hubs, has gained significant attention in recent years. These hybrid projects directly connect offshore energy production to a cross-border interconnector (Nieuwenhout, 2022). In this way, the grid has a dual functionality, combining electricity interconnection between two or more Member States and the transportation of offshore renewable electricity.

Furthermore, to integrate energy from offshore projects into the internal energy market, in literature, two main approaches are considered. Firstly, the Home Market approach (HM); Where the offshore generated electricity is added to one existing onshore bidding zone based on its connection point to the mainland network. Secondly, the Offshore Bidding Zones approach (OBZ); Where bidding zones are defined to reflect structural congestion in the network, potentially resulting in the creation of new bidding zones that only include offshore generation with its wholesale electricity price (European Commission, Directorate-General for Energy, THEMA consulting group, 2020). In the strategy published by the EC (European Commission, 2020), OBZs seem to be a cornerstone when integrating this offshore renewable energy into the internal energy market when obtained in a hybrid project (European Commission, Directorate-General for Energy, THEMA consulting group, 2020).

A consequence addressed explicitly in the master thesis will be that because of OBZs, the producers' surplus of offshore wind farm owners decreases, and the congestion rent for TSOs will increase (Kenis et al., 2022). Another effect of these OBZs for OWF owners will be the volume risk due to limited transmission capacity. It results in not all produced electricity being distributed even though the variable cost of the offshore produced electricity will be lower than that produced in the home market (Laur et al., 2022). Improving investment incentives and investment stability for offshore wind generators seems inevitable. This will be further elaborated in this thesis.

Furthermore, On 14 March 2023, the EC published a proposal to reform the EU electricity market (Commission, 2023). The proposal, among other things, focuses particularly on enhancing market access to more stable long-term contracts and markets due to PPAs and CfDs (Meeus et al., 2022). PPAs are long-term contracts between renewable energy generators and private consumers (Ambec et al., 2023), and CfDs are a form of long-term public support through which a government is guaranteed a minimum price for the energy produced by a producer (Kitzing, 2023). There are many different forms of CfDs with different characteristics. A design choice the proposal of the EC mainly focuses on is two-sided CfD. These CfDs contain a minimum price which a producer will definitely earn, and a maximum price, above which revenues are paid back to a public actor by the producer. An overview is given of this design in Figure 1.1. This public actor can channel money back to electricity consumers to ease the effects of high prices. The proposal stated that these CfDs should be the preferential support scheme for different renewable and nuclear energy forms.

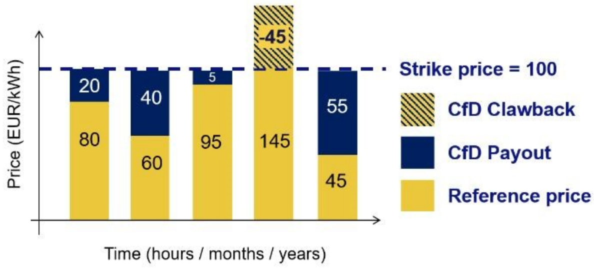


Figure 1.1: Standard two-sided CfD design. By (Kitizing, 2023)

1.1. Problem Definition

In the electricity sector, several actors are therefore active with their interests. In this report, Contracts for Differences will be discussed further as to how these CfDs influence the decisions of offshore wind farm owners. This will be further scoped to some specific characteristics of offshore wind offered in the OBZs. Furthermore, some main features of flow-based market coupling (FBMC) and advanced hybrid coupling (AHC) will be discussed in this paper to give more insights into the effects of the different CfDs for this specific case.

1.2. Knowledge gap

The OBZ approach in the context of FBMC and hybrid projects has some specific characteristics, resulting in a need for a proactive and top-down approach in the planning and development of offshore networks (ACER & CEER, 2022a). Nevertheless, hybrid systems aren't extensively developed in Europe yet. Therefore, it is difficult to establish the rules for these systems at this early stage. For these projects, not all challenges are known and understood, and more research in this field seems inevitable.

Previous research stated that when implementing the OBZ approach, the average price for offshore generated electricity will decrease, and the congestion rent for TSOs will increase. This will result in a transition of welfare because the revenues of offshore wind farm owners will decrease. Furthermore, there will also be a volume risk for OWF owners not to sell all their possible produced electricity in the day-ahead market due to congestion on the grid. Therefore, there seems to be a demand for an improvement in the investment stability of these OWF owners. Transmission Access Guarantees (TAGs) are pushed forward by Laur et al. (2022), using congestion revenues to support investments in OWFs. TAGs also have some drawbacks, as discussed by ACER and CEER (2023) and ENTSO-E (2023). With this in mind and the fact that two-sided CfDs seem to be pushed by the EC, the effects of different two-sided CfD designs need further investigation. Eventually, when implementing these CfDs, there will be a risk that the financial incentives of generators to behave in a market-efficient way will be distorted. More research requires which scheme is optimal for OBZs and how these schemes will influence decision-making, especially for OBZs in hybrid projects. Furthermore, it is also notable that in the current debate around OBZs, stakeholders have different opinions and objectives, which results in other preferences for the design around CfDs. Additionally, those actors in the electricity sector will try to maximise their welfare and exhibit strategic behaviour around OBZs if the opportunity arises. How this exactly affects the process also requires more research.

1.3. Research question

This research will help to answer the following research question:

"What are the advantages and disadvantages of different CfD designs for offshore wind farms considering the offshore bidding zone approach in the North Sea?"

The research question above will be answered through a series of sub-questions as follows:

1. *"How will the different CfD designs influence the bidding strategy of offshore wind generators?"*
2. *"How will OBZs impact the bidding of offshore wind farms in hybrid projects?"*
3. *"How will the different CfD designs influence the decisions of generators in hybrid projects in the OBZs?"*
4. *"Which possible strategic behaviour can be recognised with the implementation of CfDs and what are the consequences?"*
5. *"How will the TSO be affected by the different designs around the OBZ?"*

Sub-questions 1 and 2 will give some fundamental insights into the effects of CfDs and the impact of the OBZs. In sub-question 3, questions 1 and 2 come together, ultimately merging both concepts of CfDs and OBZs. Furthermore, it can also be seen that implementing CfDs in OBZs can eventually result in strategic behaviour in the bidding strategy of OWF owners, which will be elaborated by answering sub-question 4. Sub-question 5 will analyse the impact on TSOs, focusing on congestion revenues and balancing.

1.4. Relevance for CoSEM

The master thesis works towards a system design in a given institutional setting of the energy market. This makes the study relevant for the master thesis program, especially because the system is a complex socio-technical system with clear technology components and technical issues. The thesis will further be specified within the energy domain within the CoSEM program. CoSEM methods and tools will be used for creatively designing and assessing the impact of technical solutions for the future electricity market. Furthermore, complex design issues are dealt with systematically and creatively, and the subject, addressed by CfDs and OBZs, covers values originating from both the public and private domains.

1.5. Contribution to literature

This thesis elaborates further on the existing literature around OBZs and CfDs. When linking those two concepts together, certain characteristics will arise. The thesis will give certain insights through numerical analyses, followed by a comprehensive overview of the possible CfD designs for OBZs with their advantages and drawbacks. The main focus of this thesis will be on bringing together the effects of congestion on the different CfD designs when implemented in OBZs.

1.6. Outline paper

In Chapter 2, a theoretical background is given. This chapter discusses some main concepts of European electricity markets, some specific characteristics of offshore wind, the strategy of the European Commission to harness the potential of offshore wind and possible CfD designs with the requirements for OBZs. Chapter 3 gives the research methodology, where the research sub-questions will be given to answer the main research question, followed by the approaches to answer these sub-questions. Furthermore, this section will also explain how data is collected and give some insights into the quantitative part of the research. In Chapter 4, the institutional rules of the European Electricity market will be discussed, as well as the actors involved. Eventually, these rules and the roles and powers of the different actors will be specified for offshore bidding zones. Then, in the next chapters, some numerical analyses of OBZs where CfDs are implemented are executed and discussed, and a comprehensive overview is given of the different CfD designs with their basic elements, advantages and disadvantages. Eventually, the paper will be finalised with a discussion and a conclusion where the main research question is answered.

2
Theoretical background

This chapter gives an overview of some of the main concepts important to understand when answering the main research question and how these different concepts are linked to each other. This section first discusses key policies of electricity markets and how these are linked to the physical network. Furthermore, some characteristics of offshore renewable energy are given, followed by the strategy of the European Commission to harness the potential of offshore renewable energy. Furthermore, different CfD designs will be elaborated, followed by a clarification of the requirements of CfDs for OBZs.

2.1. Key Policies of electricity markets

Electricity has physical characteristics that make it different from other commodities. First of all, large volumes of electricity cannot be stored economically yet. Furthermore, electricity flows follow the laws of physics, and there is a need for transmission infrastructure.

All these physical characteristics of electricity influence the properties of generating intermittent offshore wind and the properties of the offshore transmission infrastructure. These characteristics of offshore wind will be further discussed in section 2.2.

2.1.1. Multiple electricity markets

Furthermore, demand and supply must match each other continuously. However, demand seems to be partly inelastic, and many power stations can only change their output slowly. Therefore, flexibility on short notice also has value. These characteristics explain why there is not one electricity market but why electricity is exchanged in several markets until delivery in real-time (Schittekatte et al., 2020). In these electricity markets, different electricity components can be traded. These components can be divided into:

- Energy
- Transmission capacity
- Reserves and flexibility

These components are also traded in different time frames. Trading can start many years in advance in so-called forward markets. These markets aim to hedge producers and consumers and continue until one day before delivery, and in these forward markets, transmission capacity and energy are traded separately (Schittekatte et al., 2020).

Closer in real-time, electricity is traded in short-term markets. These markets consist of the day-ahead market, intra-day markets and balancing markets. The day-ahead market is an auction conducted one day prior to electricity delivery. Furthermore, in most cases within the EU, cross-zonal transmission capacity is allocated in conjunction with energy through implicit market coupling in the day-ahead market. In many cases, the day-ahead market serves as the principal mechanism for establishing the price of electricity. After the day-ahead market, producers and consumers can adjust their position through the intra-day market. Afterwards, supply and demand are balanced near real-time through the balancing mechanism. The balancing mechanism is supported by two balancing markets where the TSO is the single buyer for both markets. The first is a balancing market for capacity, which takes place from one year to one day before real-time. The second is the balancing energy market, where bids must be submitted before the balancing energy gate closure. In real-time, the TSO activates the least cost resources to make sure supply and demand are in balance (Schittekatte et al., 2020).

To conclude, the sequential electricity markets in Europe can be subdivided into the forward market, day-ahead market, intraday market and balancing markets. An overview of these markets in their specific timeframe is given in Figure 2.1.

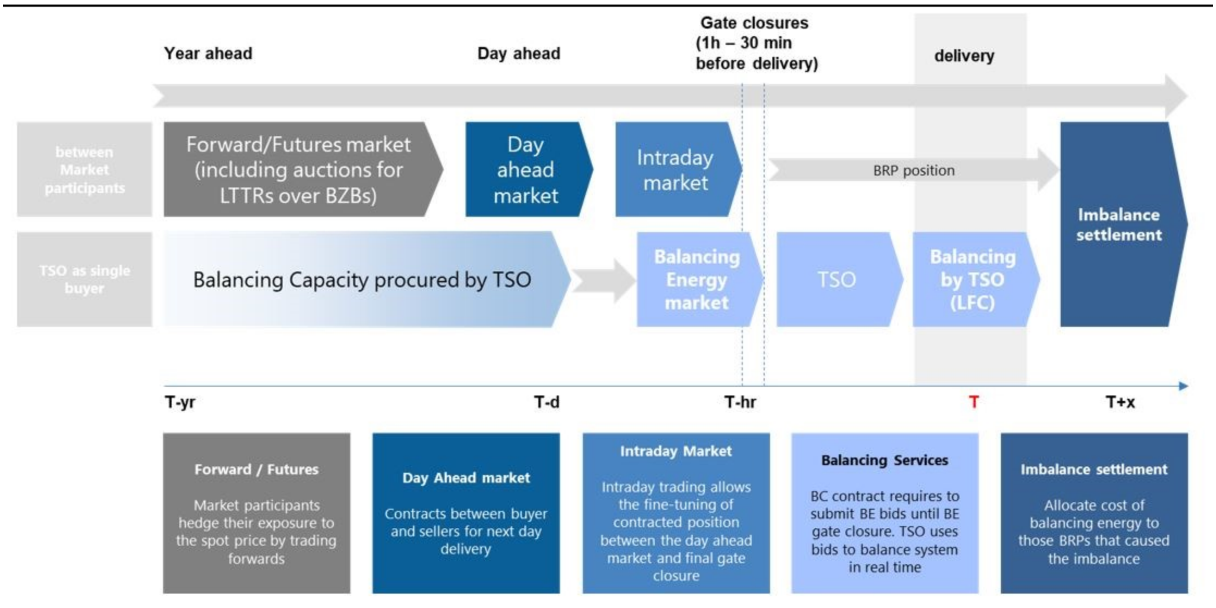


Figure 2.1: Multiple sequential electricity markets, by (ACER, 2023)

The day-ahead electricity market will mainly determine the electricity price for the electricity sold in OBZs when there will be no support schemes, bilateral arrangements or other measures that influence the price. Because OBZs is a day-ahead market concept and the intraday market and balancing markets are mainly focused on their own bidding zone. Furthermore, OBZs will also influence the balancing mechanism because at these OBZs there will be no demand agents or supply that can be scaled up.

2.1.2. Key concepts in the EU linking the markets with the grid

In the European Union, the traded electricity from the different electricity markets, as discussed in subsection 2.1.1, are matched with the physical network due to zonal pricing in the European Union. Zonal pricing in electricity markets is a pricing method that divides the market area into distinct geographic zones, the so-called bidding zones (Lété et al., 2022). The electricity price will be the same within these zones, and the electricity price can differ between different bidding zones. Furthermore, are these bidding zones connected with each other due to cross-zonal interconnectors. In Figure 2.2, an overview of the different bidding zones in Europe is given.

Figure 2.2: Overview bidding zones Europe, by (Schittekatte et al., 2020)

Furthermore, when implementing OBZs, zonal pricing is still the pricing method that divides the market area into bidding zones. Within these zones, the electricity price will be the same, and the electricity price can differ between different bidding zones, including the OBZ. All these BZs will be connected due to interconnectors.

2.2. Characteristics offshore renewable energy

A first thing to note is that renewable electricity from offshore wind generators is intermittent (Sovacool, 2009). This intermittency needs to be predicted, managed and mitigated. This results in some technical barriers due to practical obstacles created by the characteristics of the existing traditional electricity generation system (Sovacool, 2009). Looking at data provided by Energinet, (European Commission, Directorate-General for Energy, THEMA consulting group, 2020), the forecast of wind in the time frame of the day-ahead market will be off 10% of installed capacity on average compared to the real production. This data also makes it clear that this error in the forecast one day ahead can exceed up till 30% of installed capacity in extreme cases (European Commission, Directorate-General for Energy, THEMA consulting group, 2020).

Furthermore, an important characteristic of these offshore wind generators is that they have a zero variable cost energy contribution. Therefore, these renewable energies will automatically replace, when connected to the network, more expensive fossil-fuel electricity production (Pérez-arriaga & Batlle, 2012).

Eventually, as a result of the 'merit order effect' and 'intermittency', several studies have shown that increasing renewable electricity production increases the price variance on spot markets for electricity. In the research of Wozabal et al. (2016), a model predicts that the overall effect of this intermittency of renewables depends on the produced amount. A small number of renewables will decrease the price variance, but a large amount of renewable electricity from wind and solar will increase this variance, attracting variance-absorbing technologies. Some well-known variance-absorbing technologies are smart grids, energy storage, or grid interconnection (Wozabal et al., 2016). The strategy of the European Commission to harness the potential of offshore renewable energy will be further elaborated in the next section.

2.3. Strategy European Commission to harness the potential of offshore renewable energy

On 19 November 2020, the European Commission published the EU Strategy to harness the potential of offshore renewable energy for a climate-neutral future (European Commission, 2020). According to the report, the strategy sets targets for an installed capacity of at least 60 GW of offshore wind and 1 GW of ocean energy by 2030, and 300 GW of offshore wind and 40 GW of ocean energy by 2050.

Hybrid projects

Hybrid projects are a key concept in order to step up the renewable energy and grid infrastructure in a cost-efficient and sustainable way. Hybrid projects bring together offshore generation and transmission capacities, connecting multiple onshore bidding zones. This way, these projects combine the role of a traditional interconnector, allowing for the transmission of power between bidding zones, as well as the ability to produce power offshore and bring it to the onshore power grid (European Commission, Directorate-General for Energy, THEMA consulting group, 2020). Because these hybrid projects combine both tasks, they reduce the overall need for physical infrastructure by shortening the required offshore cabling length and reducing the need for converter stations. This results in lower deployment costs. Additionally, these projects minimize the environmental impact because of the efficient use of maritime space (European Commission, Directorate-General for Energy, THEMA consulting group, 2020). One way to integrate generators from a hybrid project to the market of the mainland can be due to the OBZ approach (European Commission, Directorate-General for Energy, THEMA consulting group, 2020).

Offshore Bidding zone approach

With the OBZ approach, a separate bidding zone is established for offshore electricity generators. It has its own wholesale price, and it is connected to other markets through interconnectors, resulting in all flows being cross-zonal flows (Nieuwenhout, 2022).

Additionally, when there is a lack of balancing units in the OBZ, balancing and redispatch will be a significant challenge. Because when an OBZ exists entirely out of variable renewable generation, imbalances can only be resolved with electricity from other zones. Furthermore, when these imbalance activities can be carried out, because there are some balancing assets in the offshore zone, there is the issue of what imbalance price should be applied to balancing responsible parties in an offshore zone (European Commission, Directorate-General for Energy, THEMA consulting group, 2020).

At last, with the OBZ approach, there will be a distribution of income between the transmission and generation entities. An important characteristic is that congestion can occur between offshore generators and the home market. The distribution of income depends on the transmission capacity, the configuration of offshore assets and the location of structural congestion. Compared with the HM approach, the generator will receive lower revenues, while the transmission owners receive higher revenues in the form of congestion income (European Commission, Directorate-General for Energy, THEMA consulting group, 2020). The concepts FBMC and AHC will further influence the revenues of the generators and the transmission owners and will be further discussed in the next section.

Flow-Based Market Coupling & Advanced Hybrid Coupling

To integrate different electricity markets across borders in Europe, Flow-Based Market Coupling (FBMC) is implemented in several countries. With FBMC, the allocation of cross-zonal capacity is jointly done together with market clearing. Therefore, the market decides to a certain extent on the relative availability of cross-zonal transmission capacity for trade between different bidding zones (Schittekatte et al., 2020). Flow-based market coupling is a method for determining the optimal exchange of electricity between multiple electricity markets. It is a system based on algorithms and is designed to increase market efficiency, reduce congestion and make the most efficient use of existing transmission capacities. Flow-Based market coupling is implemented in Europa's Core Region Capacity Calculation Methodology (Core-FB, 2022). Furthermore, in the Nordic region, the flow-based capacity calculation seems to go live in 2024 (Nordpool, 2023). This approach has proven to be an effective tool for promoting cross-border trade and improving the overall functioning of electricity markets by coupling different electricity markets (Van den Bergh et al., 2016).

With this flow-based market coupling on AC lines on the mainland and DC lines on the offshore grid, an additional aspect needs to be considered. The flow-based domains in Europe are currently modelled due to Standard Hybrid Coupling (SHC), but the target model of the European TSOs is Advanced Hybrid Coupling (AHC). With AHC, TSOs include the impact of DC lines on AC lines as well as their interdependence in the representation of the flow-based domain (Kenis et al., 2022).

70% margin available for cross-zonal electricity trade

According to ACER (2023), meeting the minimum target of 70% for available cross-zonal capacity by 2026 is crucial for achieving the ambitious political goals of producing significant offshore renewable energy resources that would benefit a large portion of Europe.

This 70% rule implies that 70 per cent of the capacity on the cross-zonal cable must be available for international trade. The current 70% target is applicable only to the long-term and day-ahead timeframe and provides a clear benchmark that bidding zones must adhere to. The impact of one bidding zone on a neighbouring bidding zone, for example, via loop flows, also needs to be addressed at its root. Therefore, The 70% target can only be considered successfully achieved when all bidding zones reach it simultaneously. If this objective is met, it will also impact OWFs in OBZs and CfD payouts.

2.4. Contracts for Differences

As already mentioned, when implementing OBZs under Advanced Hybrid Coupling to include off-shore DC transmission lines in Flow-Based Market Coupling, there will be the following transfer of revenues: The revenues of offshore wind farm owners decrease as a result of a lower average price, and the congestion rent for TSOs increases (Kenis et al., 2022). Eventually, these OBZs will signal transmission scarcity better, but because of these lower producer revenues for offshore wind farm owners, there will be a need for supporting offshore wind developments and an improvement of the investment stability for offshore wind developers. Considering the proposal by the European Commission to reform the electricity market and the suggestion that two-sided CfDs should be the preferential support scheme, the following section will discuss Contracts for Differences (CfDs). This section will elaborate on the different designs of CfD with their specific characteristics. Eventually, in this section, there will also be a focus on offshore wind attributes when using the OBZ approach and their relevance for the design of CfDs.

Traditionally, CfDs are signed through a tender between governmental bodies and specific types of power producers (Laur et al., 2022). The contracts provide the successful bidders with a predetermined 'strike' price for the output they can dispatch, as determined by regulators or Member States, effectively eliminating any price uncertainty (Kitzing, 2023). These CfD can be seen as a financial hedge contract and will de-risk renewable energy investments, which are capital-intensive (Jansen et al., 2020). Eventually, prices will be reduced by bringing down financing costs which have a much higher share in renewables compared to fossil investments (Đukan & Kitzing, 2021).

To summarize, a two-sided mechanism guarantees a fixed level of revenue based on the pre-agreed strike price. If the wholesale market price is below the strike price, generators will receive an extra payout from the CfD counterparty, mostly the government.

In case the revenue generated through the wholesale market surpasses the CfD strike price, the generator is obligated to pay back the difference to the CfD counterparty (Wild, 2017). In addition, two-sided long-term CfDs hedge against electricity price developments by long-term contracts and, as a consequence, allow governments to support vulnerable consumers during high-price periods because these governments can refund the payback from generators back to consumers.

In Contrast, CfDs should be designed to avoid any decisions made by plant operators that could impact the efficient design and operation of the plant. This refers to the following characteristics in different stages (Schlecht et al., 2023):

- Optimal design and siting (investment stage)
- Optimal utilization (operational stage)
- Optimal retrofit and repowering (re-investment stage)

To conclude, to achieve an optimal design, price signals for plant owners are highly relevant to support efficient decision-making and an efficient design. Since, these price signals reflect the power system's needs. Furthermore, it can also be noted that investors don't only need to maximise their output but need to be incentivised to make choices to optimise the overall system (Schlecht et al., 2023). Therefore, price signals need to incentivize decision-making aligned with the needs of the overall system. However, a well-designed long-term CfD should also reduce exposure towards price and volume risks.

2.4.1. The current status of Contract for Differences

For now, the optimal design for CfDs is not exactly known yet and will therefore be further investigated in this master thesis with a focus on OBZs. In the current literature, some different designs of CfDs are already discussed with their specific characteristics. In this part of the paper, the following two-sided CfD designs will be elaborated further:

- The conventional CfD
- The advanced CfD
- The capability-based CfD
- The financial CfD

The conventional CfD

The Conventional CfD can be seen as the simplest contract. This contract is similar to the initial contract that was introduced in the UK back in 2014 (Bunn & Yusupov, 2015). This contract has the following main characteristics.

- The volumes considered are the produced volumes in every hour.
- The contract has a fixed strike price.
- The price is linked to the hourly day-ahead spot price.
- The CfD is linked to a specific physical asset.

