Electricity market design for meshed offshore grids

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Abstract

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ABSTRACT

Most of the current Offshore Wind Farms (OWFs) are connected to shore via a point-to-point connection. However, hybrid assets constitute an alternative: they combine both offshore wind energy and cross-border capacity. Consequently, they create either a radial multi-terminal or a meshed offshore grid. While radial offshore grids are currently under development and there is already one operational, meshed offshore grids could shortly become a reality. In a mainstream OWF, no congestion can occur between the national country and the OWF because the rating of the connection is generally the nominal power of the OWF. As a result, the OWF belongs to the electricity market of its home country. Nonetheless, congestions can appear for radial and meshed offshore grids. Thus, a pertinent market design is needed for hybrid assets.

In this context, this master thesis aims at, for both radial and meshed offshore grids, (i) analysing possible electricity market arrangements for hybrid assets, (ii) recommending one of these market designs, and (iii) establishing economic redistribution mechanisms for alternative market designs.

The methodology is the following: firstly, an analysis of possible electricity market designs for radial offshore grids is performed. Different points of view are considered: regulatory, operational, and economic. Two market arrangements are analysed: Home Market (HM), and Offshore Bidding Zone (OBZ), which is a nodal approach. Secondly, the electricity market is simulated for each possible configuration. Thirdly, possible redistribution mechanisms are proposed. Finally, the same process is done for meshed offshore grids, where a third design is added: single OBZ.

After the assessment, it is observed that all the electricity market configurations must tackle regulatory barriers. These barriers hamper the development of hybrid assets. Nevertheless, some exemptions of the current EU framework are required in the short-term to foster the implementation of hybrid assets. This has been the case for the first-ever hybrid asset, the Kriegers Flak Combined Grid Solution. Besides, in the long-term, a particular regulation for hybrid assets is needed.

The results from the simulation show that, in the HM design, the OWFs receive the same income as conventional OWFs. In contrast, the nodal and single OBZ configurations offer lower revenues. Thus, there must be a redistribution of the congestion rent collected by the Transmission System Operators (TSOs) to OWFs operators. Contract for differences and free-of-charge financial transmission rights are interesting redistribution mechanisms to apply under these market arrangements.

Without regulatory barriers and with a redistribution mechanism, the market design makes the difference between the possible configurations. Hence, the nodal electricity market is recommended for both radial multi-terminal and meshed hybrid assets, due to its more beneficial market design. Nevertheless, further analysis of the topic is suggested. In particular:

- The impact of offshore load in the electricity market design.
- The conditions of the recommended redistribution mechanisms.
- The balancing responsibility of TSOs and OWFs operators.
- The conditions of a possible particular European regulation for hybrid assets.

To my maternal grandmother,
who accompanied me during my university studies

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LIST OF ACRONYMS

ARR	Auction Revenue Right
BRP	Balancing Responsible Party
BZ	Bidding Zone
CfD	Contract for Differences
CGS	Combined Grid Solution
CNE	Critical Network Element
EEZ	Exclusive Economic Zone
EU	European Union
FAV	Final Adjustment Value
FB	Flow-Based
FCA	Forward Capacity Allocation
FRM	Flow Reliability Margin
FTR	Financial Transmission Right
GSK	Generation Shift Key
HM	Home Market
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
NEP	NEt Position
NTC	Net Transfer Capacity
O&M	Operation and Maintenance
OBZ	Offshore Bidding Zone
OPF	Optimal Power Flow
OWF	Offshore Wind Farm
PTDF	Power Transfer Distribution Factor
PtX	Power to X
RAM	Remaining Available Margin
SDS	Sustainable Development Scenario
SEW	Socio-Economic Welfare
STEPS	STated Energy Policies Scenario
TSO	Transmission System Operator
VoLL	Value of Lost Load

Chapter 1

Introduction

1.1 General context

In the last decade, electricity generation from renewable sources has increased. This is due to the huge development of renewable power plants: mainly thermal and photovoltaic solar installations, and wind turbines (both onshore and offshore). Offshore wind energy has drastically grown in the last decade: while the total installed capacity was 29.1 GW by the end of 2019 [4], it was only 3 GW in 2010 [8]. Figure 1 shows the yearly installed capacity:

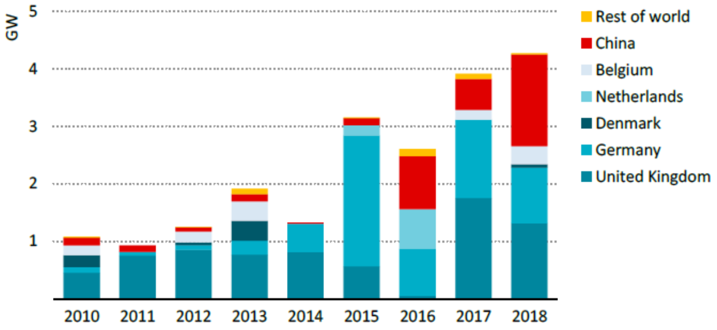

Figure 1. Yearly offshore wind developments per country [8]

Besides, offshore wind installations are expected to keep increasing in the upcoming decades. The European Union Strategy on Offshore Renewable Energy[1] to reach carbon neutrality in 2050 plans *"to increase Europe's offshore wind capacity from its current level of 12 GW*[2] *to at least 60 GW by 2030 and to 300 GW by 2050"*. Figure 2 shows the total installed capacity for 2030 and 2040 under two different scenarios: Stated Energy Policies Scenario (STEPS), and Sustainable Development Scenario (SDS), according to the International Energy Agency [8].

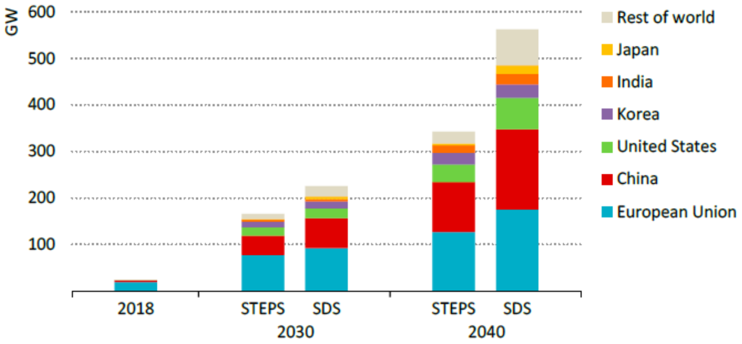

Figure 2. Total offshore wind installed capacity per country for different future scenarios[3] *[8]*

Nowadays, most of the Offshore Wind Farms (OWFs) are connected via a point-to-point connection to their home country, according to the Exclusive Economic Zones (EEZs)[4] [25]. Thus, there is mainly a national approach: OWFs are independent of interconnectors. Nevertheless, to optimally integrate this expected huge amount of offshore wind energy in the European power system, radial multi-terminal or meshed offshore grids are required.

Hybrid assets constitute an alternative to this conventional design. They combine both offshore wind energy and cross-border capacity: not only are the OWFs connected to their home country, but also to other countries. Thus, they create either a radial multi-terminal or a meshed offshore

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[1] *Boosting offshore renewable energy for a climate neutral Europe. (2020).* European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_20_2096

[2] Without including the UK.

[3] In the European Union, the UK is also included.

[4] Part of the sea where a coastal State has jurisdiction.

grid. This makes the offshore grid have a twofold aim: transport the offshore wind electricity to onshore, and exchange electricity among countries [15]. While radial multi-terminal offshore grids are currently under development and there is already one operational, meshed offshore grids could become a reality in the near future.

1.2 Motivation and objectives of this master thesis

With the expected development of offshore wind energy, the offshore grid design may move towards a hybrid one. In a mainstream OWF, since the rating of the connection to the home country is the nominal power of the OWF[5], no congestion can occur between the national country and the OWF. Consequently, the OWF belongs to the electricity market of its home country: it bids in that market and it receives the electricity price of the domestic country. Nonetheless, for radial multi-terminal[6] and meshed offshore grids, congestions can appear between an OWF and its national bidding zone. Thus, a pertinent market design is needed for hybrid assets, different from the conventional design. Here is where the motivation of this master thesis appears.

Thus, this master thesis aims at, for both radial and meshed offshore grids, (i) analysing possible electricity market arrangements for hybrid assets, (ii) recommending one of these market designs, and (iii) establishing economic redistribution mechanisms for alternative market designs.

To reach these aims, firstly, a literature review of market designs for hybrid assets is performed for both radial and meshed offshore grids. Secondly, different market setups for hybrid assets are compared from several perspectives. Thirdly, to dig deeper from an economic view, the electricity market is simulated for each possible configuration. This analysis is performed for both radial and meshed hybrid offshore grids. Finally, possible redistribution mechanisms are considered.

1.3 Structure of this master thesis

The content of this master thesis is organised as follows:

- **Chapter 2** is firstly devoted to the current offshore wind developments. Secondly, it explains the main principles of conventional OWFs (offshore grid and electricity market design) and hybrid assets (radial and meshed offshore grids, and possible alternative electricity market designs) in order to understand the following chapters.

- **Chapter 3** corresponds to electricity market designs for radial offshore grids. Given that there are ongoing radial hybrid assets, this chapter is partially based on an analysis of the state of the art, which will constitute the foundations of the next chapter. Firstly, this chapter defines the study market arrangements and establishes the comparison criteria. Secondly, the different market designs are analysed from each criterion. Thirdly, for the economic perspective, the electricity market is simulated for each configuration. Finally, some conclusions are set, and possible redistribution mechanisms are analysed.

- **Chapter 4** is devoted to electricity market designs for meshed offshore grids, where the same process as in Chapter 3 is repeated. In contrast to the radial hybrid assets, there is no ongoing meshed hybrid asset to take as a reference, and there are fewer performed studies about their electricity market. Consequently, this chapter becomes more original and challenging, and it expands the analysis made in the previous chapter for radial offshore grids.

- **Chapter 5** summarises the main conclusions of this master thesis.

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[5] Unless overplanting, but it is not a common practice.

[6] From now on referred to as radial offshore grids most of the time.

Chapter 2

Context

2.1 Motivation and structure of the chapter

First of all, it is worth analysing the offshore wind energy installations and their distribution around the world. Besides, to better understand the following chapters, the main concepts of offshore grids and electricity market designs must be mentioned.

Firstly, section 2.2 shows the worldwide and European offshore wind installations. Secondly, section 2.3 describes the offshore grid design for both conventional OWFs and hybrid assets. Finally, section 2.4 displays the electricity market design for mainstream OWFs and the alternatives for hybrid assets.

2.2 Offshore wind energy

Throughout the last year (2019), 6.1 GW of offshore wind electricity capacity were worldwide installed, making a total installed capacity of 29.1 GW. The share among countries of the annual (2019) and cumulative installed capacity can be appreciated in Figure 3 and Figure 4, respectively.

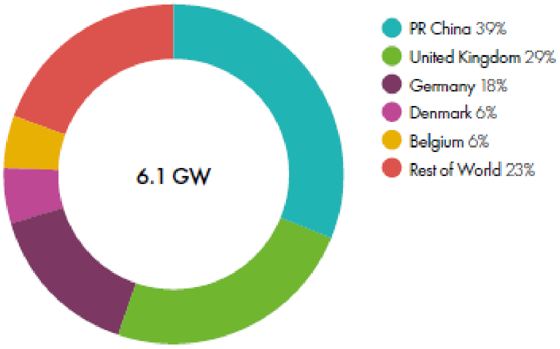

Figure 3. Installed offshore wind capacity in 2019: share among countries [4]

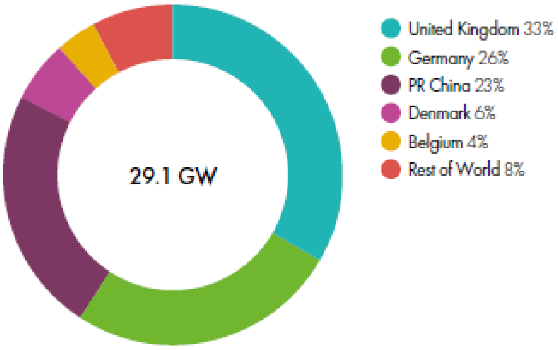

Figure 4. Cumulative installed offshore wind capacity until 2019: share among countries [4]

Thus, Europe[7] and China are currently leading this offshore wind development, with 75% and 23.4% of the cumulative installed capacity, respectively, while the rest of the world only accounts for 1.6%[8]. In Europe, this 75% is mainly concentrated in four countries: only Germany, Denmark, Belgium, and the United Kingdom represent 69% of the total installed capacity in the world.

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[7] Including the UK.

[8] Note that Figure 4 indicates 8% for the rest of the world because some European countries are included.

2.2.1 European offshore wind energy

As stated, Europe represents the main share of installed offshore wind capacity in the world (75%). Hence, European offshore wind energy is worth to be emphasised.

Currently (excluding 2020 installations), Europe has a total offshore wind capacity of 22 GW, with 5047 wind turbines spread in 110 offshore wind farms. Though there are 12 European countries with offshore wind farms, these 22 GW are shared in an irregular way among countries. Indeed, 99% of the total European capacity, is represented by only five countries: the UK 45%, Germany 34%, Denmark 8%, Belgium 7%, and the Netherlands 5%:

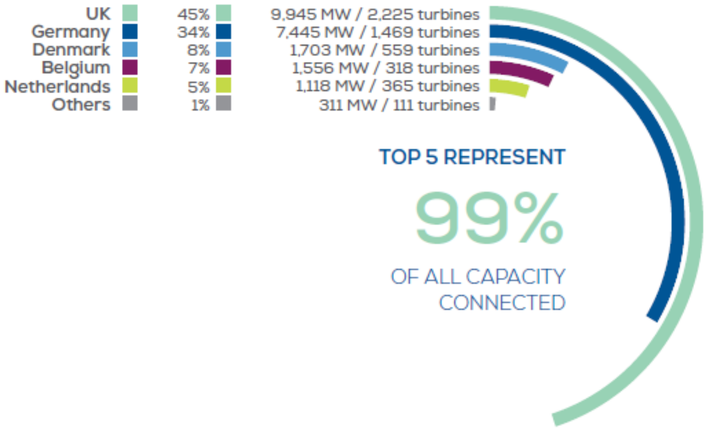

Figure 5. Total offshore wind capacity and turbines per European country [28]

Thus, the United Kingdom, followed by Germany, is leading the offshore wind energy in Europe.

If the 22 GW of European offshore wind power is classified in seas instead of in countries, the North Sea appears to have the greatest share with 77% (Figure 7). The North Sea is located in the Atlantic Ocean in Europe, surrounded by seven European countries: Belgium, Denmark, Germany, France, Netherlands, Norway, and the UK.

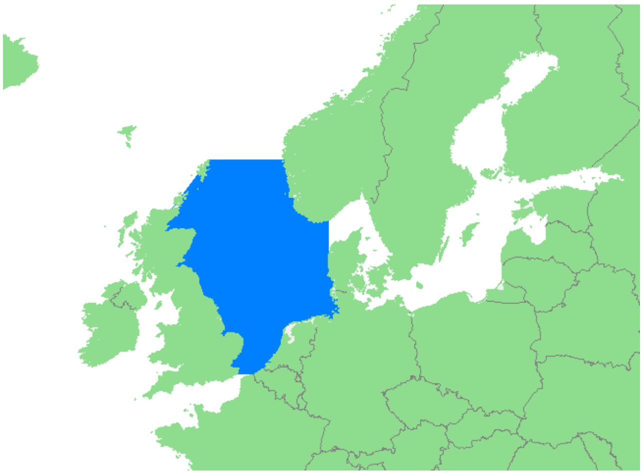

Figure 6. North Sea location in Europe[9]

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[9] *The North Sea.* Wikipedia. https://es.wikipedia.org/wiki/Mar_del_Norte

This is not surprising as the countries with a major share (Figure 5) own part of this sea. On the other hand, the Irish Sea accounts for 13%, the Baltic Sea 10%, and the Atlantic Sea less than 1%:

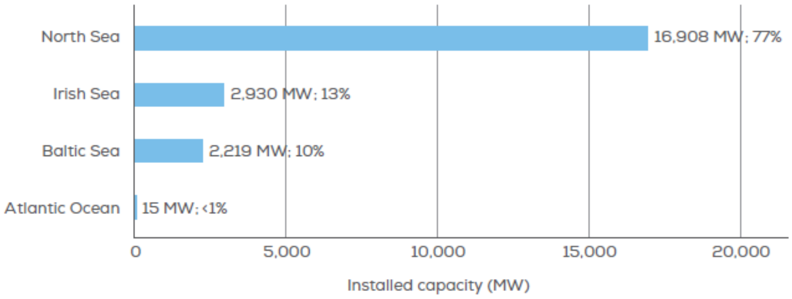

Figure 7. Offshore wind capacity in Europe per sea [28]

Moreover, according to the North Sea Wind Power Hub [15], the North Sea will still account for a great share in the future, with an expected range of 70-150 GW by 2040:

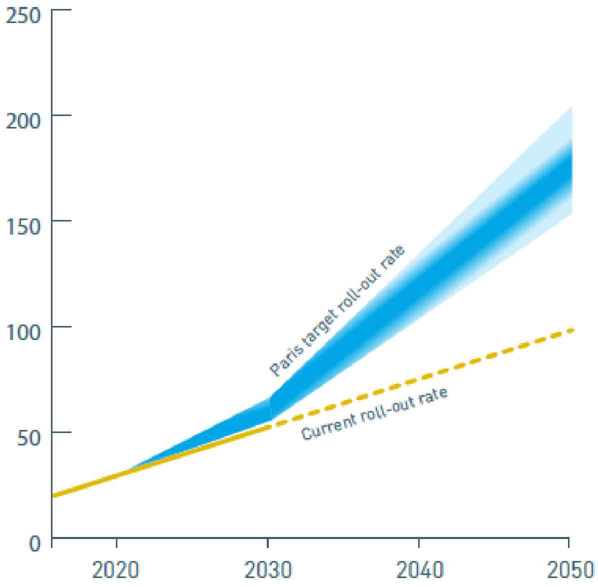

Figure 8. Expected offshore wind capacity (GW) in the North Sea[10] [15]

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[10] The Paris target consists of limiting global warming to below 2ºC in comparison to pre-industrial levels. It was agreed by 196 parties at COP 21 in 2015. Source: *The Paris Agreement*. United Nations Framework Convention on Climate Change (UNFCCC). https://unfccc.int/

2.3 Offshore grid design

As argued above, OWFs are expected to keep growing as during the last decade, with Europe at the head. However, the most favourable sites near the coast to install these OWFs are becoming exhausted for the European countries with higher offshore wind capacity.

Hence, new OWFs are obliged to go further from shore. Consequently, in Europe, clusters of wind farms are supposed to be very close to each other while belonging to different countries in the upcoming years. This makes Europe attractive for hybrid assets. Figure 9 shows how close various EEZs are in the North Sea.

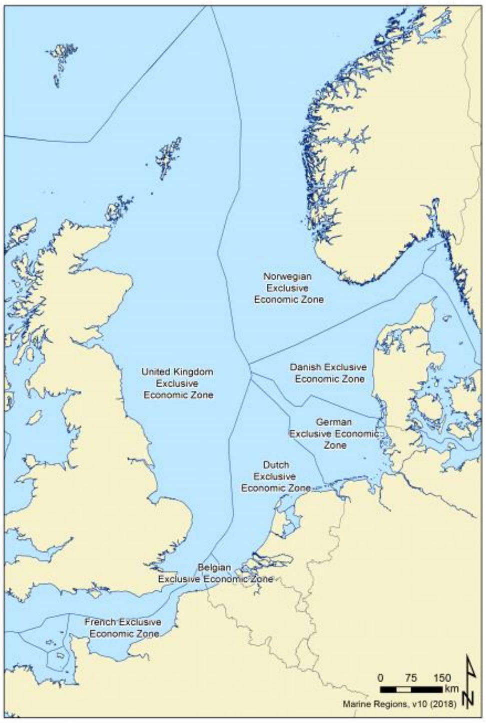

Figure 9. Exclusive Economic Zones in the North Sea [11]

Thus, the offshore grid design is essential to optimally integrate these expected amounts of offshore wind turbines:

- Conventional design. Figure 10 represents the mainstream offshore grid designs: OWFs belonging to different countries are not connected among them, whereas they are only connected through a point-to-point connection to its domestic country. Thus, they are not used as offshore interconnectors, which could be in parallel.