If the strike price exceeds the spot price, generators receive payment from the government and vice versa. As a result, this stabilises the revenues for generators, even though revenues still remain uncertain because of the uncertainties in the volumes of production. Eventually, the hour-by-hour payment is calculated as follows (Bunn & Yusupov, 2015):

$$Payment = (\textit{strike price} - \textit{spot price}) \cdot \textit{produced volume} \tag{2.1}$$

In the end, there are issues in three main categories when looking at the conventional CfD (Schlecht et al., 2023):

- Produce-and-forget incentives
- Volume risk remains unhedged

Produce-and-forget incentives refer to the generator just wanting to maximise its output and isn't incentivised to produce when most needed. The fact that volume risk remains unhedged refers to the uncertainty about the production of an offshore wind farm due to weather conditions to both low wind speeds resulting in less energy produced or high wind speeds resulting in not all electricity being dispatched (Schlecht et al., 2023).

The advanced CfD

To deal with some drawbacks of the conventional CfD, the advanced CfD is designed. This design ensures that generators don't produce electricity when the prices are negative because there will be no CfD payout when prices are negative. This longer reference price is mostly based on the monthly or yearly average spot price. A result of this measure is that the uncertainty for revenue owners will increase because their revenues will now also depend on the frequency of the positive electricity price. To mitigate this risk, it is also an option that the fix is only applied when the price is negative for a longer period (Bunn & Yusupov, 2015).

Another tweak to update the conventional CfD is by using a longer reference period instead of the hourly spot price. This results in the following equation:

$$Payment = (\textit{strike price} - \textit{reference price}) \cdot \textit{produced volume} \tag{2.2}$$

When using this reference price computed over a longer period, the revenues of the generator are no longer unaffected by intra-period price differences. This incentive optimization of dispatch and maintenance within the reference period. Unfortunately, these longer reference periods only provide incentives to optimise within periods and not across the different periods.

The capability-based CfD

Another CfD is the Capability-based CfD. The capability-based CfD relies on the potential to be produced by a generator instead of the actual production. So, during the auction, power plant owners compete for a fixed strike price based on the potential volumes that 'could' be produced by their installation, taking into account the technical characteristics and local weather conditions. The payment is calculated based on this estimated capacity rather than the actual amount of electricity generated (ENTSO-E, 2023). This results in the following equation:

$$Payment = (\textit{strike price} - \textit{spot price}) \cdot \textit{production potential} \tag{2.3}$$

The key feature of the Capability-based CfD payment is that the amount of revenue generated by a project is not directly linked to actual electricity sold. Instead, the revenue is based on the project's "capability", which is a measure of its expected performance under normal operating conditions. The capability is then used to determine the amount of revenue that the project will receive under the CfD, reducing the volume risk (ENTSO-E, 2023).

If the project generates more electricity than expected, the additional revenue will be sold at the prevailing market price on the wholesale electricity market. If the project generates less electricity than expected due to weather conditions, the revenue from the CfD payment will cover the shortfall, ensuring that investors receive a stable income stream. So, while weather conditions can have an impact on the amount of electricity generated by a renewable energy project, the Capability-based CfD payment is designed to provide a stable income stream for investors, regardless of the actual amount of electricity generated (Schlecht et al., 2023).

The financial CfD

Another CfD discussed in the literature is the financial CfD. The main difference with the capability-based CfD is that the contract is financial rather than asset-specific. The contract involves two payments between the government and a power generator. One of these payments is that the government provides a fixed hourly payment to the generator, while the generator pays the government the hourly spot market revenues for their electricity generation. However, these revenues are not based on the actual revenues of the specific asset, but rather benchmark revenues calculated using a reference generator (Schlecht et al., 2023). Eventually, this results in the following payments and revenues:

$$\textit{CfD Payment to generator from government} = \textit{fixed hourly payment} \tag{2.4a}$$

$$\textit{Payment to the government from generator} = \textit{spot price} \cdot \textit{output reference generator} \tag{2.4b}$$

The reference generator is a method used to determine an hour-by-hour generation profile that closely matches the production of the generator but is not the actual output. Therefore, it incentivises the generator to optimise its output. Additionally, both the reference and actual production should be highly correlated, serving as a good proxy hedge and leaving little remaining basis risk. The only remaining source of revenue risk is the risk originating from the difference between the reference production and the physical production (Schlecht et al., 2023).

Ultimately, the financial CfD uses properties from different types of contracts. First of all, like conventional CfDs, it uses long contracts and generation volumes tailored to specific generation types. Furthermore, it provides a hedge against volume risks, and it is asset-independent like financial forwards (Schlecht et al., 2023).

The need for a CfD as a support scheme

In the grid, congestion occurs when the capacity of the transmission system is insufficient to transport all the electricity generated by the offshore wind farm to the onshore demand. As a consequence, during periods of congestion from the OBZ, wind energy is valued at around 0 €/MWh because there is no offshore demand. Eventually, this leads to a lower average price compared to the HM approach, where the offshore zone is just added to an onshore bidding zone market.

As a consequence of the lower average price for electricity when implementing the OBZ approach, the revenues of offshore wind farm owners decrease. Therefore, despite the fact that an off-shore bidding zone signals transmission scarcity better, this approach may reduce the willingness to invest in offshore wind farms (Kenis et al., 2022). A support scheme, like a CfD, can help in increasing the willingness to invest.

The need to improve the investment stability

Furthermore, for the CfD, there seems to be a need for providing investment stability to OBZs by mitigating the volume risk due to congestion.

This is because offshore wind farms located in OBZs face a higher risk of not being dispatched, especially when implementing the FBMC and AHC algorithms, compared to wind farms connected to conventional onshore bidding zones. Laur et al. (2022) concludes that developers in an OBZ who are experiencing operational derating should be compensated. Operational deratings of interconnectors are a measure of pre-market congestion management to mitigate congestion of critical network elements in onshore gird. The risk is unique for generators in OBZs because, in onshore bidding zones, grid congestion management is dealt with after the market clearing through re-dispatch, which is compensated. These operational deratings can have a high impact on the revenues and are very difficult to predict, creating much uncertainty for offshore wind farm owners (Laur et al., 2022).

CfDs need to incentivize operational decision-making aligned with system needs

CfDs should be designed to avoid any decisions made by plant operators that could impact the efficient design and operation of the plant, section 2.4. Of course, this is also the case for CfDs used in OBZs, even if these CfDs have to deal with the volume risk caused due to congestion. This results for an optimal design and siting in the investment stage, optimal utilisation in the operational stage and even optimal retrofit and re-powering in the re-investment stage.

3 Methodology

In this section, the research sub-questions will be given, with the approaches used to answer the main research question. Furthermore, this section will give insights into the numerical part of the research, discuss how a CfD framework can be designed, and explain how data is collected.

3.1. Research sub-questions

During the thesis, first, the different forms of two-sided CfDs need to be investigated and mapped out with their challenges and uncertainties. Literature research can help clarify the current characteristics of these CfDs by using the knowledge and research results of others.

These different CfDs will eventually impact the decision-making by the offshore generators because each generator wants to maximise its revenues. Therefore, it can be seen that the different CfD designs affect these offshore generators in hybrid projects differently, resulting in some specific challenges. Both literature research and elaborating on some numerical examples can help clarify these effects. This will help in answering the following sub-question:

"How will the different CfD designs influence the bidding strategy of offshore wind generators?"

As already stated before, OBZs will result in some specific challenges for the system and the offshore wind generators. To give more insights into these particular challenges, the OBZ approach needs to be investigated as to how this will influence offshore wind generation. For this part as well, both literature research and elaborating on some numerical examples can help in clarifying these effects, which helps in answering the following sub-question:

"How will OBZs impact the bidding of offshore wind farms in hybrid projects?"

Those effects of two-sided CfDs and how this influences the decision-making by generators in hybrid projects in the OBZ approach need to be linked to the characteristics of the OBZ approach. When linking those sub-questions to each other, the following sub-question is created:

"How will the different CfD designs influence the decisions of generators in hybrid projects in the OBZ approach?"

Furthermore, when looking at the effects of those different CfD designs in the OBZ approach, different preferences and arguments are given by multiple actors. The different interests of the actors can explain this. Investigating policy papers and interviews will be used to identify those different interests. Furthermore, when CfDs are implemented, actors will try to maximise their interests and objectives. These interests and objectives need to be linked to the results of the different CfD designs for offshore wind in the OBZ approach and arguments given to push for different measures. To investigate this, interviews and modelling technologies can be used. Eventually, different strategic behaviours can be recognised here, resulting in the following sub-question:

"Which possible strategic behaviour can be recognised with the implementation of CfDs, and what are the consequences?"

Additionally, the effects on TSOs need to be investigated with a focus on congestion revenues and balancing. This results in the following sub-question:

"How will the TSO be affected by the different designs around the OBZ?"

3.1.1. Research Flow Diagram

Eventually, the answers to all these sub-questions will help to answer the main research question as stated in section 1.3. The research flow diagram in Figure 3.1 is a visual representation of the steps in the research process of this thesis and elaborates on how the different subquestions work towards the main research question. It can be used to plan, organize, and communicate the research process and the relationships between different steps of this thesis. The research flow diagram includes boxes representing each step in the process and arrows showing the flow or progression from one step to the next.

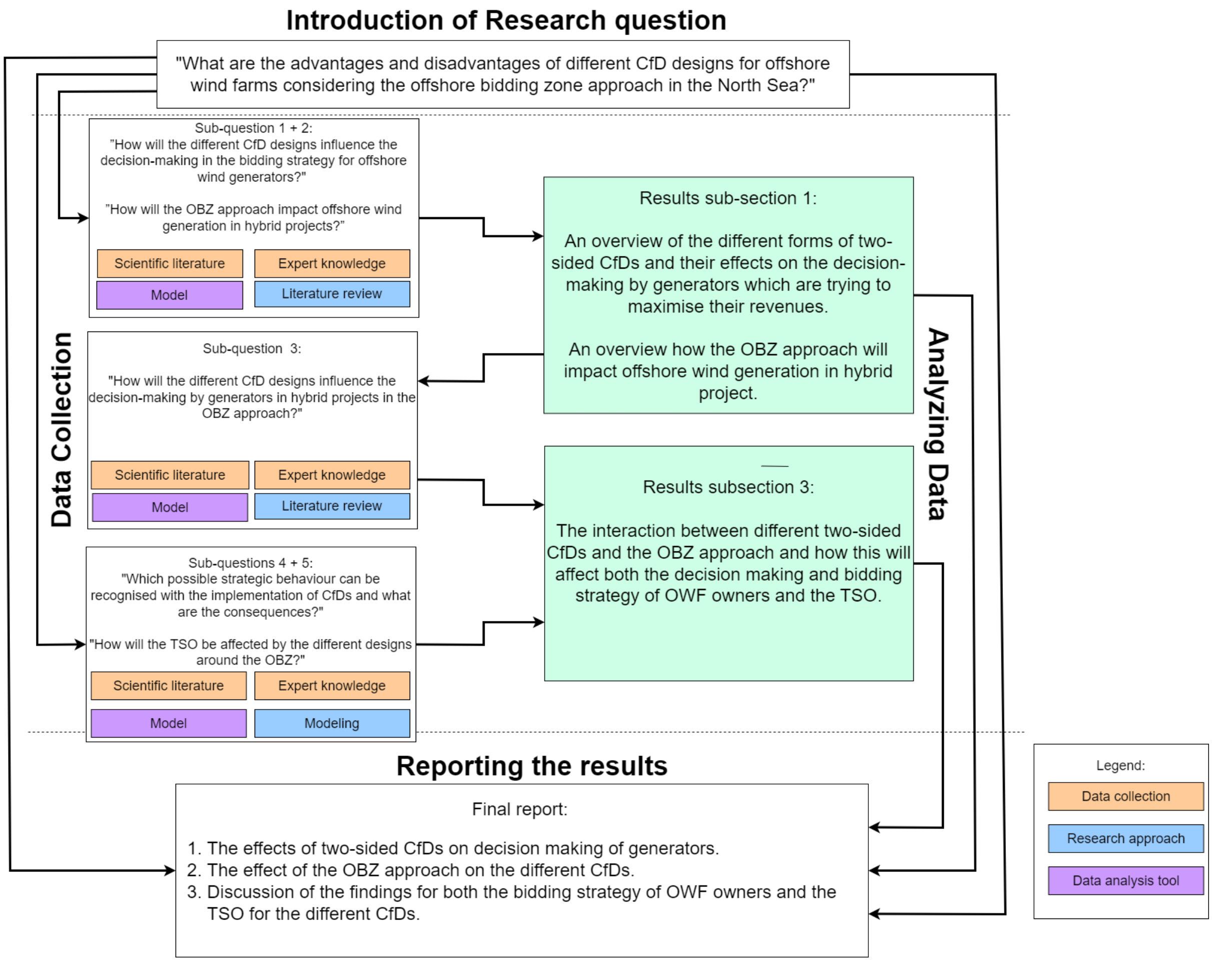


Figure 3.1: Research Flow Diagram

3.2. Approach and data collection

A qualitative approach is chosen to explore different CfD designs pushed forward by different actors. Different actors in the electricity market are pushing for specific support schemes. By using numerical examples, this research gives more insights into the effects of the different CfDs in OBZs. Within this context, each generator participating in the market aims to maximize its revenues. By analysing the market, the thesis seeks to analyze how CfDs and their interaction with OBZs influence the revenue-maximizing strategies pursued by individual stakeholders and how this eventually impacts overall social welfare.

3.2.1. Modelling

In the case of this thesis, several specific cases are mapped out in a simplified model of an offshore European electricity system to investigate the effects of CfDs in a specific case. With these insights, the different suggested support schemes for OBZs and the arguments given by strategic actors will be investigated, considering the objectives, interests and potential consequences of the measures. This thesis will eventually show the opportunities there are for strategic behaviour.

In short, previous studies have analyzed the economic effectiveness of different support schemes to stimulate OBZs in the European electricity system. Unfortunately, there are few studies on the synergies of multiple stakeholders in implementing the different support schemes. It is not enough to ensure that one support scheme is the preferred option, and the different actors with their preferred options and the possibilities of strategic behaviour need to be investigated further.

3.2.2. Advantages and disadvantages of different CfD schemes

When looking into the CfD schemes more in-depth, it can be recognised that these schemes are much more diverse than they may seem at first sight and that these different schemes have their advantages and drawbacks. Kitizing (2023) stated that the best design of a CfD scheme is highly context-specific, even though there will also be design elements every CfD scheme used in the OBZ context needs to contain. Therefore, it can be helpful to have a comprehensive overview of the advantages and disadvantages of the different CfD designs.

Additionally, to help in designing a CfD scheme for an OWF in the OBZ approach next to the technical characteristics of the possible CfD design, the institutional design and process design also need to be considered. All three of these designs need to be considered simultaneously and can be linked to each other as well.

3.2.3. Data collection

As stated earlier, primary data collection was done by analysing policy papers and conducting interviews. After analysing the stakeholders involved as discussed in Figure 4.2, their preferred market design for OBZs is mapped out by analyzing multiple policy papers published by these actors, followed up by research about the effects of the different policy measures

Policy papers

Policy papers are crucial in informing policy and decision-making processes by providing evidence-based analysis and well-researched recommendations to policymakers. In an academic context, these papers present a comprehensive assessment of complex societal issues and reliable data sources (Young & Quinn, 2002). Moreover, policy papers often include in-depth literature reviews, expert interviews, and case studies. One of the primary purposes of policy papers in academic research is to establish a bridge between theoretical research and practical applications.

Eventually, the following two main factors differentiate policy science from traditional academia (Young & Quinn, 2002):

1. Designing solutions for real-world problems
2. Presenting value-driven arguments

To be more precise, unlike traditional academia, which focuses on building knowledge, policy science must address real-world problems and therefore provide recommendations and a framework for their implementation (Young & Quinn, 2002). Therefore, the most important part of the paper is the ability to convince the audience of the suitability of the policy recommendations (Majone, 1989).

Interviews

Interviews are among the most familiar strategies for collecting qualitative data. Qualitative interviews have been categorised in a variety of ways. Unlike the highly structured survey interviews and questionnaires, the interviews conducted in this research examine less structured interview strategies in which the interviewee is more a participant in determining how the information is received (DiCicco-Bloom & Crabtree, 2006). During the research, unstructured interviews and semi-structured interviews were carried out.

Ultimately, no interview will be fully unstructured. However, an interview can be considered unstructured as it can be seen as a guided conversation. During this process, the investigator identifies one or more 'key informants' to interview on an ongoing basis and takes short notes while observing and questioning (Hampshire et al., 2014). These key informants are selected based on their knowledge and role in the context of the design measures.

Before commencing the interview, all interviewees were informed about the research topic, the author's background information and the purpose of the interview. Additional questions from participants regarding the research and usage of collected data were answered to their satisfaction.

3.2.4. Data analysis

The policy papers and knowledge gained from interviews were analyzed using the qualitative content analysis approach. Eventually, from these data, some preferences and suggested support schemes for OBZs were mapped out. Furthermore, these preferences were compared to the objectives of different stakeholders as discussed in section 4.2. Eventually, for multiple actors, possible strategic behaviour is brought forward afterwards. In the modelling part of the research, chapter 5, multiple arguments will be tested to delineate if they are justified.

4

Institutional rules and stakeholders

In this section, the current constitutional framework of the European electricity market is first mapped out. This is followed by an overview of the actors involved and their roles and objectives with OBZs.

4.1. Analysis of coordination issues & institutional environment

For these OBZs, different stakeholders have their interests. An institutional design is required to shape this and protect the system. This section gives an overview of the transactions and coordination problems, and the section ends with a discussion of a CfD scheme in this institutional environment.

4.1.1. Transactions

The technical system and the type of transactions within the scope of the system is shown in Figure 4.1. Besides these transactions, there are other transactions related to electricity trading. In Figure 4.1, the system is divided into production, distribution and consumption. The interactions are divided from this view, and so are the transactions.

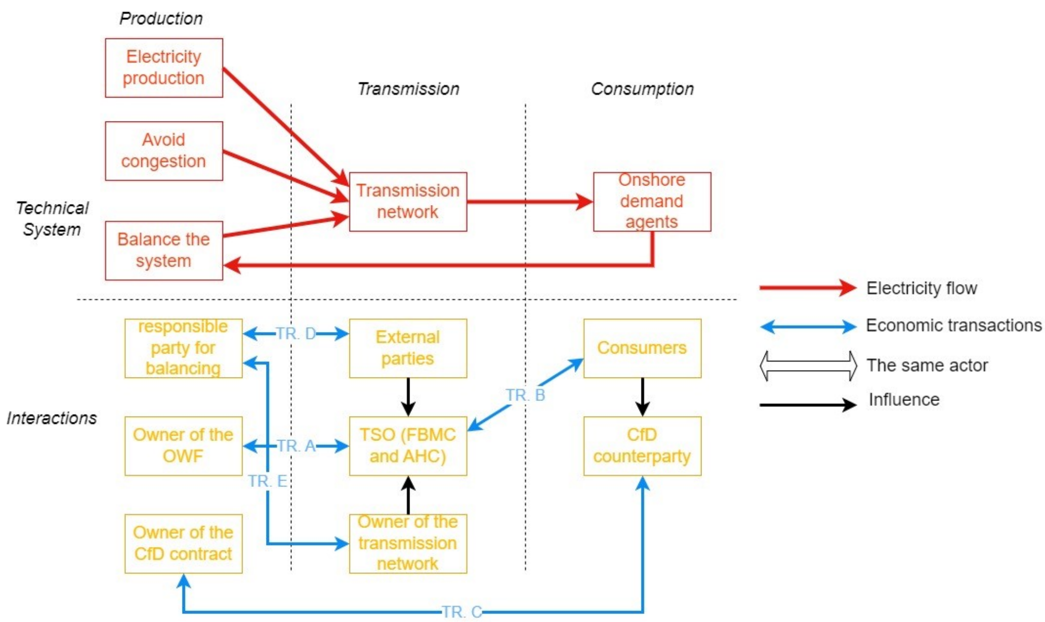


Figure 4.1: Overview of transactions within the scope of the system

The OWF owner will offer its capacity, and an algorithm including FBMC and AHC will determine if the electricity will be sold and at which price (transaction type A). The OWF owner must also deliver this electricity if the capacity is offered and sold. If an OWF is about to offer too much capacity, it must curtail its system to prevent imbalances or use intraday or balancing settlement mechanisms. Furthermore, when an OWF is about to produce insufficient capacity, extra capacity is needed in the intraday or balancing markets (transaction type D). The stakeholder responsible for a balanced network is the transmission system operator (transaction type E). Consumers will also demand electricity, which will be considered in the algorithm, including FBMC and AHC (transaction type B). Lastly, in implementing CfDs for the OBZs, there will also be a transaction between the owner of the CfD contract, the OWF owner and the CfD counterparty, which is mostly the government (transaction type C).

4.1.2. Coordination problems

The purpose of an institutional design is to have a solution for a certain coordination problem. The problem depends on the transactions between different actors, which require structure to realize a sustainable, affordable and reliable electricity system (European Commission, 2019). A tailored selection of coordination problems has been carefully chosen to address the unique aspects of OBZs in this situation. Additionally, the formulated coordination problems are mostly related to financial risks due to the design and the uncertainty around OBZs. Eventually, these risks have to be (partly) solved to support the roll-out and development of these OBZs. These coordination problems can be subdivided into:

- **Responsibility of electricity production:** Who is responsible for producing enough electricity for consumers so supply meets demand?
- **Responsible for a balanced network:** Who is responsible for a balanced transmission network? Which party needs to pay for redispatch?

- **Responsible for transmission capacity:** Which party needs to ensure electricity can be distributed from the supplier to the consumer? Is there an obligation here? Which party needs to pay for this capacity?
- **Managing investment risk:** Is OWF owners' investment risk too high?
  - **Managing investment risk I:** How can OWF owners be protected from lower electricity prices because of the OBZ approach?
  - **Managing investment risk II:** How can OWF owners be protected against the volume risk of being unable to dispatch all their produced electricity?
- **Different interests between Member States:** How can be dealt with the inequalities between Member States? How can be dealt with different political views? How can be dealt with different objectives?
- **Efficient market design:** Are generators incentives to produce electricity when it is most needed?

Based on the coordination problems, there is still a lot of uncertainty about OBZs and the future offshore electricity network. This can withhold stakeholders from participating, resulting in more delay. It seems necessary to support stakeholders to participate and ensure the market will work most efficiently. Therefore, the framework around OBZs must be designed carefully based on a certain role's risks and who can best manage these.

4.1.3. CfD scheme in the institutional environment

A CfD support scheme as an intervention in OBZs will affect the market and the stakeholders' role in the market. There is still great uncertainty about developments in the future, which results in financial risks. Therefore, a straightforward market design is required where system costs and responsibilities are divided. Additionally, the international aspect of OBZs needs to be considered with the additional features and problems this brings. The coming sections will discuss how the CfD design can help in this institutional environment and how they deal with the coordination problems of OBZs.

4.2. Relevant stakeholders

The European electricity market is a complex, extensive market with many actors involved. Some key stakeholders can be subdivided into the following main subgroups, as shown in Figure 4.2:

- The European Union
- Regulatory authorities
- Transmission system operators

All three key stakeholders can be subdivided further into a European body and a body on an Individual Member state level. For the governmental section, on the European level, the European Commission is portrayed compared to Individual Member states and EFTA states on the national level; for regulatory Authorities on the European level, ACER is portrayed compared to NRAs on the national level. Lastly, for transmission System Operators, ENTSO-E is the European body compared to individual TSOs on a lower scale. Eventually, these different stakeholders have other interests and roles in OBZs. This is also reflected in their preference for the various CfD designs.

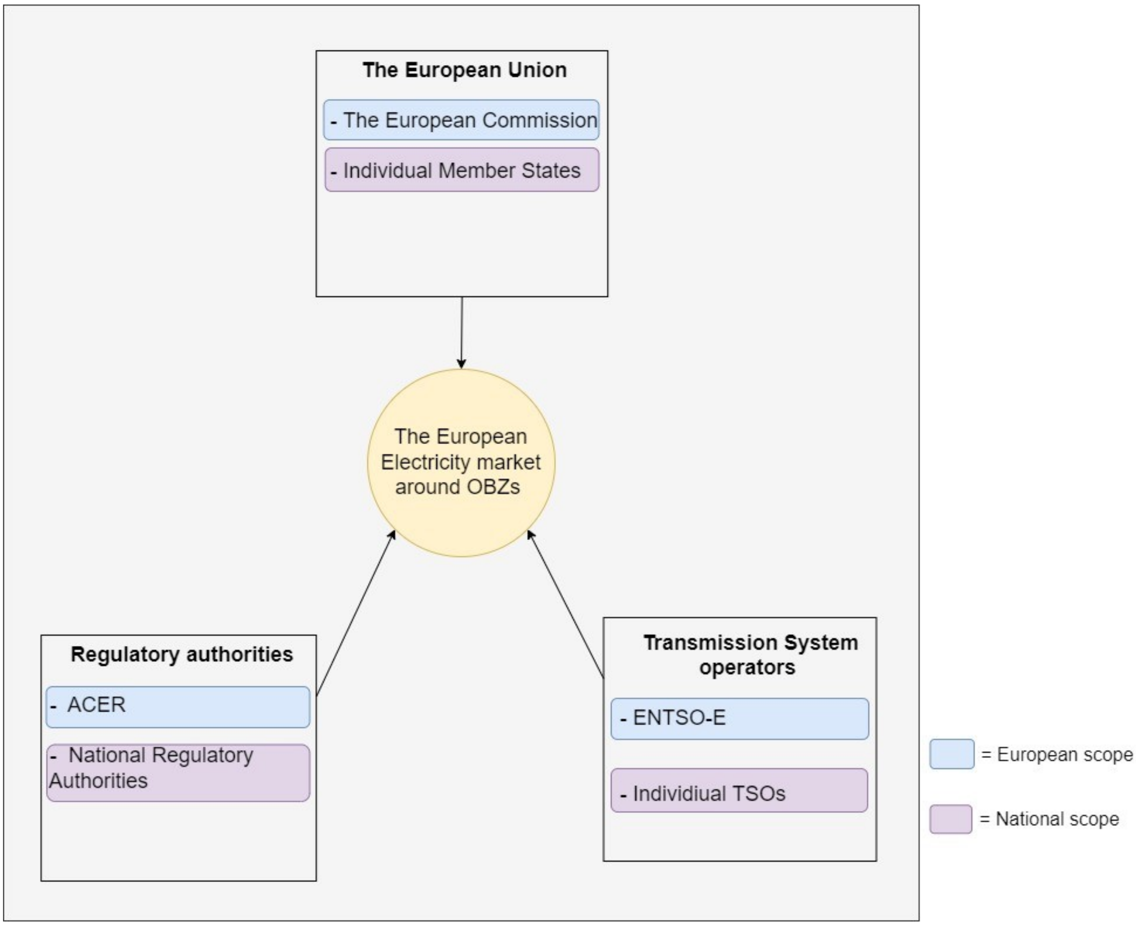


Figure 4.2: Actors in the European Electricity market

4.2.1. The European Union

The European Union is largely based on agreements and compromises between these member states. It has several divisions with its power and responsibilities in the EU. The divisions in the European Union important for OBZs are (De Jong, 2009):

- European Commission
- Individual national governments
- EEA EFTA states

The European Commission

The European Union has a significant role and high interest in implementing OBZs. They play a critical role in electricity grid policy by focusing on creating an integrated and sustainable electricity market across member states. Its key roles include promoting market integration, encouraging grid interconnection, establishing a common regulatory framework, and supporting the integration of renewable energy sources

(European Commission, 2020). The EC published the EU Strategy to harness the potential of offshore renewable energy for a climate-neutral future (European Commission, 2020). discussed in section 2.3, covering the definition of hybrid projects and the OBZ approach. As a result of this strategy, (Laur et al., 2022) commissioned and published on behalf of the EC a consultation paper discussing electricity market arrangement and exploring some of the investment challenges facing market-based investments in offshore renewable energy and focusing particularly on those projects that are connected to more than one market. This study aimed to investigate the options regarding congestion income. It provides the recommendation that TAGs, section 1.2, are the preferred design. Controversy, this is certainly not a given solution, and in the EU, there are supporters and opponents of this support scheme. Discussing this will be out of scope in this research.

Individual national governments

Furthermore, individually, national governments also have high power and interest in the development of the European electricity grid and market around OBZs. While the European Union tries to maximize the overall social welfare in Europe, this is not necessarily the case for individual national governments who try to maximize their welfare. In addition, implementing OBZs and the policy framework around them will influence member states differently (Kitzing & Garzón González, 2020). This is one of the reasons why Member States can look differently at OBZs and the framework around them, including the possible support schemes. Furthermore, a different political viewpoint between Member States can also influence the preferences and needs to be considered in the decision-making process (Bocquillon & Maltby, 2021).

EEA EFTA states

Eventually, the member states of the European Union, together with the following three EEA EFTA States, Iceland, Liechtenstein, and Norway, have an internal electricity market governed by the same basic rules called the European Economic Area (EEA). The agreement on the EEA entered into force in 1994 and guarantees equal rights and obligations within the internal market for individuals and economic operators in the EEA (EFTA, 1994).

The connection between the EEA and the offshore grid lies in their shared energy cooperation and integration objectives. In the EEA, the energy policies of the offshore grid, including particular OWFs, will be aligned along EU member states and Norway, Iceland and Liechtenstein. This will also result in the same framework around OBZs.

4.2.2. Regulatory Authorities

In the European Union, all Member States have established a sector-specific national regulatory authority (NRA). In the European Union, a national regulatory authority in the electricity sector typically has several tasks and responsibilities, which are formalized in Directive 2003/54/EC (Article 23). Furthermore, entities like ACER and CEER connect those national authorities in the European context.

National Regulatory Authorities

A NRA is crucial in ensuring fair competition, consumer protection, and efficient operation of the electricity system with or without OBZs. They make and implement policies around OBZs from their viewpoint, making them powerful actors. Furthermore, they can have an advisory role, which refers to their function as experts providing recommendations and advice to governments, policymakers, and other stakeholders around these OBZs. The preferred design, including the preferred support schemes, can differ around hybrid projects and OBZs.

It's important to note that an NRA's specific tasks and responsibilities may vary from country to country. Still, because EU electricity markets have become increasingly integrated, the impact of market decisions will not be constrained to national boundaries.

ACER & CEER

To improve this international aspect, in 2011, by the Third Energy Package legislation, the European Union Agency for the Cooperation of Energy Regulators (ACER) was established. This independent agency's primary role is to enhance cooperation and coordination among national energy regulatory authorities in the EU. It tries to foster the integration and completion of the European internal energy market for electricity and natural gas. ACER ensures that the integration of national energy markets and the implementation of legislation align with the EU's energy policy objectives and regulatory frameworks (ACER & CEER, 2023).

Furthermore, In 2000, the Council of European Energy Regulators (CEER) was founded as a self-initiative of regulatory authorities, and it still serves as a platform for cooperation and coordination among regulatory authorities (CEER, 2020). Through its academic research and publications, CEER contributes to decision-making by providing valuable insights and analysis on various energy-related topics.

Around OBZs, ACER can be seen as an actor with high power and interest, among others, due to the international scope and the market integration aspect of OBZs.
In 2022, ACER and CEER (2022b) published a paper reflecting on the EU strategy to harness the potential of offshore renewable energy. In their reflection, they support the approach towards the creation of OBZs, but they also discuss some critical challenges of the OBZ model. The paper stated that the OBZ approach provides efficient price signals to all actors involved and fully corrects interconnector flows. Furthermore, it has more choice in selling its energy efficiently to the market where energy is most needed, compared with the HM approach and provides incentives to connect OBZs among themselves (ACER & CEER, 2022b). The paper finalizes with the conclusion that the OBZ approach is preferred above the HM approach from a market design and efficiency perspective but also highlights this needs to be balanced with the necessary changes to ensure OBZs have equal access to trading as close to real-time, as in the HM approach (ACER & CEER, 2022b).

Furthermore, in February 2023, ACER and CEER also responded to the European Commission's public consultation on the EU's electricity market design, (ACER & CEER, 2023), which will also influence the OBZ design. In their response, they state that there seems to be a need for support schemes to stimulate renewables, like offshore wind, and CfD can be a solution here, but if Member States implement CfDs, they need to be designed in an intelligent way (ACER & CEER, 2023). Some of the measures given to improve traditional CfDs are:

1. Settlement based on predefined/reference volumes.

2. Replace single strike price by cap and floor.
3. Resell CfDs as financial contracts in forward markets.

When looking at offshore wind, more specifically, ACER and CEER (2023) acknowledged a legal framework that needs to be developed for offshore wind. Furthermore, ACER doesn't support TAGs but admits that investment stability is needed, so other options must be explored (ACER & CEER, 2023).

4.2.3. Transmission system operators and ENTSO-E

Transmission System Operators (TSOs) operate, maintain, and develop high-voltage electricity transmission systems. Every member state in the European Union has at least one active TSO, and the transmission networks of these TSOs are also connected.

Individual transmission system operators

TSOs can be seen as an essential component of the energy sector, acting as the backbone of the electricity transmission system. Eventually, these individual TSOs must build the offshore grid and efficiently connect the offshore wind farms to the mainland, making them irreplaceable actors. The design around the support schemes of offshore wind farm owners will have an excessive impact on TSOs, even more so if congestion revenues are used to support offshore wind farm owners or CfD designs aren't designed efficiently.

ENTSO-E

The European Network of Transmission System Operators for Electricity (ENTSO-E) is the overarching organization representing TSOs in Europe. It comprises 43 members from 36 countries, including TSOs from EU member states and other European countries (ENTSO-E, 2020). It was established in 2008 due to the EU's efforts to promote cross-border trade and integrate the electricity system. ENTSO-E promotes cooperation among TSOs and facilitates the development of pan-European electricity transmission network codes and guidelines.

Furthermore, ENTSO-E plays a crucial role in the coordination and development of offshore grids in Europe and the design of this transmission network. They will collaborate with regional TSOs and stakeholders to plan and develop offshore grid infrastructure. This involves identifying suitable locations for offshore generation sources, determining efficient transmission routes, and coordinating the connection of offshore assets to the onshore grid. Furthermore, ENTSO-E also provides policy support to facilitate the integration of offshore renewable energy sources.
In April 2023, ENTSO-E published a position paper on the EC proposals on market design, where they also discussed OBZs (ENTSO-E, 2023).

In this paper, they stated that the use of congestion income, like TAGs, should not be used to finance support for generators in offshore hybrid projects because this is not an effective support mechanism and would be an implicit and non-transparent subsidy paid by consumers at the expense of grid tariffs (ENTSO-E, 2023). As an alternative, they suggest two-sided capability-based CfDs or financial CfDs to give revenue guarantees to offshore generators. These schemes will comprehensively cover the volume risk of generators while avoiding market distortions and any discriminatory use of congestion income (ENTSO-E, 2023). In this paper, they underline that CfDs must be very carefully designed to avoid distortions in short-term and balancing markets or increases in system costs.

4.3. Stakeholder requirements

As already stated, when a CfD design for an OBZ is designed, many stakeholders come together with their interests and objectives. In conclusion, there have to be enough incentives for OWF developers to invest in OWFs in the OBZ approach and to produce electricity. This means that developers of offshore wind farms must have sufficient certainty from CfDs that they will recoup their investments and generate revenue with minimal risk. On the contrary, for other stakeholders, it is important that the market will still be efficient and that the physical system can also be constructed. This electricity must be transmitted and distributed to OnBZs where it is most needed. This means that OWF owners must generate electricity during peak demand, and infrastructure investments are crucial. The regulators have the responsibility of designing and upholding the regulatory structure that governs the operation of the OBZs. They establish the rules, laws, and guidelines that OWF, network operators, traders and other stakeholders must follow. Additionally, these regulators establish rules to protect consumers.

The institutional part of OBZs have been discussed in the previous chapters, and regarding the societal part, it is essential that the CfD design doesn't impact other stakeholder negatively because multiple stakeholders are needed for the proper development of an offshore grid, including OBZs. Some specific effects of the different CfD designs in OBZs will be further discussed in the coming sections.

5
Analysis 1 - Numerical examples

The aim of CfDs with regard to OBZs is to stimulate investment and development in offshore renewable energy projects within these designated zones. However, there is a possibility that CfDs might have a negative impact on decision-making around an efficient market. This section will explore the influence of different CfD designs on the market by providing some specific examples using a simplified model. Furthermore, the impact of uncertainty on available capacity due to the intermittency of offshore wind will be examined, taking into account the different CfD designs. This will be followed by an analysis of how congestion costs in one bidding zone affect CfD payments in another.

5.1. Base case

In this numerical example, the models are applied to a stylized example of one OBZ and two OnBZs, which represent a simplified version of a real-world OBZ in a fictive power system. The bidding zones are connected by offshore DC transmission lines between the different BZs, integrated as interconnectors. An overview of the grid is given in Figure 5.1.

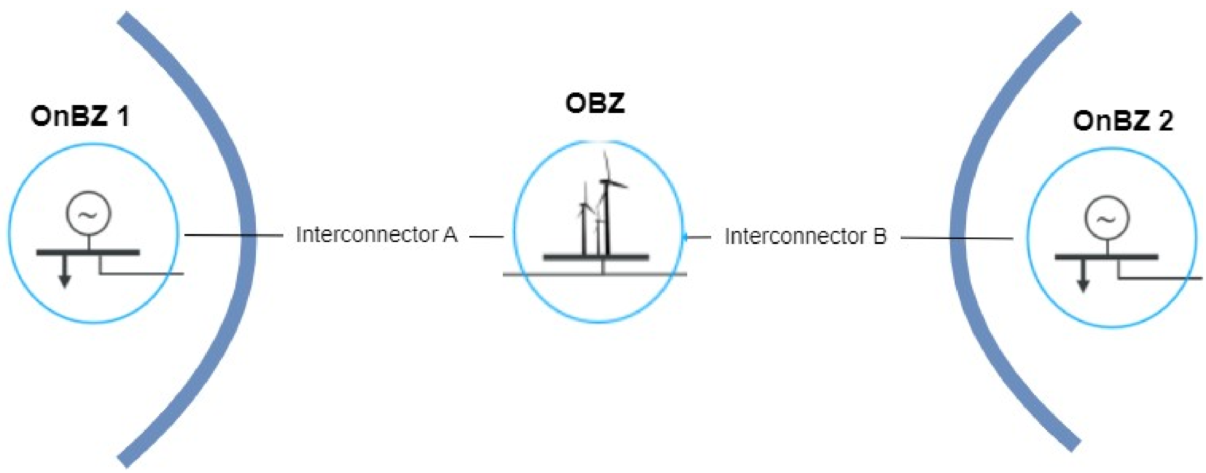


Figure 5.1: Three OBZs + three OnBZs + interconnectors

To clarify how different scenarios will affect the electricity price, three cases are presented. In all three cases, the capacity of the OWF in the OBZ is 800 MW in the DAM. Furthermore, in all three cases, the electricity price of OnBZ 1 is 30 €/MWh, while the electricity price for OnBZ 2 is 50 €/MWh. The difference lies in the capacity of the interconnectors. In the first case, both interconnectors have a capacity of 1000 MW. In the second case, the capacity of both interconnectors is 500 MW. In the third case, the capacity of interconnector A is 300 MW, while the capacity of interconnector B is 400 MW. An overview of the properties of the base cases is given in Table 5.1.

Table 5.1: Properties base cases

	Output OWF in DA [MW]	**Electricity price OnBZ 1 { [€/MWh]**	**Electricity price OnBZ 2 [€/MWh]**	**Capacity interconnector A [MW]**	**Capacity interconnector B [MW]**
CASE 1	800	30	50	1000	1000
CASE 2	800	30	50	500	500
CASE 3	800	30	50	300	400

The electricity price of the OBZ will be based on the electricity price of the OnBZs that have the lowest electricity price and are connected to the OBZ. However, there may be exceptions when the OBZ cannot dispatch all the electricity it generates due to grid congestion (European Commission, Directorate-General for Energy, THEMA consulting group, 2020). In this case, the electricity price in the OBZ will be zero. This is an assumption that is made that an OWF will bid rationally, meaning it will bid an amount that covers its operational costs, which are approximately zero for a wind farm. An overview of the electricity flows and prices for the different cases can be found in Table 5.2.

Table 5.2: Results base cases

	Flow interconnector A [MW]	Flow interconnector B [MW]	Electricity price OBZ [€/MWh]
CASE 1	200	1000	30
CASE 2	300	500	30
CASE 3	300	400	0

When analysing the results of the base cases without support schemes, it becomes evident that there is a volume risk for OWF owners because they face the risk of zero electricity prices when all generated electricity cannot be dispatched. As discussed in Chapter 2, a properly designed grid may experience congestion at times to avoid over-investment in the grid. In such cases, the TSO would receive the monetary value of investments in new transmission capacity through congestion income, as explained in chapter 2.

The different CfD designs will influence the market and revenues of the OWFs in different ways. The way in which different revenues for OWF owners and the price for the government are determined is shown for the non-congested grid, cases 1 and 2, Table 5.3 and a congested grid, case 3, Table 5.4. It is important to keep in mind that with conventional CfD, the OWF will always receive the strike price times its capacity and will bid even when the electricity price is negative. These formulas will be explained in more detail and implemented in the upcoming section

Table 5.3: CfD non-congested grid

case 1 + 2	**Price electricity OBZ [€/MW]**	**Revenues OWF [€]**	**CfD payment from government for government [€]**
Conventional CfD	30	strike price * 800	(strike price - spot price) * 800
Advanced CfD	30	(strike price - reference price) * 800	(strike price - reference price) * 800
Capability-based CfD	30	strike price * 800	(strike price - spot price) * 800
Financial CfD	30	Fixed hourly remuneration + (spot price * (physical capacity - reference generator))	fixed hourly remuneration - (spot price * reference generator)

Table 5.4: CfD congested grid

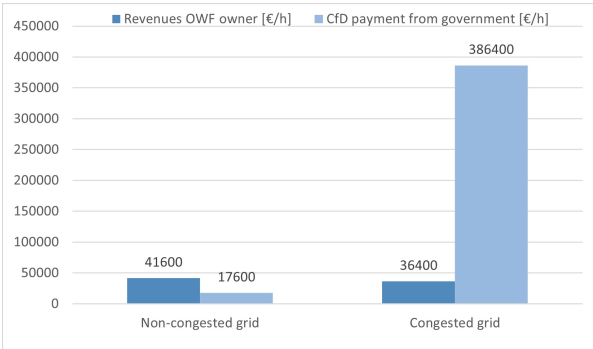
case 3	**Price electricity OBZ [€/MW]**	**Revenues OWF [€]**	**CfD payment from government [€]**
Conventional CfD	negative	strike price * 700	(strike price - spot price) * 700
Advanced CfD	0	(strike price - reference price) * 700	(strike price - reference price) * 700
Capability-based CfD	0	strike price * 800	(strike price - spot price) * 700 + strike price * 100
Financial CfD	0	Fixed hourly remuneration + (spot price * (physical capacity - reference generator))	fixed hourly remuneration - (spot price * reference generator)

The conventional CfD

The conventional CfD is the basic CfD design without any special characteristics or tweaks, subsection 2.4.1. The results of the conventional CfD for the non-congested grid, case 1 and the congested grid, case 3, are shown in Figure 5.2. For the strike price, an amount of 52 €/MWh is chosen because this is the CfD strike price of the Hornsea project, a large offshore project in the North Sea (Upton et al., 2014). Furthermore, as the minimum bid price, an amount of -500 €/MWh is chosen even though this number is an assumption because the minimum bid price depends on the specific case (Swinand et al., 2019). When implementing a two-sided conventional CfD, the OWF owner will always receive the strike price, rendering the electricity price irrelevant. Consequently, a rational OWF will bid the minimum bid price.

	Non-congested grid	**Congested Grid**
Capacity OBZ [MW]	800	800
Capacity interconnectors A + B [MW]	2000	700
Electricity dispatched OBZ [MW]	800	700
Strike price [€/MW]	52	52
Spot price OBZ [€/MWh]	30	Minimum bid price
Revenues OWF owner in DAM [€/h]	36400	36400
CfD payment from government [€/h]	17600	386400

(a) Base case conventional CfD



(b) Conventional CfD implemented in base case

Figure 5.2: Conventional CfD implemented in base case

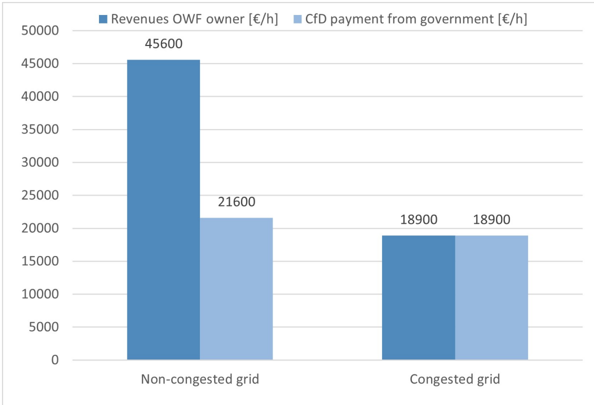
When looking at these results, when the grid is not congested, the revenues of the OWF are the CfD payout together with the revenues from the wholesale market. Additionally, OWF owners still want to dispatch as much electricity as possible when congestion occurs. When optimising their bidding strategy, they will bid as the electricity price is negative because they will receive the strike price times their dispatched electricity as revenue. This inefficient market design means that a lot of the CfD payout will not end up with the OWF, as shown in Figure 5.2b.

The advanced CfD

In the advanced CfD, some modifications are made to the conventional CfD, as discussed in section 2.4. One of the significant changes is the inclusion of a reference price that depends on the average spot price of the preceding reference period, which will be very time-dependent. In this model, 25 €/MWh is implemented as the reference price. By implementing this model, the system can optimize its production when the day-ahead spot price of electricity is higher within a reference period. An overview of the results of the advanced CfD for the non-congested and congested grid is given in Figure 5.3.

	Non congested grid	Congested Grid
Capacity OBZ [€/MW]	800	800
Capacity interconnectors [MW]	2000	700
Electricity dispatched OBZ [MW]	800	700
Strike price [€/MW]	52	52
Spot price OBZ [€/MWh]	30	0
Reference price [€/MWh]	25	25
Revenues OWF owner [€/h]	45600	18900
CfD payment from government [€/h]	21600	18900

(a) Base case advanced CfD



(b) Advanced CfD implemented in base case

Figure 5.3: Advanced CfD implemented in base case

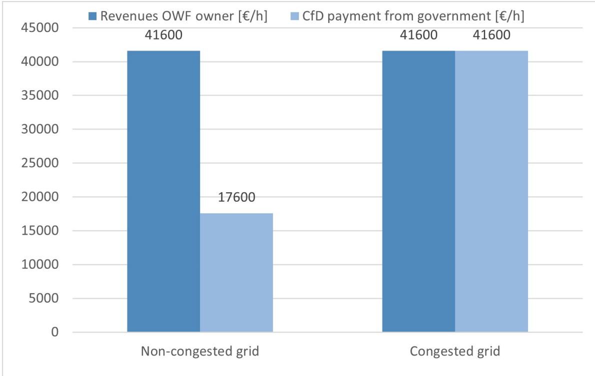
In contrast to conventional CfD, the advanced CfD ensures that an OWF is not incentivised to produce electricity when the electricity price in the OBZ is negative, because there will be no CfD payout at negative prices, section 2.4. Of course, this means that the OWF will not generate electricity when the price is negative. Furthermore, in Figure 5.3a, it is evident that the revenues for the OWF owner in a congested grid will be proportionally lower than in a non-congested grid.

The capability-based CfD

In contrast to other schemes, the capability-based Contract for Difference (CfD), as explained in section 2.4, evaluates production potential rather than actual electricity production. Figure 5.4 presents the outcomes for the capability-based CfD on both a non-congested and a congested grid.

	Non congested grid	Congested Grid
Capacity OBZ [€/MW]	800	800
Capacity interconnectors [MW]	2000	700
Electricity dispatched OBZ [MW]	800	700
Strike price [€/MW]	52	52
Spot price OBZ [€/MWh]	30	0
Revenues OWF owner [€/h]	41600	41600
CfD payment from government [€/h]	17600	41600

(a) Base case advanced CfD



(b) Capability-based CfD implemented in base case

Figure 5.4: Capability-based CfD implemented in base case

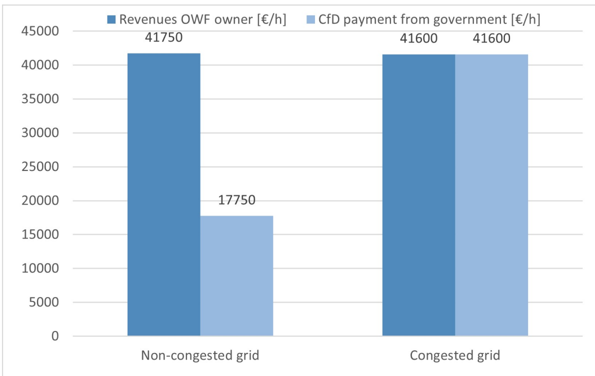
The results presented in Figure 5.4b show that when electricity cannot be entirely dispatched, and the electricity price is zero, the losses are transferred from the OWF owner to the entity responsible for the CfD disbursement, such as the government. This support scheme guarantees a fixed payout regardless of the capacity available on the grid, providing certainty to the OWF owner.