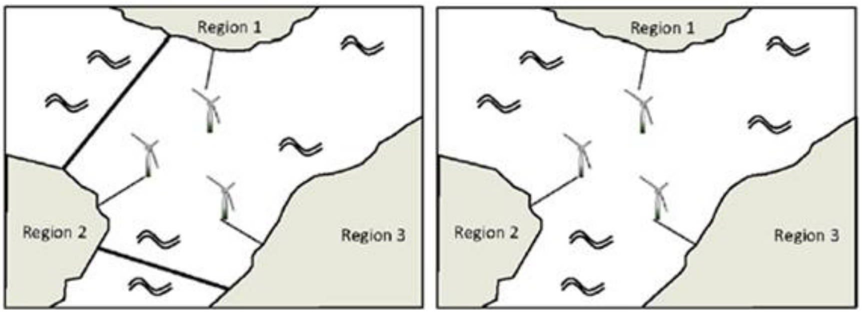

Figure 10. Offshore grid design: conventional configurations [7]

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[11] *Exclusive economic zones in the North Sea*. Marine Regions. https://www.marineregions.org/

- Hybrid assets. As mentioned in Chapter 1, hybrid assets are an alternative to the conventional design (Figure 11): offshore wind energy and interconnectors are combined. Thus, they constitute a radial multi-terminal or meshed offshore grid.

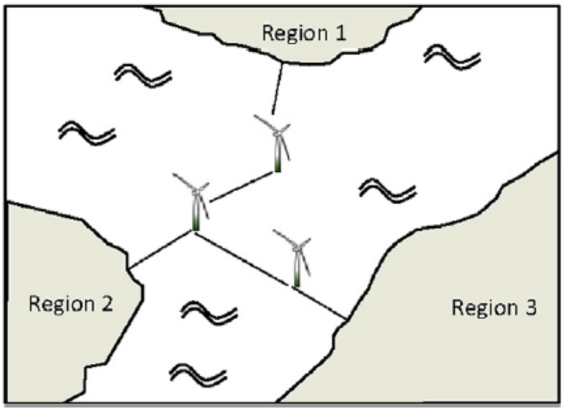

Figure 11. Offshore grid design: hybrid assets [7]

At the moment, there is only one operational hybrid asset: the Kriegers Flak Combined Grid Solution (CGS) in the Baltic Sea (Europe). The two Transmission System Operators (TSOs) involved are Energinet (Danish) and 50Hertz (German): the OWFs Baltic 1 (48 MW) and Baltic 2 (288 MW) are inside the German EEZ, while the OWF Kriegers Flak (under development, expected to be operational by the end of 2021 with 600 MW) inside the Danish EEZ. Baltic 2 and Kriegers Flak OWFs are only 30 kilometres away from each other, connected by a 400 MW interconnector, creating a radial multi-terminal offshore grid in the Baltic Sea [11] [12].

This first-ever hybrid asset is recently in operation: since the 15th of December of 2020[12].

Figure 12. Kriegers Flak CGS: first-ever hybrid asset [12]

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[12] *Combined Grid Solution completely connected to the grid*. (2020, December). 50Hertz. https://www.50hertz.com/

2.3.1 Offshore grid designs comparison

The advantages and drawbacks of the offshore grid design for hybrid assets are analysed in comparison to the mainstream design.

Hybrid assets opportunities

- Decrease in wind curtailment [7]. In the mainstream design, in case there is an outage of the connection of the OWF with its country, or it is congested, the wind generation must be curtailed. In contrast, in the hybrid design, there are alternative paths.
- More efficient market [7] [23]. Consequently, higher wind generation leads to cheaper electricity, which means higher socio-economic welfare and thus, a more efficient market.
- Growth of offshore cable use [23]. In the conventional design, the offshore cables are only used to transport the offshore wind electricity to the onshore network. As a result, its use rate is around 40 %, which is the average offshore wind load factor. However, for a combined solution, even if there is no wind, the cables are still used for cross-border exchanges. Indeed, the cables use rate of the Kriegers Flak CGS is expected to reach 80%.
- Lower connection cost. If Figure 10 left (conventional design with offshore interconnectors) and Figure 11 (hybrid design) are compared, it can easily be appreciated the decrease in cables. This is especially appealing when the OWFs move further away from the coast. To illustrate this with an example, a study of Roland Berger for the European Commission found five hybrid assets in the North Sea with 10% of cost savings [18]. This also has a consequent decrease in environmental impact.
- Onshore network enhancement. If the onshore interconnection between two countries is congested, hybrid assets offer a parallel route to keep exchanging power between both countries via the offshore grid. Thus, it increases the robustness and resilience of the onshore network.
- Possibility to incentivise storage or Power to X (PtX) [18]. Depending on the electricity market design, hybrid assets may lead to more hours when the electricity price for the OWF is null. During those hours, this free electricity can be either stored offshore to sell in the market when the price will be higher or transformed into another type of energy (PtX)[13]. This will be analysed in more detail in the next sections.

Hybrid assets challenges

- Regulation modification [2] [18]. Since hybrid assets mean a new grid configuration, new regulatory changes are needed. This will be analysed in later sections.
- Operational challenges. Most of the hybrid assets may be HVDC cables because they are undersea, and the distances may be long enough. In comparison to HVAC, the investment cost is higher for HVDC due to the AC/DC converter of each substation, which also induces higher power losses. However, the operating cost is lower since there are fewer cable losses and there is no need to compensate for the reactive power. This difference is higher when the cables are underground or undersea and when the distances increase[14]. In contrast, in the Kriegers Flak CGS, the offshore cables are HVAC because distances are short, and thus, HVDC cables were not economically feasible.

  The control and stability of HVDC grids are still a challenge [7], and there is less experience on multi-terminal grids. However, the continuous innovations in HVDC technologies are evolving in such a way that they can support multi-terminal HVDC grids [2].
- Higher risk [18]. More stakeholders are involved in contrast to the conventional design, which leads to a need for coordination among them. Besides, Kriegers Flak CGS is the only hybrid asset that is operational. Thus, they are still immature and there are few references.
- Rules of cost allocation [18]. Depending on the electricity market design, OWFs belonging to the hybrid assets may receive fewer revenues than conventional OWFs, since the TSOs will

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[13] Such as hydrogen through an electrolyser (power-to-gas).

[14] Bram Van Eeckhout. (2018). *The economic value of VSC HVDC compared to HVAC for offshore wind farms.* https://homes.esat.kuleuven.be/~dvherten/eindwerk_vsc_hvdc_bram_van_eeckhout.pdf

have a higher income. Thus, a rule of allocation of those incomes is required. This will also be studied in detail in the next sections.

- Cooperation is needed [18]. Despite the efforts of the European Union for an integrated electricity market, there is still a strong national approach in Europe. However, cooperation between national TSOs is a must for hybrid assets.

2.3.2 Radial and meshed hybrid assets

Two configurations are possible for hybrid assets: radial (Figure 13 left) or meshed (Figure 13 right) offshore grids. The main difference is that, for the meshed offshore grids, the offshore connections create loops. Thus, to transport the generation of a given OWF to an onshore country, there may be various possible offshore paths. In contrast, there is only one possibility for radial offshore grids. Figure 13 shows this statement.

Figure 13. Offshore grid design: radial (left) and meshed (right) hybrid asset [25]

Both grid designs offer the same advantages and disadvantages explained below. However, some may be intensified for the meshed design.

Meshed hybrid assets opportunities

- Lower connection cost [2]. As it can be noticed in Figure 13, the meshed design may reduce the total cable length, decreasing the connection cost even more than the radial design.
- Offshore network enhancement. The offshore grid is more reliable and with higher operational flexibility, as there are more alternative paths in case of outages or congestions.

Meshed hybrid assets challenges

- Operational challenges [25]. If the innovations in control and stability of HVDC grids are still evolving for radial multi-terminal, for meshed offshore grids there is even less knowledge.
- More complex design. In contrast to the radial multi-terminal, the meshed configuration creates offshore loops. This makes the design of the offshore grid (e.g., sizing the cables) and the cross-border capacity calculation and allocation mechanism more complex. This will be analysed in detail in the next sections.

2.4 Offshore electricity markets

In this section, firstly, the electricity market configuration for conventional OWFs is mentioned. Secondly, possible market designs for hybrid assets are presented, together with the configuration used for the state-of-the-art hybrid asset, the Kriegers Flak CGS.

2.4.1 Conventional electricity market

As explained before, in the mainstream offshore grid design, the OWF is connected to its home country (depending on the EEZ) via a point-to-point connection, without interconnection with another country (Figure 14).

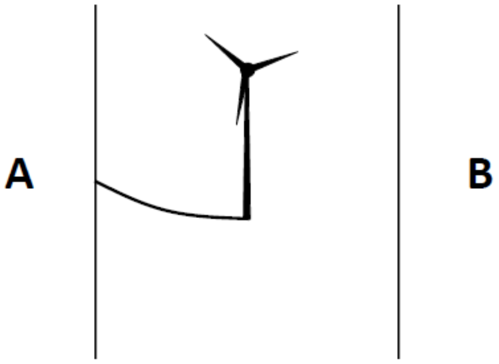

Figure 14. Conventional offshore grid design [19]

Since the rating of the connection to the home country is generally the nominal power of the OWF, no congestion can occur between the national country and the OWF. Consequently, for the example in Figure 14, the OWF belongs to the electricity market of country A[15]: it bids in this market and it receives the electricity price of country A.

2.4.2 Possible electricity markets for hybrid assets

While the market arrangement for the OWF seems obvious for the conventional offshore grid design, it becomes more complex for radial and meshed offshore grids. This is because congestions can appear between an OWF and its national Bidding Zone (BZ). Roland Berger proposed several electricity market configurations for hybrid assets[16] [18]:

- Home Market (HM). This is the status quo since there is no change of bidding zones: the OWF belongs to the BZ of its home country, according to the EEZs.

  This is the configuration applied in the first-ever hybrid asset, the Kriegers Flak CGS. The OWFs Baltic 1 and Baltic 2 belong to the German EEZ and, therefore, they bid in the German market and receive its price. The same for the Kriegers Flak OWF from the Danish side (when it will be operational). Once the wind forecast is done, the remaining connection capacity[17] is available as cross-border capacity for the day-ahead market. There is thus a de facto priority of the transmission capacity for the home market, and the national approach applies.

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[15] Considering country A as a bidding zone.

[16] Note that other configurations were presented. However, they are not mentioned since they are not compliant with the main principles of the European Internal Energy Market.

[17] The TSOs may take some security margins.

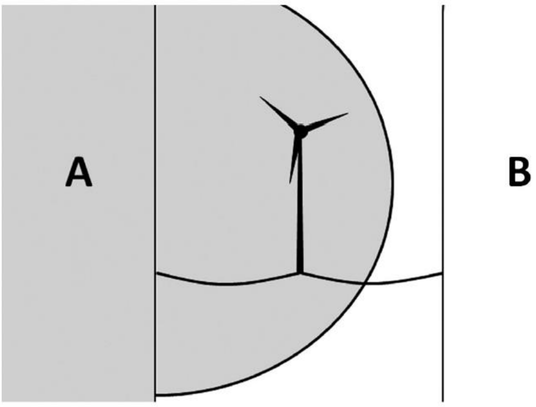

Figure 15. Electricity market design for hybrid assets: home market [21]

- Offshore Bidding Zone (OBZ). In this market arrangement, the OWF belongs to its dedicated BZ[18]. This offshore bidding zone is a BZ without demand[19], only with generation: the OWF bids in its BZ, and then, the market coupling algorithm matches the offshore generation with the onshore demand. After the market clearing, the OWF receives the highest price of the BZ to which it is connected via an uncongested connection in the case of radial offshore grids [15]. For several OWFs in a meshed offshore grid, each OWF obtains a price that depends on how the node faces the congestions.

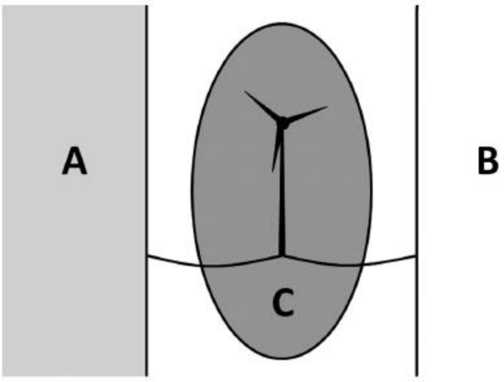

Figure 16. Electricity market design for hybrid assets: offshore bidding zone [21]

Apart from those proposed by Ronald Berger, another configuration could be of interest [17]:

- Single offshore bidding zone. In the case of several OWFs close to each other with strong connections between them[20], a unique OBZ could be an alternative to individual OBZs and the home market configurations. All the OWFs belong to a unique BZ without demand[19], where the OWFs bid, and then, the market coupling algorithm matches the offshore generation with the onshore demand. Under this configuration, all the OWFs obtain the same price, which will depend on how the congestions are distributed.

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[18] In the case of several OWFs, each OWF will have its dedicated OBZ.

[19] Offshore loads could be developed, such as electrolysers.

[20] This could be the case of a meshed offshore grid.

Chapter 3

Electricity market design for radial offshore grids

3.1 Motivation and structure of the chapter

This third chapter aims at performing a study of the electricity market design for radial hybrid assets. Given that there are ongoing radial hybrid assets, this chapter is partially based on the state of the art, which will constitute the foundations of the next chapter. From the market configurations explained in section 2.4.2, two are considered for this radial case: home market and offshore bidding zone. The single offshore bidding zone is not studied in this chapter because this arrangement makes more sense for meshed offshore grids, where various OWFs may be close to each other with strong connections between them.

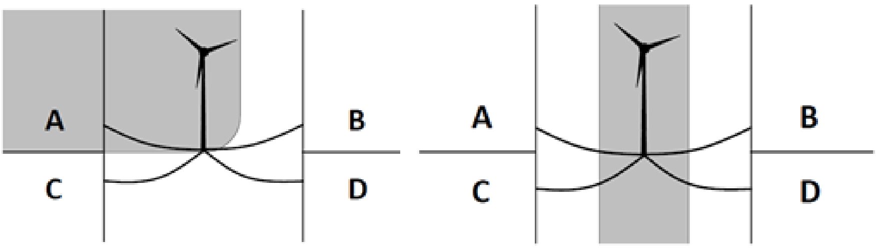

Figure 17. Electricity market design for radial hybrid assets: HM (left) and OBZ (right) [20]

To study both market arrangements, some assessment criteria are established. The analysis is done under a European context since most of the worldwide OWFs are located in Europe (Figure 4), where EEZs of several countries belonging to different BZs are close to each other (Figure 9). Thus, Europe is where hybrid assets have more potential. Moreover, this master thesis is developed in a European university.

Table 1. Electricity market design for radial hybrid assets: evaluation criteria

Criterion	Description
Compliance with EU regulations	The compatibility with the EU regulations is considered in this stage. Besides, regulatory challenges are taken into account.
System operation	In this criterion, different aspects are analysed: • The balancing role of each party: TSO and OWF[21]. • The role of TSOs in wind forecast. • Priority of internal exchanges over interconnections.
Economic perspective	Various study topics: • Market efficiency: the efficiency of the dispatch, and the effects on the Socio-Economic Welfare (SEW). • Price formation for the OWF. • How the SEW is distributed among market players. • OWF revenues.

The content of this chapter is the following: sections 3.2, 3.3, and 3.4 assess both market configurations under each criterion of Table 1, respectively. Section 3.5 performs the annual simulation of both market configurations for a study case. Finally, section 3.6 concludes with a summary of the assessment and main outcomes of the simulation and recommends a market configuration.

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[21] From now on in this report, when talking about OWFs, it refers to the OWFs that are part of the hybrid assets.

3.2 Alignment with EU regulations

Regarding cross-border capacity, article 16(8) of the Internal Market for Electricity Regulation[22] states that: *"Transmission system operators shall not limit the volume of interconnection capacity to be made available to market participants as a means of solving congestion inside their own bidding zone or as a means of managing flows resulting from transactions internal to bidding zones… The minimum capacity shall be 70 % of the transmission capacity"*. Thus, 70% of the cross-border capacity must be available for the capacity calculation and allocation process.

Article 2(1) of the same regulation defines an interconnector as: *"a transmission line which crosses or spans a border between Member States and which connects the national transmission systems of the Member States"*. Therefore, not all the cables belonging to the hybrid offshore grid are interconnectors. However, the 70% rule must be applied to Critical Network Elements (CNEs), not only to interconnectors[22]: *"The total amount of 30 % can be used for the reliability margins, loop flows and internal flows on each critical network element"*. CNEs are network elements that are considerably impacted by cross-border trades [9], which is generally the case of all the cables of the hybrid offshore grid.

For the HM setup, the domestic market has a de facto priority of the transmission capacity over other countries. The OWF bids in its home market and then, the remaining capacity is available for cross-border transmission[23]. In case that the OWF output is higher than 30% of the capacity of the connection to its home market, less than 70% can be used for cross-border exchanges. As a result, if there is no exemption of the rule, the TSO may resort to redispatch down the OWF output or to countertrade to comply with the EU regulation.

In contrast, for the OBZ market, this issue is absent because the capacity of all the offshore cables is 100% available for the market. The OWF bids in its dedicated BZ and then, depending on the market coupling, the capacity is used without priority of dispatch over any country.

In short, the OBZ configuration is aligned with the 70% rule, while the HM setup needs an exemption, as it may not be always respected and significant countertrade and/or redispatch is not desirable [15].

Another regulatory aspect to consider is the bidding zones definition. The OBZ configuration means a new BZ arrangement, whereas the HM setup is the status quo and there is no need to modify the current BZ definition. Hence, the OBZ is more challenging from a regulatory perspective, since a decision of the European Union to modify the current biddings zone is needed. However, article 14(1) of the Internal Market for Electricity Regulation[24] states that: *"Member States shall take all appropriate measures to address congestions. Bidding zone borders shall be based on long-term, structural congestions in the transmission network"*. Thus, as hybrid assets may create structural congestions[25], the new BZs definition of the OBZ configuration is in line with the European regulation [24].

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[22] Regulation (EU) 2019/943 on the internal market for electricity, art. 16(8).

[23] The TSOs may take some security margins.

[24] Regulation (EU) 2019/943 on the internal market for electricity, art. 14(1).

[25] Predictable, frequent, and stable over time congestions.

3.3 System operation

In the HM configuration, imbalances entail higher costs and responsibilities for TSOs [15]. The OWF operator can also own other onshore generation assets in the home market. As a Balancing Responsible Party (BRP), the OWF operator can compensate onshore imbalances with the offshore assets and vice versa. As both onshore and offshore assets belong to the same BZ, the imbalance price is the same. Consequently, the OWF operator solves the imbalance without paying the imbalance price.

If this power imbalance compensation leads to overload in the connection of the OWF to onshore, the TSO of the home country must cope with it. As a result, the TSO resorts to redispatch and/or countertrade.

However, for the OBZ case, even if the OWF operator owns other onshore assets, they belong to different BZs. The fact that the imbalance price can be different in both BZs incentivises the OWF operator to compensate for its offshore imbalance with its offshore assets. For his part, the TSO may also cope with final imbalances but does not incur extra costs because the OWF operator pays the imbalance price.

To better understand this point, Figure 18 illustrates a short study case:
- Two countries (country A and country B) are interconnected through a hybrid asset.
- Electricity market design: home market, OWF belongs to country A.
- OWF owns onshore assets in country A.
- Capacity between country A and OWF: 1 GW.
- Capacity between country B and OWF: 1 GW.
- OWF scheduled generation: 800 MW.
- Country B exports to country A 200 MW.
- Grid status: no overloads.

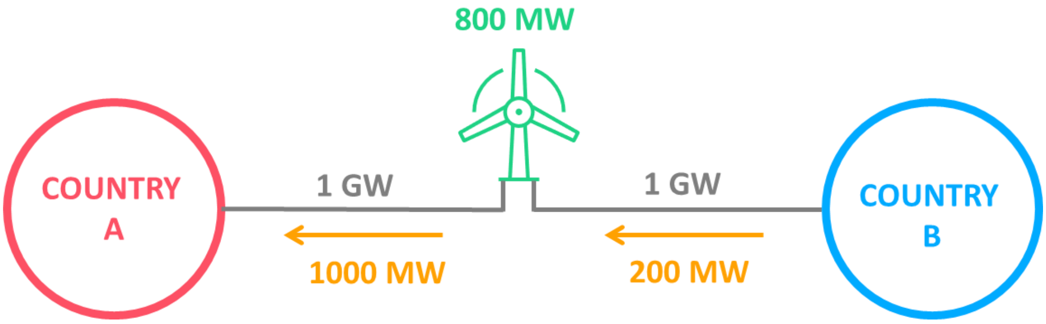

Figure 18. Radial hybrid assets: balancing responsibility, situation I

This is the dispatch after the day-ahead market. Then, in due time, the OWF generates 50 MW more. This leads to overload in the connection of the OWF to its home market (Figure 19). As the OWF operator owns another onshore power plant in A, they decrease in 50 MW the generation of this onshore asset. As a result, the OWF does not have to pay for the imbalance. However, the TSO must tackle the overload and pay for it by using countertrade or redispatch.

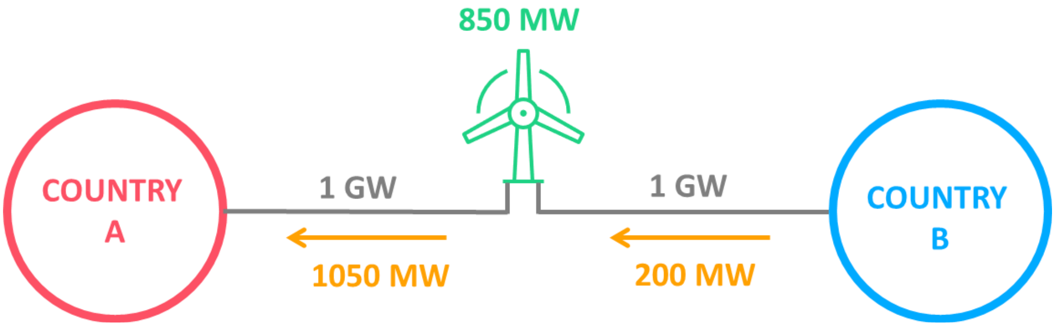

Figure 19. Radial hybrid assets: balancing responsibility, situation II

In the same situation but under the OBZ configuration, one of the two TSOs (either country A or B) should cope with the overload but it is the OWF who incurs extra costs by paying the imbalance price[26].

Another point to discuss is the role of the TSO in wind forecasting. In the HM setup, the domestic TSO needs to forecast in advance the OWF generation to compute the available cross-border capacity. However, in the OBZ configuration, the TSO does not need to anticipate the OWF generation to proceed with the capacity calculation and allocation process [3].

Finally, the OBZ does not curtail international exchanges to prioritise internal flows. In the HM configuration, as the OWF is inside the country's BZ, all the trades from the OWF are possible. Then, to avoid overload in the connection of the OWF to its domestic market, the TSO may limit the interconnection capacity, which is discriminatory.

In summary, the HM gives a de facto priority of the transmission capacity to internal exchanges. Besides, the TSO implicitly bears the balancing responsibility and needs to anticipate the OWF generation to calculate the available cross-border capacity, with extra expenses and risks[27].

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[26] Except if there are available transmission capacity and relevant platforms for cross-zonal balancing.

[27] The TSO may take a margin to have less responsibility. However, the market would be less efficient.

3.4 Economic perspective

In this section, different topics are analysed. They are described and compared for both markets in a qualitative manner and with simple examples. Then, in the next section, a simulation of the annual electricity market is performed for both configurations to quantify this comparison.

3.4.1 Market efficiency

The electricity market configuration is expected to be efficient. To become such, a market design must optimise the socio-economic welfare, defined as the total surplus of the market participants: producers, consumers, and TSOs (through the congestion rent). If the demand is inelastic, maximising the SEW is equivalent to minimize the generation cost. Consequently, an efficient dispatch is such that minimizes the total generation cost.

Let us compare both setups from an efficiency point of view. In absence of negative prices in the onshore bidding zones (or more generic, onshore prices lower than the OWF marginal cost) the generation dispatch is the same for both configurations (the SEW and generation cost are equal). As a result, the HM is as efficient as the OBZ. Nonetheless, in the case of onshore negative prices, the HM configuration can lead to inefficiencies of dispatch, whereas the OBZ becomes more efficient [3] [15].

To better assimilate this point, Figure 20 shows a practical example:
- Country A electricity price: -2 €/MWh.
- Country B electricity price: 10 €/MWh.
- Marginal cost of the OWF: 0 €/MWh.
- Country A-OWF capacity: 2 GW.
- Country B-OWF capacity: 3 GW.
- Maximum OWF generation: 2 GW.
- OWF inside the EEZ of country A.

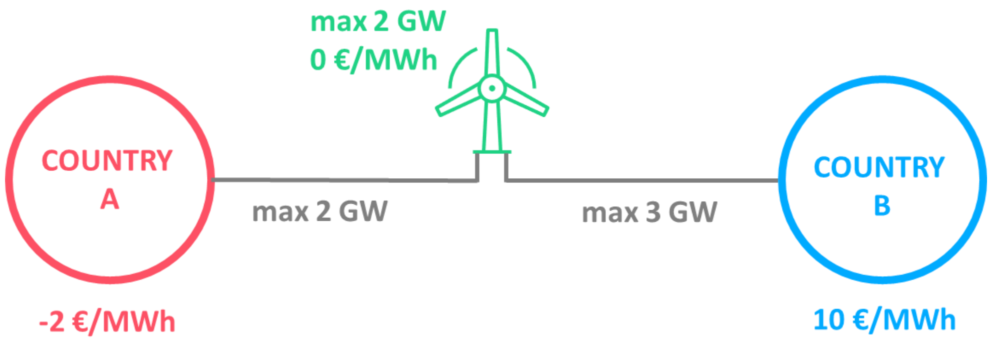

Figure 20. Market efficiency for radial hybrid assets: problem definition

For the HM case, being country A the domestic market, the OWF does not bid in the country A market as its marginal cost is higher than the onshore electricity price. Then, after the market coupling, country A exports to country B, as it is cheaper. As a result, the dispatch is the following:

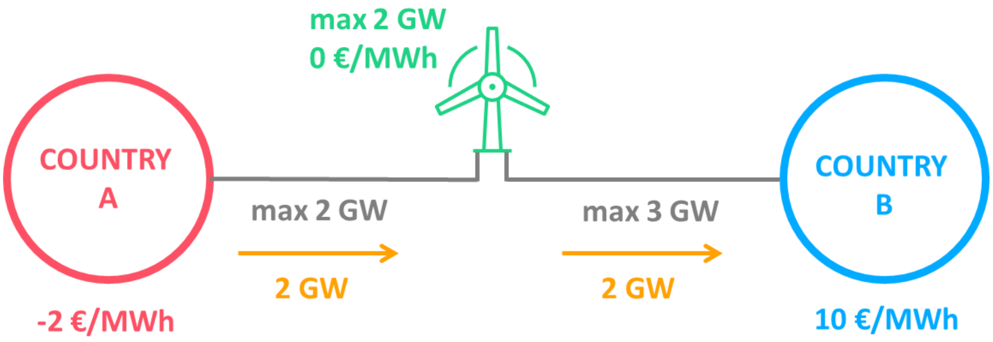

Figure 21. Market efficiency for radial hybrid assets: HM dispatch

In contrast, in the OBZ setup, the OWF can be dispatched during the market coupling. Firstly, country A exports until reaching the maximum capacity of the connection between country A and the OWF (2 GW). Then, as the capacity of the connection between the OWF and country B is higher, the OWF is dispatched, even though its marginal cost is higher than the price of country A:

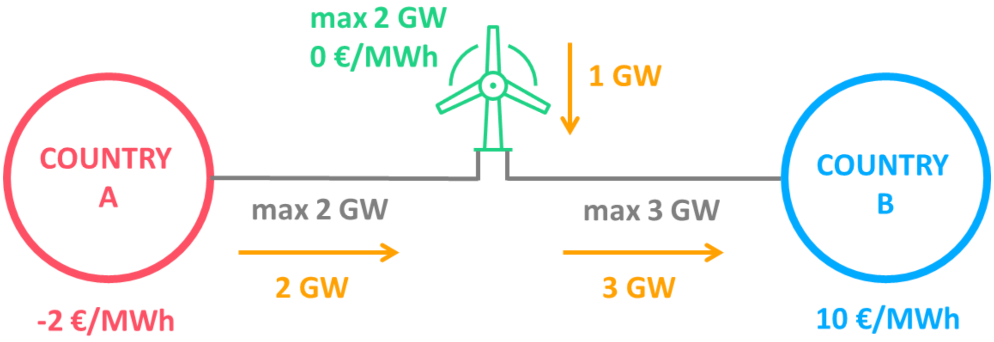

Figure 22. Market efficiency for radial hybrid assets: OBZ dispatch

In short, country B needs to generate 1 GW more in the HM case. The cost of this 1 GW is 10 €/h, while it is supplied by the OWF at zero cost in the OBZ configuration. Therefore, the generation cost is lower for the OBZ design, and thus, the market is more efficient.

3.4.2 Price formation

For the HM, the price formation mechanism is simple. The OWF always receives the electricity price of its domestic market, regardless of the possible congestions of the connection to the domestic onshore network. Besides, the OWF marginal price is not directly dependent on the other zonal prices.

For the OBZ case, it is more complex. The OWF price depends on both congestions and other zonal prices: the electricity price of the offshore bidding zone is the highest onshore zonal price to which the OWF is connected without congestions. Besides, in case of congestions on all the connections, the OWF price is null[28] [15].

Congestions tend to happen first with countries with high marginal prices, since they attract cheaper power from everywhere, including the OWFs. Thus, the connection between the OWF

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[28] If there are no subsidy schemes.

and the onshore country with the highest price is most of the time congested[29]. Thus, the OWF normally gets the second or third highest price.

Let us use a simple study case with OBZ configuration to demonstrate this point (Figure 23):
- Country A electricity price: 30 €/MWh. The highest price.
- Country B electricity price: 10 €/MWh. The third highest price.
- Country C electricity price: 20 €/MWh. The second highest price.
- OWF marginal cost: 0 €/MWh.
- Country A-OWF capacity: 2 GW.
- Country B-OWF capacity: 1 GW.
- Country C-OWF capacity: 3 GW.

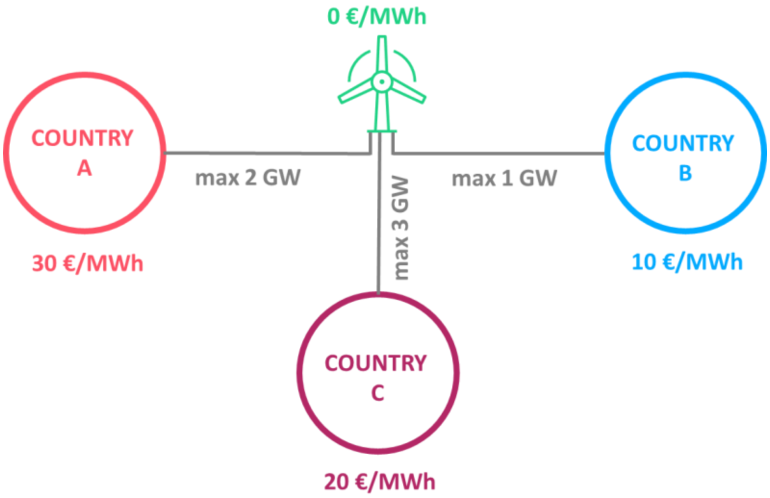

Figure 23. Price formation for radial hybrid assets: study case, problem definition

If the available OWF power is 3 GW, the dispatch and the power flows are the following:

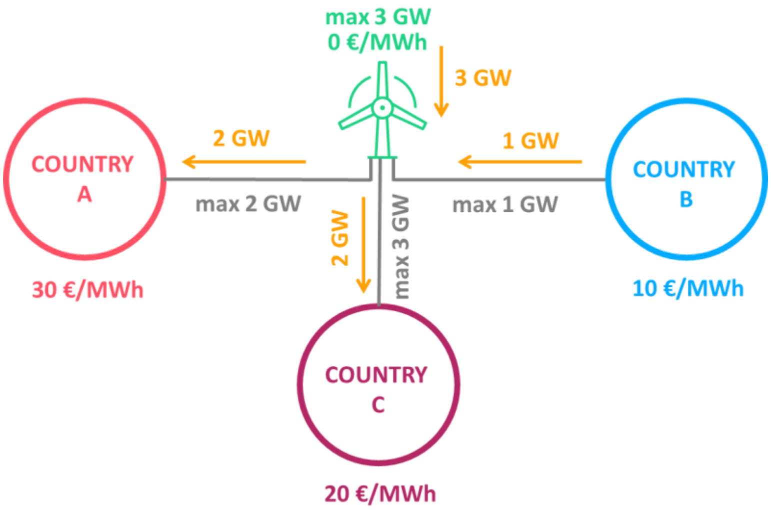

Figure 24. Price formation for radial hybrid assets: study case, situation I

As the line connecting the OWF to the country with the highest price (country A) is congested, the OWF receives the price of country C, since the connection is not congested and it is the second highest price. Thus, for this situation, the OWF gets the middle price.

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[29] Unless the connection is oversized.

Let us consider the following situation, with 4 GW of available offshore wind power:

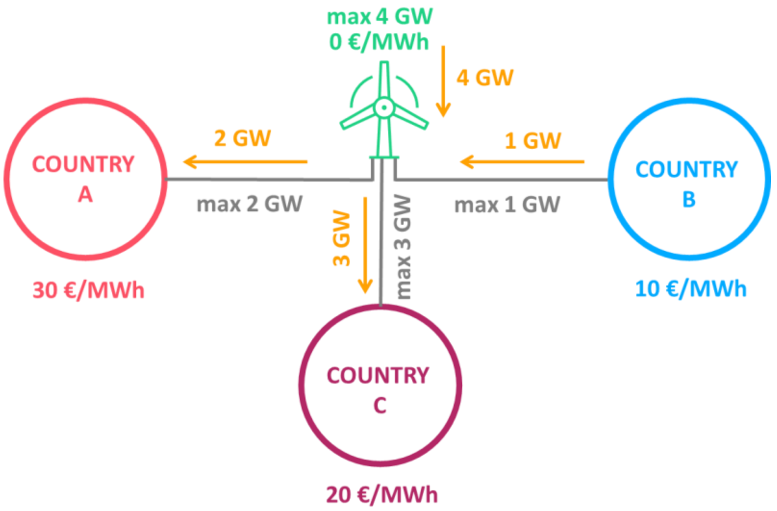

Figure 25. Price formation for radial hybrid assets: study case, situation II

In this situation, the OWF connections to the BZs with both the highest (country A) and the second highest (country C) prices are congested. Hence, the OWF obtains the lowest zonal price (country B).

In summary, the OBZ marginal price tends to be lower than the one of the HM case, as the OBZ generally receives the second or third highest price. Thus, the OBZ configuration entails a higher cost risk for the OWF operators, which is discriminatory in comparison to OWFs that do not belong to hybrid assets[30].

3.4.3 Distribution of the SEW

As argued before, the generation cost and the SEW is the same for both market configurations without negative prices. However, the SEW distribution among market players is not the same: producers, consumers, and TSOs.

For instance, comparing the two situations of the previous example, the consumers in each country pay the same price for the same demand independently of whether the OWF price is the second or the third highest onshore price. Therefore, if the SEW is the same and so is the consumers' surplus, the lower OWF revenues in the second situation mean a higher surplus for the TSOs (through the congestion rent).

In short, the SEW distribution is different depending on the market design, even though the total SEW could be the same. In general, the OBZ offers lower revenues for the OWF and higher congestion rent [3] [15].

In the next section, the annual electricity market is simulated for both configurations for a study case to quantify and better understand these distributional effects of the SEW.

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[30] Against the European Internal Energy Market principles.

3.5 Simulation of the annual electricity market

In this section, the electricity market of a radial hybrid asset is simulated for one year, in order to quantify both market arrangements from an economic point of view[31].

3.5.1 Assumptions

The following considerations have been assumed before developing the formulation of the problem:

- The offshore grid cables are HVDC cables[32]. Consequently, the power injections and withdrawals can be controlled at each AC/DC interface.
- Converter losses and limits are not considered, in order to simplify.
- Nodes voltages are assumed to be close to their nominal values, and thus, the power losses through the cables are neglected.
- The 70% rule[33] is not applied for this preliminary study to simplify the formulation of the problem.
- Absence of uncertainties in demand and generation. In this way, only the day-ahead market is simulated, since it is not considered necessary to have other markets such as intraday or balancing.
- For simplification, intertemporal constraints, start-up costs and time, and no-load costs are not taken into account, and the minimum generation is zero.
- The demand is inelastic: the consumers' demand is the same regardless of the market price.
- To have the same market efficiency for both electricity market configurations, negative prices are not present.
- Each country network is considered a copper plate, and thus, their internal congestions are not considered. The only congestions to take into account are those in the offshore cables belonging to the hybrid asset.
- The same generator types have the same characteristics. That is to say, there is no consideration of individual generators, they are grouped by technologies. Thus, all solar, offshore, and onshore wind generators belonging to the same country have the same hourly load profiles regardless of their location in the country, respectively.
- The hydroelectric generators are always available at their maximum capacity.
- There is no offshore load, only generation, since this is out of the scope of this master thesis.

3.5.2 Study grid

The studied grid consists of a radial hybrid asset with two countries belonging to their own BZ, and connected to an OWF via a radial offshore grid:

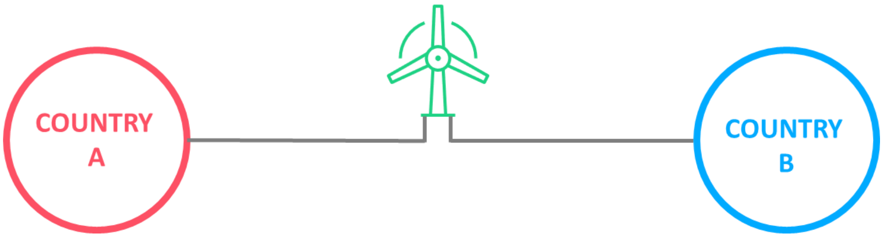

Figure 26. Market simulation of radial hybrid asset: study grid

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[31] The programming language used to simulate the market designs is Python.

[32] As explained in section 2.3.1, given that they are undersea cables and the distances may be long enough, HVDC is more economically profitable than HVAC.

[33] Regulation (EU) 2019/943 on the internal market for electricity, art. 16(8).

In each country, there are nine possible generation technologies: gas, hard coal, lignite, nuclear, oil, hydro, solar, onshore wind, and offshore wind. The OWF belonging to the hybrid asset is studied under three possible market configurations:

- Home market A: OWF is part of the country A market.
- Home market B: OWF is part of the country B market.
- Offshore bidding zone: as defined before, the OWF has its dedicated BZ.

3.5.3 Problem formulation

The problem becomes an Optimal Power Flow (OPF): given the hourly onshore demand, the output of each generator must be computed in such a way that the objective function is minimised, and the constraints are respected. Then, the OPF is solved for each hour of the year.

Hereunder, the mathematical formulation of the problem is given. State variables, control variables, objective function, equality and inequality constraints, and equations used to implement the OPF problem are defined for a period of time. In contrast to the meshed case (section 4.3.4), given that there are no offshore loops, the Kirchhoff laws are not needed to determine the power flows in the offshore cables. As a result, the capacity calculation and allocation mechanism is simpler and there is no need for a dedicated mechanism.

Indices and variables

- g: generator.
- n, m: nodes. In total, there are three nodes: country A (node A), country B (node B), and the offshore platform (node C).
- z: bidding zone.
- P_g: power output of generator g (MWh).
- P_g^{max}: maximum power output of generator g (MWh).
- P_g^{min}: minimum power output of generator g (MWh).
- C_g: marginal cost of generator g (€/MWh).
- $Load_n$: load in node *n* (MWh).
- $VoLL_n$: Value of Lost Load in node *n* (€/MWh)[34].
- $P_{n\rightarrow m}$: power flow in line n→m (MWh).
- $P_{n\rightarrow m}^{max}$: maximum power flow of line n→m (MWh).
- C_z: zonal price of bidding zone *z* (€/MWh).
- $\mathbb{I}_{ng}$: binary variable. $\mathbb{I}_{ng} = 1$ if generator g is connected to node *n*, $\mathbb{I}_{ng} = 0$ if otherwise.
- $\mathbb{I}_{zn}$: binary variable. $\mathbb{I}_{zn} = 1$ if node *n* belongs to zone *z*, $\mathbb{I}_{zn} = 0$ if otherwise.
- $\mathbb{I}_{zg}$: binary variable. $\mathbb{I}_{zg} = 1$ if generator g belongs to zone z, $\mathbb{I}_{zg} = 0$ if otherwise.

State variables

The state variables are the power output of each generator unit.

Control variables

Some variables must be modified to find the optimal solution: those are the control variables. In this problem, the control variables are the same as the state variables.

Inequality constraints

- Firstly, the power output of each generation unit must be between the maximum and minimum value. This is expressed as:

$$P_g^{max} \geq P_g \geq P_g^{min} \quad \forall g \tag{1}$$

---

[34] Note that load shedding is not allowed. The value of lost load is only used to compute the consumers' willingness to pay, in order to determine the consumers' surplus.