The financial CfD

The financial CfD is a more complex CfD support scheme compared to other CfD schemes. Its payout is not dependent on the asset but rather on a reference generator. This makes it similar to a forward/futures contract, as discussed in section 2.4. For the base cases, a fixed hourly remuneration rate of 41600 €/h is chosen. This rate is calculated by multiplying the given strike price with the offshore wind farm's capacity. A value of 795 MW, which is close to the actual capacity, is used for the capacity of the reference generator. Therefore, slight changes in the revenues and payout may still occur. You can find an overview of the results for both the non-congested and congested grid of the base cases in Figure 5.5.

	Non congested grid	Congested Grid
Capacity OBZ [€/MW]	800	800
Capacity interconnectors [MW]	2000	700
Electricity dispatched OBZ [MW]	800	700
Fixed hourly remuneration [€/h]	41600	41600
Capacity reference generator [€/MWh]	795	795
Spot price OBZ [€/MWh]	30	0
Revenues OWF owner [€/h]	41750	41600
CfD payment from government [€/h]	17750	41600

(a) Base case financial CfD



(b) Financial CfD implemented in base case

Figure 5.5: Financial CfD implemented in base case

The results presented in Figure 5.5 indicate that the effects of a congested grid are reflected in the CfD payout from the government rather than the revenues generated by the OWF. As seen in Figure 5.5, the revenue earned by the OWF depends on the difference between the physical generation and the generation of the reference generator, but only when the grid is not congested. In the case of a congested grid, such as in Figure 5.5, the difference between the actual and reference generator becomes irrelevant.

5.2. Scenarios base cases

The effectiveness of the CfD designs for the base cases depends on multiple time-dependent properties that will change over time for the system. In particular, for these specific cases, the properties are the capacity of electricity that the OWF can produce, the electricity price of the lowest connected OnBZ, the reference price, and, due to the implementation of FBMC and AHC, the available transmission capacity from offshore to onshore.

To assess the impact of different variables on the revenues for the OWF and the CfD payment from the government, three different scenarios were considered. These scenarios represent 80%, 100% and 120% of the base case amount. The resulting figures are presented in the table shown in Table 5.5.

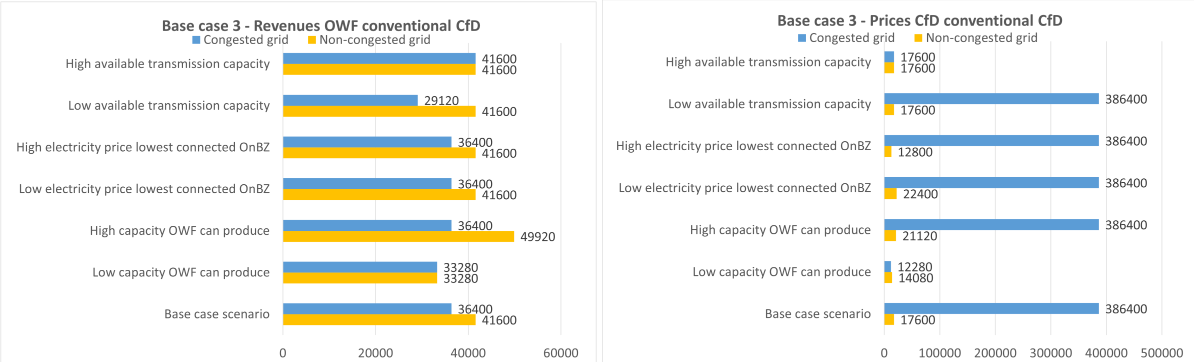
Table 5.5: Scenarios for base cases

	80% (Low case)	**100% (Base case)**	**120% (High case)**
Capacity of Offshore Wind Farm (OWF)	640	800	960
Lowest Connected Onshore BZ Electricity Price	24	30	36
Reference Price	20	25	30
Available Transmission Capacity (Case 1)	1600	2000	2400
Available Transmission Capacity (Case 2)	800	1000	1200
Available Transmission Capacity (Case 3)	560	700	840

Based on the variables discussed in Table 5.5, the different CfD designs affect both the price of the CfD and the revenues for the OWF owner in various ways. The tables and figures in Appendix B provide a detailed overview of these results. The data shows that changing circumstances have different impacts on the costs and revenues of the project when different CfD designs are implemented. However, for case 1 and case 2, the results are the same. Therefore, it can be concluded that the results are dependent on whether or not the grid is congested. In the following sections, we will highlight some significant observations that can be made from these results.

Difference in results for changing circumstances

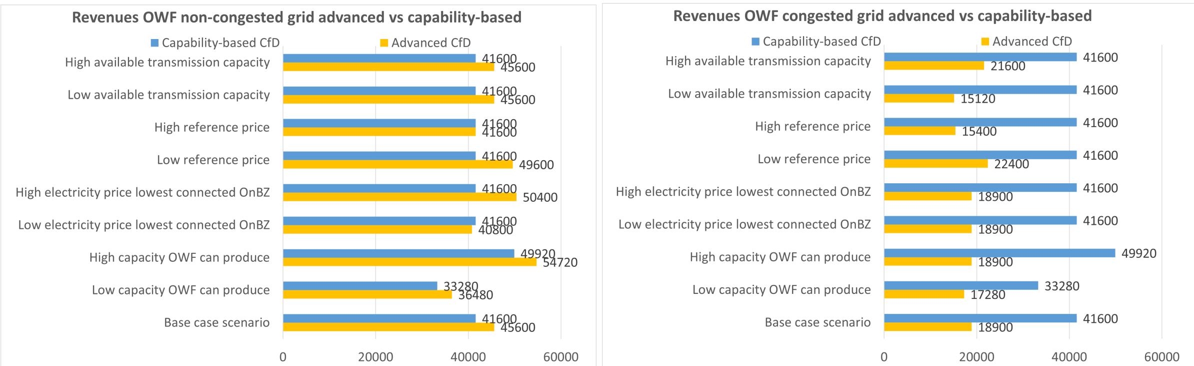
When looking at the revenues for the OWF owner with the conventional CfD, as shown in Figure 5.6a, it is clear that the revenues depend on the amount of electricity that will be dispatched. As shown for the CfD payout in Figure 5.6b, for the non-congested grid, the payout is also dependent on the electricity that will be dispatched. However, in a congested grid, the payout for the CfD is proportionally lower when the transmission capacity is higher than the capacity of the OWF. This is illustrated in Figure 5.6b.



(a) Base case 3 - Revenues OWF conventional CfD **(b)** Base case 3 - Prices CfD conventional CfD

Figure 5.6: Conventional CfD scenarios

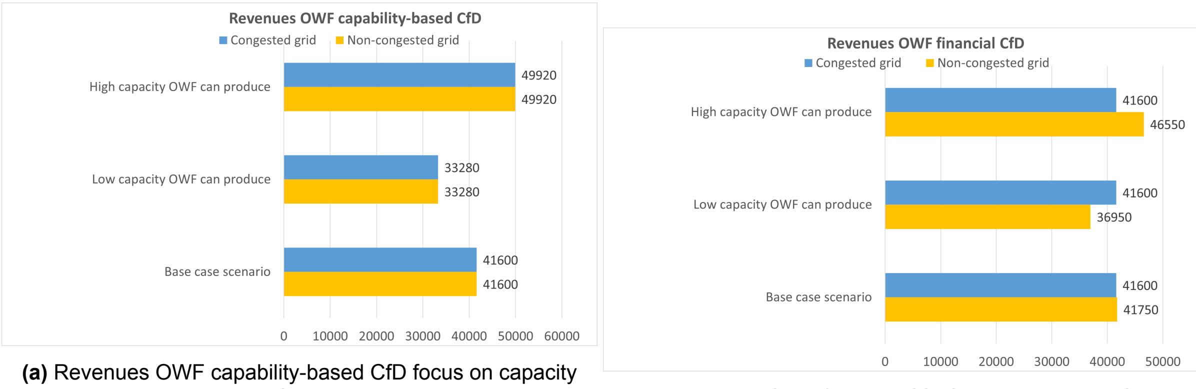
When analyzing the congested grid, the advanced and capability-based CfD are affected differently by the changing circumstances of the reference price and the availability of the transmission capacity. In the case of the capability-based CfD, transmission capacity doesn't appear to impact the revenues. However, for the advanced CfD, an increase in transmission capacity leads to higher revenues for the OWF. Finally, Figure 5.7 indicates that while a changing OWF production results in higher revenue changes with the capability-based CfD, the magnitude of these changes is the same as those with the advanced CfD, as shown in Figure 5.7b.



(a) Base case 3 - Revenues OWF non-congested grid advanced vs capability-based **(b)** Revenues OWF congested grid advanced vs capability-based

Figure 5.7: Revenues OWF in different scenarios, advanced vs capability based

Comparing the impact of various factors on the capability-based CfD and financial CfD, it can be observed that the changes are mostly identical for both schemes, except for certain scenarios. Specifically, changes occur when the electricity price of the OnBZ changes for a non-congested grid or changes in capacity that an OWF can generate during both congested and non-congested grids. These changes are illustrated in **??**.



(a) Revenues OWF capability-based CfD focus on capacity OWF

(b) Revenues OWF financial CfD focus on capacity OWF

Figure 5.8: Revenues OWF focused on capacity OWF, capability-based CfD vs Financial CfD

The financial CfD incentivizes OWF owners to invest in their OWF and produce the most electricity when the market needs it the most. This results in a change in revenues for the OWF owner, which depends on the onshore electricity price and the availability of transmission capacity to transport the produced electricity. This is a feature of the financial CfD that incentivises the OWF owner to design its OWF to produce the most electricity when the market needs it. This will be further concluded in chapter 8.

5.3. Uncertainty of available capacity because of the intermittency of offshore wind

As discussed in section 2.2, the day-ahead market has an average forecast error of 10% of installed wind capacity compared to the actual production in real-time. This error in the forecast one day ahead can exceed to 30% of installed capacity in extreme cases (European Commission, Directorate-General for Energy, THEMA consulting group, 2020). These forecast errors imply the need for corrections after the day-ahead dispatch solution of this order of magnitude. These 'corrections' require a combination of intraday market trading and redispatch measures by the TSO. It is worth noting that in OBZs, there are no demand agents or generators that can ramp up their generation. On the contrary, these wind farms can be curtailed after the day-ahead market clearing.

These uncertainties and effects could possibly be taken into account in the bidding strategy of OWFs. The different CfD designs will also impact these effects and, thus, the bidding strategy. Given that wind farms can be curtailed but cannot be ramped up,it is reasonable to assume that OWFs will always bid below their expected capacity. In Figure 5.9a, an overview can be found of possible forecast errors and in Figure 5.9b. Additionally, an overview of possible bidding strategies can be found in Figure 5.9b.

Forecast error	Actual production [MW]
100%	800
110%	880
130%	1040
90%	720
70%	560

(a) Overview possible forecast errors

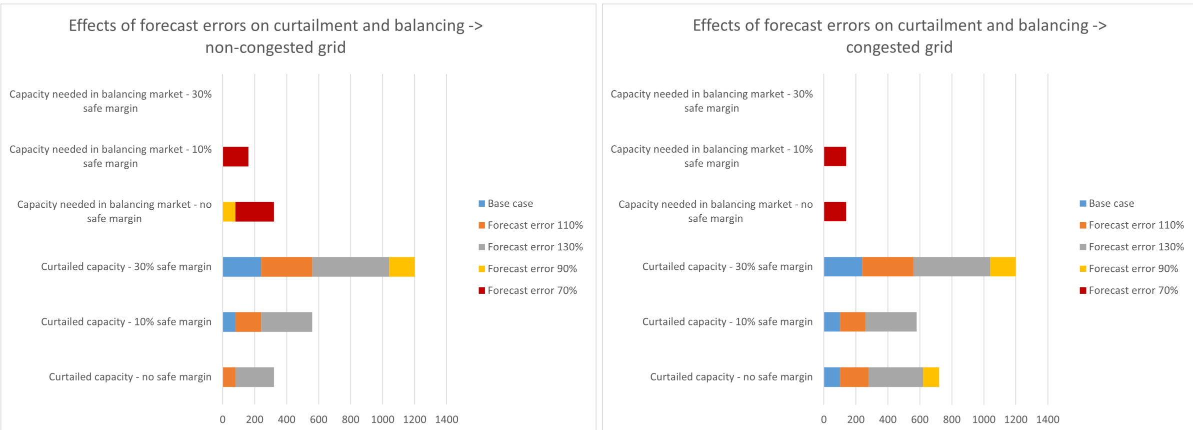
Safe margin	Percentage of capacity offered	Actual bid [MW]
0%	100%	800
10%	90%	720
20%	80%	640
30%	70%	560

(b) Overview of possible bidding strategies

Figure 5.9: overview of forecast errors and bidding strategies

In Appendix C, you can find the outcomes of the various bidding strategies and forecast errors. The tables reveal that purchasing additional electricity after the day-ahead market is only necessary when the actual production appears to be lower than the actual bid, taking into account the forecast and the safe margin. Upon examining these tables, several observations might be made.

In the congested case, the effects of a safe margin can influence the revenues differently. If the bid amount becomes lower than the available transmission capacity because of this safe margin, the spot price of the day-ahead market can become as high as the OnBZ with the lowest electricity price connected. Furthermore, to ensure efficiency in the market and maximize revenues for the OWF, the balancing costs must also be considered in addition to the base case revenues. In Figure 5.10, an overview is given of the different forecasting errors and what the effects will be in these scenarios on the curtailed capacity and the capacity needed in the balancing market for both a non-congested grid,Figure 5.10a, as a congested grid, Figure 5.10b. Furthermore, it can also be recognised in Table C.1 that forecasting errors of the reference generator will not influence the curtailed capacity and the capacity needed in the balancing market.



(a) Effects forecast errors on curtailment and balancing non-congested grid

(b) Effects forecast errors on curtailment and balancing congested grid

Figure 5.10: Effects forecast errors on curtailment and balancing

When observing the data presented in Figure 5.10, it becomes evident that a higher safe margin generally leads to a greater curtailment of capacity. However, an exception to this trend occurs when the grid is congested, and a higher safe margin results in lower bidding. Despite the lower bidding, it may still exceed the available transmission capacity on the grid, as shown by the data for a safe margin of 10% in Figure 5.10b.

To conclude, an OWF owner should be incentivised to curtail in a market-efficient way. However, to an OWF owner, it can be expensive to pay for the imbalance price. This is especially the case in OBZs because there are no demand agents or generators that can ramp up capacity. This leads to OWFs using a safety margin, as shown in Figure 5.10, to minimize the need for costly balancing capacity and to increase free curtailment. For the capability-based and financial CfD payout, the safe margin is irrelevant in both congested and non-congested grids. Even though for all implemented CfDs a higher safe margin means lower revenues from the day-ahead market. This incentivises OWF owners to reduce the safe margin, even though there is a risk of the need for expensive balancing.

It can be unfair that the focus of capability-based schemes is on the capability rather than the actual production, which should be considered a safe margin. However, balancing can also be expensive for other schemes. Moreover, in the case of conventional and advanced CfD, it is important to consider that a safe margin may result in an increase in the spot price since the offered capacity will be lower than the transmission capacity. All of these consequences have a risk of strategic behaviour and will be discussed further in the chapter 8.

5.4. The costs of internal congestion in one bidding zone for the CfD payout done by the government of another bidding zone

As already discussed in chapter 2, Flow-based market coupling (FBMC) is widely used across Europe. Furthermore, when this FBMC is implemented together with Advanced Hybrid Coupling (AHC), TSOs will include both AC lines and DC lines as well as their interdependence in the representation of the flow-based domain. The allocation of cross-zonal transmission capacity is decided jointly by the market clearing process, which determines the relative availability of capacity for trade between different bidding zones chapter 2. To map out how different situations, considering different CfDs, in one OnBZ can influence other bidding zones, including the bidding zone paying the CfD, Figure 5.1 can be extended with four more OnBZs and six extra interconnections. This grid is displayed in Figure 5.11.

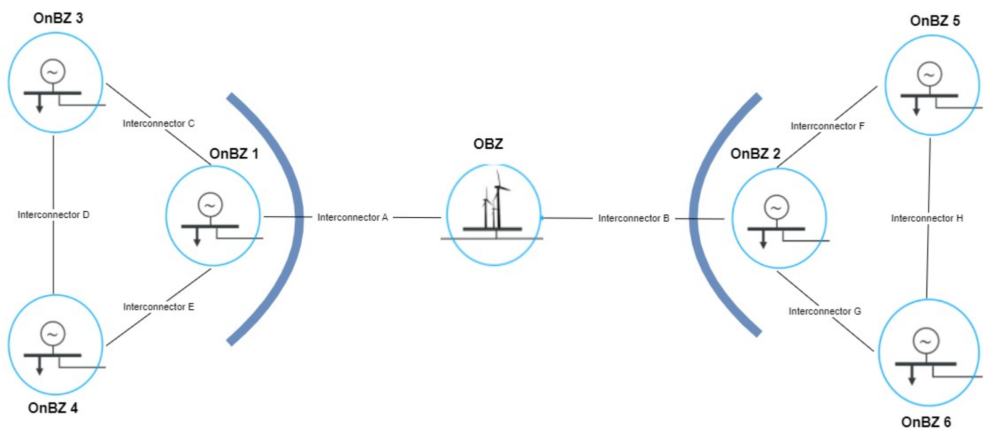


Figure 5.11: Extended grid base case, to implement FBMC and AHC

How this will affect the different onshore zones will be expressed due to changing the following properties as shown in Table 5.6, considering the grid used in Figure 5.11.

Table 5.6: Effects congestion in different onshore zones

	Capacity OBZ [MW]	Electricity price OnBZ 1 [€/MWh]	Electricity price OnBZ 2 [€/MWh]	Capacity interconnector A [MW]	Capacity interconnector B [MW]
CASE 1	800	30	50	1000	1000
CASE 2	800	30	50	450	450
CASE 3	800	30	50	200	450
CASE 4	800	30	50	450	200

5.4.1. Different possibilities of offshore bidding zones causing the congestion on the interconnector

When considering the grid in Figure 5.11, multiple OnBZs can cause congestion. In Table 5.7, an overview is given of eight different cases where the congestion of different OnBZs causes at least one of the interconnectors connected to the OBZ cannot be fully used. In Table 5.7, a distinction is made if the electricity produced by the OBZ can be fully dispatched, cases A, B, C and D or cannot be fully dispatched, cases E, F, G and H.

Table 5.7: Cases with onshore congestion for extended grid base case, to implement FBMC and AHC

	Electricity OBZ fully Dispatched	Electricity price OnBZ 1 [€/MWh]	Electricity price OnBZ 2 [€/MWh]	Congested OnBZ causing curtailment Interconnector	Congested Interconnector	OnBZ disbursing CfD-payout	Relevant base cases
CASE A	YES	30	50	OnBZ 2	Interconnector B	OnBZ 2 OR OnBZ 1 + 2	1 + 2
CASE B	YES	30	50	OnBZ 5	Interconnector B	OnBZ 2 OR OnBZ 1 + 2	1 + 2
CASE C	YES	30	50	OnBZ 1	Interconnector A	OnBZ 2	No
CASE D	YES	30	50	OnBZ 3	Interconnector A	OnBZ 2	No
CASE E	NO	30	50	OnBZ 2	Interconnector A + B	OnBZ 1 + 2	4
CASE F	NO	30	50	OnBZ 5	Interconnector A + B	OnBZ 1 + 2	4
CASE G	NO	30	50	OnBZ 1	Interconnector A + B	OnBZ 1 + 2	3
CASE H	NO	30	50	OnBZ 3	Interconnector A + B	OnBZ 1 + 2	3

Cases A, B, C and D

When in the grid of Figure 5.11, base cases 1 and 2,from section 5.1, become relevant. First of all, it is good to mention here that if both interconnectors connected to the OBZ are the same size, because of the 70% rule as discussed in chapter 2, it cannot be the case that the interconnector connecting the OnBZ with the lowest electricity price is congested and the interconnector connected to the OnBZ with the highest electricity price isn't. This results in cases C and D being irrelevant. Furthermore, when looking at how congestion in one OnBZ can influence the CfD payout in another OnBZ for case A, case 2 is relevant, and for case B, cases 1 and 2 are both relevant.

For Case A, because of the congestion in OnBZ 2, less electricity can be dispatched to OnBZ 2. Therefore, more electricity will be dispatched to OnBZ 1 from the OBZ, resulting in the need for a CFD payment for this extra electricity. This extra CfD payment will, for all different CfD designs, be the payment for every extra MW for a non-congested grid as discussed in section 5.1. Furthermore, OnBZ 1 can scale down its generators with the highest variable costs, and the electricity price in this bidding zone can properly go down.

For Case B, it is not an OnBZ connected to the OBZ that causes congestion on the offshore interconnector, but it is another OnBZ affecting both the OnBZ that is connected to the OBZ and pays the CfD. First of all, when looking at case 1, the CfD payout stays the same. Only the amount of electricity received from the interconnector will change. Furthermore, when looking at case 2, for OnBZ 1, it doesn't really matter if OnBZ 2 or OnBZ 5 causes the congestion on interconnector B. Therefore, for OnBZ 1, there is no difference between cases A and B in the results, but for OnBZ 2, when comparing case B with case A. For case B, the effects aren't caused by OnBZ 2 own onshore congestion. In this case, even though it is not by the congestion in its own bidding zone, the CfD payout will go down, but the OnBZ will receive less electricity from the OBZ, resulting in the need for other electricity with higher variable costs.

Cases E and F

It gets more complicated when an OBZ cannot dispatch all its electricity anymore because of onshore congestion. In cases E and F, Table 5.7, this can be linked to case 4 as discussed in Table 5.6. For both cases, E and F, it means that because of the congestion, the CfD pay-out or the revenues of the OWF owner change. The only difference here is that in case E for OnBZ 2, the change in CfD payout or revenues is due to OnBZ 2 own onshore congestion. In all other cases, the change in CfD payout or in revenues for the OWF owner is due to congestion in another bidding zone.

The curtailment on interconnector B means that more electricity will flow to OnBZ 1 instead of OnBZ 2 till interconnector A is also at full capacity. Of course, more electricity means more demand for a CfD payout and less electricity means a lower demand for a CfD payout. Furthermore, there will also be a change in payout and/or revenues because the grid will become congested due to the change in the electricity price at the OBZ. This will be the case for both OnBZ 1 and OnBZ 2. How this congestion eventually impacts both CfD payout and revenues for every CfD design can be found in section 5.1

Cases G and H

In Cases G and H, the congestion is caused by interconnector A connecting the OBZ with the OnBZ with the lowest electricity price. The distribution of electricity in the day-ahead market is organised so that electricity will be sold to the onshore market with the highest electricity price. In cases G and H, OnBZ 2 has the highest electricity price, but interconnector B is already at full capacity. So, then the electricity that has not been distributed yet will be sold to the OnBZ 1. In Cases G and H, interconnector A is curtailed, limiting the amount of electricity that can flow to OnBZ 1 and changing the CfD payout or revenues for the different CfD designs, as discussed in section 5.1. Additionally, for case G, this will be due to OnBZ 1 it's own congestion. By contrast, for case H, it will be due to congestion in another bidding zone. Furthermore, for OnBZ 2, the amount of electricity received will not change because interconnector B was already at full capacity and has nothing to do with the curtailment of interconnector A. The change here will be in the switch from a non-congested grid to a congested grid as discussed in section 5.1. For OnBZ 2, in both cases, G and H, the change is caused by congestion in another bidding zone.