- Secondly, the power flows in each line must be limited as well. The power flows through the two lines are obtained by a power balance in each onshore node (total generation minus total demand). They are given by the following formulas (MWh):

$$P_{A\rightarrow C} = \sum_{g} P_g * \mathbb{I}_{Ag} - Load_A \tag{2}$$

$$P_{C\rightarrow A} = -P_{A\rightarrow C} \tag{3}$$

$$P_{B\rightarrow C} = \sum_{g} P_g * \mathbb{I}_{Bg} - Load_B \tag{4}$$

$$P_{C\rightarrow B} = -P_{B\rightarrow C} \tag{5}$$

Thus, the inequality constraints are given by Equation (6) and Equation (7). Note that the limits are the same in both directions.

$$P_{A\rightarrow C}^{max} \geq P_{A\rightarrow C} \geq -P_{A\rightarrow C}^{max} \tag{6}$$

$$P_{B\rightarrow C}^{max} \geq P_{B\rightarrow C} \geq -P_{B\rightarrow C}^{max} \tag{7}$$

Equality constraints

There is only one equality constraint: the power balance at each node. When defining the power flows, the power balance at countries A and B are considered: Equation (2) and Equation (4), respectively. Thus, the only remaining power balance constraint is at the offshore platform:

$$\sum_{g} P_g * \mathbb{I}_{Cg} = P_{C\rightarrow A} + P_{C\rightarrow B} \tag{8}$$

Objective function

The objective function consists of maximising the socio-economic welfare, expressed in Equation (15). As the demand is inelastic, this is equivalent to minimise the total generation cost. This cost is the sum of the generation cost of each unit, which is equal to its marginal cost times its generation. This is given by the following formula (€):

$$Generation\ cost = \sum_{g} P_g * C_g \tag{9}$$

Equations

Once the market is simulated, some variables are calculated. The equations used to compute these variables are listed below.

- Electricity prices (€/MWh):
  - Country A and B: it is the marginal cost of the cheapest generator that can supply one extra megawatt of demand in the country, regardless of the BZ of the generator.
  - OWF: it depends on the market configuration. If it belongs to a home market, it receives the domestic price (country A for HM A, and country B for HM B). For the OBZ configuration, the price formation mechanism is the one explained in section 3.4.2.

- Generators' revenues (€): revenues of each generator. They are paid their zonal price for their dispatched power.

$$Revenues_g = P_g * \sum_z \mathbb{I}_{zg} * C_z \quad \forall g \tag{10}$$

- Consumers' payments (€): total payments in each node. The consumers pay their zonal price for their demand.

$$Payments_n = Load_n * \sum_z \mathbb{I}_{zn} * C_z \quad \forall n \tag{11}$$

- Producers' surplus (€): part of the SEW that corresponds to the producers. This is the difference between their revenues and their cost to produce their dispatched power.

$$Producers\ surplus = \sum_g Revenues_g - Generation\ cost \tag{12}$$

- Consumers' surplus (€): part of the SEW corresponding to the consumers. This is the difference between their willingness to pay (obtained from the VoLL) and their payments.

$$Consumers\ surplus = \sum_n Load_n * VoLL_n - \sum_n Payments_n \tag{13}$$

- Congestion rent (€): part of the SEW corresponding to the TSOs. This is the difference between total payments and total revenues, given by Equation (11) and Equation (10), respectively.

$$Congestion\ rent = \sum_n Payments_n - \sum_g Revenues_g \tag{14}$$

- Socio-economic welfare (€): it is the surplus of all the market players. This is the sum of the producers' surplus, consumers' surplus, and congestion rent, given by Equation (12), Equation (13), and Equation (14), respectively.

$$SEW = Producers\ surplus + Consumers\ Surplus + Congestion\ rent \tag{15}$$

3.5.4 Study cases

The input data to define both countries is obtained from the ENTSO-E website[35]: load demand (2025 scenario), installed capacity by technology (2025 scenario), and the marginal cost of each generator (both scenarios for 2025).

Being the peak load 92 GW and 85 GW in country A and B, respectively, Table 2 shows that the security of supply of country A mainly relies on renewable[36] and nuclear, whereas country B on renewable and coal and lignite.

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[35] *Maps & Data*. European Network of Transmission System Operators for Electricity (ENTSO-E). https://tyndp.entsoe.eu/maps-data/

[36] Solar, wind, and hydroelectric energy.

Table 2. Market simulation of radial hybrid asset: installed capacity of each technology

Technology	Gas	Hard Coal	Lignite	Nuclear	Oil	Hydro	Solar	Onshore Wind	Offshore Wind
Country A (MW)	11496	0	0	52200	990	28600	21400	26300	3500
Country B (MW)	27643	20900	11417	0	871	24908	57650	55500	10964

Regarding the marginal costs, for the solar, offshore wind, and onshore wind technologies, their marginal cost is assumed to be null. For the hydroelectric generator, 1 €/MWh. And, finally, for the other technologies the marginal cost is computed with the following formula:

$$Marginal\ cost\ = \frac{Fuel\ cost}{Efficiency} + \frac{CO_2\ price\ * CO_2\ factor}{Efficiency} + O\&M\ cost \qquad (16)$$

For the CO_2 and fuel costs, two scenarios for 2025 are considered, where the CO_2 price is the main difference: scenario I is the current trend (25.7 €/ton), and scenario II is a great increase (54 €/ton).

Table 3. Market simulation of radial hybrid asset: generation costs

Technology	Gas	Hard Coal	Lignite	Nuclear	Oil
Efficiency (%)	58	46	46	33	35
O&M cost (€/MWh)	1.6	3.3	3.3	9	1.1
CO_2 factor (kg/GJ)	57	94	101	0	78
Fuel cost I (€/GJ)	7.4	2.5	1.1	0.47	18.7
Fuel cost II (€/GJ)	7	2.1	1.1	0.47	15.5
Marginal Cost I (€/MWh)	56.62	41.77	32.22	14.12	214
Marginal Cost II (€/MWh)	64.15	59.46	54.59	14.12	203.9

The solar, offshore wind and onshore wind hourly load profiles for both countries and the OWF are obtained from the European Commission website[37], taking the hourly load profiles of 2015 as a reference. Finally, other input data:

- OWF installed capacity: 1000 MW.
- VoLL[38]: different values are used for each country[39].
- Connections capacity: different values considered[40].
  - Both connections 1000 MW: for HM A, HM B, and OBZ.
  - 500 MW for country A, and 1000 MW for country B: for HM B and OBZ.
  - 1000 MW for country A, and 500 MW for country B: for HM A and OBZ.

Thus, six study cases are performed combining different CO_2 prices and connections capacities, being case 1 the base case:

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[37] *EMHIRES datasets*. European Commission. https://setis.ec.europa.eu/EMHIRES-datasets

[38] *Study on the estimation of the value of lost load of electricity supply in Europe*. (2018). Cambridge Economic Policy Associates Ltd (CEPA). https://www.cepa.co.uk/

[39] Country A 6920 €/MWh, and country B 12410 €/MWh. Although different values are used for each country, they do not impact the comparison between electricity market configurations.

[40] The case of a rating of the connection between the OWF and its home market lower than the OWF installed capacity is not considered: case 2 and 5 not applied for HM B, and case 3 and 6 not applied for HM A.

Table 4. Market simulation of radial hybrid asset: applied cases

Case		**1**	**2**	**3**	**4**	**5**	**6**
Capacity (MW)	**A → OWF**	1000	1000	500	1000	1000	500
	B → OWF	1000	500	1000	1000	500	1000
CO_2 prices (€/ton)		25.7	25.7	25.7	54	54	54

3.5.5 Results

The electricity market is simulated for the six previous cases, computing the total congestion rent, offshore wind farm revenues, and average OWF electricity price[41] for the three market configurations (HM A, HM B, and OBZ).

The average zonal prices[42] for both countries remain constant regardless of the market design for these study cases. For the HM A and HM B setup, the OWF price is the same as country A and B, respectively, while for the OBZ it does not necessarily coincide with the zonal price of any country.

For the base case (case 1), the results are shown in Table 5. On average, the zonal price in country A is lower than the one in country B. This is due to their generation technologies (Table 2): while country A dispatches nuclear after renewable technologies, country B generates from lignite and hard coal, which are more expensive than nuclear. As a result, the average OWF price in the HM A is 38% of the one in the HM B design, and in the OBZ only 33% (Figure 27). The OBZ setup offers the lowest OWF average price because each hour it receives the lowest onshore zonal price.

Table 5. Market simulation of radial hybrid asset: results, base case

Market configuration	Congestion Rent (MEUR)	OWF revenues (MEUR)	Average OWF price (€/MWh)
HM A	202	48	13
HM B	146	104	34
OBZ	213	37	11

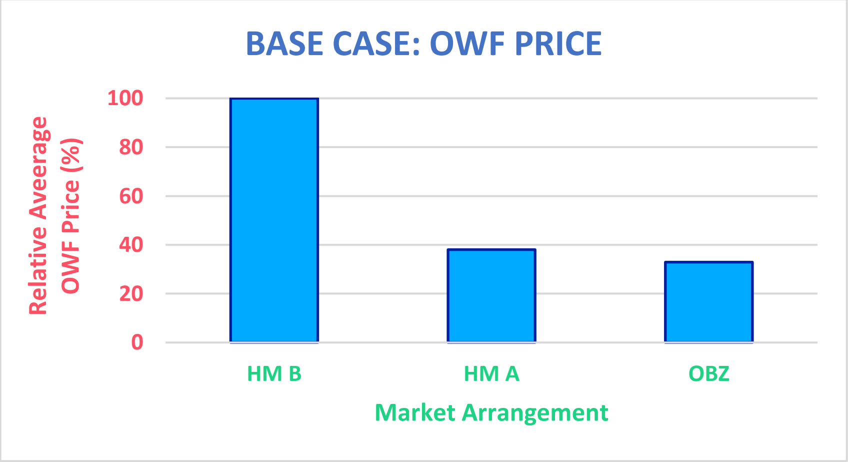

Figure 27. Market simulation of radial hybrid asset: relative OWF price, base case

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[41] Yearly average electricity price that receives the OWF per period.
[42] Yearly average zonal price per period.

A lower average OWF price means lower OWF revenues (Figure 28). Thus, the same tendency as Figure 27 is observed for the OWF revenues.

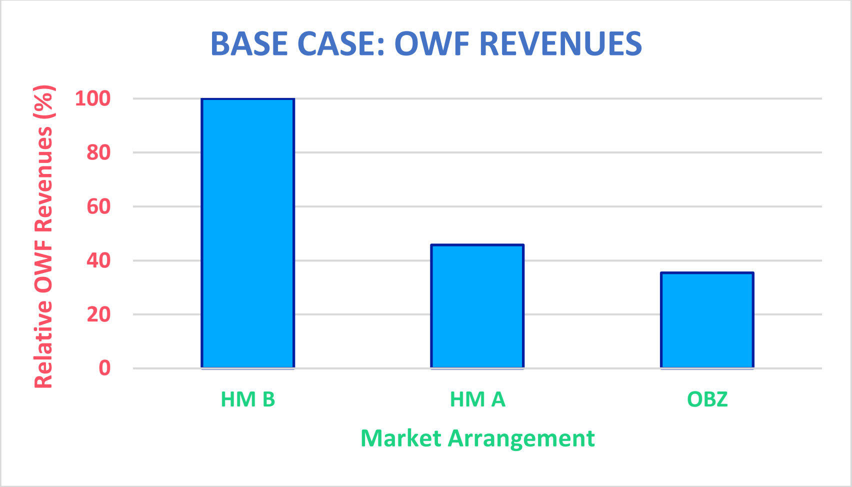

Figure 28. Market simulation of radial hybrid asset: relative OWF revenues, base case

A decrease in the OWF revenues leads to an increase in the congestion rent (Figure 29). Indeed, the OWF revenues drop the same amount as the congestion rents grow (same SEW, onshore producers' surplus, and consumers' surplus). The congestion rent in the HM A is 39% higher than the one in the HM B, and in the OBZ, 46%.

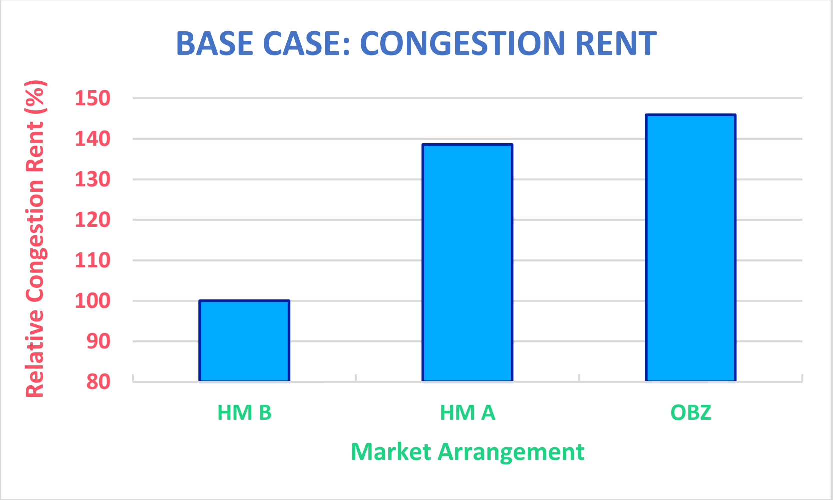

Figure 29. Market simulation of radial hybrid asset: relative congestion rent, base case

Then, a sensitivity analysis is performed by changing the capacity of the connections between the offshore platform and the onshore networks (case 2-3). On the one hand, as Figure 30 shows, the average OWF prices practically remain constant, and thus, so do the revenues. This is because, most of the time, the onshore marginal generators are the same since this is a small disturbance in comparison to the size of the system. When decreasing the offshore connection rating by 0.5 GW, the importing country must increase the internal generation by 0.5 GW. In comparison to the 92 GW and 85 GW of the peak load of country A and B, respectively, these 0.5 GW are not a significant variation for the system.

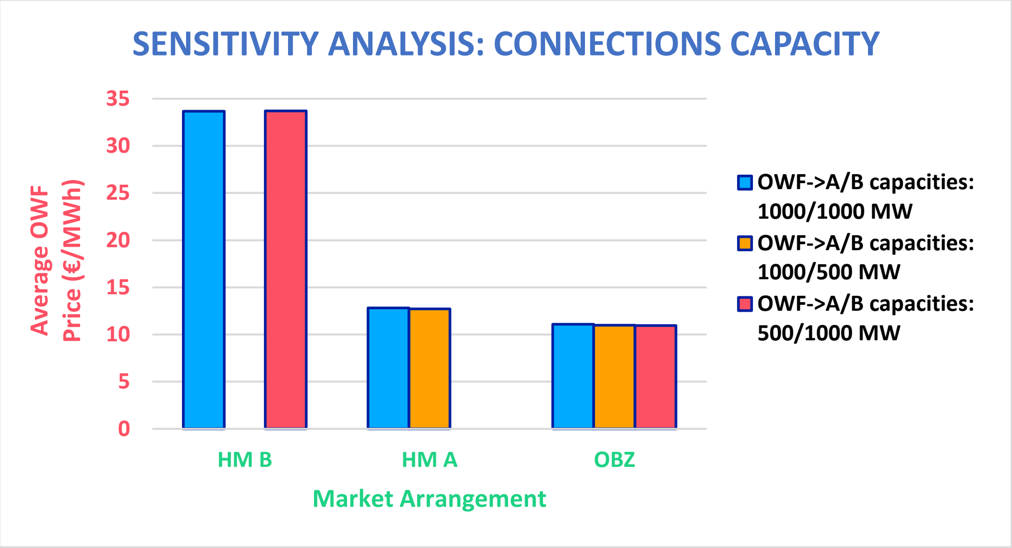

Figure 30. Market simulation of radial hybrid asset: OWF price, sensitivity analysis I[43]

On the other hand, congestion rent decreases, as Figure 31 displays. Even though the onshore marginal generators are more or less the same (and thus the marginal prices), the cross-border exchanges are lower since there is less available capacity. Therefore, the product of both is lower: the congestion rent.

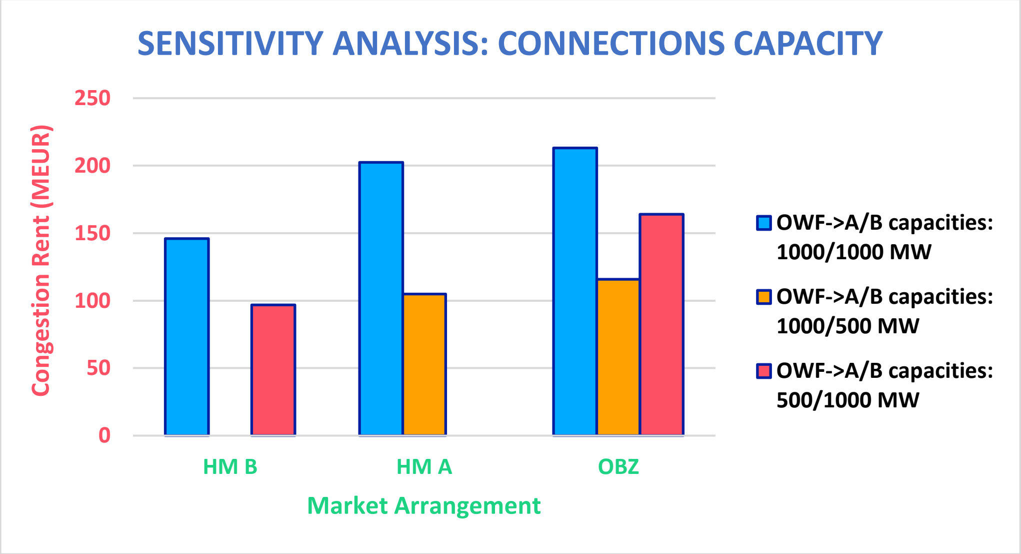

Figure 31. Market simulation of radial hybrid asset: CR, sensitivity analysis I[43]

The second sensitivity analysis consists of higher CO_2 prices[44] (cases 4-6). For the HM B configuration, the average OWF price grows considerably, as country B relies on hard coal and lignite for its security of supply. In contrast, for the HM A, it remains practically constant, as country A relies more on nuclear. Finally, since for the OBZ setup the hourly OWF price is generally the lowest between country A and B, the price is close to the one of country A, and thus,

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[43] The case of a rating of the connection between the OWF and its home market lower than the OWF installed capacity is not considered: case 2 and 5 not applied for HM B, and case 3 and 6 not applied for HM A.

[44] Cases 1-3 are referred to as CO_2 cost 1 and cases 4-6 CO_2 as cost 2.

it does not experiment perceptible changes. Figure 32 shows these trends, being the same for the OWF revenues. As for cases 1-3, there is almost no difference among cases 4-6, and thus, only cases 1 and 4 are represented.

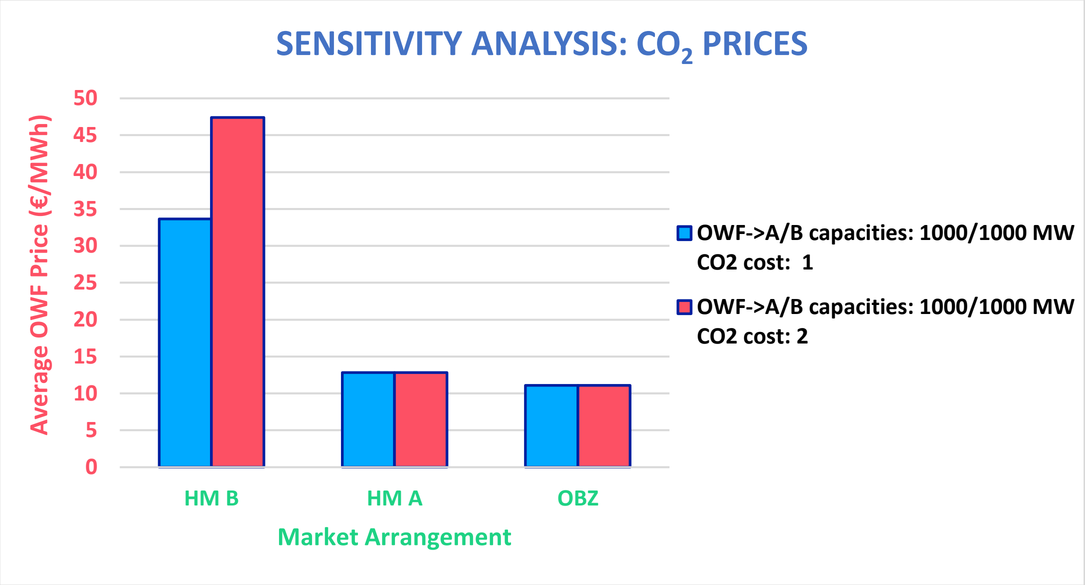

Figure 32. Market simulation of radial hybrid asset: OWF price, sensitivity analysis II

Regarding the congestion rent, it becomes higher: the cross-border exchanges are the same, but the zonal price difference is bigger.

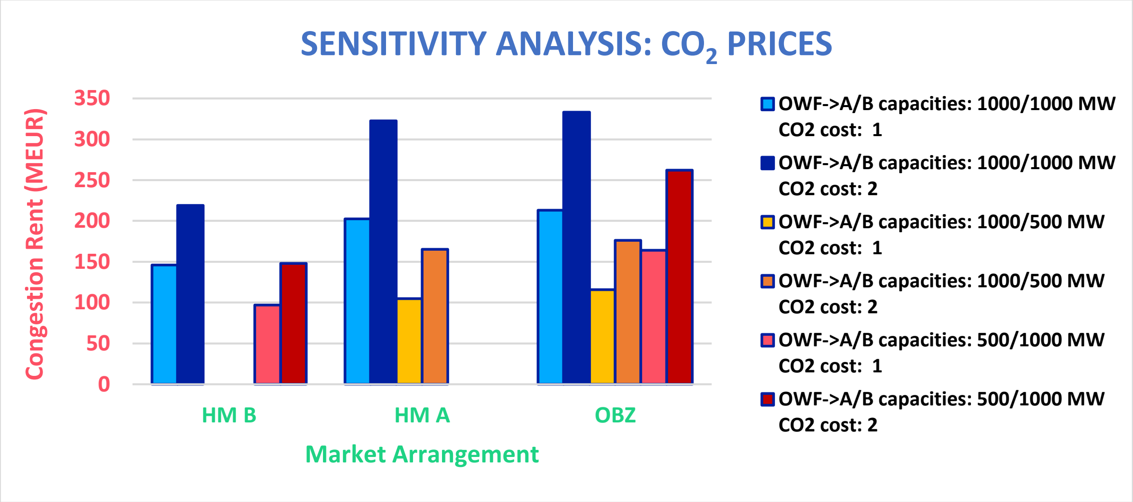

Figure 33. Market simulation of radial hybrid asset: CR, sensitivity analysis II[43]

In short, the OBZ offers lower revenues for OWF and higher congestion rent for TSOs. On the one hand, changing the connection capacity has a big influence on the congestion rent, while it is insignificant on the OWF revenues[45]. On the other hand, the impact of future increase in CO_2 prices on the OWF revenues depends on the generation technologies of each country. However, the congestion rent considerably grows in case that some countries have a dependency on coal and/or lignite and others do not, since it would increase the price difference between BZs.

In Appendix A, more information about the results from the study cases can be found.

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[45] As long as the variation stays limited.

3.6 Conclusions

To finalise this chapter, firstly, section 3.6.1 summarises the assessment and the results of the simulation of both electricity market configurations. Secondly, section 3.6.2 analyses possible SEW redistribution mechanisms for the OBZ, and section 3.6.3 discusses the main regulatory barriers for hybrid assets. Finally, section 3.6.4 concludes the chapter with a recommendation of an electricity market design for radial offshore grids.

3.6.1 Main outcomes of the chapter

Table 6 displays the main outcomes of the evaluation criteria and the simulation, which has been developed in section 3.2 (regulatory criterion), section 3.3 (operational point of view), and sections 3.4 and 3.5 (economic perspective).

Table 6. Electricity market design for radial hybrid assets: comparison summary

Criterion	Home Market	Offshore Bidding Zone
Compliance with EU regulations [15] [24]	• Need for exemption of 70% rule[46]. • Status quo.	• Compliance with 70% rule[46]. • New European bidding zones definition, but it addresses structural congestions.
System operation [3] [15]	• Implicitly, the TSO assumes the balancing responsibility, leading to higher risk and cost. • TSO needs to forecast OWF generation to compute cross-border capacity. • De facto priority for internal exchanges: discriminatory.	• The OWF operator pays for imbalances[47]. • No need from the TSO to anticipate the OWF generation for capacity calculation and allocation. • No curtailment of cross-border exchanges due to national flows.
Economic perspective [3] [15]	• Possibility of inefficient dispatch in case of negative prices. • Higher OWF revenues.	• The dispatch is the most efficient. • Lower OWF revenues, as higher congestion rent: discriminatory.

After this assessment, it can be concluded that there is a conflict between market design, regulation, and policy objectives for both configurations.

From a market design point of view, the offshore bidding zone is more beneficial: the dispatch is the most efficient (whereas the home market may be inefficient in case of negative prices), the TSO does not need to forecast the OWF generation and assumes fewer risks and costs due to imbalances. Besides, national exchanges are not prioritised over cross-border flows.

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[46] Regulation (EU) 2019/943 on the internal market for electricity, art. 16(8).

[47] Except if there are available transmission capacity and relevant platforms for cross-zonal balancing.

As seen in section 1.1, the European Union fosters the development of offshore wind energy to reach its environmental targets. The HM configuration is in line with the European renewable energy policy since this design incentivises the development of offshore wind farms. This is because the OWF operators receive the same price as conventional OWFs[48]. For its part, the OWFs generally obtain lower revenues in the offshore bidding zone market. Thus, this configuration will not encourage offshore wind energy to grow unless a redistribution of the socio-economic welfare takes place (section 3.6.2).

While the lower revenues for OWFs hampers the OBZ configuration, the regulation complicates the implementation of the HM design. Without an exemption of the 70% rule, the HM will not be desirable, as it would lead to significant countertrade and/or redispatch from the TSOs.

3.6.2 SEW redistribution mechanisms

To mitigate the OWF financial risks in the OBZ setup and to make this configuration non-discriminatory, a fair cost allocation between OWFs and TSOs is required.

Some SEW redistribution mechanisms are presented below [10] [16] [27]. These mechanisms consist of agreements between the OWF and the domestic TSO: part of the TSO congestion rent income is redistributed to the OWF operators.

- Contract for Differences (CfD). For the power generated by the OWF (and until an agreed amount), the TSO pays the price difference between onshore and offshore BZ prices. If the price difference is negative, the OWF must pay the TSO. With this mechanism, the OWF receives the home market zonal price.
- Financial Transmission Rights (FTRs). The OWF owns part of the FTRs of the connection to the home market: the TSO reimburses part of the congestion rent generated by the OWF when injecting power into its domestic market. These FTRs can be either mandatory or optional.
- Auction Revenue Rights (ARRs). Part of the TSO's revenues from auctioning FTRs are allocated to the OWF.

The CfD is more flexible and can thus cover more power volume than the FTRs. Besides, from the economic point of view, the OBZ is generally equivalent to the HM configuration.

Even though the FTRs are riskier because the OWFs may hedge less volume, if they are not mandatory, when the domestic market price is lower, the OWF can keep its higher price. Nevertheless, the OWF must pay the TSO for these rights, since the Forward Capacity Allocation (FCA) Regulation[49] states that FTRs must be auctioned and cannot be allocated without charge, which makes this mechanism less attractive [16]. Without an exception of this regulation, the OBZ configuration together with FTRs that are not free-of-charge is not economically feasible for OWF operators since the conventional OWFs would be more profitable.

Finally, the ARRs are not recommended. Since there is no direct relation between congestion rent and redistribution to the OWF, the OWF obtains fixed extra revenues but there is no hedge.

Furthermore, all these mechanisms are incompatible with Article 19 of Regulation (EU) 2019/943[50], which states that the congestion rent allocation must be prioritised to secure or increase cross-zonal capacities. And then, if these aims are fulfilled, the congestion rent could be used to reduce network tariffs. Thus, this article limits the TSO's capacity of redistributing the congestion rent [27].

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[48] Connected individually to the home country by a point-to-point connection.

[49] Commission Regulation (EU) 2016/1719: Establishing a guideline on forward capacity allocation.

[50] Regulation (EU) 2019/943 on the internal market for electricity, art. 19.

Therefore, even though the redistribution mechanisms will align the OBZ configuration with the European renewable energy policy, there are still some constraining regulations.

3.6.3 Regulatory barriers

The main regulatory barrier for the home market is the 70% rule, whereas for the offshore bidding zone configuration the congestion income management. However, hybrid assets are only referred to in the European legislation[51] as: *"where necessary, the regulatory framework should duly consider the specific situation of those assets to overcome barriers to the realisation of societally cost-efficient offshore hybrid assets"*.

Therefore, they are considered as a particular case that requires further regulation, and thus, specific considerations must be taken into account. Indeed, the Kriegers Flak CGS has received a derogation of Article 16(8) of Regulation (EU) 2019/943: the 70% rule[52].

To the same extent, exemptions of the congestion income management and financial transmission rights allocation could be analysed for hybrid assets to unblock the offshore bidding zone configuration.

3.6.4 Conclusions

As seen in the Kriegers Flak CGS, the European regulatory framework requires special considerations for hybrid assets, and thus, some exemptions must be awarded. As a result, the development of hybrid assets will be fostered.

Without the above-mentioned regulatory barriers and with redistribution mechanisms of the socio-economic welfare, the offshore bidding zone configuration is preferred to the home market. By using contracts for differences or allocation of free-of-charge financial transmission rights, the OBZ design mitigates the financial risks of the OWF operators, while the market design is more advantageous than the home market arrangement.

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[51] Regulation (EU) 2019/943 on the internal market for electricity, recital (66).

[52] *50Hertz welcomes derogation of the EU Commission for Combined Grid Solution*. (2020, October). 50Hertz. https://www.50hertz.com/

Chapter 4

Electricity market design for meshed offshore grids

4.1 Motivation and structure of the chapter

As stated in section 1.1, to optimally integrate the expected huge amount of offshore wind energy in the European power system, radial multi-terminal or meshed offshore grids are required. The main difference between both grid configurations is that, for the meshed offshore grids, to transport the generation of a given OWF to an onshore country there may be various possible offshore paths. This is because offshore loops are present (Figure 13 of section 2.3.2). Therefore, while radial multi-terminal offshore grids are currently under development and there is already one operational, meshed offshore grids could become a reality in the near future because the offshore grid is more reliable and with higher operational flexibility.

Consequently, this fourth chapter aims at analysing different electricity market configurations for meshed offshore grids. In contrast to the radial hybrid assets, there is no ongoing meshed hybrid asset to take as a reference and there are fewer performed studies about their electricity market designs. Therefore, while the previous chapter was partially based on the state of the art, this chapter becomes more challenging and original, and the previous study for radial offshore grids constitute the foundations of this chapter. One main study is considered for this chapter: PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks [17].

Whereas two electricity market arrangements were evaluated for the radial case, now a third configuration is added: single offshore bidding zone.

- Small Bidding Zones (Small BZs). Each OWF belongs to its dedicated BZ, different from the onshore BZs. Thus, each offshore node is a BZ without demand[53], only generation (nodal approach, same as OBZ configuration in radial hybrid assets). Consequently, each OWF bids in its dedicated BZ, and then, the market coupling matches its generation with the onshore demand.

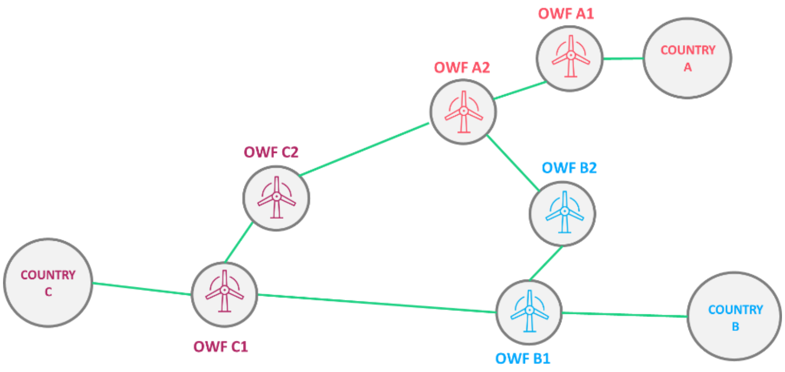

Figure 34. Electricity market design for meshed hybrid assets: small BZs

- Single Offshore Bidding Zone (Single OBZ). As discussed in section 2.4.2, under a meshed configuration, several OWFs may be close to each other with strong connections between them. Consequently, a unique OBZ, different from the domestic countries' BZs, may be of interest. Like in the small BZs, this single OBZ does not have demand[53]. Thus, all the OWFs bid in this unique OBZ, and afterwards, their generation is matched with the onshore demand.

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[53] Offshore loads could be developed, such as electrolysers.

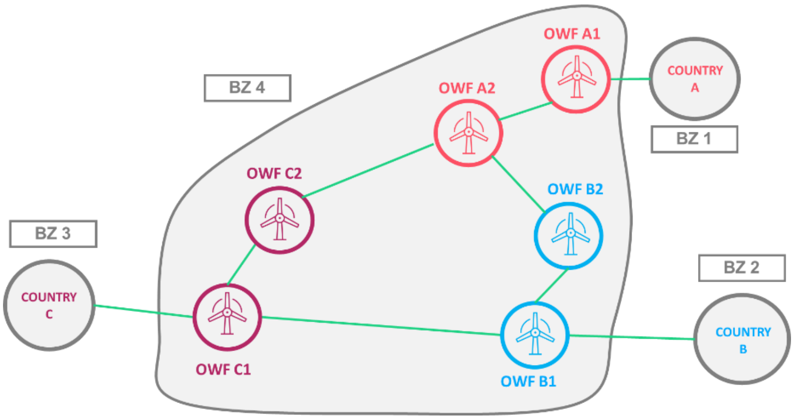

Figure 35. Electricity market design for meshed hybrid assets: single OBZ

- Home market. In this case, there are not OBZs different from the onshore BZs. Each OWF belongs to its domestic country BZ, according to the EEZs. Hence, each OWF bids in its onshore BZ, and then, the remaining capacity is available for cross-border exchanges[54]. Therefore, there is a de facto priority of the transmission capacity for the national country over the other BZs.

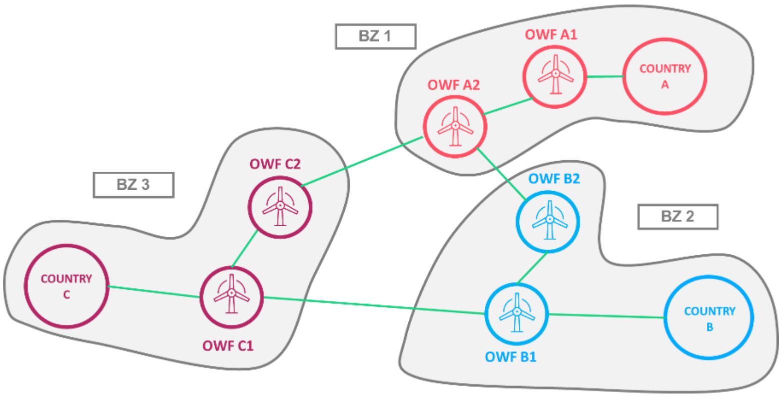

Figure 36. Electricity market design for meshed hybrid assets: home market

These three market arrangements are analysed and compared under different criteria, like in the previous chapter:

- European regulation. Whether they are in line with the current European regulatory framework.
- System operation:
  - Balancing roles.
  - Capacity calculation and allocation process.
  - Priority of internal trades over cross-border exchanges.
  - The need for redispatch.
- Economic perspective. Various topics to consider:
  - Market efficiency.
  - Price formation mechanism for OWFs.
  - OWF revenues.
  - Incentives to invest in storage or PtX.

For the same reasons as explained for the radial hybrid assets, the analysis is done under a European context. The organisation of this fourth chapter is the following: section 4.2 evaluates the three configurations under the above-mentioned criteria. Then, section 4.3 simulates the annual electricity market for the three arrangements. Finally, section 4.4 concludes the chapter with a recommendation of a market configuration.

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[54] The TSOs may take some security margins.

4.2 Analysis of electricity market designs

As mentioned in the previous section, the three electricity market configurations are analysed from a regulatory, operational, and economic point of view.

4.2.1 EU regulation

As in section 3.2, two regulatory aspects are considered: the 70% rule for cross-border capacity[55], and the definition of BZs based on structural congestions[56].

In general, all the offshore cables may be CNEs[57], and thus, 70% of their capacity must be available in the capacity calculation and allocation process. This is not the case for the HM configuration, where only the remaining capacity after the internal trades between the OWFs and their national market is available for interconnections. Consequently, most of the time this 70% rule is not de facto accomplished, which will oblige TSOs to countertrade or redispatch down the OWFs to respect it.

In the small BZs and single OBZ arrangements, since there are no power flows due to trades within BZs, 100% of the offshore capacity is available for cross-border exchanges. Therefore, this 70% rule is respected. However, note that, in the case of significant demand in the offshore nodes, intrazonal trades will appear in the single OBZ, and thus, this configuration may not naturally accomplish this rule.

Considering the BZs definition, while the HM configuration is the status quo, the small BZs and the single OBZ need a decision of the European Union to modify them. According to the European Union Regulation, the BZs definition must be based on structural congestions. Since hybrid assets connect BZs with different prices, they may induce this type of congestions[58] in the offshore grid. Whereas the single OBZ arrangement may not reflect these structural congestions that are expected in their internal offshore cables[59], the small BZs configuration is the BZ definition that better reflects these congestions.

4.2.2 System operation

As seen in section 3.3, on the one hand, for the HM setup, the TSO implicitly bears the balancing responsibility and entails higher costs. Given that the OWF operators may own other onshore assets, they can compensate for onshore imbalances with the OWF, and vice versa, without paying the imbalance price. On the other hand, in the small BZs and single OBZ, the OWF operators are incentivised to compensate for offshore imbalances with their offshore assets. Otherwise, they must pay the imbalance price[60].

Regarding the capacity calculation and allocation process, in contrast to the radial case, given that there are offshore loops, the Kirchhoff laws are needed to determine the power flows in the offshore cables. As a result, the capacity calculation and allocation mechanism becomes more complex for the zonal approach (single OBZ and HM designs), and a dedicated mechanism is

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[55] Regulation (EU) 2019/943 on the internal market for electricity, art. 16(8).

[56] Regulation (EU) 2019/943 on the internal market for electricity, art. 14(1).

[57] Network elements that are considerably impacted by cross-border trades.

[58] Predictable, frequent, and stable over time congestions.

[59] Although it does not mean that the EU will reject this BZ definition since there are currently BZs with internal structural congestions.

[60] Except if there are available transmission capacity and relevant platforms for cross-zonal balancing.

required. This will lead to ex-post redispatch to solve overloads, whereas no redispatch is needed in the small BZs configuration.

Another aspect discussed in section 3.3 was that, in the HM design, the TSO must forecast the OWF generation for the capacity calculation and allocation process. For the small BZs configuration, there is no need because there are no internal trades. This is the same case for the single OBZ unless there are offshore nodes with demand, where TSOs would need to forecast the OWF generation.

Finally, the de facto priority to internal trades limits the cross-border exchanges in the HM configuration, which is not the case for the single OBZ (unless there is offshore demand) and the small BZs, where there are no trades within BZs.

4.2.3 Economic perspective

In this section, there are different topics to consider. Firstly, the efficiency of each market arrangement. Secondly, the price formation mechanism for OWFs. And finally, the OWFs revenues and the possible incentives for storage and PtX.

4.2.3.1 Market efficiency

A market is considered efficient when the dispatch is such that the SEW is maximised, which is equivalent to minimise the generation cost if the demand is assumed to be inelastic. In absence of negative prices in the onshore bidding zones (or more generic, onshore prices lower than the OWF marginal cost), the generation dispatch is the same for the three configurations. Otherwise, the HM design may be less efficient[61].

Let us illustrate this with the numerical example of Figure 37. It consists of an HVDC meshed offshore grid where, inside each country's EEZ, two OWFs belong to the hybrid assets. Figure 37 displays the onshore electricity prices, the offshore connections rating, and the OWFs available power. Besides, the OWFs marginal cost is null and the resistance of line OWF A2-OWF C1 is double the resistance of lines OWF A2-OWF B1 and OWF B1-OWF C1, which are equal between them.

Figure 38 shows the dispatch and power flows[62] for the HM configuration: OWFs A1 and A2 are not dispatched as their marginal costs are higher than the onshore electricity price.

In contrast, Figure 39 displays the dispatch for the single OBZ and small BZs. Under these configurations, OWFs A1 and A2 can be dispatched since they do not belong to the BZ of country A. Due to congestions, the OWF A1 is not selected, but the OWF A2 generates its maximum available power.

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[61] In the case of significant offshore load, it could be different for the single OBZ case. However, this is out of the scope of this master thesis.

[62] The power flow equations are assumed to be linear, and thus, the nodal PTDFs can be used to determine the power flows through the grid. See Appendix B for the definition of these nodal PTDFs.