5.4.2. Conclusion FBMC and AHC

Onshore congestion can potentially hinder the full dispatch of an OWF. This can have an impact on the payout and may differ between the OBZ and HM approach. Furthermore, because of FBMC and AHC, it can occur that there is reduced transmission capacity in one bidding zone due to internal congestion in another bidding zone. Therefore, internal congestion in a bidding zone can influence the CfD payout by the government in another bidding zone. Eventually, this results in the taxpayer in a bidding zone having to pay for congestion in another bidding zone, which will be further discussed in chapter 8.

CfDs will increase the risks for different governments because part of the risk and uncertainties will be covered by these governments, making them less willing to give out CfDs. FBMC and AHC will only increase the risk because it can also happen that a government has to pay for the internal congestion in another bidding zone. If we look at the different CfD designs, it can be recognised that the conventional CfD will encounter the highest risk because a congested grid will have the highest impact. The advanced CfD will also mean risk for governments who give out CfDs because

6 Analysis 2 - Comprehensive overview of advantages and disadvantages of different CfD designs

Based on the characteristics of offshore wind OBZs and the findings from previous sections, this section will provide a detailed overview of various CfD designs used for electricity generated from OWFs in OBZs. The advantages and disadvantages of these designs will also be analyzed and compared.

As stated in chapter 2, offshore wind, specifically in the OBZ approach, has specific characteristics. Previous research suggests that implementing the OBZ approach for hybrid OWFs will decrease the average price of offshore-generated electricity while increasing the congestion rent for TSOs. In addition to operational risks, there is also a significant volume risk for OWF owners as they may be unable to sell all the electricity they produce. In Conclusion, when we consider all the aspects of offshore wind farms in the OBZ approach, there is a need for improving the investment climate for OWF owners (European Commission, Directorate-General for Energy, THEMA consulting group, 2020).

There are various support schemes available for offshore wind in OBZs, but the most preferred options are TAGs and two-sided CfDs. There is a push for two-sided CfDs as a support scheme for renewables in the electricity market (Commission, 2023). The conventional, advanced, capability-based and financial CfDs designs are presented in section 2.4, and their advantages and drawbacks will be elaborated further in this chapter.

Reading guide

In this section, first, the possibilities of the design of a CfD will be analysed more in-depth, followed by some requirements & dilemmas of the CfD design. The following section outlines the results of the generation and selection phases of various CfDs for offshore-generated electricity from OWFs in OBZs. It concludes with a recommendation for a CfD design.

6.1. Analysis of the design options for a CfD

When designing a CfD for a specific project, it's essential to follow a thorough process that considers various factors unique to that project. A CfD support scheme is not a one-size-fits-all solution but a customized mechanism that aligns with multiple goals. Tailoring the CfD to the specific project is important to ensure its success.

CfD designs can vary depending on the approach taken, each with its advantages and disadvantages. This makes CfDs more diverse than they may initially appear. Design specifications are highly dependent on the context in which they are used. Some of the design elements of CfD implementations include contract design, clawback design, and strike price design (Kitizing, 2023).

In this article, we discuss four types of CfDs: conventional, advanced, capability-based, and financial, and their specific characteristics that impact OWFs in the OBZs. There are additional design elements that can be chosen for the CfD, and they affect the results of the CfD. The following section delves deeper into these design elements to provide a better understanding of their influence.

Design elements

When it comes to contract design, the strike price determination methods vary, with auctions being the most common option. Additionally, the length of the contract can be determined by either time or volume, and the duration may vary for each option. Finally, Appendix D, Table D.1, provides an overview of the design choices for CfD contracts, including the possibility of exiting a contract.

There are various options for designing the strike price, each with its own considerations. The strike price can be based on a reference price, and the averaging period can be hourly, monthly, or annual. The method of determining the averaging period can also vary; it can be based on a settlement, a technology-specific volume-weighted price, or a flat (base) average.

With an hourly settlement, the OWF consistently achieves the strike price, and it serves as an incentive to maximize production and minimize costs. Technology-specific volume-weighted average ensures that the OWF's production pattern is the same as the rest of the technology. This incentivizes the OWF to perform better than other wind farms and maximize maintenance with the averaging period.

For the flat (base) average, the OWF achieves the strike price only if its production is the same as the rest of the technology. Therefore, there is an incentive for the OWF to beat the market.

Further, if inflation is adjusted, the price needs to be determined in the CfD design for both the strike and reference price. Furthermore, how the CfD responds to negative prices can vary depending on its design. An overview of those options is given in Appendix D, Table D.2.

The clawback design in the CfD can vary based on a few elements. Firstly, the payment direction can be either one-sided or two-sided. The clawback at low prices can also be the entire strike price or the max spot. For a detailed overview of the different design options in the clawback design of the CfD, please refer to appendix d, **??**.

When implementing different CfD designs, issues may still arise with intraday/balancing markets, self-consumption, and hybrid plants.

ACER & CEER suggested design elements

ACER and CEER have highlighted that while Contracts for Differences (CfDs) present opportunities, they also come with risks that need to be addressed through a smarter design. In response to the European Commission's public consultation on electricity market design in February 2023, they have suggested some measures to mitigate these risks (ACER & CEER, 2023):

1. Capability-based CfDs: Power plant owners compete in an auction for a fixed strike price. The payment is based on the volumes that "could" be produced by the installation based on technical characteristics and local weather conditions.
2. A cap and floor instead of a single strike price. The floor price can replace the system of subsidies, whereas the cap price can replace the inframarginal revenue cap to channel revenues excessively back to consumers. This measure will be elaborated further in the next section.
3. Reselling of CfDs as financial contracts in forward markets closer to delivery.

System of interest

As discussed in previous sections, OBZs will reduce the revenues for OWF owners in hybrid projects. Furthermore, these CfDs will also create a volume risk for these OWF owners because, in an optimal design, they cannot dispatch all their electricity at all times, chapter 2. Therefore, these CfDs must be seen as a support scheme by increasing revenues and creating investment stability for these OWF owners, making OWF investments more attractive.

Additionally, CfDs can also impact the decision-making of these OWF owners because their incentives will change. When these decisions change next to the OWF owners, other stakeholders will be influenced by the CfD. As a consequence of this, the CfD must be designed in a way that does not underline the efficiency of the market.

Scope

When designing a CfD, there are two main things to consider in the system of interest. Firstly, the CfD must encourage OWF owners to invest in OWFs. Secondly, the market must continue to operate efficiently.

The decision will impact multiple stakeholders as discussed in chapter 4. Additionally, for OBZs, it's important to consider the international nature of the system. Stakeholders from various bidding zones will have different interests and will be affected differently by the CfD for the OWF of the OBZ.

The primary objective of the European electricity system, where the CfD will be implemented, is to enhance overall social welfare and promote renewable investments by ensuring a profitable return on investment.

Conclusion of scope, system of interest and design elements

Combining the functions of the CfD with the already identified scope, system of interest and possible design choices, considering both the design elements discussed in this section and the suggested CfD designs, as discussed in section 2.4, multiple requirements come forward.

To ensure that the CfD in the OBZ approach provides the required functionalities, design choices must be made that meet the following requirements:

- Increase revenues OWFs because of the lower average electricity price.
- Deal with the volume risk of OWF owners.
- Incentive the market to work efficiently.
- Deal with the interest of multiple stakeholders influenced by OBZs.
- Deal with inequalities between different stakeholders because of the international scope and the different impacts they will experience.
- Strategic behaviour that will influence the market negatively is not incentivised.

6.2. Synthesis: Artefacts, program of requirements & dilemmas

As explained in the previous sections, Different factors affect the design of an efficient CfD support scheme for a specific case. This section presents an adjusted problem statement, identifies basic design elements for every CfD in the OBZ context, and discusses the dilemmas and trade-offs between stakeholders that arise.

6.2.1. Summary & adjusted problem statement

In Chapter 4, we talked about the institutional environment surrounding OBZs and the challenges that a CfD design must address. One significant consideration is that any intervention in the market, such as a CfD support scheme, must not disrupt market efficiency. Moreover, it is necessary to have a responsible party for transporting electricity from OBZ suppliers to onshore consumers and ensuring the balancing and re-dispatch of the network..

In the current institutional environment, owners of OWFs located in OBZs face a certain level of risk. This is because, in the OBZ approach, the electricity price will fall to zero if there is insufficient capacity to dispatch all the electricity generated by the OWFs. As a result, OWF owners will not be able to deliver all of their electricity.

The complexity of the problem is due to the involvement of various stakeholders and differences between different OnBZs. The CfD design involves several key stakeholders, including OWF owners, the European Commission, individual member states, national regulatory authorities, ACER, Individual TSOs, and ENTSO-E, as described in section 4.2. For OWF investors, the objective of the CfD scheme should be to encourage investment in OWFs. Currently, without any support scheme in the institutional environment, investments in OWFs located in the OBZ approach seem unprofitable and too risky.

Considering these factors and the initial research question about the preferred CfD design for OWFs located in the OBZ approach in the North Sea. The following problem statement can be developed, resulting in a standardised CfD scheme that needs to be adjusted for every specific OWF in the OBZ because of the different characteristics of every case:

A CfD design, to be adjusted in every case, must create a profitable business case for OWF owners and an efficient market design with agreeable risk for all stakeholders by implementing some basic design elements.

6.3. Results of generation and selection phases

As explained in section 2.4, some basic CfD designs are already discussed for OBZs, which all have their benefits and drawbacks, section 2.4 & chapter 5. Every basic design can be adjusted for a particular case, considering multiple design elements as discussed in section 6.1.

6.3.1. Design elements for every option

When looking at CfD design elements, for every opportunity, several design elements, Appendix D, can be considered necessary. An overview of these design elements, obligated for every CfD in the OBZ context, is given in Table 6.1.

Table 6.1: Basic design elements filled in

Basic design elements				
Strike price determination	**Duration**	**Price indexation**	**Payout at negative prices**	**Payment direction**
Administrative	12-15 years	None (fixed price)	Full stop	Nettled
Auctioned	20 years	Inflation-adjusted	Max strike	Two-sided
Negotiated	Volume-based		Stop if 6h <0	

As mentioned earlier, auctions are commonly used in the context of CfDs. They provide a transparent and market-driven price discovery process and are generally more efficient than administrative or negotiated processes, which benefits consumers (Welisch & Poudineh, 2020). Additionally, it also seems wise to choose for a long-term contract of at least 20 years. Doing so creates revenue stability and mitigates risks for OWF owners and other stakeholders involved (Welisch & Poudineh, 2020). To further reduce the risk for OWF owners, these contracts need to be adjusted for inflation.

Another basic element is that these CfD contracts need to be two-sided, as discussed in chapter 2. As explained here, this is the aim of the EU market reform (Commission, 2023) because these two-sided CfDs offer benefits in terms of risk sharing and consumer protection (Neuhoff et al., 2022). Furthermore, according to the calculations based on conventional design presented in chapter 5, a CfD payout at negative prices would lead to an inefficient design. This means that revenues generated by the OWFs would be zero despite the CfD payout still being present.

6.3.2. Possible designs

In addition to the design elements discussed in the previous section, some other design elements are more suitable for CfDs in the OBZ context. Five different CfD design alternatives have been identified for an OWF in the OBZ approach using morphological charts provided in Appendix D, section D.2. These different combinations of options are reported in Table 6.2 and are further explained in this section.

Table 6.2: CfD alternatives to deal with different functions of CfD design

Function	Advanced CfD Design	Capability-based CfD design	Capability-based CfD design with a cap and floor strike price	Financial CfD with a reference generator	Financial CfD with weather data
Stimulate investments	Reference price	Strike price	Strike price with cap and floor	Fixed hourly remuneration	Fixed hourly remuneration
Deal with volume risk		Capability-based	Capability-based	Fixed hourly remuneration	Fixed hourly remuneration
Incentivice the market to work efficiently	Actual produced electricity plays a role + Reference price		Cap and floor strike price	Actual produced electricity plays a role + Difference between actual production and reference generator	Actual produced electricity plays a role + Difference between actual production and expected production due to weather forecast

The advanced CfD design, discussed in section 2.4, uses a reference price to determine the CfD payout. This encourages the OWF to optimize production by maximizing output during high electricity prices and minimizing it during low prices. However, this design has no provision to address the volume risk for the OWF itself.

The capability-based CfD, as discussed in section 2.4, mitigates volume risk for OWF owners by assessing their capacity instead of actual production. As a result of this support scheme, it doesn't matter if not all electricity can be dispatched. See chapter 5. Additionally, a capability-based CfD will use a standard strike price to determine the CfD payout because using a reference price will not have any effects.

Capability-based CfD with cap and floor strike price

On the other hand, the strike price of the capability-based CfD can be adjusted to include a cap and a floor price determined by the actual electricity spot price. A cap and floor mechanism linked to the electricity price in a CfD is designed to adjust the cap price and floor price based on changes in the prevailing market electricity price. This approach ensures that CfD payments are tied to market conditions.

- Cap price linked to electricity price.
  - The cap price, in this scenario, is set as a certain percentage or fixed amount above the current strike price.
  - For example, if the market price for electricity is €50 per MWh, and the cap price is set at 110% of the market price, the cap price would be €55 per MWh in this case.
  - The project developer will receive payments based on the actual market price or the cap price, whichever is lower. If the market price exceeds the cap price, the developer will receive payments based on the cap price.
- Floor price linked to the electricity price.
  - Similarly, the floor price is set as a certain percentage or fixed amount below the current market electricity price.
  - For example, if the market price for electricity is €50 per MWh, and the floor price is set at 90% of the market price, the floor price would be €45 per MWh in this case.

   - The project developer will receive payments based on the actual market price or the floor price, whichever is higher. If the market price falls below the floor price, the developer will receive payments based on the floor price.

By linking the cap and floor to the electricity price, the CfD scheme ensures that project developers are exposed to some level of market risk in their CfD payment while still providing a safety net. This approach can make CfDs align incentives for renewable energy projects to optimize performance. However, it also requires careful monitoring and periodic adjustments to maintain the desired balance between risk and reward (ACER & CEER, 2023).

Different reference technologies for financial CfD

A different design is the financial CfD, as discussed in section 2.4. In this CfD design, a physical reference generator is used. Next to the fixed hourly remuneration, the OWF owner receives or pays the difference between the actual production and the expected production of the reference generator. As a result, the OWF owner tries to maximise its own production relative to the reference generator.

It can also be possible that the financial CfD uses weather data to predict the expected production. A mathematical model generates a reference output from weather data, which is used for contracted wind farms. Although averaging weather data for a region may not perfectly match a specific turbine, it can be a sufficient hedge for many wind farms. Additionally, it is not reliant on other generators. In this case, the owner of an offshore wind farm receives a fixed hourly remuneration along with the difference between the actual and expected production based on weather data. Therefore, offshore wind farms aim to perform better than the expected revenues from the weather data.

6.3.3. Selection of the most preferred design

To choose the most desirable CfD design, the Priority Checkmark Method (PCM) is utilized, Table 6.3. The table presents the prioritized objectives and characteristics of the CfD design.

- High priority $\rightarrow$ ✓✓✓
- Medium priority $\rightarrow$ ✓✓
- Low priority $\rightarrow$ ✓

Firstly, the constraints of the CfD designs are discussed. If the CfDs cannot meet these constraints, the specific design is discarded as a possible design. In the table, this will be displayed with a $\times$. The CfDs for an OWF in an OBZ will be characterised by the following constraints discussed in Chapter 1, as the main reason for initializing a CfD. In addition to what was discussed in chapter 4, it is important to ensure that OWF's operations are feasible within the institutional environment. Furthermore, Chapter 5 indicates that there will be no payout in case it would be better for the OWF not to produce. These factors result in certain constraints that need to be taken into consideration.

- The presence of lower average electricity prices, which may result in less revenues for OWF owners, is a challenge (partly) addressed by the CfD, Chapter 1.
- The volume risk because of congestion on the grid, resulting in not all electricity being dispatched by the OWF, is a challenge (partly) addressed by the CfD, Chapter 1.
- Implementing the CfD is feasible in the current institutional environment, Chapter 4.
- No CfD payout if electricity price is negative, Chapter 5.

Additionally, the objectives of the different CfD designs are elaborated. These objectives have been marked with checkmarks if they meet the objective ”satisfactory”. Otherwise, they will be marked with a $\times$ as well. The objectives of the CfD design are discussed throughout the thesis. Eventually, the different objectives of the CfD schemes are as follows:

- Increase willingness to invest through CfD effect in the non-congested grid.
- Increase willingness to invest through CfD effect in the congested grid.
- CfD payout incentives the market to work efficiently.
- CfD payout does not increase risk through unnecessary incentives.
- Address inequalities between stakeholders due to international scope and different impacts.
- The CfD payout needs to align with the actual bids and, therefore, must consider the bidding strategy of OWFs.

Based on the findings in Table 6.3, it is evident that the advanced CfD design has been rejected due to its inability to meet all the constraints. Specifically, the advanced CfD design has not addressed the issue of volume risk that arises due to grid congestion, which leads to the OWF being unable to dispatch all the electricity. This fact is also evident in chapter 5.

Table 6.3: Priority Checkmark Method (PCM) different CfD designs

Constraint and objectives of CfD design	Priority	Advanced CfD design	Capability-based CfD design	Capability-based CfD design with a cap and floor strike price	Financial CfD with a reference generator	Financial CfD with weather data
Constraint: The presence of lower average electricity prices, which may result in less revenues for OWF owners, is a challenge (partly) addressed by the CfD.	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Constraint: The volume risk because of congestion on the grid, resulting in not all electricity being dispatched the OWF, is a challenge (partly) addressed by the CfD.	✓✓✓	×	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Constraint: Implementing the CfD is feasible in the current institutional environment.	✓✓✓		✓✓✓	✓✓✓	✓✓✓	✓✓✓
Constraint: No CfD payout if electricity price is negative.	✓✓		✓✓	✓✓	✓✓	✓✓
Objective: Increase willingness to invest through CfD effect in the non-congested grid.	✓✓		✓✓	✓✓	✓✓	✓✓
Objective: Increase willingness to invest through CfD effect in the congested grid.	✓✓		✓✓	✓✓	✓✓	✓✓
Objective: CfD payout incentives the market to work efficiently.	✓✓		✓✓	✓✓	✓✓	✓✓
Objective: CfD payout does not increase risk through unnecessary incentives.	✓✓		✓✓	×	✓✓	✓✓
Objective: Address inequalities between stakeholders due to international scope and different impacts.	✓✓		×	×	×	×
Objective: CfD payout takes bidding under expected capacity because of forecasting errors into account.	✓		×	×	✓	×

As objectives for the CfD design, it can be seen that it is a high priority that it incentivises investments in OWFs, as discussed in chapter 1. Therefore, the CfD needs to affect the revenues positively and reduce the risk for these OWF owners in both the non-congested and the congested grid. Both situations are a medium priority in the PCM method and are partly investigated in chapter 5. On the contrary, the CfD design must influence the market decision-making as little as possible. Therefore, the CfD payout must incentivise the OWF to produce electricity when demand is high. This can be seen as a medium priority. Of course, the impact of the effects here is crucial, but low-scale has implications in both the day-ahead and balancing markets, in Table 6.3.

Overall, a CfD has two main objectives. Firstly, it aims to increase the expected revenues of the OWF. Secondly, it aims to reduce the risk for the OWF. Therefore, any unnecessary risks associated with CfD payments are unfavourable.
Furthermore, it is good to note that Member States look differently to OBZs because they are affected differently, even more so when FBMC and AHC are implemented. A CfD design must deal with these differences and strive for maximum fairness between the different member states. In Table 6.3, dealing with the inequalities between different stakeholders is seen as a medium priority.
Lastly, the objective is to align the CfD payout with the bidding strategy of OWFs because of strategic behaviour. In Table 6.3, dealing with adjusted bidding strategies because of intermittent wind can be seen as low priority.

When zooming in on the Capability-based CfD design with and without a cap and floor strike price, it can be concluded that all constraints of the CfD designs will be met. Furthermore, this CfD design will increase the willingness to invest by OWF owners due to effects in both the non-congested and congested grid scenario. Additionally, This CfD payout will not interfere extensively with the market working efficiently.

Moreover, when the capacity-based CfD is put into practice, an OWF attempts to increase its bid in the spot market. Introducing a cap and floor strike price would generate two-fold incentives for an OWF to generate electricity when the prices are high, which would not outweigh the added risks involved.

One of the drawbacks of a capability-based CfD design is that it fails to address the inequalities that arise among Member States. Additionally, the CfD payout does not consider bidding below the expected capacity due to strategic behaviour resulting from forecasting errors.

When looking at the financial CfD when using both a reference generator or weather data, it can be recognised that the following objectives will be achieved:

- Increase willingness to invest through CfD effect in the non-congested grid.
- Increase willingness to invest through CfD effect in the congested grid.
- CfD payout incentives the market to work efficiently.
- CfD payout does not increase risk through unnecessary incentives.

Financial CfDs are limited in their ability to address all the negative impacts and consequences of OBZs. Firstly, regardless of the reference used, this CfD cannot address inequalities among stakeholders due to their international scope and varying impacts. Secondly, only a reference generator is likely to consider adjusted bidding in their CfD payout because such a generator is expected to engage in strategic behaviour, which weather data as a reference cannot do.

6.4. Conclusion of generation and selection phases

When implementing OBZs for OWFs in the North Sea, there will be a need to support investments in OWFs. CfDs can be used as a support scheme to support investments in these projects. This chapter gives an overview of the generation and selection phases of different CfD designs considering the technical, institutional and process design.

In the previous chapter, the Priority Check Method (PCM) is used to discard CfD designs which do not deal with all the constraints a CfD design needs to deal with. The following CfD design can be discarded because it doesn't deal with the volume risk constraint:

Discarded CfD designs:

- The advanced CfD design

This means that the following CfD designs need to be considered when comparing how the different designs achieve the objectives of this support scheme:

Considered CfD designs in comparing objectives:

- The capability-based CfD design
- The capability-based CfD design with a cap and floor strike price
- The financial CfD design with a reference generator

- The financial CfD design with weather data

When evaluating the results of both capability-based CfDs in Table 6.3, it can be concluded that the capability-based CfD with a fixed strike price outperforms the Capability-based CfD with a cap and floor strike price. Because the cap and floor strike price will create a double incentive, increasing the risk for the OWF owner. Therefore, the capability-based CfD with a fixed strike price will be preferred over the other.

It can be concluded, based on the results in Table 6.3, that a financial CfD using a reference generator performs better than a financial CfD using weather data as a reference, as well as a capability-based CfD with a fixed strike. This is because the CfD payout takes safe margins in the bidding strategy into account due to the uncertainty of intermittent wind, making it a more reliable option. However, it should be noted that this has a lower priority.

7 Discussion

The discussion provides the platform to delve into the implications of the research findings. In this section, the results will be explored and critically analyzed in the context of existing literature, followed by different CfD designs in the offshore bidding zone approach. This section will eventually finalise by discussing the limitations of this research and possible future research.

In previous sections, the implementation of CfDs for OBZs is discussed. As this thesis shows, CfD designs can be much more diverse than they may seem at first sight. Before delving into the discussion, it is imperative to recap the primary objectives of this research briefly. The study sought to give a comprehensive overview of the advantages and disadvantages of different CfD designs for OWFs in the OBZ approach in the European electricity system. Throughout the subsequent discussion, an assessment will be made regarding the extent to which these objectives have been met.

7.1. Findings and previous research

In this chapter, the results of the study will be compared with existing literature to identify similarities and differences. This will position this research within the broader context of CfDs and OBZs.

The results of Chapter 5 align with the previous research on the implications of CfD support schemes for supporting renewable energy as can be found in the literature and Chapter 2. Although there is not much empirical evidence to generalise all findings, a pattern is visible. Arguably, the context of OBZs creates certain situations that aren't discussed extensively in the literature yet and ask for more research.

In section 5.1, for OBZs specifically, the cost of a CfD scheme and the revenues for OWF owners are discussed for the conventional, advanced, capability-based and financial CfD. The results of section 5.1 can be best compared to the qualitative findings of Schlecht et al. (2023). The key message of this paper is that price signals play a crucial role in guiding efficient decision-making. Therefore, long-term CfD contracts should be well-designed to preserve these signals. This will incentivize decision-making that aligns with system needs, while also reducing or eliminating exposure to non-controllable risks, such as long-term price developments and volume risks (Schlecht et al., 2023).