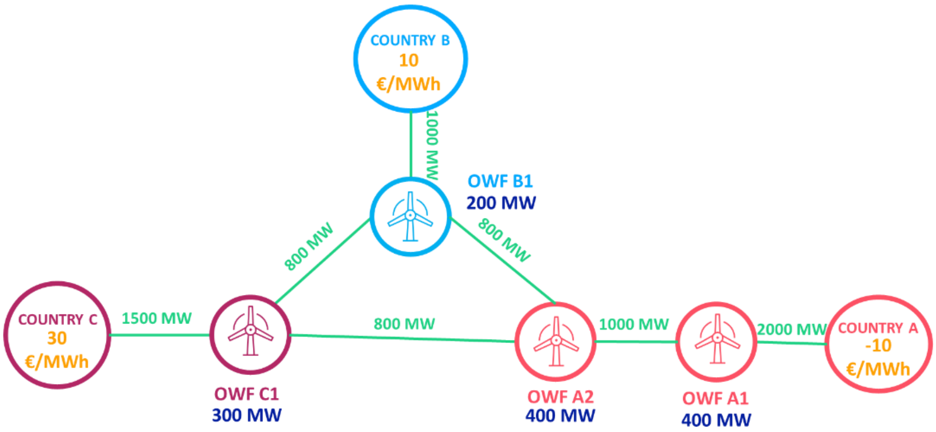

Figure 37. Market efficiency for meshed hybrid assets: problem definition

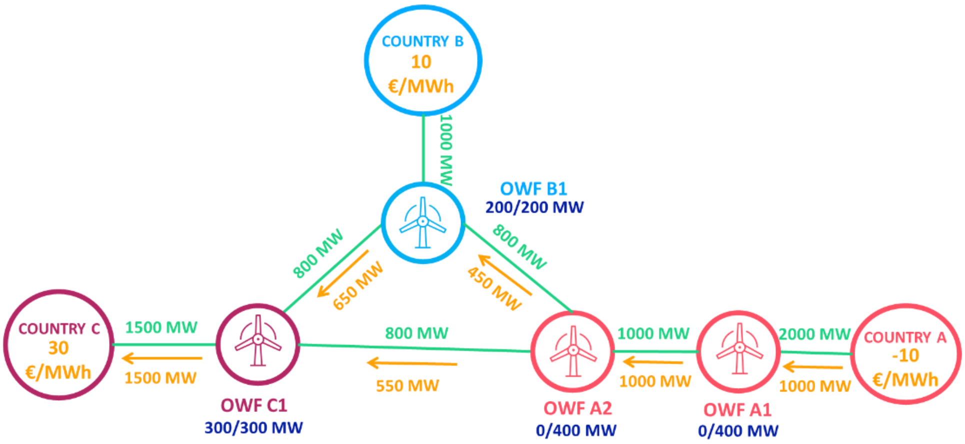

Figure 38. Market efficiency for meshed hybrid assets: HM dispatch

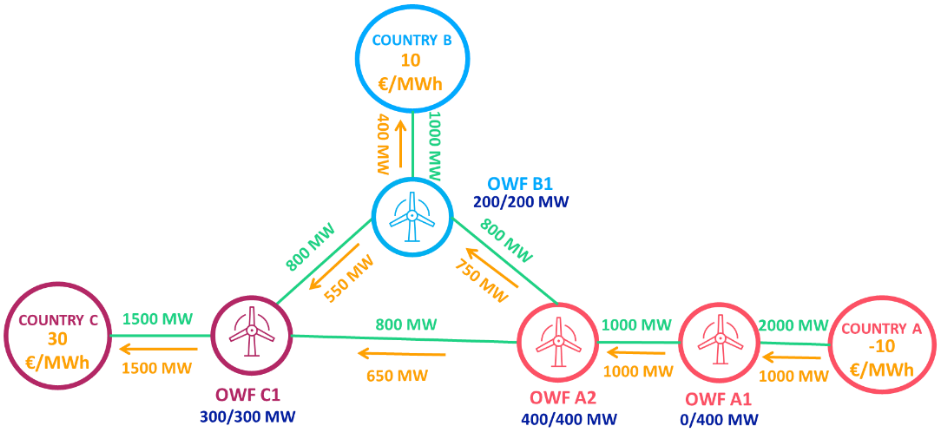

Figure 39. Market efficiency for meshed hybrid assets: small BZs and single OBZ dispatch

When comparing both dispatches, the difference lies in the 400 MW generated by the OWF A2 at null cost and by country B at 10 €/MWh, for the small BZs and the single OBZ, and the HM configuration, respectively. Therefore, the generation cost in the HM design is 4000 €/h higher, and thus, less efficient than small BZs and single OBZ.

4.2.3.2 Price formation

The OWFs price formation mechanism for the HM configuration is simple: each OWF receives the price of its domestic country. However, for the other two configurations, it becomes more complex since it depends on where the OWFs are located and how they face the congestions. For these two designs, the OWFs may obtain a combination of the onshore electricity prices, an onshore electricity price, or a null price.

For the grid represented in Figure 34, whose possible electricity market designs are simulated in section 4.3, the OWFs price formation is analysed under the three market arrangements for three periods of time: high, medium, and low OWF generation. Highlight that cable losses are neglected and the marginal cost of all the OWFs is the same: null cost. Otherwise, the price formation mechanism would be trickier.

Figure 40 displays the power flows and OWFs generation for the high OWF generation scenario. They are the same for the three market configurations, and the congested lines are coloured in red. Table 7 shows the electricity price of each OWF for the three markets.

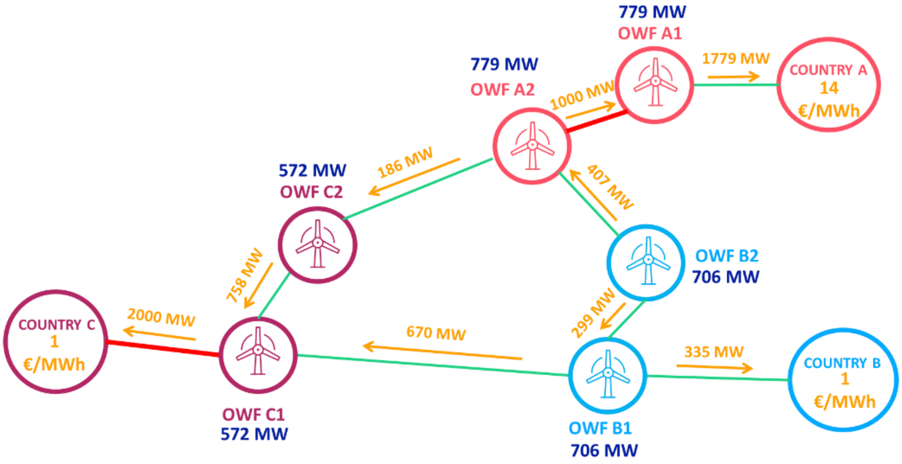

Figure 40. Price formation for meshed hybrid assets: high OWF generation scenario

For the small BZs case, the electricity price of each node corresponds to the decrease in the total generation cost if the generation in the given node increases by 1 MW, while the cable limits must be respected and the SEW must be maximised. Since lines C1-C and A2-A1 are congested, all the OWFs less A1 would inject this 1 MW in country B, and thus, their electricity price is the same as country B. In contrast, OWF A1 can inject this extra MW in the most expensive country: country A. Consequently, its electricity price is 14 €/MWh.

For the single OBZ, all the OWFs obtain the same price. Their price is the reduction of the total generation cost if the generation in this OBZ increases by 1 MW. This extra generation is shared between OWFs depending on the Generation Shift Keys (GSKs)[63]. Because the GSK for OWF A1 is 0.19, 0.19 MW of the extra 1 MW are injected in country A and 0.81 MW in country B.

Table 7. Price formation for meshed hybrid assets: high OWF generation scenario

	OWF A1	OWF A2	OWF B1	OWF B2	OWF C1	OWF C2
Home market (€/MWh)	14	14	1	1	1	1
Single OBZ (€/MWh)	3.5	3.5	3.5	3.5	3.5	3.5
Small BZs (€/MWh)	14	1	1	1	1	1

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[63] They indicate the proportion of this 1 MW that is provided by each node of the zone. See Appendix B for the mathematical formulation.

Figure 41 and Table 8 show the results for the medium OWFs generation. For the small BZs, each OWF receives a different price. The OWF A1 obtains the electricity price of country A because the line A1-A2 is congested. While the OWF C1 can inject the extra MW in the most expensive country (country C), the OWF B1 cannot because it would increase the flow in the already congested line C2-C1. Thus, the OWF B1 obtains the electricity price of the second most expensive country (country B) since there is no congestion. For the remaining OWFs, if they inject this extra MW in country B or C, they will congest even more the line C2-C1.

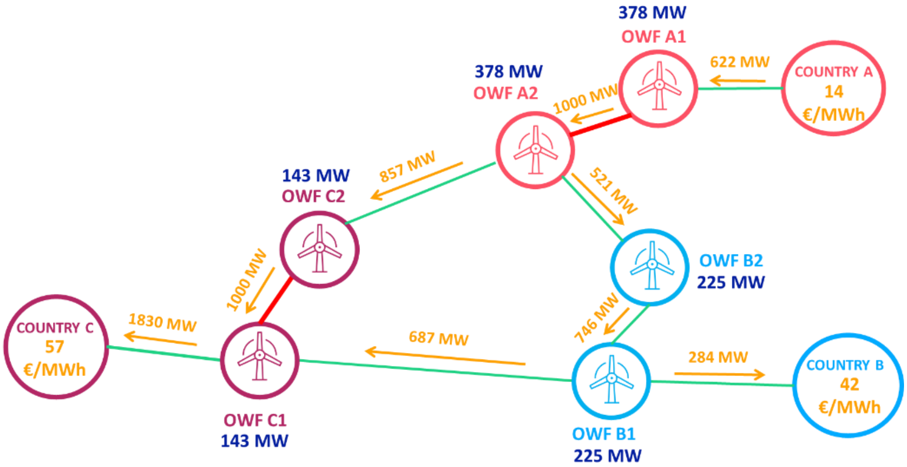

Figure 41. Price formation for meshed hybrid assets: medium OWF generation scenario

However, if they inject in country A, even though they may use line C2-C1 in the congested direction (the case of OWF C2), the generation in country A will decrease. Therefore, so will the power flow in the line C2-C1, since part of the generated power in country A flows through this line. Besides, when the OWF B2 injects in country A, part of this power flows through line C2-C1 in the opposite direction of the congestion, and thus, it relieves this line. As a result, these three OWFs receive an electricity price that is a combination of the onshore prices.

For the single OBZ, the zonal price also depends on the GSKs, apart from how each node faces the congestions (as explained above).

Table 8. Price formation for meshed hybrid assets: medium OWF generation scenario

	OWF A1	OWF A2	OWF B1	OWF B2	OWF C1	OWF C2
Home market (€/MWh)	14	14	42	42	57	57
Single OBZ (€/MWh)	30	30	30	30	30	30
Small BZs (€/MWh)	14	30	42	36	57	21

Finally, Figure 42 and Table 9 display the low OWFs generation scenario. Highlight that, for the small BZs, the OWF A1 can only inject in country A. For the other OWFs, since there is no congestion in the offshore loop, they all receive the same price.

To summarise, the OWFs receive the domestic price for the HM case. For the small BZs, each OWF obtains an electricity price that depends on how they face the congestions. If there is no congestion in the offshore loop, all the OWFs connected to this loop receive the same price. Finally, for the single OBZ, all the OWFs have the same electricity price that depends on the GSKs and the nodal marginal prices (which depend on how each node faces the congestions).

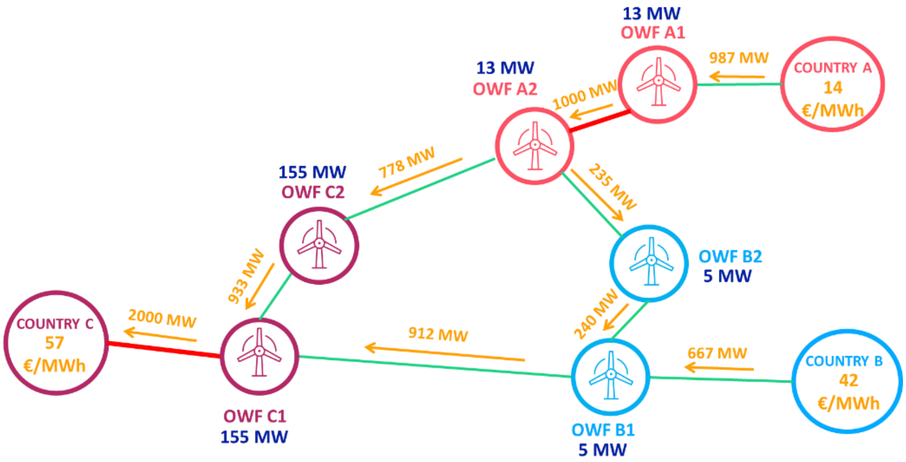

Figure 42. Price formation for meshed hybrid assets: low OWF generation scenario

Table 9. Price formation for meshed hybrid assets: low OWF generation scenario

	OWF A1	OWF A2	OWF B1	OWF B2	OWF C1	OWF C2
Home market (€/MWh)	14	14	42	42	57	57
Single OBZ (€/MWh)	41	41	41	41	41	41
Small BZs (€/MWh)	14	42	42	42	42	42

4.2.3.3 OWFs revenues

As seen in the previous tables, in the single OBZ all the OWFs receive the same price, which is generally between the second and the third lowest onshore price. This is more favourable for the OWFs that belong to the country with the lowest price, but it is the opposite for the OWFs belonging to the other two countries.

For the small BZs, each OWF may receive a different price. Some nodes can obtain the lowest or the highest onshore price, but the others receive a price between the second and third lowest price. Therefore, this option may be more convenient than single OBZs or HM for some OWFs.

Nevertheless, considering the global OWFs revenues, the home market is more beneficial than the other two market configurations. For the small BZs and the single OBZ, the lower OWFs revenues lead to higher congestion rents. Table 10 and Table 11 show the total OWF revenues and congestion rent, respectively, for the study cases of the previous section. It can be appreciated that the single OBZ and small BZs offer similar congestion rents and OWFs revenues.

Table 10. OWF revenues for meshed hybrid assets

Scenario	High OWF	Medium OWF	Low OWF
Home market (k€/h)	24.6	45.8	18.4
Single OBZ (k€/h)	14.3	45.3	14.1
Small BZs (k€/h)	14.3	45.3	14.1

Table 11. Congestion rent for meshed hybrid assets

Scenario	High OWF	Medium OWF	Low OWF
Home market (k€/h)	2.9	61	53.1
Single OBZ (k€/h)	13.1	61.5	57.4
Small BZs (k€/h)	13.1	61.5	57.4

4.2.3.4 Locational incentives

As seen in section 4.2.3.2, in the small BZs configuration each OWF can receive a different price. In some cases, depending on the formation of congestions, the prices in some nodes are much lower than in others, and they can even be null. In contrast, even if the marginal price of an OWF is null, in the HM and single OBZ designs, the OWF obtains the electricity price of the home country and the OBZ, respectively.

Therefore, under the small BZs electricity market design, there may be more hours of null price in the offshore nodes. This creates locational incentives for storage or PtX [17]. In case that the marginal price of an offshore node is zero, this given node can store electricity at zero cost to sell it in the market afterwards, when the market price will be higher. Another possibility is to transform this free electricity into another type of energy, such as hydrogen through an electrolyser (power-to-gas), and transport it onshore.

4.3 Simulation of the annual electricity market

This section performs an annual simulation of the electricity market for the three proposed configurations[64]. The small bidding zone arrangement corresponds to a nodal approach, while the home market and the single offshore bidding zone configurations to a zonal approach. Therefore, a different formulation of the problem is needed for both approaches.

Firstly, section 4.3.1 considers some assumptions, and section 4.3.2 defines the study grid and electricity market configurations. Secondly, sections 4.3.3 and 4.3.4 develop the formulation of the electricity market for both nodal and zonal approach, respectively. The problem is formulated for a period of time (one hour), and then the process is repeated for each hour of the year. Finally, section 4.3.5 defines the study case, and section 4.3.6 shows the results of the simulation.

4.3.1 Assumptions

The following considerations have been assumed before developing the formulation of the problem, being some of them the same as those explained in section 3.5.1 for the simulation of radial hybrid assets.

- The offshore grid cables are HVDC cables[65].
- The node voltages are close to their nominal value. Consequently, the power losses through the cables are neglected and the DC power flow equations are linearised around the nominal voltage. This will increase the linearity, and thus, enhance the convergence of the OPF while having good accuracy. Therefore, no limits are imposed on the voltage of the nodes in the OPFs.
- Converter limits and losses are not considered, in order to simplify.
- The 70% rule[66] is not applied for this preliminary study to simplify the formulation of the problem.
- Absence of uncertainties in demand and generation. In this way, only the day-ahead market is simulated, since it is not considered necessary to have other markets such as intraday or balancing.
- For simplification, intertemporal constraints, start-up costs and time, and no-load costs are not taken into account, and the minimum generation is zero.
- The demand is inelastic: the consumers' demand is the same regardless of the market price.

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[64] The programming language used to simulate the market designs is Python.

[65] As explained in section 2.3.1, given that they are undersea cables and the distances may be long enough, HVDC is more economically profitable than HVAC.

[66] Regulation (EU) 2019/943 on the internal market for electricity, art. 16(8).

- To have the same market efficiency for all the electricity market configurations, negative prices are not present.
- Each country network is considered a copper plate, and thus, their internal congestions are not considered. The only congestions to take into account are those in the offshore cables belonging to the hybrid asset.
- The same generator types have the same characteristics. That is to say, there is no consideration of individual generators, they are grouped by technologies. Thus, all solar, offshore, and onshore wind generators belonging to the same country have the same hourly load profiles regardless of their location in the country, respectively.
- The hydroelectric generators are always available at their maximum capacity.
- There is no offshore load, only generation, since this is out of the scope of this master thesis.
- All the generation units must participate in the redispatch process.
- N-1 security constraints are neglected because they are not needed to have a perception of the revenues and price formation for OWFs.

4.3.2 Study grid

Figure 43 shows the study grid, which has already been defined in section 4.1. It consists of three countries represented by a node and six OWFs belonging to the hybrid assets. OWFs A1 and A2 are inside the EEZ of country A, B1 and B2 of country B, and C1 and C2 of country C. As a result of their connections, they constitute a meshed offshore grid.

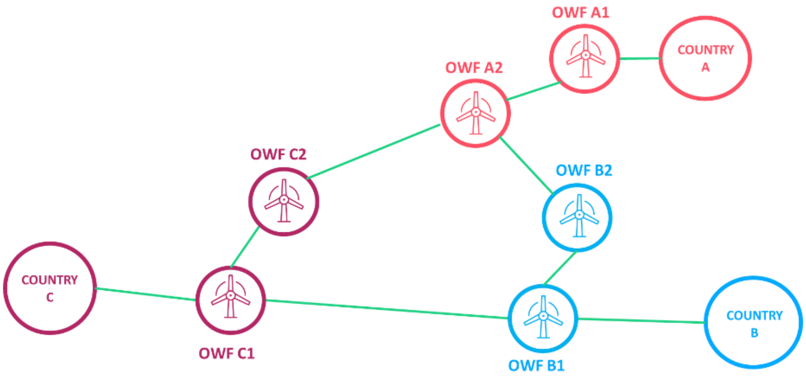

Figure 43. Market simulation of meshed hybrid asset: study grid

In each country, there are nine possible generation technologies: gas, hard coal, lignite, nuclear, oil, hydro, solar, onshore wind, and offshore wind. The three electricity market arrangements of the study grid are small bidding zones (Figure 34) with 9 BZs, single offshore bidding zone (Figure 35) with 4 BZs, and home market (Figure 36) with 3 BZs.

4.3.3 Nodal approach

For the small bidding zones configuration, there is no need for a dedicated capacity calculation and allocation mechanism. Given that this corresponds to a nodal approach, all the cable capacity is available for cross-border exchanges.

The problem becomes an optimal power flow: given the demand in each node for a given hour of the year, the output of each generator in each onshore and offshore node must be computed. Moreover, the objective function is minimised, and the constraints are respected.

Hereunder, the mathematical formulation of the problem is given for this nodal approach.

Indices and variables

- g: generator.
- n, m: nodes. In total, there are nine nodes: the three onshore countries and the six OWFs.
- C_g: marginal cost of generator g (€/MWh).
- P_g: generation output of generator g (MWh).
- P_g^{max}: maximum output of generator g (MWh).
- P_g^{min}: minimum output of generator g (MWh).
- P_{nm}: power flow of line n→m (MWh).
- P_{nm}^{max}: maximum power flow of line n→m (MWh).
- R_{nm}: resistance of line n→m (Ω).
- p_{nm}: type of circuit of line n→m. On the one hand, $p_{nm} = 1$ if the circuit is monopolar, where there is only one conductor. On the other hand, $p_{nm} = 2$ if the circuit is bipolar, where there are two conductors (one with positive and another with negative polarity).
- V_n, V_m: voltage at nodes n and m, respectively (kV).
- V_N: nominal voltage (kV).
- $Load_n$: load demand at node n (MWh).
- $\mathbb{I}_{ng}$: binary variable. $\mathbb{I}_{ng} = 1$ if generator g belongs to node n, $\mathbb{I}_{ng} = 0$ if otherwise.

State and control variables

On the one hand, the state variables of the problem are the power output of each generation unit and the voltage at each node. On the other hand, some variables must be modified to find the optimal solution: these are the control variables. In this problem, the control variables are the same as the state variables.

Inequality constraints

- Firstly, the power output of each generation unit must be between the maximum and minimum value. This is expressed as:

$$P_g^{max} \geq P_g \geq P_g^{min} \quad \forall g \tag{17}$$

- Secondly, the power flows in each line must be limited as well. The power flow in each line is given by the following formula (MWh):

$$P_{nm} = \frac{V_n - V_m}{R_{nm}} * p_{nm} * V_n \quad \forall n, m \tag{18}$$

However, if they are linearised around the nominal operation point[67], Equation (18) leads to Equation (19).

$$P_{nm} = \frac{V_n - V_m}{R_{nm}} * p_{nm} * V_N \quad \forall n, m \tag{19}$$

Thus, the inequality constraint is given by Equation (20). Note that the limits are the same in both directions.

$$P_{nm}^{max} \geq P_{nm} \geq -P_{nm}^{max} \quad \forall n, m \tag{20}$$

---

[67] The node voltages are assumed to be close to their nominal value (section 4.3.1).

Equality constraints

- There are two equality constraints. The first one is the power balance at each node. It consists of, for each node, the difference between the total generation and load must be the sum of all the power flows that leave the node. This condition is expressed by Equation (21).

$$\sum_{g} \mathbb{I}_{ng} * P_g - Load_n = \sum_{m} P_{nm} \quad \forall n \tag{21}$$

- The second constraint is the reference voltage. Since the node voltages are not limited, one node must be the reference one. For this problem, the voltage in the node represented by country A is assumed to be equal to the nominal voltage:

$$V_A = V_N \tag{22}$$

Objective function

The objective function consists of maximising the socio-economic welfare. As the demand is inelastic, this is equivalent to minimise the total generation cost. This cost is the sum of the generation cost of each unit, which is equal to its marginal cost times its generation. This is given by the following formula (€):

$$Generation\ cost = \sum_{g} P_g * C_g \tag{23}$$

4.3.4 Zonal approach

As stated in section 4.2.2, a dedicated capacity calculation and allocation mechanism is required for the HM and the single OBZ arrangements. Two models are currently implemented in Europe [1]:

- Net Transfer Capacity (NTC) approach: static modelling of the cross-border capacity since it does not take into account the real power flows between other zones. Thus, to compute the available interconnection capacity between two zones, an assumption is made for the exchanges between other zones. As a result, it leads to higher security margins and lower optimal use of the cross-border capacity.
- Flow-Based (FB) approach: more complex dynamic modelling because it considers the real flows between other bidding zones. However, it decreases security margins and increases the available cross-border capacity. This is the approach implemented in the European Central-Western region (Belgium, France, Netherlands, Germany, Austria, and Luxembourg). Besides, it will be extended to other European regions[68].

The capacity calculation and allocation approach used for this simulation is the flow-based approach since it offers more capacity for the market, and thus, it is more efficient. Besides, this approach is expected to be implemented in most of Europe[69].

The methodology and equations to simulate the flow-based market are based on reference [6]:

- Simulation of the base case: in order to compute some of the flow-based market parameters, a base case is required to know the expected generation dispatch and power flows.
- Computation of zonal parameters: needed parameters to simulate the flow-based market.
- Simulation of the flow-based market: once the previous two steps are executed, the flow-based market can be performed.

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[68] Central-Eastern and Nordic regions.

[69] At least wherever relevant.

- Simulation of the redispatch: firstly, verify if the flow-based market leads to overloads in some lines. Secondly, if this is the case, a redispatch process is applied.

Hereunder, the mathematical formulation of the problem is given for this zonal approach.

Indices and variables

Apart from those already displayed in section 4.3.3:
- z: bidding zone.
- k: critical network element.
- P_g^0: generation output of generator g after the flow-based market (MWh).
- P_g^{up}: upward redispatch for generator g after redispatch (MWh).
- P_g^{down}: downward redispatch for generator g after redispatch (MWh).
- NEP_z: net position of zone z (MWh).
- RAM_k: remaining available margin for CNE k (MWh).
- $PTDF_{zk}$: zonal PTDF associated with zone z and CNE k.
- $\mathbb{I}_{zn}$: binary variable. $\mathbb{I}_{zn} = 1$ if node n belongs to zone z, $\mathbb{I}_{zn} = 0$ if otherwise.
- $\mathbb{I}_{zg}$: binary variable. $\mathbb{I}_{zg} = 1$ if generator g belongs to zone z, $\mathbb{I}_{zg} = 0$ if otherwise.

4.3.4.1 Base case

To determine the expected generation dispatch and power flows, a nodal electricity market is simulated (base case). Consequently, the optimal power flow process is the same as the nodal approach (section 4.3.3):
- State and control variables: power output of each generation unit and the voltage at each node.
- Inequality constraints: generation limits (Equation (17)) and power flow limits (Equation (19) and Equation (20)).
- Equality constraints: power balance at each node and the reference voltage: Equation (21) and Equation (22), respectively.
- Objective function: to minimize generation cost, expressed in Equation (23), which is equivalent to maximise the socio-economic welfare since the demand is inelastic.

4.3.4.2 Zonal parameters

Two parameters are required to perform the flow-based market. On the one hand, the zonal Power Transfer Distribution Factors (PTDFs) associated with each CNE. These values represent the power flow variation in the CNE *k* when injecting 1 MW in zone *z*.

On the other hand, the estimated available power for cross-border exchanges in the CNEs is required: the Remaining Available Margin (RAM). These values are obtained from the results of the base case. CNEs are network elements that are considerably impacted by cross-border trades. To be considered as such, its maximum zonal PTDF must be higher than 5% [9], which is the case of all the offshore lines of the study case.

A detailed formulation of these two parameters can be found in Appendix B.

4.3.4.3 Flow-based market

Once the RAM and zonal PTDFs are computed for each CNE, the flow-based market is simulated. The OPF consists of, given the demand in each zone, the output of each generation unit must be computed in such a way that the objective function is minimised, and the constraints are respected. Since the simulation corresponds to a zonal approach, no voltage consideration is present, because they are associated with a node, not with a zone.

State and control variables

The state and control variables are the same: the power output of each generation unit.

Inequality constraints

- There are two inequality constraints. The first one consists of limiting the power output of each generation unit. This constraint has already been defined for the nodal approach, and it is given by Equation (17).

- In contrast to the nodal approach, the power flows through the lines are not limited. Instead, the power flows due to cross-border exchanges are restricted in the CNEs, which corresponds to all the offshore lines. On the one hand, the maximum cross-border power flows are given by the RAM (right side of Equation (24)). On the other hand, the cross-border power flows are obtained from the Net Position (NEP) of each zone and the zonal PTDFs (left side of Equation (24)). As a result, the constraint is expressed as:

  $$\sum_{z} PTDF_{zk} * NEP_z \leq RAM_k \quad \forall\, k \tag{24}$$

  The net position of each zone is the exported (positive value) or imported (negative value) power in each zone. It corresponds to the difference between generation and load in each zone, and it is given by the following expression (MWh):

  $$NEP_z = \sum_{g} \mathbb{I}_{zg} * P_g - \sum_{n} \mathbb{I}_{zn} * Load_n \quad \forall\, z \tag{25}$$

Equality constraints

In contrast to the nodal approach, there is no consideration of voltages in the zonal approach. Consequently, the only equality constraint is the power balance in the system. This is obtained by imposing the sum of NEPs to be null:

$$\sum_{z} NEP_z = 0 \tag{26}$$

Objective function

The objective function is the same as in the nodal approach: to minimize generation cost (expressed in Equation (23)).

4.3.4.4 Redispatch

Firstly, it must be verified if the flow-based market leads to overloads in any transmission line[70]. Secondly, in case that any transmission line is overloaded, a redispatch is needed. The problem becomes an OPF. The OPF consists of, given the demand in each node and the generation dispatch after the flow-based market, some units endure an upward or downward redispatch. Besides, the objective function is minimised, and the constraints are respected. Therefore, it corresponds to a nodal approach.

It is assumed that there is cooperation between TSOs, and thus, this includes countertrade: after the redispatch, the NEP of each zone can be different from the NEP after the flow-based market.

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[70] See Appendix B for the formulation.

State and control variables

Again, the state and control variables are the same. In this problem, they are the upward and downward redispatch of each generation unit and the voltage at each node.

Inequality constraints

- Firstly, the power output of each generation unit must be between its maximum and minimum value. This constraint is expressed in Equation (17). In this case, the power output of each generation unit is the dispatched power after the flow-based market plus the upward redispatch and minus the downward redispatch. This is given by the following equation:

$$P_g = P_g^0 + P_g^{up} - P_g^{down} \quad \forall g \tag{27}$$

- Secondly, the power flow in each line must be limited. As in the nodal approach, the power flows are given by Equation (19), and the constraint by Equation (20).
- Thirdly, the upward and downward redispatch of each generator must be non-negative.

$$P_g^{up}, P_g^{down} \geq 0 \quad \forall g \tag{28}$$

Equality constraints

- Firstly, the power balance at each node must be accomplished. This restriction has already been defined in Equation (21).
- Secondly, the node represented by country A is the reference voltage node: Equation (22).

Objective function

The objective function consists of minimizing the redispatch cost, given by Equation (29). On the one hand, units that endure an upward redispatch are paid their marginal cost for this extra generation apart from their market revenues (first term of the right side of Equation (29)). On the other hand, units that undergo a downward redispatch keep their market revenues but return their marginal cost for the decreased power (second term of the right side of Equation (29)). This is the current methodology in the European Central-Western region [6].

$$RD\ cost = \sum_g [C_g * P_g^{up} - C_g * P_g^{down}] \tag{29}$$

4.3.5 Study case

The input data to define both countries is obtained from the ENTSO-E website[71], 2025 scenario: load demand, installed capacity by technology, and marginal generation costs. The peak load is 92 GW, 85 GW, and 60 GW in country A, B, and C, respectively. Consequently, Table 12 shows that the security of supply of country A mainly relies on renewable[72] and nuclear technologies, country B on renewable and coal and lignite, and country C on renewable, nuclear, and gas.

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[71] *Maps & Data*. European Network of Transmission System Operators for Electricity (ENTSO-E). https://tyndp.entsoe.eu/maps-data/

[72] Solar, wind, and hydroelectric energy.

Table 12. Market simulation of meshed hybrid asset: installed capacity of each technology

Technology	Gas	Hard Coal	Lignite	Nuclear	Oil	Hydro	Solar	Onshore Wind	Offshore Wind
Country A (MW)	11496	0	0	52200	990	28600	21400	26300	3500
Country B (MW)	27643	20900	11417	0	871	24908	57650	55500	10964
Country C (MW)	29695	0	0	10715	575	16044	18803	15220	17130

Regarding the costs, they are the same as the ones considered for the simulation of radial hybrid assets: scenario I of Table 3, section 3.5.4. The solar, offshore wind and onshore wind hourly load profiles are obtained from the European Commission website[73], taking the hourly load profiles of 2015 as a reference.

Unlike the simulation of radial hybrid assets, no sensitivity analysis is performed for the meshed case because the impact has already been analysed. Finally, other input data:

- Lines capacity: two different ratings:
  - Circuits connecting the country with the offshore grid[74]: 2000 MW. Consequently, the offshore generation can always be transported to the home country because each country has 2 GW of offshore wind capacity in its EEZ (and being part of the hybrid assets).
  - The other circuits: 1000 MW.
- All circuits are bipolar.
- The installed capacity of the six OWFs belonging to the hybrid asset is 1000 MW.
- Connections length (km):

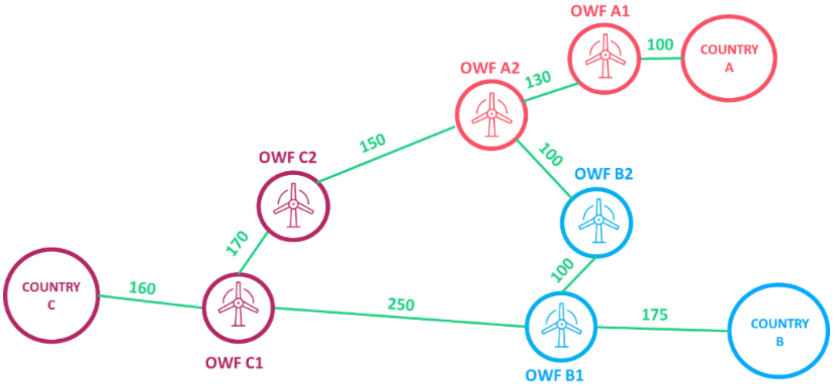

Figure 44. Market simulation of meshed hybrid asset: connections length (km)

- Line resistance: all the cables have the same resistance per km. Considering that the nominal voltage of the DC grid is ±320 kV, the line resistance is assumed to be 0.01 Ω/km[75].
- VoLL[76]: different values are used for each country[77].

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[73] *EMHIRES datasets*. European Commission. https://setis.ec.europa.eu/EMHIRES-datasets

[74] Lines A-A1, B-B1, and C-C1.

[75] Gu, X., Liu, Y., Xu, Y., Yan, Y., Cong, Y., Xie, S., & Zhang, H. (2018). Development and qualification of the extruded cable system for Xiamen ± 320 kV VSC-HVDC project. *CIGRE*, 1–7. https://www.cigre.org/

[76] *Study on the estimation of the value of lost load of electricity supply in Europe*. (2018). Cambridge Economic Policy Associates Ltd (CEPA). https://www.cepa.co.uk/

[77] Country A 6920 €/MWh, country B 12410 €/MWh, and country C 15900 €/MWh. Although different values are used for each country, they do not impact the comparison between electricity market configurations.

4.3.6 Results

Once the market is simulated, some variables are calculated. In Appendix B, the mathematical formulation to compute these variables is given.

For the three market arrangements, the generation cost and the SEW is the same: since there are no negative prices, the dispatch is the most efficient for the three cases. However, the distribution of the SEW among market players is different.

Figure 45 displays this effect, where the different components of the SEW are compared for the three market configurations taking the home market as a reference (100%). Firstly, it can be appreciated that the surplus of the consumers and the onshore producers practically remains the same. This is because the average price in the onshore nodes do not significantly vary, given that the offshore capacity is small in comparison to the size of the system.

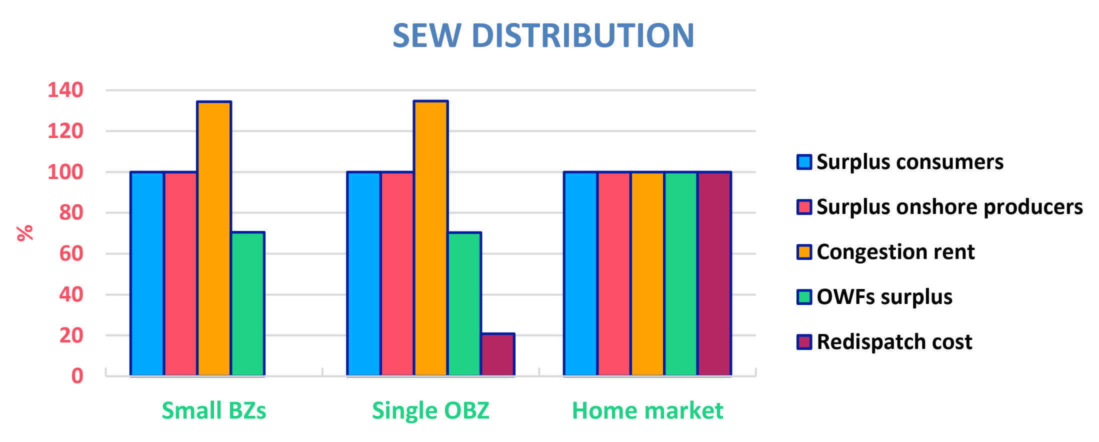

Figure 45. Market simulation of meshed hybrid asset: SEW distribution

Secondly, relevant differences are found in the OWFs surplus, as explained in section 4.2.3.3. The OWFs surplus is similar for the small BZs and single OBZ configuration because, on average, the offshore nodes receive a price between the second and third lowest onshore price. Nevertheless, the home market offers a higher total revenue for OWFs (as Figure 46 shows): the OWFs belonging to the lowest price country are less favourable but the others receive either the highest or the second highest onshore price.

Thirdly, regarding the redispatch cost[78], it is null for the small BZs configuration because no dedicated capacity calculation and allocation mechanism is required. However, this is not the case for the other market arrangements. For the home market and the single OBZ, an assumption is made for the GSK factors to apply the flow-based market. These factors do not necessarily represent the real contribution of each node to a change in the zonal NEP. This issue is exacerbated for the home market since part of the power flow in the CNEs in the base case is due to internal trades. In contrast, they are absent in the single OBZ. Highlight that the redispatch cost difference between market configurations is relatively low in comparison to the differences in congestion rent and OWFs surplus (Table 18, Appendix C).

Finally, the higher OWFs surplus for the home market means lower congestion rent, and the other way around for single OBZ and small BZs. This is because the SEW is the same and the main difference between market configurations is the congestion rent and the OWFs surplus.

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[78] Discussed in section 4.2.2.

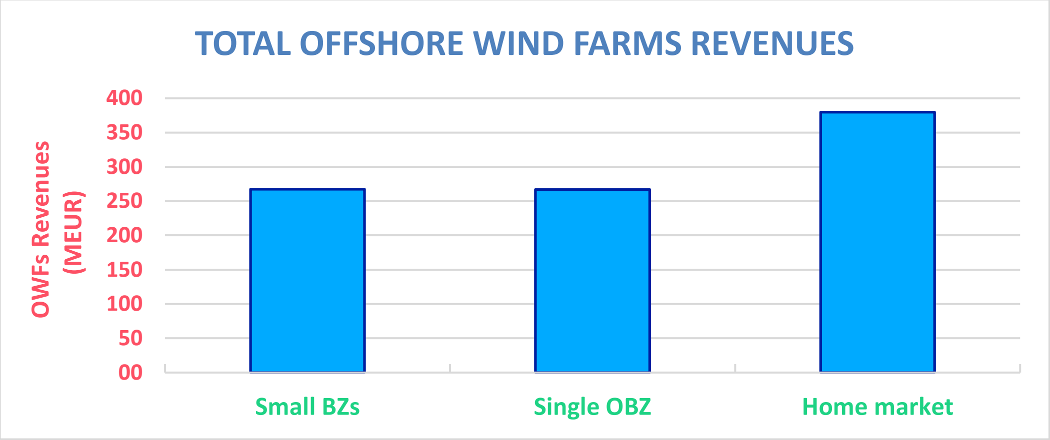

Figure 46. Market simulation of meshed hybrid asset: total OWFs revenues

However, the distribution of these revenues among OWFs is not the same (Figure 47) since it depends on the onshore prices and where the congestions arise. For the OWFs B1 and B2, and the OWFs C1 and C2, the home market is the most beneficial design because the average price of their domestic market is the highest and the second highest, respectively. However, for the OWFs A1 and A2, it is the single OBZ setup given that, in general, all the OWFs receive a price between the second and third lowest. Consequently, this is more favourable than the country A price (the lowest onshore price on average). Between small BZs and single OBZ, one is more beneficial than the other depending on the OWF: where the OWF is located and how the node faces the congestions.

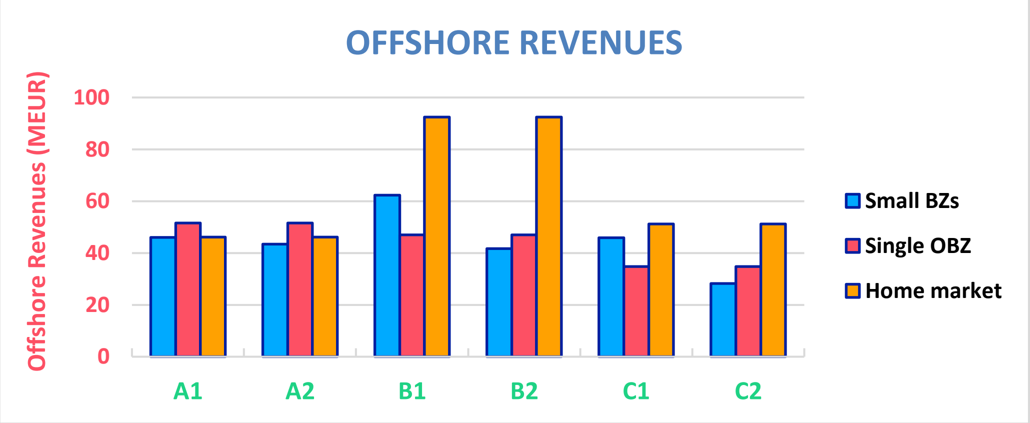

Figure 47. Market simulation of meshed hybrid asset: individual OWFs revenues

Finally, another interesting chart is Figure 48, which shows the number of hours with a null price for each OWF. Country B has a null price in 212 hours of the year. Thus, so do the OWFs B1 and B2 when they belong to this market. Nevertheless, the price is always positive for all OWFs in the single OBZ since they receive a unique price that is between the second and the third lowest market most of the time. Therefore, even if the onshore price in country B is null, all the OWFs obtain a higher price. However, for the small BZs, each node may receive a different price, and thus, more hours of null price are present, as discussed in section 4.2.3.4.

In Appendix C, more information about the results from the study case can be found.