For the conventional CfD in the paper by Schlecht et al. (2023), the following three problems are mentioned when implementing this support scheme:

- Produce-and-forget
- Intraday and balancing distortion
- Volume risk unhedged

Without going further into these drawbacks of the conventional CfD, section 5.1 shows for OWFs in the OBZ specifically that the revenues are dependent on how much electricity is produced and offered and not on the demand for electricity. To conclude, the market will work inefficiently, and electricity will be sold when the market price is negative because OWFs don't receive the incentive not to produce.

Compared to conventional CfD, the advanced CfD system has a longer reference period and does not offer support payments at negative prices. However, implementing CfDs in OBZs still poses a significant volume risk for OWF owners when the grid is congested, leading to zero revenue for them, Section 5.1 provides more details on this issue.. Taking into account the uncertainties of future offshore developments and the capital-intensive investments associated with the advanced CfD scheme, investment in OWFs seems risky and unattractive. Moreover, high financing costs compared to fossil investments add to the burden, making it difficult to justify investing in OWFs. Moreover, the quantitative paper authored by Schlecht et al. (2023), proposes a capability-based CfD as a way to address volume risk for OWFs. Decoupling payments from an asset's production is suggested and instead relying on the asset's potential to produce, creating the capability-based CfD. Such a CfD scheme would decouple payments from an asset's production and instead rely on the asset's potential to produce. However, the implementation of a CfD scheme poses several challenges, such as intraday and balancing distortions, which have already been mentioned Schlecht et al. (2023). Moreover, the results of the study presented in section 5.3 highlight the problem of uncertainty in the forecast for wind availability and the consequence that OWFs will implement safe margins in their bidding strategy (European Commission, Directorate-General for Energy, THEMA consulting group, 2020) because balancing costs could be high (van der Veen & Hakvoort, 2016). It is important to note that setting safe margins for OWFs leads to an inefficient market design. This is because OWF owners may choose to set disproportionately high safe margins to reduce the risk. Additionally, with the capability-based CfD, the volume risk increases for the party that pays the CfD payout, which is usually the government. This is because the government has to pay extra to ensure that the OWF owner does not suffer losses when the electricity price is zero. This is due to the fact that when the electricity price is zero, the producers' surplus of off-shore wind farm owners decreases and the congestion rent for TSOs increases, as discussed by Kenis et al. (2022). The additional CfD payout from the government, resulting from the market price of zero euro, will eventually be transferred from the government to the TSOs. This is because the government pays the owner of the OWF, and the money that the owner would receive in a non-congested grid will then go to the TSO. In essence, taxpayers' money will go to OWF owners, while tariff payers won't be affected. Congestion rent can be utilized to extend the offshore grid (Laur et al., 2022).

As a CfD design where full incentives remain to design and operate plants according to price signals and volume risk for OWF owners are covered, (Schlecht et al., 2023) suggests the financial CfD. In this qualitative literature, by Schlecht et al. (2023), it is mentioned that the financial CfD creates incentives for:

- Efficient generation profile
- Efficient repowering, retrofit and maintenance investments
- Efficient power plant maintenance scheduling
- Stopping to produce at negative day-ahead prices
- Continuing to produce at low prices in clawback times
- Efficient intraday dispatch

Furthermore, it will be a financial hedge for:

- Price risk
- Volume risk

The results of Chapter 5 demonstrate that financial CfDs placed specifically in OBZs socialize the volume risk if not all electricity can be dispatched. As mentioned by Schlecht et al. (2023), the revenues of the OWF depend on the difference between physical generation and the generation of the reference generator. This difference becomes irrelevant when the grid is congested because the spot price is zero (Kenis et al., 2022).

When implementing OBZs, there will be varying effects among different onshore bidding zone markets, as shown by Kitzing and Garzón González (2020). In contrast, none of the CfD designs discussed in **??** provide any incentives to address the differences in impacts of implementing CfDs across different bidding zones, as demonstrated in section 5.4. Furthermore, section 5.4 suggests that congestion in one onshore bidding zone can have an impact on the CfD payout in another bidding zone. As a result, member states may have different perspectives and preferences on the appropriate CfD design, making the process of determining the right CfD design even more complicated. According to ACER (2023), achieving the European Union's energy objectives of a 70% margin for cross-zonal electricity trade is crucial to reducing differences between Member States. The minimum target of 70% in 2026 is a key tool for achieving ambitious political objectives for offshore renewable generation. If this objective is met, it will also impact CfD payouts, as explained in section 5.4.

7.2. The different CfD designs in the offshore bidding zone approach

CfDs are a type of support scheme that aims to encourage the adoption of renewable or nuclear energy sources (Kitzing, 2023). As discussed in the Schlecht et al. (2023) and concluded in chapter 6.

Because of the complexity and case-by-case dependency, it is difficult to design one CfD design that can be implemented for every specific OBZ. On the contrary, there are some basic design elements that every CfD needs to contain, independent of the specific case. To summarise, every CfD needs to be auctioned, is preferred to have a long duration of at least 20 years, needs to be inflation-adjusted, has no payout at negative prices and needs to be two-sided.

To conclude, when looking at some design types, it can also be concluded that the conventional CfD will not work properly in the OBZ environment (Schlecht et al., 2023). Additionally, the advanced CfD will also work inefficiently in the OBZ environment (Schlecht et al., 2023) because it will not be able to cope with the volume risk constraint necessary to be implemented in OBZs, Chapter 5. Furthermore, a cap and floor strike price will work inefficiently because it creates a double incentive, increasing the risk for investors. Chapter 6 concludes that the following CfD can be best implemented in OBZs because it includes safe margins in the bidding strategy because of the balancing costs:

- The financial CfD with a reference generator

7.3. Standpoint stakeholders different policy papers compared with results

As discussed in section 4.2, the European electricity market is a complex, extensive market with many stakeholders involved. Three main types of stakeholders are outlined in this thesis:

- The European Union and Member States
- Regulatory Authorities
- Transmission System Operators

The different stakeholders have different preferences for OBZs, which can also differ per Member State because this needs to be taken into account for OBZs. This difference can be caused by political preferences or different expected consequences by CfDs, as shown in chapter 5. In this section, some policy papers of different stakeholders will be discussed:

7.3.1. ENTSO-E

In April 2023, ENTSO-E published a position paper on the EC proposals on market design, where they also discussed OBZs (ENTSO-E, 2023).

The paper argues against the use of congestion income such as TAGs to finance support for offshore hybrid project generators because it is not an effective support mechanism and would result in an implicit and non-transparent subsidy paid by consumers through grid tariffs. Instead, the paper suggests two-sided capability-based CfDs or financial CfDs to provide revenue guarantees to offshore generators. These schemes will fully cover the volume risk of generators and avoid market distortions and any discriminatory use of congestion income. However, the paper emphasizes that the design of CfDs must be carefully crafted to prevent distortions in short-term and balancing markets or increases in system costs.

After comparing the results of Chapter 2 and Chapter 5, it becomes apparent that a CfD must be carefully designed to ensure that day-ahead, intra-day and balancing markets' price signals are in line with preferred market choices. However, Chapter 5 also highlights that there will be issues with the balancing markets as there will be no incentive for OWF owners to reduce their safe margin in their bidding strategy in the CfD payout.
Moreover, when utilizing CfD designs, governments may be responsible for paying for congestion in another bidding zone. This results in taxpayers paying for congestion in another country, which is the responsibility of a TSO with which these taxpayers have no affiliation., section 5.4.
In conclusion, after analyzing the goals and objectives of ENTSO-E as mentioned in Appendix A and the results of Chapter 5, it is evident that TSOs prefer CfDs over TAGs when dealing with congestion income. However, it is important to consider the negative consequences of balancing payments, which haven't been discussed in those policy papers but have been presented in this thesis. These consequences will be further addressed and concluded in chapter 8.

7.3.2. ACER & CEER

In 2022, a paper was published by ACER and CEER (2022b) reflecting on the EU's strategy to maximize the potential of offshore renewable energy. The authors of the paper support the creation of OBZs but also discuss some of the critical challenges associated with the OBZ model. The OBZ approach provides efficient price signals to all actors involved and fully corrects interconnector flows. Furthermore, it allows for more choice in efficiently selling energy to the market where it is most needed compared to the HM approach and provides incentives to connect OBZs among themselves (ACER & CEER, 2022b). The paper concludes that the OBZ approach is preferred over the HM approach from a market design and efficiency perspective. However, the authors also highlight the need to balance this preference with the changes required to ensure that OBZs have equal access to trading as close to real-time as in the HM approach (ACER & CEER, 2022b).

In February 2023, ACER and CEER responded to the European Commission's public consultation on the EU's electricity market design, which will also influence the OBZ design. According to their response, support schemes are needed to stimulate renewable energy sources like offshore wind, and CfDs can be a viable solution. However, if Member States implement CfDs, they need to be designed in a smart way. ACER and CEER suggested some measures to improve traditional CfDs.

1. Settlement based on predefined/reference volumes.
2. Replace single strike price by cap and floor.
3. Resell CfDs as financial contracts in forward markets.

Offshore wind power is a promising source of renewable energy. However, there is a pressing need to develop a legal framework to regulate it, as ACER and CEER (2023) has pointed out. Additionally, ACER does not endorse TAGs, but acknowledges the necessity of exploring alternative options to improve investment stability (ACER & CEER, 2023).

Upon comparing this policy paper with the findings from Chapter 5 and Chapter 6, it becomes evident that there is a preference for either the capability-based CfD with a cap and floor strike price or a financial CfD in both situations. However, as demonstrated in Chapter 5 and Chapter 6, there are some drawbacks associated with both designs. These limitations will be further elaborated in Chapter 8.

Considering ACER's goals, objectives and mission of achieving increased energy market integration with low-carbon supply in Europe, as discussed in detail in Appendix A, it makes more sense to prefer CfDs over TAGs that utilize congestion income. Moreover, when analyzing various CfD designs, ACER will have a significant role in aligning the NRAs with their own preferences based on the OBZ characteristics.

8
Conclusion

In this final section, the thesis will be concluded. This conclusion will be subdivided into three key subsections, In the first subsection, the main research question will be answered, followed by the scientific contribution of the thesis, to finalise with limitations and possible future research.

8.1. Answering the main research question

The main research question: *”What are the advantages and disadvantages of different CfD designs for offshore wind farms considering the offshore bidding zone approach in the North Sea?”* is answered through a series of sub-questions.

8.1.1. Answer to the subquestions

The first sub-question, *”How will the different CfD designs influence the bidding strategy of offshore wind generators?”*, is mainly answered in Chapter 2 and Chapter 6. Literature review and interviews are mainly used to understand how the different CfD designs influence OWFs.

The different designs of CfD will affect OWF generators differently. The conventional CfD scheme means that demand no longer plays a role in the decision-making process for OWF generators. Under this scheme, OWFs aim to maximize their production because it is the only factor that affects their revenues. In other words, if an OWF can dispatch all of its electricity, it will receive the same payment regardless of the market price, but dependent on the strike price. Moreover, if the market price increases, the CfD payment decreases to maintain the same level of revenue.

One major difference between the advanced CfD and the conventional CfD is the use of a reference price. The purpose of this reference price is to encourage optimization of dispatch and maintenance during the reference period by prioritizing production during high-priced periods, thereby capturing the highest prices and making investment decisions accordingly. However, the reference periods only incentivize optimization within these periods and not across different periods.

The capability-based CfD have different impacts on the decision-making of OWF generators. In terms of CfD payment, the capability-based CfD considers the potential of electricity generation rather than the actual production. This means that the amount of CfD payout received by an OWF generator is not based on the amount of electricity sold, but on its ability to generate electricity. Even if an OWF generator produces less electricity than expected, it can still receive a stable income due to the CfD payment. Conversely, if it produces more, the excess electricity can be sold in the wholesale market. As a result, the OWF generator's risk and consequences are reduced, making it less effective to optimize its bidding strategy based on actual prices, although optimizing the OWF still has an impact.

The capability-based CfD can have a cap and floor strike price, which allows for adjustments. With this cap and floor strike price, the strike price of the OWF generator depends on the electricity market price. This means that not only the wholesale market, but also the CfD payout itself, will encourage OWFs to produce electricity when prices are highest.
The last CfD is the financial CfD. This CfD is financial rather than asset-specific. The scheme involves two payments between the government and the OWF generator. The government pays a fixed hourly remuneration to the OWF generator, and the OWF generator pays the government the hourly spot market revenues considering a reference generator. This reference generator can be a physical reference generator or data based on a mathematical model considering weather data. This results in that the OWF generator wants to outperform this reference generator.

The second sub-question, *"How will OBZs impact the bidding of offshore wind farms in hybrid projects?"* is mainly answered in Chapter 1 and Chapter 2. Literature review and interviews are mainly used to understand the impact of OBZs.

Hybrid projects combine offshore generation and transmission capacities in an efficient manner. This results in a reduced need for physical transmission capacity and converter stations. To integrate these hybrid projects efficiently, the OBZ approach can be used. This OBZ has its own wholesale electricity price and is connected to the mainland through interconnectors. As a result, all the flows become cross-zonal flows.

In these hybrid projects, the OBZ will have varying effects on the OWF. First of all, the revenues of OWF owners will most likely decrease because when congestion occurs on the interconnectors, there will be a distribution of income between the transmission and generation entities because of an increase in congestion rents. If FBMC and AHC are implemented, they will likely affect congestion.

In an OBZ, managing the balance of electricity supply and demand can be difficult. This is because OBZs usually rely on intermittent offshore generation units and do not have any dedicated balancing units. As a result, imbalances in the OBZ can only be resolved by accessing balancing capacity from other zones or by curtailing generators. Even if there are balancing units in an offshore unit, there is still the issue of determining the imbalance price that should be charged to balancing responsible parties in the offshore zone.

The third sub-question, *"How will the different CfD designs influence the decisions of generators in hybrid projects in the OBZ approach?"*, is answered by combining sub-questions 1 and 2 and is further analysed in Chapter 5 and Chapter 6.1. To answer this sub-question literature review, interviews and modelling are used.

Before designing a CfD for OBZ and optimizing the decision-making for OWFs, it is important to recognize that certain design elements can be implemented, regardless of the eventual CfD design. The following design elements should be considered:

- The strike price will be determined by an auction.
- The duration of a CfD scheme will be long, around 20 years.
- To reduce the risk for OWFs, the price will be inflation-adjusted.
- The CfD payment needs to be two-sided.

Next, the design choices for the CfD design will depend on the specific situations of the OBZ, which will be addressed in the following section.

When a conventional CfD is implemented for an OWF in an OBZ, it can be concluded that the OWF will receive the strike price times the electricity that it produces and dispatches. On the contrary, because an OWF only wants to produce as much as possible and the level of demand doesn't play a role. When the CfD is congested, the CfD payoutcan become disproportionately high. To conclude, a lot of the CfD payout will be lost due to an inefficient market design.

When comparing conventional CfD with advanced CfD, it is clear that the market price in the OBZ will not go extremely low. However, it can be seen that the revenues for the OWF owner in a congested grid will be lower than in a non-congested grid. This is because the market price will be zero, reducing the reference price in the next round. Also, not all electricity will be produced, resulting in volume risk, which can influence the decision-making of the OWF.

The Capability-based CfD recognizes that the volume risk caused by OBZs no longer affects the OWF owner as it does in the Advanced CfD. This means that the CfD payout will cover any potential losses due to a congested grid. On the other hand, the OWF will still aim to maximize its production and sell any extra electricity in the wholesale market, but this will not impact the CfD payout. Therefore, the consequences of producing less electricity during high demand will be lower. One way to enhance this basic Capability-based CfD design is to implement a cap and floor strike price that is determined by the electricity price. This CfD payout would incentivize OWFs to adjust their bidding strategy and produce more electricity when demand is high. However, this creates a double incentive that increases investors' risk, without the benefits outweighing it in the OBZ context. In conclusion, the cap and floor strike price in the CfD scheme can lead to higher risks for investors without generating enough benefits.

The challenge of balancing and redispatch will affect the decision-making process of OWFs that depend on different CfD schemes. In order to mitigate the costs associated with balancing and curtailment, it may be fair to implement a safe margin. While implementing a safe margin can be market efficient in resolving congestion, it is not included in the payout for the capability and financial CfD. However, for a physical reference generator, this safe margin is likely to be implemented in the bidding strategy.

Finally, due to the international nature of OWFs, it is important to consider the impact of congestion in one bidding zone on the CfD payouts of another bidding zone, particularly in the case of FBMC and AHC. This applies to all types of CfDs and cannot be resolved through design. As a result, there are disparities between stakeholders in different bidding zones, which are compounded by future uncertainties. This makes the use of CfD schemes less appealing, which can affect the decision-making of offshore wind farms.

The fourth sub-question *"Which possible strategic behaviour can be recognised with the implementation of CfDs and what are the consequences?"*, is mainly answered in Chapter 5, Chapter 6.1 and Chapter 7 by investigating policy papers and interviews.

When looking at the strategic behaviour, it can be recognised that OWF will take the differences in revenues into account with different market prices, especially when the grid becomes congested. Furthermore, they will introduce a safe margin in their bidding strategy in the day-ahead market because of forecast errors of intermittent wind.

Additionally, TSOs will also take the effects of congestion into account even though the 70% rule, which will be implemented in 2026, can solve parts of this problem because it will reduce the effects of the internal congestion in a bidding zone on other bidding zones.

The last subquestion, *"How will the TSO be affected by the different designs around the OBZ?"*, continues on the effects of the different CfD schemes for TSOs and is mainly answered in Chapter 1 and Chapter 7 due to literature review and interviews. The payments made through CfD schemes won't directly impact TSOs. However, the decision-making of OWF owners can affect them. Different CfD designs can encourage the development of OWF projects around OBZs. This means that TSOs will need to incorporate these projects into their grid planning, which may involve upgrading the transmission infrastructure both offshore and onshore. Additionally, coordination between neighbouring TSOs will be more important. Because OWFs generate power intermittently, TSOs need to look into the effect of CfD schemes on the intra-day and balancing markets.

8.1.2. Answer to the main research question

When combining the answers from the subquestions, the following main research question can be answered: *"What are the advantages and disadvantages of different CfD designs for offshore wind farms considering the offshore bidding zone approach in the North Sea?"*

To sum up, implementing CfD schemes in the OBZ context can be challenging due to a combination of financial, regulatory, technical, risk management, contractual, and market-related factors. Successfully navigating these complexities requires a deep understanding of the energy sector and institutional frameworks. However, supporting investments in OWF is necessary as OWF owners face lower revenues under the OBZ approach due to a lower average electricity market spot price and volume risk.

In Table 6.3, the constraints and objectives of the different CfD designs are shown, making the advantages and disadvantages of the different support schemes clear. When analysing these results, the following CfD design choices seem preferable:

- The capability-based CfD design with a fixed strike price
- The financial CfD design with a reference generator
- The financial CfD design with weather data as reference

When looking at the intermittency of offshore wind and the effects of forecasting errors in the balancing markets. It can be concluded that a financial CfD using a reference generator performs better than a financial CfD using weather data as a reference, as well as a capability-based CfD with a fixed strike price. This is because the CfD payout considers safe margins in the bidding strategy due to the uncertainty of intermittent wind, making it a fairer option. However, it should be noted that this has a lower priority. A well-defined market structure is crucial for the effective functioning of the CfD scheme. It is important that all the stakeholders are assigned specific roles and responsibilities. In order to ensure that the system works as intended, it is imperative to involve stakeholders in the design process. One of the most critical aspects to consider is the uncertainty of financial risks that the stakeholders may face. Therefore, the institutional design should aim to cover these risks partially, in order to provide stakeholders and market participants with incentives to participate in the system with OBZs.

Ensuring certainty is a crucial aspect of implementing OBZs and CfDs, and the process design should prioritize it. In order to prevent delays in the development of offshore wind farms at a later stage, it's important to involve all relevant stakeholders in the process of designing the CfD. Early involvement and communication with stakeholders will lead to a smoother process in the future and will help ensure certainty for all parties involved. Additionally, trust between all parties involved in the project is crucial for successful agreement-making. Although stakeholder involvement is important, it's the responsibility of governments and regulators at both national and European levels to take the lead in designing the CfD support scheme.

8.2. Scientific contribution

Chapter 1 identifies that hybrid projects with OBZ have not yet been extensively developed in Europe, and not all challenges are known and understood. As a result, the main scientific contribution of this study is to provide a thorough overview of various CfD schemes, highlighting their benefits and drawbacks in the OBZ context.

The purpose of this study is to identify the potential outcomes that would arise from implementing different CfD schemes in the context of the OBZ. Firstly, the study specifies the necessary design elements that each CfD design must include when implemented in the OBZ context. Additionally, this study provides an overview of the design choices that can be made for the CfD design, which may not be superior to another for OWFs in OBZs in every situation.

8.3. Academic reflection

The electricity system is a complex system with unique characteristics and many involved actors. The offshore grid is something that gets a lot of attention in the sector and can be seen as an interesting topic to discuss with the current energy transition on its way. Additionally, OBZs are a hot topic as well to integrate OWFs.

Reflecting on my master's thesis and internship at ACER, I can confidently say that ACER is an ideal place to gain extensive knowledge about electricity markets, especially while working in the market codes team of the electricity department. Moreover, this agency actively participates in the discussion around the regulatory context of OBZs. During my internship, this involvement significantly enhanced the quality of my thesis and augmented my knowledge of the subject.

On the contrary, the electricity market can be seen as really complex and even though you can learn a lot about this topic in six months it is not possible to master everything. Therefore, for a master thesis, it seems necessary to scale down at an early stage and to try to become good at understanding one particular field very well. Personally, I see this as one of the hardest things about writing a master thesis, and it is something I learnt during the process.

Additionally, to give better-substantiated conclusions when answering the main research question, a more extensive model would be preferred where FBMC and AHC are implemented. To model this will be challenging within the timeframe of a master's thesis, particularly when combined with quantitative research. However, it would make a good topic for follow-up research.

Lastly, when reflecting on the process of writing this master thesis, it can be concluded that when writing this thesis, knowledge has been acquired during the internship. Therefore, when looking back at the research different steps would have been taken because the electricity system is better understood. On the contrary, this can be seen as a normal process that shows that things were learned during the research. Some of the changes would for example be in the research question: Can balancing of the offshore bidding zone really be done in an onshore bidding zone without consequences? Or by implementing a more extensive model with ADMM. This will be further discussed in section 8.4.

8.4. Limitations and future research

European electricity markets can be seen as complex systems, and the implementation of OBZs results in a few specific characteristics that modify the system in a certain way.

This thesis provides a comprehensive overview of the advantages and drawbacks of different CfD design choices, although there may be limitations due to various factors.

8.4.1. Limitations of research

First of all, in Chapter 5 a simplified grid is used. In the future, a significant development in offshore energy infrastructure is expected to be the creation of a large-scale offshore grid in the North Sea. In the future, the development of offshore wind farms (OWFs) and an expanded grid, along with the installation of interconnectors, will create a vast network for generating and distributing renewable energy. This network will ultimately affect the decision-making process of OWFs in OBZs, which is not considered in this thesis.

Additionally, where FBMC and AHC are discussed in this thesis, they aren't used in the quantitative part of the research because they aren't implemented in the model, limiting the results.

In Chapter 5, the electricity price in the OnBZs is assumed, instead of being a result of analysis that considers generator capacity with variable costs and fluctuating demand. This simplification leads to the analysis of only a few base case results, which are used in the conclusion.

There is uncertainty surrounding the future of electricity generation and distribution, which can significantly impact CfDs designed to ensure revenue certainty.

The thesis does not account for certain uncertainties, such as fluctuations in electricity prices. These fluctuations can be influenced by various factors, including weather patterns, fuel costs, supply and demand dynamics, and geopolitical events. As a result, it remains unclear how these events could impact the effectiveness of the different CfD schemes that were not considered in this thesis.

The energy transition is surrounded by numerous uncertainties, including the direction and pace of the transition. Continuous advancements in renewable energy technologies, energy storage, grid integration, and the hydrogen market will significantly reshape the energy sector. Consequently, the effects of CfDs and the revenues of OWFs might be affected. However, these developments have not been considered in this thesis.

Furthermore, government policies and regulations play a critical role in shaping the landscape around OBZs. The international aspect of considering multiple bidding zones enhances these uncertainties. In this thesis, changes in subsidies, tax incentives, and carbon pricing mechanisms, which can impact offshore wind farms and the value of a CfD, are not taken into account.

8.4.2. Possible future research

Although this thesis has provided valuable insights into various CfD schemes in the OBZ environment, it is important to acknowledge that it is only a small part of the wider academic field, and further research on OBZs is necessary.

In this section, potential areas for future research are suggested, particularly considering the limitations of this thesis and the new questions it has raised in the field.

In future research, it would be beneficial to use a more extensive model with a larger grid, fluctuations in onshore demand, and onshore generation with variable costs. Implementing FBMC and AHC can also provide further insight into the field around OBZs and the different CfD schemes. To investigate this, researchers can use the Alternating Direction Method of Multipliers (ADMM) optimization algorithm to find the equilibrium solution of the market. This algorithm can be utilized to optimize the optimal pricing strategy for the generators and understand the effects of different two-sided CfD when implementing the OBZs approach.

It is important to remember that a bigger model has its own set of challenges, such as increased computational requirements, data needs, and a possibility of greater uncertainty. Therefore, in future research, it's crucial to maintain a balance between complexity and the research goals. However, a bigger model, when properly designed and utilized, can significantly enhance our understanding of the complex electricity system around OBZs and CfD schemes.

Furthermore, as previously discussed in subsection 8.4.1, the uncertainty of future developments will have an impact on the effectiveness of CfDs schemes. Therefore, it is important to investigate various scenarios related to the electricity sector and the effects of different CfD schemes. This research can utilize a range of technologies and methodologies, including energy systems modelling which can simulate different future energy scenarios such as The Integrated MARKAL-EFOM System (TIMES)

(Amorim et al., 2014), as well as machine learning, data analytics, and energy market simulations. However, these technologies will need to address the future uncertainties highlighted in subsection 8.4.1, including fluctuations in electricity prices, the pace and direction of the energy transition, and uncertainties around government policies and regulations.

Lastly, where this thesis focuses mainly on the different CfD designs and their effects on OBZs. In the current political debate, there seems to be a growing interest towards TAGs as well. Therefore, it would be a good addition to this research to compare the different CfD designs with TAGs to give well-considered recommendations in the current policy debate around the design around OBZs.

References

ACER. (2023). Cross-zonal capacities and the 70 percent margin available for cross-zonal electricity trade (maczt) 2023 market monitoring report. www.acer.europa.eu

ACER & CEER. (2022a). Acer and ceer reflection on the eu strategy to harness the potential of offshore renewable energy for a climate neutral future. *https://www.acer.europa.eu/*. https://www.acer.europa.eu/news-and-events/news/acer-and-ceer-publish-their-reflections-european-commissions-offshore-renewables-strategy

ACER & CEER. (2022b). Acer and ceer reflection on the eu strategy to harness the potential of offshore renewable energy for a climate neutral future. *https://www.acer.europa.eu/*. https://www.acer.europa.eu/news-and-events/news/acer-and-ceer-publish-their-reflections-european-commissions-offshore-renewables-strategy

ACER & CEER. (2023). Acer-ceer reaction to the european commission's public consultation on electricity market design. *Reaction to the European Commission's public consultation on electricity market design*.

Ambec, S., Banal, A., Cantillon, E., Crampes, C., Creti, A., Decarolis, F., Fabra, N., Gerlagh, R., Kneuhoff, K., Landais, C., et al. (2023). Electricity market design: Views from european economists. *CEPR Policy Insight*, (120).

Amorim, F., Pina, A., Gerbelová, H., Pereira da Silva, P., Vasconcelos, J., & Martins, V. (2014). Electricity decarbonisation pathways for 2050 in portugal: A times (the integrated markal-efom system) based approach in closed versus open systems modelling. *Energy*, *69*, 104–112. https://doi.org/https://doi.org/10.1016/j.energy.2014.01.052

Bocquillon, P., & Maltby, T. (2021). Eu energy policy integration as embedded intergovernmentalism: The case of energy union governance, 38–56.

Bunn, D., & Yusupov, T. (2015). The progressive inefficiency of replacing renewable obligation certificates with contracts-for-differences in the uk electricity market. *Energy Policy*, *82*, 298–309. https://doi.org/https://doi.org/10.1016/j.enpol.2015.01.002

CEER. (2020). Articles of association of the council of european electricity regulators asbl-consolidated on 13 october 2020. *CEER Statutes as of 13 October 2020*.

Commission, E. (2023). Reform of the eu electricity market design. https://ec.europa.eu/commission/presscorner/detail/en/IP_23_1591

Core-FB. (2022). Core-fb-launch of flow-based market coupling in the core region enhances energy transition flow-based market coupling mechanism optimises day-ahead european electricity market for 13 countries.

De Jong, H. M. (2009). Towards a single european electricity market. a structured approach to regulatory mode decision-making.

DiCicco-Bloom, B., & Crabtree, B. F. (2006). The qualitative research interview. *Medical Education*, *40*(4), 314–321. https://doi.org/https://doi.org/10.1111/j.1365-2929.2006.02418.x

Đukan, M., & Kitzing, L. (2021). The impact of auctions on financing conditions and cost of capital for wind energy projects. *Energy Policy*, *152*, 112197. https://doi.org/https://doi.org/10.1016/j.enpol.2021.112197

EFTA. (1994). The european free trade association | european free trade association. https://www.efta.int/about-efta/european-free-trade-association

ENTSO-E. (2020). Entso-e ten-year network development plan 2020 – main report – november 2020 – version for public consultation.

ENTSO-E. (2023). European network of transmission system operators for electricity electricity market design reform entso-e position on the ec proposals on market design.

European Commission. (2019). Boosting offshore renewable energy. https://ec.europa.eu/commission/presscorner/detail/en/ip_20_2096

European Commission. (2020). Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions. https://ec.europa.eu/environment/nature/natura2000/management/pdf/guidance_on_energy_transmission_infrastr

European Commission, Directorate-General for Energy, THEMA consulting group. (2020). *Market arrangements for offshore hybrid projects in the north sea*. Publications Office. https://doi.org/doi/10.2833/36426

Hampshire, K., Iqbal, N., Blell, M., & Simpson, B. (2014). The interview as narrative ethnography: Seeking and shaping connections in qualitative research. *International Journal of Social Research Methodology*, *17*(3), 215–231. https://doi.org/10.1080/13645579.2012.729405

Jansen, M., Staffell, I., Kitzing, L., Quoilin, S., Wiggelinkhuizen, E., Bulder, B., Riepin, I., & Müsgens, F. (2020). Offshore wind competitiveness in mature markets without subsidy. *Nature Energy*, *5*(8), 614–622.

Kenis, M., Bruninx, K., Dominguez, F., & Delarue, E. (2022). Off-shore bidding zones under flow-based market coupling.

Kitizing, L. (2023). Contracts-for-difference (cfds). *Florence School of Regulation*. https://fsr.eui.eu/contracts-for-difference/

Kitzing, L. (2023). Contracts-for-Difference. *Florence School of Regulation*. https://fsr.eui.eu/contracts-for-difference/

Kitzing, L., & Garzón González, M. (2020). Market arrangements for offshore wind energy networks [NSON-DK, Deliverable 5.2].

Kitzing, L., & Weber, C. (2014). Support mechanisms for renewables: How risk exposure influences investment incentives. *EWL Working Paper*, (03/2014). https://doi.org/10.2139/ssrn.2505976

Laur, A., Küpper, G., & Henneaux, P. (2022). Support on the use of congestion revenues for offshore renewable energy projects connected to more than one market acknowledgments. *Engie Impact*. https://energy.ec.europa.eu/system/files/2022-09/Congestion%20offshore%20BZ.ENGIE%20Impact.FinalReport_topublish.pdf

Lété, Q., Smeers, Y., & Papavasiliou, A. (2022). An analysis of zonal electricity pricing from a long-term perspective. *Energy Economics*, *107*, 105853. https://doi.org/https://doi.org/10.1016/j.eneco.2022.105853

Majone, G. (1989). *Evidence, argument, and persuasion in the policy process*. Yale University Press.

Meeus, L., Batlle, C., Glachant, J.-M., Hancher, L., Pototschnig, A., Ranci, P., & Schittekatte, T. (2022). Policy brief the 5 th eu electricity market reform: A renewable jackpot for all europeans package? https://cadmus.eui.eu/handle/1814/69266.

Neuhoff, K., Kroger, M., & Richstein, J. (2022). Workshop summary:"the role of contracts for differences (cfds)".

Nieuwenhout, C. (2022). Dividing the sea into small bidding zones? the legal challenges of connecting offshore wind farms to multiple countries. *Journal of Energy & Natural Resources Law*, *40*(3), 315–335. https://doi.org/10.1080/02646811.2021.2011034

Nordpool. (2023). Flow-based - nordic regional coordination centre. *Nordic RCC*. https://nordic-rcc.net/flow-based/

Pérez-arriaga, I. J., & Batlle, C. (2012). Impacts of intermittent renewables on electricity generation system operation. *Economics of Energy Environmental Policy*, *1*(2), 3–18. Retrieved December 5, 2022, from http://www.jstor.org/stable/26189488

Schittekatte, T., Reif, V., & Meeus, L. (2020). The eu electricity network codes (2020 ed.) | florence school of regulation. *Florence school of Regulation*. https://fsr.eui.eu/publications/?handle=1814/67610

Schlecht, I., Maurer, C., & Hirth, L. (2023). Financial contracts for differences [Older version: https://www.econstor.eu/handle/10419/267597]. http://hdl.handle.net/10419/268370

Sovacool, B. K. (2009). The intermittency of wind, solar, and renewable electricity generators: Technical barrier or rhetorical excuse? *Utilities Policy*, *17*(3), 288–296. https://doi.org/https://doi.org/10.1016/j.jup.2008.07.001

Swinand, Peter, G., Natraj, & Ashwini. (2019). The value of lost load (voll) in european electricity markets: Uses, methodologies, future directions, 1–6. https://doi.org/10.1109/EEM.2019.8916400

Upton, R., Widd, P., & Glasson, J. (2014). The planning act 2008 (as amended) hornsea project one examining authority's report of findings and conclusions and recommendation to the secretary of state for energy and climate change.

Van den Bergh, K., Boury, J., & Delarue, E. (2016). The flow-based market coupling in central western europe: Concepts and definitions. *The Electricity Journal*, *29*(1), 24–29. https://doi.org/https://doi.org/10.1016/j.tej.2015.12.004

van der Veen, R. A., & Hakvoort, R. A. (2016). The electricity balancing market: Exploring the design challenge. *Utilities Policy*, *43*, 186–194. https://doi.org/https://doi.org/10.1016/j.jup.2016.10.008

Welisch, M., & Poudineh, R. (2020). Auctions for allocation of offshore wind contracts for difference in the uk. *Renewable Energy*, *147*, 1266–1274. https://doi.org/https://doi.org/10.1016/j.renene.2019.09.085

Wild, P. (2017). Determining commercially viable two-way and one-way 'contract-for-difference' strike prices and revenue receipts. *Energy Policy*, *110*, 191–201. https://doi.org/https://doi.org/10.1016/j.enpol.2017.08.020

Williamson, O. E. (1998). Transaction cost economics: How it works; where it is headed. *De Economist*, *146*, 23–58. https://doi.org/10.1023/A:1003263908567

WindEurope. (2021). Denmark to build energy island: Cross-border “hybrid” offshore wind farms are on their way | windeurope. https://windeurope.org/newsroom/news/denmark-to-build-energy-island-cross-border-hybrid-offshore-wind-farms-are-on-their-way/#

Wozabal, D., Graf, C., & Hirschmann, D. (2016). The effect of intermittent renewables on the electricity price variance. *OR Spectrum*, *38*, 687–709. https://doi.org/10.1007/S00291-015-0395-X/FIGURES/6

Young, E., & Quinn, L. (2002). Writing effective public policy papers. *Open Society Institute, Budapest*.

A

Appendix - Institutional rules and stakeholders

A.1. Four-level scheme of economics of institutions by Williamson

The four-level scheme of the economics of institutions, provided by Williamson (Williamson, 1998), categorizes the institutional arrangements into four levels. These levels are depending on two criteria. The first one is the frequency of change, the second one is the opportunity to change the institutional part to increase economic effectiveness and/ or efficiency. The four-level scheme is presented on the right.

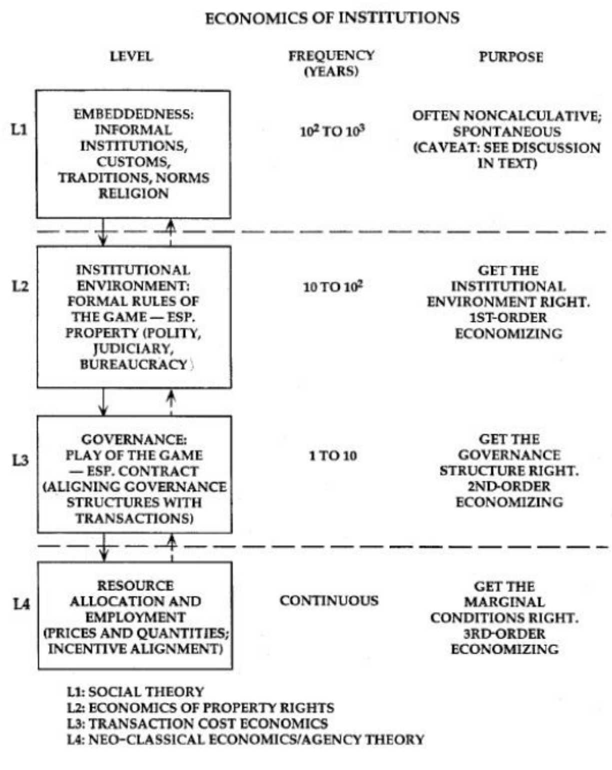


Figure A.1: Four-level scheme of economics Williamson

L1 Embeddedness

The first layer describes the societal norms and values due to decarbonising the electricity sector and the willingness to participate in OWFs. The European Union has the ambition to install 300 GW of offshore wind by 2050 (European Commission, 2019).

In the different member states, there is a certain awareness of the need for both offshore wind and OBZs, but the willingness to participate is not the case for every Member state due to political views, social acceptance and the expected benefits. Eventually, this can take Decennia to change and to be aligned.

L2 Institutional environment
The second level describes the formal institutions that constitute legal rules around OBZs. First, there is the EU, which can give directives to the different Member states. Subsequently, the different member states have to implement these directives into rules.

The second level is also related to the property rights theory. When this property rights theory is focused on OBZs, it is about providing stakeholders with ownership of any factors of production and goods.

L3 Governance
The third level gives more context to the play of the game. Here the rules of levels 1 and 2 are translated into specific rules, for instance, specific CfD contracts. These contracts will specify the terms and conditions, obligations, responsibilities, tasks, and roles of the involved parties and users of a specific OBZ. So here, the transactions can be facilitated. The contracts can be changed much more easily than, for instance, the institutional environment level, which gives structure to these contracts. Changes will be made as a consequence of developments and experiences in the real world by the involved parties and users. The main reason to change something in the contracts is to improve the system.

L4 Resource allocation
The fourth layer is about the structure of the markets, the connections between the involved parties and the users of the system. In general, electricity will be generated in OWF located in OBZs and sold in OnBZs with the highest demand. This electricity will be transported from the OBZ to the OnBZ with the highest electricity price by an interconnector owned by the TSO to be consumed by demand agents in an OnBZ.

A.2. Description of relevant stakeholders

This section will discuss some key stakeholders, which can be subdivided into the following subgroups.

- The European Union
- Regulatory authorities
- Transmission system operators

A.2.1. The European Union

The European Union is largely based on agreements and compromises between these member states. Ultimately and has several divisions with its own power and responsibilities in the EU. The divisions in the European Union important for OBZs are (De Jong, 2009):

- European Commission
- Individual national governments
- EEA EFTA states

The European Commission

The European Union has a significant role and high interest in implementing OBZs. They play a critical role in electricity grid policy by focusing on creating an integrated and sustainable electricity market across member states. Its key roles include promoting market integration, encouraging grid interconnection, establishing a common regulatory framework, and supporting the integration of renewable energy sources (European Commission, 2020). The EC published the EU Strategy to harness the potential of offshore renewable energy for a climate-neutral future (European Commission, 2020). This will be further discussed in section 2.3, which will cover the definition of hybrid projects and the OBZ approach. As a result of this strategy, (Laur et al., 2022) commissioned and published on behalf of the EC a consultation paper discussing electricity market arrangement and exploring some of the investment challenges facing market-based investments in offshore renewable energy and focusing particularly on those projects that are connected to more than one market. This study aimed to investigate the options regarding congestion income. It provides the recommendation that TAGs, section 1.2, are the preferred design. Controversy, this is certainly not a given solution, and in the EU, there are supporters and opponents of this support scheme. Discussing this will be out of scope in this research.

Individual national governments

Furthermore, individually, national governments also have high power and interest in the development of the European electricity grid and market around OBZs. Where the European Union tries to maximise the overall social welfare in Europe, this is not necessarily the case for individual national governments who try to maximise their own welfare. In addition, the implementation of OBZs and the policy framework around them will influence member states differently (Kitzing & Garzón González, 2020). This is one of the reasons why Member States can look differently at OBZs and the framework around them, including the possible support schemes. Furthermore, a different political viewpoint between Member States can also influence the preferences and needs to be considered in the decision-making process (Bocquillon & Maltby, 2021).

EEA EFTA states

Eventually, the member states of the European Union, together with the following three EEA EFTA States, Iceland, Liechtenstein, and Norway, have an internal electricity market governed by the same basic rules called the European Economic Area (EEA). The agreement on the EEA entered into force in 1994 and guarantees equal rights and obligations within the internal market for individuals and economic operators in the EEA (EFTA, 1994).

The connection between the EEA and the offshore grid lies in their shared objectives of energy cooperation and integration. In the EEA the energy policies of the offshore grid, including particular OWFs, will be aligned along EU member states and Norway, Iceland and Liechtenstein. This will also result in the same framework around OBZs.

A.2.2. Regulatory Authorities

In the European Union, all Member States have established a sector-specific national regulatory authority (NRA). In the European Union, a national regulatory authority in the electricity sector, typically has several tasks and responsibilities, which are formalised in Directive 2003/54/EC (Article 23). Furthermore, there are also entities, like ACER and CEER, connecting those national authorities in the European context.

National Regulatory Authorities

A NRA is crucial in ensuring fair competition, consumer protection, and efficient operation of the electricity system with or without OBZs. They make and implement policies around OBZs from their own viewpoint, making them powerful actors. Furthermore, they can have an advisory role, which refers to their function as experts providing recommendations and advice to governments, policymakers, and other stakeholders around these OBZs. Around hybrid projects and OBZs, the preferred design can differ, including the preferred support schemes.

It's important to note that the specific tasks and responsibilities of a NRA may vary from country to country, but because EU electricity markets have become increasingly integrated, the impact of market decisions will not be constrained to national boundaries.

ACER & CEER

To improve this international aspect, in 2011, by the Third Energy Package legislation, the European Union Agency for the Cooperation of Energy Regulators (ACER) was established. This independent agency's primary role is to enhance cooperation and coordination among national energy regulatory authorities in the EU. It tries to foster the integration and completion of the European internal energy market for electricity and natural gas. Eventually, ACER ensures that the integration of national energy markets and implementation of legislation is in line with the EU's energy policy objectives and regulatory frameworks (ACER & CEER, 2023).

Furthermore, In 2000, the Council of European Energy Regulators (CEER) was founded as a self-initiative of regulatory authorities, and it still serves as a platform for cooperation and coordination among regulatory authorities (CEER, 2020). Through its academic research and publications, CEER contributes to decision-making by providing valuable insights and analysis on various energy-related topics.

Around OBZs, ACER can be seen as an actor with high power and interest, among others, due to the international scope and the market integration aspect of OBZs.

A.2.3. Transmission system operators and ENTSO-E

Transmission System Operators (TSOs) are entities responsible for the operation, maintenance, and development of high-voltage electricity transmission systems. Every member state in the European Union has at least one active TSO, and the transmission networks of these TSOs are also connected with each other.

Individual transmission system operators

TSOs can be seen as an essential component of the energy sector, acting as the backbone of the electricity transmission system. Eventually, these individual TSOs have to build the offshore grid and connect the offshore wind farms to the mainland efficiently, making them irreplaceable actors. The design around the support schemes of offshore wind farm owners will have an excessive impact on TSOs, even more so if congestion revenues are used to support offshore wind farm owners or CfD designs aren't designed efficiently.

ENTSO-E

The European Network of Transmission System Operators for Electricity (ENTSO-E), is the overarching organization representing TSOs in Europe. It consists of 43 members from 36 countries, including TSOs from EU member states and other European countries (ENTSO-E, 2020). It was established in 2008 as a result of EU's efforts to promote cross-border trade and integrate the electricity system. ENTSO-E promotes cooperation among TSOs, and facilitates the development of pan-European electricity transmission network codes and guidelines.

Furthermore, ENTSO-E plays a crucial role in the coordination and development of offshore grids in Europe and the design of this transmission network. They will collaborate with regional TSOs and stakeholders to plan and develop offshore grid infrastructure. This involves identifying suitable locations for offshore generation sources, determining efficient transmission routes, and coordinating the connection of offshore assets to the onshore grid. Furthermore, ENTSO-E also provides policy support to facilitate the integration of offshore renewable energy sources.

B

Appendix - Results base case scenarios different CfD designs

Table B.1: Results scenario case 1

Base case 1

	Base case scenario	Low capacity OWF can produce	High capacity OWF can produce	Low electricity price lowest connected OnBZ	High electricity price lowest connected OnBZ	Low reference price	High reference price	Low available transmission capacity	High available transmission capacity
Changing Cells:									
Capacity OWF can produce	800	640	960	800	800	800	800	800	800
Electricity price lowest connected OnBZ	30	30	30	24	36	30	30	30	30
Reference price	25	25	25	25	25	20	30	25	25
Available transmission capacity	2000	2000	2000	2000	2000	2000	2000	1600	2400
Result Cells:									
Conventional CfD									
Electricity produced OBZ	800	640	960	800	800	800	800	800	800
Price electricity OBZ	30	30	30	24	36	30	30	30	30
Price CfD	17600	14080	21120	22400	12800	17600	17600	17600	17600
Revenues OWF	41600	33280	49920	41600	41600	41600	41600	41600	41600
Advanced CfD									
Electricity produced OBZ	800	640	960	800	800	800	800	800	800
Price electricity OBZ	30	30	30	24	36	30	30	30	30
Price CfD	21600	17280	25920	21600	21600	25600	17600	21600	21600
Revenues OWF	45600	36480	54720	40800	50400	49600	41600	45600	45600
Capability-based CfD									
Electricity produced OBZ	800	800	800	800	800	800	800	800	800
Price electricity OBZ	30	30	30	30	30	30	30	30	30
Price CfD	17600	14080	21120	22400	12800	17600	17600	17600	17600
Revenues OWF	41600	33280	49920	41600	41600	41600	41600	41600	41600
Financial CfD									
Electricity produced OBZ	800	800	800	800	800	800	800	800	800
Price electricity OBZ	30	30	30	30	30	30	30	30	30
Price CfD	17750	17750	17750	22520	12980	17750	17750	17750	17750
Revenues OWF	41750	36950	46550	41720	41780	41750	41750	41750	41750

Table B.2: Results scenario case 2

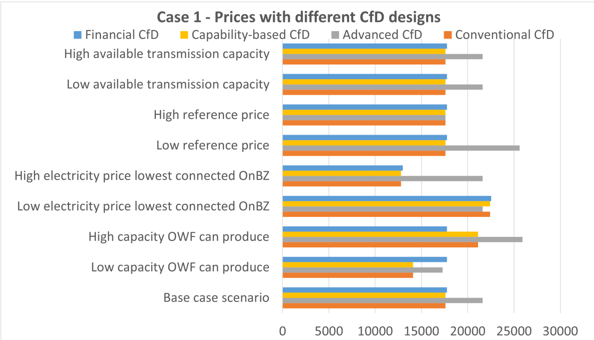
Base case 2

	Base case scenario	Low capacity OWF can produce	High capacity OWF can produce	Low electricity price lowest connected OnBZ	High electricity price lowest connected OnBZ	Low reference price	High reference price	Low available transmission capacity	High available transmission capacity
Changing Cells:									
Capacity OWF can produce	800	640	960	800	800	800	800	800	800
Electricity price lowest connected OnBZ	30	30	30	24	36	30	30	30	30
Reference price	25	25	25	25	25	20	30	25	25
Available transmission capacity	1000	1000	1000	1000	1000	1000	1000	800	1200
Result Cells:									
Conventional CfD									
Electricity produced OBZ	800	640	960	800	800	800	800	800	800
Price electricity OBZ	30	30	30	24	36	30	30	30	30
Price CfD	17600	14080	21120	22400	12800	17600	17600	17600	17600
Revenues OWF	41600	33280	49920	41600	41600	41600	41600	41600	41600
Advanced CfD									
Electricity produced OBZ	800	640	960	800	800	800	800	800	800
Price electricity OBZ	30	30	30	24	36	30	30	30	30
Price CfD	21600	17280	25920	21600	21600	25600	17600	21600	21600
Revenues OWF	45600	36480	54720	40800	50400	49600	41600	45600	45600
Capability-based CfD									
Electricity produced OBZ	800	800	800	800	800	800	800	800	800
Price electricity OBZ	30	30	30	30	30	30	30	30	30
Price CfD	17600	14080	21120	22400	12800	17600	17600	17600	17600
Revenues OWF	41600	33280	49920	41600	41600	41600	41600	41600	41600
Financial CfD									
Electricity produced OBZ	800	800	800	800	800	800	800	800	800
Price electricity OBZ	30	30	30	30	30	30	30	30	30
Price CfD	17750	17750	17750	22520	12980	17750	17750	17750	17750
Revenues OWF	41750	36950	46550	41720	41780	41750	41750	41750	41750

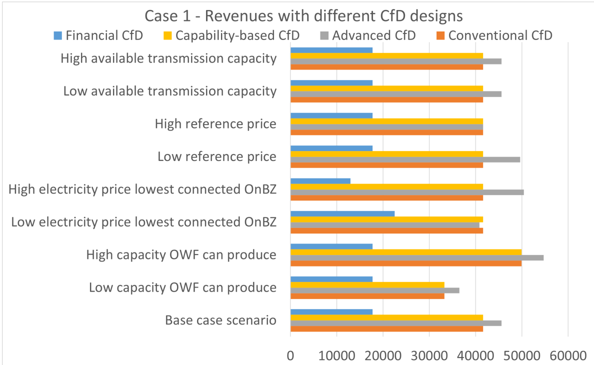
Table B.3: Results scenario case 3

Base case 3

	Base case scenario	Low capacity OWF can produce	High capacity OWF can produce	Low electricity price lowest connected OnBZ	High electricity price lowest connected OnBZ	Low reference price	High reference price	Low available transmission capacity	High available transmission capacity
Changing Cells:									
Capacity OWF can produce	800	640	960	800	800	800	800	800	800
Electricity price lowest connected OnBZ	30	30	30	24	36	30	30	30	30
Reference price	25	25	25	25	25	20	30	25	25
Available transmission capacity	700	700	700	700	700	700	700	560	840
Result Cells:									
Conventional CfD									
Electricity produced OBZ	700	640	700	700	700	700	700	560	800
Price electricity OBZ	-52	30	-52	-52	-52	-52	-52	-52	30
Price CfD	36400	14080	36400	36400	36400	36400	36400	29120	17600
Revenues OWF	0	33280	0	0	0	0	0	0	41600
Advanced CfD									
Electricity produced OBZ	700	700	700	700	700	700	700	700	700
Price electricity OBZ	0	0	0	0	0	0	0	0	0
Price CfD	18900	17280	18900	18900	18900	22400	15400	15120	21600
Revenues OWF	18900	17280	18900	18900	18900	22400	15400	15120	21600
Capability-based CfD									
Electricity produced OBZ	700	640	700	700	700	700	700	560	800
Price electricity OBZ	0	0	0	0	0	0	0	0	0
Price CfD	41600	33280	49920	41600	41600	41600	41600	41600	41600
Revenues OWF	41600	33280	49920	41600	41600	41600	41600	41600	41600
Financial CfD									
Electricity produced OBZ	700	640	700	700	700	700	700	560	800
Price electricity OBZ	0	0	0	0	0	0	0	0	0
Price CfD	41600	41600	41600	41600	41600	41600	41600	41600	41600
Revenues OWF	41600	41600	41600	41600	41600	41600	41600	41600	41600

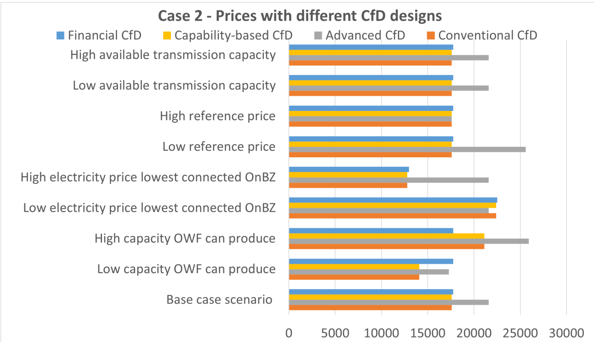


(a) Case 1 - Prices with different CfD designs

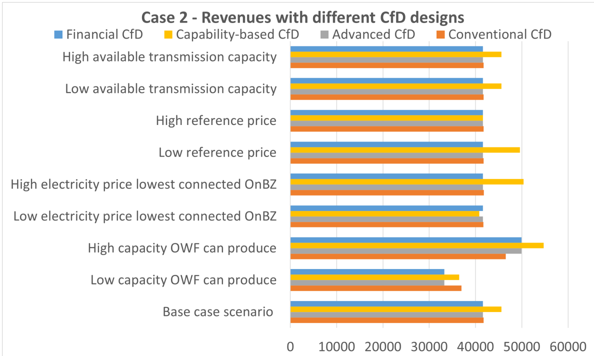


(b) Case 1 - Revenues with different CfD designs

Figure B.1: Case 1 - base case scenarios for different CfD designs

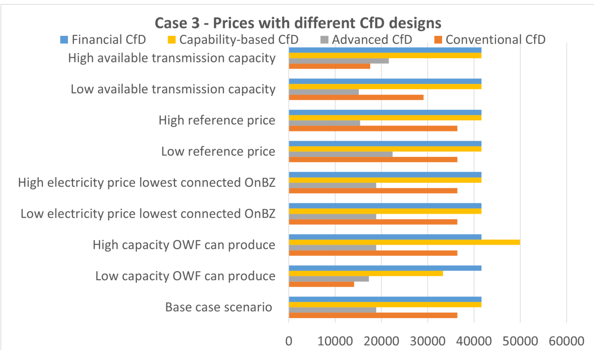


(a) Case 2 - Prices with different CfD designs

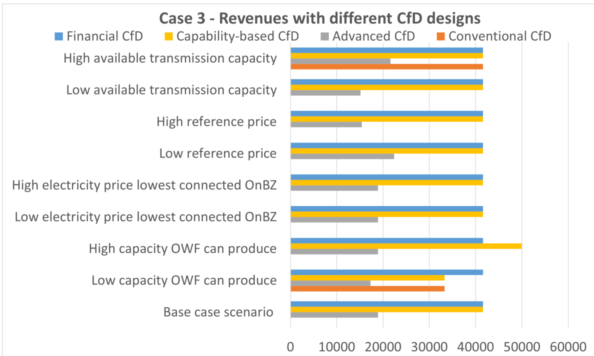


(b) Case 2 - Revenues with different CfD designs

Figure B.2: Case 2 - base case scenarios for different CfD designs



(a) Case 3 - Prices with different CfD designs



(b) Case 3 - Revenues with different CfD designs

Figure B.3: Case 3 - base case scenarios for different CfD designs

C

Appendix - Results Bidding strategy - Forecast errors

Table C.1: Bidding strategy - Forecast errors - no safe margin

bidding strategy - forecast errors	**base case**	**Forecast error 110%**	**Forecast error 130%**	**Forecast error 90%**	**Forecast error 70%**	**Forecast error ref gen 110%**	**Forecast error ref gen 130%**	**Forecast error ref gen 90%**	**Forecast error ref gen 70%**
Changing cells:									
Capacity OBZ	800	880	1040	720	560	800	800	800	800
Offered capacity	800	800	800	800	800	800	800	800	800
Capacity ref gen	795	795	795	795	795	875	1034	716	557
Result cells:									
Curtailed capacity	0	80	240	0	0	0	0	0	0
Capacity needed in balancing market	0	0	0	80	240	0	0	0	0
Two sided Conventional CfD									
Electricity prod. OBZ	800	800	800	720	560	800	800	800	800
Price Elec. OBZ	30	30	30	30	30	30	30	30	30
Price CfD	17600	19360	22880	15840	12320	17600	17600	17600	17600
Revenues OWF	41600	43360	46880	37440	29120	41600	41600	41600	41600
Two Sided Advanced CfD									
Electricity prod. OBZ	800	800	800	720	560	800	800	800	800
Price Elec. OBZ	30	30	30	30	30	30	30	30	30
Price CfD	21600	23760	28080	19440	15120	21600	21600	21600	21600
Revenues OWF	45600	47760	52080	41040	31920	45600	45600	45600	45600
Two-sided Capability based CfD									
Electricity prod. OBZ	800	800	800	720	560	800	800	800	800
Price Elec. OBZ	30	30	30	30	30	30	30	30	30
Price CfD	17600	19360	22880	15840	12320	17600	17600	17600	17600
Revenues OWF	41600	45760	54080	37440	29120	41600	41600	41600	41600
Two-sided Financial CfD									
Electricity prod. OBZ	800	800	800	720	560	800	800	800	800
Price Elec. OBZ	30	30	30	30	30	30	30	30	30
Price CfD	17750	17750	17750	17750	17750	15350	10580	20120	24890
Revenues OWF	41750	41750	41750	39350	34550	39350	34580	44120	48890

Table C.2: Bidding strategy - Forecast errors - 10% safe margin

bidding strategy - forecast errors	**base case**	**Forecast error 110%**	**Forecast error 130%**	**Forecast error 90%**	**Forecast error 70%**	**Forecast error ref gen 110%**	**Forecast error ref gen 130%**	**Forecast error ref gen 90%**	**Forecast error ref gen 70%**
Changing cells:									
Capacity OBZ	800	880	1040	720	560	800	800	800	800
Offered capacity	720	720	720	720	720	720	720	720	720
Capacity ref gen	795	795	795	795	795	875	1034	716	557
Result cells:									
Curtailed capacity	80	160	320	0	0	80	80	80	80
Capacity needed in balancing market	0	0	0	0	160	0	0	0	0
Two sided Conventional CfD									
Electricity prod. OBZ	720	720	720	720	560	720	720	720	720
Price Elec. OBZ	30	30	30	30	30	30	30	30	30
Price CfD	17600	19360	22880	15840	12320	17600	17600	17600	17600
Revenues OWF	39200	40960	44480	37440	29120	39200	39200	39200	39200
Two Sided Advanced CfD									
Electricity prod. OBZ	720	720	720	720	560	720	720	720	720
Price Elec. OBZ	30	30	30	30	30	30	30	30	30
Price CfD	21600	23760	28080	19440	15120	21600	21600	21600	21600
Revenues OWF	43200	45360	49680	41040	31920	43200	43200	43200	43200
Two-sided Capability based CfD									
Electricity prod. OBZ	720	720	720	720	560	720	720	720	720
Price Elec. OBZ	30	30	30	30	30	30	30	30	30
Price CfD	17600	19360	22880	15840	12320	17600	17600	17600	17600
Revenues OWF	41600	45760	54080	37440	29120	41600	41600	41600	41600
Two-sided Financial CfD									
Electricity prod. OBZ	720	720	720	720	560	720	720	720	720
Price Elec. OBZ	30	30	30	30	30	30	30	30	30
Price CfD	17750	17750	17750	17750	17750	15350	10580	20120	24890
Revenues OWF	39350	39350	39350	39350	34550	36950	32180	41720	46490

Table C.3: Bidding strategy - Forecast errors - 30% safe margin

bidding strategy - forecast errors	**base case**	**Forecast error 110%**	**Forecast error 130%**	**Forecast error 90%**	**Forecast error 70%**	**Forecast error ref gen 110%**	**Forecast error ref gen 130%**	**Forecast error ref gen 90%**	**Forecast error ref gen 70%**
Changing cells:									
Capacity OBZ	800	880	1040	720	560	800	800	800	800
Offered capacity	560	560	560	560	560	560	560	560	560
Capacity ref gen	795	795	795	795	795	875	1034	716	557
Result cells:									
Curtailed capacity	240	320	480	160	0	240	240	240	240
Capacity needed in balancing market	0	0	0	0	0	0	0	0	0
Two sided Conventional CfD									
Electricity prod. OBZ	560	560	560	560	560	560	560	560	560
Price Elec. OBZ	30	30	30	30	30	30	30	30	30
Price CfD	17600	19360	22880	15840	12320	17600	17600	17600	17600
Revenues OWF	34400	36160	39680	32640	29120	34400	34400	34400	34400
Two Sided Advanced CfD									
Electricity prod. OBZ	560	560	560	560	560	560	560	560	560
Price Elec. OBZ	30	30	30	30	30	30	30	30	30
Price CfD	21600	23760	28080	19440	15120	21600	21600	21600	21600
Revenues OWF	38400	40560	44880	36240	31920	38400	38400	38400	38400
Two-sided Capability based CfD									
Electricity prod. OBZ	560	560	560	560	560	560	560	560	560
Price Elec. OBZ	30	30	30	30	30	30	30	30	30
Price CfD	17600	19360	22880	15840	12320	17600	17600	17600	17600
Revenues OWF	41600	45760	54080	37440	29120	41600	41600	41600	41600
Two-sided Financial CfD									
Electricity prod. OBZ	560	560	560	560	560	560	560	560	560
Price Elec. OBZ	30	30	30	30	30	30	30	30	30
Price CfD	17750	17750	17750	17750	17750	15350	10580	20120	24890
Revenues OWF	34550	34550	34550	34550	34550	32150	27380	36920	41690

Table C.4: Bidding strategy - Forecast errors - no safe margin - congested grid

bidding strategy - forecast errors	**base case**	**Forecast error 110%**	**Forecast error 130%**	**Forecast error 90%**	**Forecast error 70%**	**Forecast error ref gen 110%**	**Forecast error ref gen 130%**	**Forecast error ref gen 90%**	**Forecast error ref gen 70%**
Changing cells:									
Capacity OBZ	800	880	1040	720	560	800	800	800	800
Offered capacity	800	800	800	800	800	800	800	800	800
Capacity ref gen	795	795	795	795	795	875	1034	716	557
Result cells:									
Curtailed capacity	100	180	340	100	0	100	100	100	100
Capacity needed in balancing market	0	0	0	0	140	0	0	0	0
Two sided Conventional CfD									
Electricity prod. OBZ	700	700	700	700	560	700	700	700	700
Price Elec. OBZ	-52	-52	-52	-52	-52	-52	-52	-52	-52
Price CfD	36400	36400	36400	36400	12320	36400	36400	36400	36400
Revenues OWF	0	0	0	0	-24080	0	0	0	0
Two Sided Advanced CfD									
Electricity prod. OBZ	700	700	700	700	560	700	700	700	700
Price Elec. OBZ	0	0	0	0	0	0	0	0	0
Price CfD	18900	18900	18900	18900	15120	18900	18900	18900	18900
Revenues OWF	18900	18900	18900	18900	15120	18900	18900	18900	18900
Two-sided Capability based CfD									
Electricity prod. OBZ	700	700	700	700	560	700	700	700	700
Price Elec. OBZ	0	0	0	0	0	0	0	0	0
Price CfD	41600	45760	54080	37440	29120	41600	41600	41600	41600
Revenues OWF	41600	45760	54080	37440	29120	41600	41600	41600	41600
Two-sided Financial CfD									
Electricity prod. OBZ	700	700	700	700	560	700	700	700	700
Price Elec. OBZ	0	0	0	0	0	0	0	0	0
Price CfD	41600	41600	41600	41600	41600	41600	41600	41600	41600
Revenues OWF	41600	41600	41600	41600	41600	41600	41600	41600	41600

Table C.5: Bidding strategy - Forecast errors - 10% safe margin - congested grid

bidding strategy - forecast errors	**Base case**	**Forecast error 110%**	**Forecast error 130%**	**Forecast error 90%**	**Forecast error 70%**	**Forecast error ref gen 110%**	**Forecast error ref gen 130%**	**Forecast error ref gen 90%**	**Forecast error ref gen 70%**
Changing cells:									
Capacity OBZ	800	880	1040	720	560	800	800	800	800
Offered capacity	720	720	720	720	720	720	720	720	720
Capacity ref gen	795	795	795	795	795	875	1034	716	557
Result cells:									
Curtailed capacity	100	180	340	20	0	100	100	100	100
Capacity needed in balancing market	0	0	0	0	140	0	0	0	0
Two sided Conventional CfD									
Electricity prod. OBZ	700	700	700	700	560	700	700	700	700
Price Elec. OBZ	-52	-52	-52	-52	-52	-52	-52	-52	-52
Price CfD	36400	36400	36400	36400	12320	36400	36400	36400	36400
Revenues OWF	0	0	0	0	-24080	0	0	0	0
Two-sided Advanced CfD									
Electricity produced OBZ	700	700	700	700	560	700	700	700	700
Price electricity OBZ	0	0	0	0	0	0	0	0	0
Price CfD	18900	18900	18900	18900	15120	18900	18900	18900	18900
Revenues OWF	18900	18900	18900	18900	15120	18900	18900	18900	18900
Two-sided Capability-based CfD									
Electricity produced OBZ	800	880	1040	720	560	800	800	800	800
Price electricity OBZ	0	0	0	0	0	0	0	0	0
Price CfD	41600	45760	54080	37440	29120	41600	41600	41600	41600
Revenues OWF	41600	45760	54080	37440	29120	41600	41600	41600	41600
Two-sided Financial CfD									
Electricity produced OBZ	700	700	700	700	560	700	700	700	700
Price electricity OBZ	0	0	0	0	0	0	0	0	0
Price CfD	41600	41600	41600	41600	41600	41600	41600	41600	41600
Revenues OWF	41600	41600	41600	41600	41600	41600	41600	41600	41600

Table C.6: Bidding strategy - Forecast errors - 30% safe margin - congested grid

bidding strategy - forecast errors	**base case**	**Forecast error 110%**	**Forecast error 130%**	**Forecast error 90%**	**Forecast error 70%**	**Forecast error ref gen 110%**	**Forecast error ref gen 130%**	**Forecast error ref gen 90%**	**Forecast error ref gen 70%**
Changing cells:									
Capacity OBZ	800	880	1040	720	560	800	800	800	800
Offered capacity	560	560	560	560	560	560	560	560	560
Capacity ref gen	795	795	795	795	795	875	1034	716	557
Result cells:									
Curtailed capacity	240	320	480	160	0	240	240	240	240
Capacity needed in balancing market	0	0	0	0	0	0	0	0	0
Two sided Conventional CfD									
Electricity prod. OBZ	560	560	560	560	560	560	560	560	560
Price Elec. OBZ	30	30	30	30	30	30	30	30	30
Price CfD	29120	29120	29120	29120	12320	29120	29120	29120	29120
Revenues OWF	45920	45920	45920	45920	29120	45920	45920	45920	45920
Two Sided Advanced CfD									
Electricity prod. OBZ	560	560	560	560	560	560	560	560	560
Price Elec. OBZ	30	30	30	30	30	30	30	30	30
Price CfD	15120	15120	15120	15120	15120	15120	15120	15120	15120
Revenues OWF	31920	31920	31920	31920	31920	31920	31920	31920	31920
Two-sided Capability based CfD									
Electricity prod. OBZ	560	560	560	560	560	560	560	560	560
Price Elec. OBZ	30	30	30	30	30	30	30	30	30
Price CfD	17600	19360	22880	15840	12320	17600	17600	17600	17600
Revenues OWF	41600	45760	54080	37440	29120	41600	41600	41600	41600
Two-sided Financial CfD									
Electricity prod. OBZ	560	560	560	560	560	560	560	560	560
Price Elec. OBZ	30	30	30	30	30	30	30	30	30
Price CfD	17750	17750	17750	17750	17750	15350	10580	20120	24890
Revenues OWF	41750	44150	48950	39350	34550	39350	34580	44120	48890

D

Appendix - Designing of CfD

D.1. Standardised design elements

Table D.1: Design options in contract design CfD

Contract design		
Strike price determination	**Duration**	**Exit option**
Administrative	12-15 years	None
Auctioned	20 years	Once
Negotiated	Volume-based	

Table D.2: Design options in strike price design CfD

Reference price design			
Averaging period	**Averaging method**	**Price indexation**	**Payout at negative prices**
Monthly	Base	None (fixed price)	Full stop
Hourly	Peak	Inflation-adjusted	Max strike
Annual	Technology-specific volume weighted		Stop if 6h $<$ 0

Table D.3: Design options in clawback design CfD

Clawback design	
Payment direction	**Clawback at low prices**
Netted	Full
Two-sided	Max spot

D.2. Morphological charts

Table D.4: Unfilled morphological chart

Function	Mean 1	Mean 2	Mean 3	Mean 4	Mean 5
Stimulate investments	Strike price	Reference price	Strike price with cap and floor	Fixed hourly remuneration	
Deal with volume risk	Capability-based	Fixed hourly remunartion			
Incentivice market to work efficiently	Actual produced Electricity plays a role	Reference price	Cap and floor strike price	Difference between actual production andreference generator	Difference between actual production and expected production due to weather forecast

D.2.1. Option 1: Advanced CfD design

Table D.5: Morphological chart advanced CfD design

Function	Mean 1	Mean 2	Mean 3	Mean 4	Mean 5
Stimulate investments	Strike price	Reference price	Strike price with cap and floor	Fixed hourly remuneration	
Deal with volume risk	Capability-based	Fixed hourly remunartion			
Incentivice market to work efficiently	Actual produced Electricity plays a role	Reference price	Cap and floor strike price	Difference between actual production andreference generator	Difference between actual production and expected production due to weather forecast

D.2.2. Option 2: Capability-based CfD design

Table D.6: Morphological chart capability-based CfD design

Function	Mean 1	Mean 2	Mean 3	Mean 4	Mean 5
Stimulate investments	Strike price	Reference price	Strike price with cap and floor	Fixed hourly remuneration	
Deal with volume risk	Capability-based	Fixed hourly remunartion			
Incentivice market to work efficiently	Actual produced Electricity plays a role	Reference price	Cap and floor strike price	Difference between actual production andreference generator	Difference between actual production and expected production due to weather forecast

D.2.3. Option 3: Capability-based CfD design with a cap and floor strike price

Table D.7: Morphological chart capability-based CfD design with a cap and floor strike price

Function	Mean 1	Mean 2	Mean 3	Mean 4	Mean 5
Stimulate investments	Strike price	Reference price	Strike price with cap and floor	Fixed hourly remuneration	
Deal with volume risk	Capability-based	Fixed hourly remunartion			
Incentivice market to work efficiently	Actual produced Electricity plays a role	Reference price	Cap and floor strike price	Difference between actual production andreference generator	Difference between actual production and expected production due to weather forecast

D.2.4. Option 4: Financial CfD with a reference generator

Table D.8: Morphological chart financial CfD with a reference generator

Function	Mean 1	Mean 2	Mean 3	Mean 4	Mean 5
Stimulate investments	Strike price	Reference price	Strike price with cap and floor	Fixed hourly remuneration	
Deal with volume risk	Capability-based	Fixed hourly remunartion			
Incentivice market to work efficiently	Actual produced Electricity plays a role	Reference price	Cap and floor strike price	Difference between actual production and reference generator	Difference between actual production and expected production due to weather forecast

D.2.5. Option 5: Financial CfD with weather data

Table D.9: Morphological chart financial CfD with weather data

Function	Mean 1	Mean 2	Mean 3	Mean 4	Mean 5
Stimulate investments	Strike price	Reference price	Strike price with cap and floor	Fixed hourly remuneration	
Deal with volume risk	Capability-based	Fixed hourly remunartion			
Incentivice market to work efficiently	Actual produced Electricity plays a role	Reference price	Cap and floor strike price	Difference between actual production and reference generator	Difference between actual production and expected production due to weather forecast