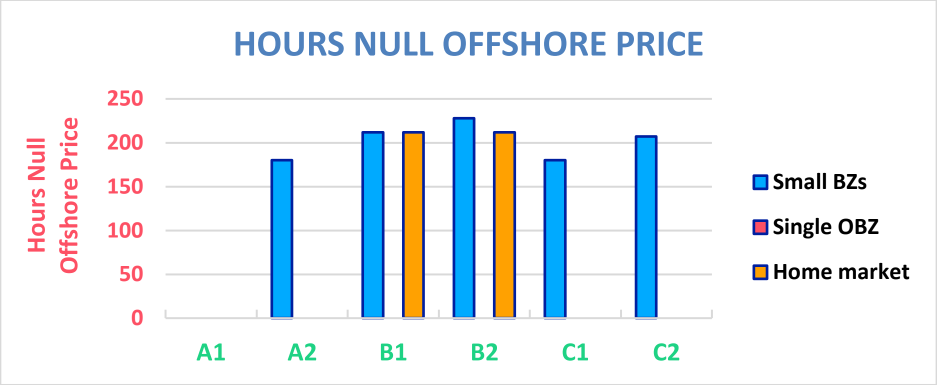

Figure 48. Market simulation of meshed hybrid asset: hours of offshore null price

4.4 Conclusions

Table 13 shows a summary of the performed analysis for each criterion in section 4.2.1 (regulatory), section 4.2.2 (operational), and sections 4.2.3 and 4.3 (economic).

Table 13. Electricity market design for meshed hybrid assets: comparison summary

	Home Market	Single OBZ	Small BZs
REGULATORY	• Need for exemption of 70% rule.	• Compliance with 70% rule[79].	• Compliance with the 70% rule.
	• Status quo.	• New European BZs definition but it may contain internal structural congestions.	• New European BZs definition based on structural congestions.
OPERATIONAL	• Implicitly, the TSO assumes higher risk and cost due to imbalances.	• The OWF operator pays for imbalances[80].	• The OWF operator pays for imbalances[80].
	• TSO needs to forecast OWF generation to compute cross-border capacity.	• No need from the TSO to anticipate the OWF generation for capacity calculation and allocation [79].	• No need from the TSO to anticipate the OWF generation for capacity calculation and allocation.
	• De facto priority for internal trades: discriminatory.	• No curtailment of cross-border exchanges due to internal trades[79].	• No curtailment of cross-border exchanges due to internal trades.
	• Zonal approach: ex-post redispatch.	• Zonal approach: ex-post redispatch.	• Nodal approach: no need for ex-post redispatch.
ECONOMIC	• Possible inefficient dispatch in case of negative prices.	• The dispatch is the most efficient[79].	• The dispatch is the most efficient.
	• Higher OWF revenues.	• Lower OWF revenues than conventional OWFs.	• Lower OWF revenues than conventional OWFs.
	• No locational incentives.	• No locational incentives.	• Locational incentives.

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[79] If there is no offshore load.

[80] Except if there are transmission capacity available and relevant balancing platforms.

As for the radial hybrid assets, there is not any configuration that fully satisfies all the criteria. And, again, there is a conflict between regulation, EU energy policy, and market design.

Considering the home market arrangement, it offers the same OWFs revenues as conventional OWFs[81], which fosters the implementation of hybrid assets (in line with the EU energy policy). However, the 70% rule[82] hampers the development of this configuration, since significant redispatch or countertrade is not desirable. Besides, from a market design point of view, this option is less convenient: ex-post redispatch, possible inefficient dispatch, de facto priority for internal trades, the TSO needs to forecast the OWF generation for the capacity calculation and allocation process and assumes higher risks and costs due to imbalances.

Regarding the other two configurations, their market design is more beneficial than the one of the home market arrangement. Nevertheless, the lower revenues for OWFs makes OWF operators prefer conventional projects unless there is a redistribution of the congestion rent collected by TSOs.

As discussed in section 3.6.2, contract for differences and financial transmission rights are SEW redistribution mechanisms that will make the single OBZ and small BZs configurations be closer to the HM design from the OWFs revenues point of view. But, again, there are two main regulatory barriers: FTRs cannot be allocated free of charge[83] (affecting only the FTRs mechanism), and the congestion rent allocation must be prioritised for other purposes[84] (affecting both mechanisms).

Concerning these regulatory barriers, the Kriegers Flak CGS shows that hybrid assets need particular considerations in the EU regulatory framework, as argued in section 3.6.3. Thus, exemptions of the 70% rule and congestion rent income must be awarded in order to unblock the development of hybrid assets. Besides, an exemption of the allocation of FTRs could be considered to make the single OBZ and small BZs configurations with FTRs economically feasible for OWFs operators.

To conclude, on the one hand, the single OBZ and small BZs configurations together with a SEW redistribution mechanism such as contract for differences or free-of-charge financial transmission rights compensate the lower revenues for OWFs operators. With these mechanisms and without regulatory barriers, these configurations are preferred to the home market arrangement because their market design is more convenient. On the other hand, it has been demonstrated that a single OBZ may be an advantageous design under a meshed configuration, where various OWFs could be close to each other with strong connections between them. Nevertheless, in the small BZs arrangement compared to single OBZ, there is no need for ex-post redispatch. Besides, not only it offers locational incentives for offshore load, but also this configuration is more flexible since the market design would adapt more easily. Therefore, as for radial hybrid assets, the small BZs configuration is the most suitable for hybrid assets under a meshed offshore grid.

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[81] Connected individually to the home country by a point-to-point connection.

[82] Regulation (EU) 2019/943 on the internal market for electricity, art. 16(8).

[83] Commission Regulation (EU) 2016/1719: Establishing a guideline on forward capacity allocation.

[84] Regulation (EU) 2019/943 on the internal market for electricity, art. 19.

Chapter 5

Conclusions

As seen in Chapter 1, offshore wind energy has drastically grown in the last decade. Moreover, it is expected to keep increasing in the upcoming decades, especially in the European Union to reach carbon neutrality in 2050. Regarding the offshore grids, nowadays most of the OWFs are connected via a point-to-point connection to their home country, according to the exclusive economic zones. Nevertheless, to optimally integrate this expected huge amount of offshore wind energy in the European power system, radial multi-terminal or meshed offshore grids are required. Therefore, hybrid assets constitute an alternative to this conventional design: they combine both offshore wind energy and cross-border capacity.

On the one hand, radial multi-terminal offshore grids are currently under development: there are several studies about their possible electricity market designs and the first-ever radial hybrid asset is already operational, the Kriegers Flak CGS. On the other hand, meshed offshore grids could shortly become a reality, because the offshore grid is more reliable and with higher operational flexibility. Consequently, there is less knowledge about their possible electricity market configurations and their study is more original and challenging.

As displayed in Chapter 2, in a mainstream OWF, since the rating of the connection to the home country is the nominal power of the OWF[85], no congestion can occur. Consequently, the OWF belongs to the electricity market of its home country: it bids in that market and it receives the electricity price of the domestic country. Nonetheless, for radial multi-terminal and meshed offshore grids, congestions can appear between an OWF and its national bidding zone.

Thus, a pertinent market design is needed for hybrid assets, different from the conventional design. While two electricity market configurations are analysed for radial hybrid assets (Chapter 3), a third option is considered for meshed hybrid assets (Chapter 4):

- Home market. This is the status quo since there is no change of bidding zones: the OWF belongs to the BZ of its home country, according to the EEZs. Each OWF bids in its domestic country and receives its zonal price. Once the wind forecast is done, the remaining connection capacity[86] is available as cross-border capacity for the day-ahead market.
- Nodal configuration, which is referred to as offshore bidding zone and small bidding zones in the radial and meshed offshore grid, respectively. Each OWF belongs to its dedicated BZ, which is a BZ without demand[87], only with generation: the OWF bids in its BZ, and then, the market coupling algorithm matches the offshore generation with the onshore demand. After the market clearing, the OWF obtains the highest price of the onshore BZs to which it is connected via an uncongested connection, in the case of radial offshore grids. For a meshed offshore grid, each OWF obtains a price that depends on how the node faces the congestions.
- Single offshore bidding zone. A third configuration could be of interest for meshed offshore grids: in the case of several OWFs close to each other with strong connections between them, a unique OBZ could be an alternative to the nodal and the home market configurations. All the OWFs belong to a unique BZ without demand[87], where the OWFs bid, and then, the market coupling algorithm matches the offshore generation with the onshore demand. Under this configuration, all the OWFs receive the same price that will depend on how the congestions are distributed.

The assessment of each configuration for both radial and meshed hybrid assets concludes that there is a conflict between market design, regulation, and policy objectives for each proposed electricity market design.

Considering the economic point of view, the HM configuration offers the same OWFs revenues as conventional configurations[88], incentivising the development of offshore wind energy, which

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[85] Unless overplanting, but it is not a common practice.

[86] The TSOs may take some security margins.

[87] Offshore loads could be developed, such as electrolysers.

[88] Connected individually to the home country by a point-to-point connection.

is the current policy of the EU. Nevertheless, the OWFs revenues are lower in the nodal and single OBZ arrangements. Consequently, a SEW redistribution mechanism is required for these configurations to mitigate this inconvenience, where part of the congestion rent income of the domestic TSOs is allocated to the OWF operators.

From the three SEW redistribution mechanisms proposed in section 3.6.2, two are recommended to compensate those lower revenues. On the one hand, contract for differences, where the domestic TSO pays the price difference between the onshore and offshore zonal prices[89] for the power generated by the OWF and until an agreed amount. On the other hand, financial transmission rights, where the TSO reimburses part of the congestion rent generated by the OWF when injecting power into its domestic market[90].

Regarding the regulatory perspective, each configuration copes with regulatory barriers. On the one hand, the 70% rule[91] hampers the HM arrangement since significant countertrade and/or redispatch is needed. On the other hand, the priority of the congestion rent allocation to other aims than redistributing to OWF operators[92] complicates the development of the nodal and single OBZ configurations because no redistribution mechanism is possible. Besides, even with an exemption of that regulation, since the FTRs cannot be allocated free of charge[93], a nodal or single OBZ arrangement without free-of-charge FTRs does not mitigate the lower OWFs revenues.

Concerning the market design, on the one hand, the HM configuration is less beneficial than the nodal and single OBZ case. On the other hand, in the small BZs arrangement compared to single OBZ, there is no need for ex-post redispatch. Besides, not only it offers locational incentives for offshore load, but also this configuration is more flexible since the market design would adapt more easily.

In conclusion, to foster the development of hybrid assets, some exemptions of the current European regulatory framework are needed in the short-term, as in the case of the Kriegers Flak CGS with the 70% rule. However, in the long-term, a particular regulation for hybrid assets is required. Without regulatory barriers, the market design makes the difference between the possible configurations. Thus, the nodal electricity market design is the most convenient for hybrid assets, for both radial and meshed offshore grids, with contract for differences or free-of-charge financial transmission rights.

Nevertheless, further analysis of the topic is suggested. In particular, the following studies are of interest:

- Offshore nodes with demand have been considered out of the scope of this master thesis. Hence, the impact of offshore load in the electricity market design needs additional analysis.
- The conditions of the recommended SEW redistribution mechanisms. Either CfD or FTRs has been presented as a must-have complement to the nodal and single OBZ designs. However, the details of the agreement between OWFs operators and TSOs, such as volume or duration, have not been evaluated.
- The balancing responsibility of TSOs and OWFs operators. Some questions must be addressed: who copes with the imbalances that arise in the new BZs or to which extent OWFs can compensate offshore imbalances with onshore assets in the HM design, among others.
- As argued, hybrid assets require a particular European regulation in the long-term. Therefore, the conditions of this possible new regulation must be assessed.

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[89] If the price difference is negative, the OWF must pay the TSO.

[90] These FTRs can be either mandatory or optional.

[91] Regulation (EU) 2019/943 on the internal market for electricity, art. 16(8).

[92] Regulation (EU) 2019/943 on the internal market for electricity, art. 19.

[93] Commission Regulation (EU) 2016/1719: Establishing a guideline on forward capacity allocation.

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Appendixes

A. Electricity market simulation for radial hybrid assets: detailed results

The annual electricity market is simulated for the six study cases (Table 4). Then, for the three market configurations (HM A and B, and OBZ), the results are computed[94]:

Table 14. Market simulation of radial hybrid asset: congestion rent (MEUR)

Cases	**1**	**2**	**3**	**4**	**5**	**6**
HM B	146	-	97	219	-	148
HM A	202	105	-	323	165	-
OBZ	213	116	164	333	176	262

Table 15. Market simulation of radial hybrid asset: OWF revenues (MEUR)

Cases	**1**	**2**	**3**	**4**	**5**	**6**
HM B	103.94	-	103.7	150.99	-	150.74
HM A	47.56	47.62	-	47.61	47.65	-
OBZ	36.87	36.62	36.47	36.94	36.67	36.55

Table 16. Market simulation of radial hybrid asset: average OWF price[95] (€/MWh)

Cases	**1**	**2**	**3**	**4**	**5**	**6**
HM B	33.66	-	33.7	47.39	-	47.41
HM A	12.81	12.72	-	12.82	12.73	-
OBZ	11.07	10.97	10.96	11.09	10.98	10.97

The hours of congestion of each offshore connection are independent of the market arrangement:

Table 17. Market simulation of radial hybrid asset: hours of congestion per connection

Cases	**1**	**2**	**3**	**4**	**5**	**6**
A→OWF	37	0	4473	37	0	4474
OWF→B	7071	7132	2633	7061	7129	2623
B→OWF	9	140	0	11	138	0
OWF→A	1348	1241	1432	1350	1241	1433

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[94] The case of a rating of the connection between the OWF and its home market lower than the OWF installed capacity is not considered: case 2 and 5 not applied for HM B, and case 3 and 6 not applied for HM A.

[95] Yearly average price that receives the OWF per period.

B. Electricity market simulation for meshed hybrid assets: further formulation

This appendix develops an additional formulation of Chapter 4. In particular, each section refers to section 4.3.4.2, section 4.3.4.4, and section 4.3.6, respectively.

B.1 Zonal parameters

Two parameters are required to perform the flow-based market. On the one hand, the first parameter is the zonal PTDFs associated with each CNE. To compute these values, firstly, the nodal PTDFs are computed. As the power flow equations are linearised, they represent the power flow variation in line *l* when injecting 1 MW in node *n*. They are given by the following equation:

$$PTDF_{nl} = [(B * A) * (A^t * B * A)^{-1}]^t \tag{30}$$

Being:

- A: incidence matrix, size $l\ x\ (n-1)$. $a_{ln} = 1$ if line *l* starts in node *n*, $a_{ln} = -1$ if line *l* ends in node *n*, and $a_{ln} = 0$ if line *l* is not connected to node *n*. The column of the reference node (country A) is removed so that the matrix can be inverted. Once the nodal PTDFs are computed, the row corresponding to this node is added: null row.
- B: conductance matrix, size $l\ x\ l$. Diagonal matrix with the conductance of each line (Ω^{-1}).

Secondly, given that the zonal PTDFs represent the power flow variation in line *l* when injecting 1 MW in zone *z*, an assumption of the nodal distribution of this 1 MW inside the zone is needed. For that, the GSKs are defined, which indicate the proportion of this 1 MW that is provided by each node of the zone. It is considered that all the generators participate proportionally to its power range:

$$GSK_{zn} = \frac{\mathbb{I}_{zn} * \sum_g \mathbb{I}_{ng} * (P_g^{max} - P_g^{min})}{\sum_n \mathbb{I}_{zn} * \sum_g \mathbb{I}_{ng} * (P_g^{max} - P_g^{min})} \quad \forall z, n \tag{31}$$

Finally, the zonal PTDFs are expressed by the following equation:

$$PTDF_{zl} = \sum_n \mathbb{I}_{zn} * GSK_{zn} * PTDF_{nl} \quad \forall z, l \tag{32}$$

On the other hand, the second parameter is the estimated available cross-border capacity in the CNEs, the RAM:

$$RAM_k = P_k^{max} - P_k^{ref'} - FRM_k - FAV_k \quad \forall\ k \tag{33}$$

$$P_k^{ref\prime} = P_k^{ref} - \sum_z NEP_z^{ref} * PTDF_{zk} \quad \forall\ k \tag{34}$$

Being:

- P_k^{max}: maximum power flow of the CNE *k* (MWh).
- $P_k^{ref\prime}$: estimated power flow of the CNE *k* without exchanges between bidding zones (MWh). This is obtained from the base case and is given by Equation (34): they correspond to the total power flow through the CNE minus the power flow due to cross-border exchanges.

- P_k^{ref}: power flow of CNE *k* for the base case (MWh).
- NEP_z^{ref}: net position of zone *z* for the base case (MWh).
- FRM_k: Flow Reliability Margin (FRM), which includes possible deviations from the expected power flows. No FRM is considered: $FRM_k = 0 \ \forall \ k$.
- FAV_k: Final Adjustment Value (FAV) to cover issues that are not considered, such as voltage control. No FAV is considered: $FAV_k = 0 \ \forall \ k$.

Thus, if also including a minimum value, Equation (33) becomes:

$$RAM_k = max\left(RAM_k^{min}, P_k^{max} - P_k^{ref'}\right) \quad \forall \ k \tag{35}$$

Since the 70% rule is not imposed, the minimum value is considered to be null: $RAM_k^{min} = 0 \ \forall \ k$.

B.2 Redispatch

To verify if the flow-based market leads to overloads in any transmission line, the power flows must be obtained. Since there is no computation of node voltages for the zonal market, the power flow in each line *l* is computed by using the nodal PTDFs (MWh):

$$P_l = \sum_n [\sum_g (\mathbb{I}_{ng} * P_g - Load_n) * PTDF_{nl}] \quad \forall l \tag{36}$$

B.3 Final results

Once the market is simulated, some variables are calculated. Hereunder, the mathematical formulation to compute these variables is given.

Indices and variables

Apart from those already displayed in sections 4.3.3 and 4.3.4:

- $VoLL_n$: value of lost load of node *n* (€/MWh)[96].
- C_z: zonal price of bidding zone *z* (€/MWh).
- $\mathbb{I}_{zm}$: binary variable. $\mathbb{I}_{zm} = 1$ if node *m* belongs to zone *z*, $\mathbb{I}_{zm} = 0$ if otherwise.

Equations

- Generators' revenues (€): revenues of each generator. It consists of two parts. Firstly, each generation unit receives the zonal price for the dispatched power after the flow-based market (first term of the right side of Equation (37)). Secondly, they are paid their marginal cost for the upward redispatch and they return the marginal cost of the downward redispatch (second term of the right side of Equation (37)).

$$Revenues_g = P_g^0 * \sum_z \mathbb{I}_{zg} * C_z + C_g * (P_g^{up} - P_g^{down}) \quad \forall g \tag{37}$$

- Consumers' payments (€): total payments in each node. The redispatch cost is not considered inside the consumers' payments but as another part of the SEW. The consumers pay their zonal price for their demand.

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[96] Note that load shedding is not allowed. The value of lost load is only used to compute the consumers' willingness to pay, in order to determine the consumers' surplus.

$$Payments_n = Load_n * \sum_z \mathbb{I}_{zn} * C_z \quad \forall n \tag{38}$$

- Producers' surplus (€): part of the SEW that corresponds to the producers. This is the difference between their revenues and their cost to produce their dispatched power.

$$Producers\ surplus = \sum_g Revenues_g - Generation\ cost \tag{39}$$

- Consumers' surplus (€): part of the SEW corresponding to the consumers. This is the difference between their willingness to pay (obtained from the VoLL) and their payments.

$$Consumers\ surplus = \sum_n Load_n * VoLL_n - \sum_n Payments_n \tag{40}$$

- Congestion rent (€): part of the SEW corresponding to the TSOs, which is the sum of the congestion rent associated with each transmission line. This is the price difference between two connected nodes times the power flow through the transmission line (after the redispatch process, if applied). Since each line will be considered twice (in both directions), the total congestion rent is half of this total sum.

$$Congestion\ rent = 0.5 * \sum_n \sum_m P_{nm} * [\sum_z \mathbb{I}_{zm} * C_z - \sum_z \mathbb{I}_{zn} * C_z] \tag{41}$$

- Socio-economic welfare (€): it is composed of four parts.

$$SEW = Producers\ surplus + Consumers\ Surplus + Congestion\ rent - RD\ cost \tag{42}$$

C. Electricity market simulation for meshed hybrid assets: detailed results

After the yearly simulation, the total annual results for the three electricity market configurations are the following:

Table 18. Market simulation of meshed hybrid asset: total annual results

Market configuration	Small BZs	Single OBZ	Home Market
Generation cost (MEUR)	9384	9384	9384
Congestion rent (MEUR)	427	428	318
OWFs revenues (MEUR)	268	267	380
SEW (MEUR)	14948374	14948374	14948374
Revenues (MEUR)	33807	33798	33915
Payments (MEUR)	34234	34225	34229
Surplus producers (MEUR)	24423	24414	24531
Surplus consumers (MEUR)	14923524	14923533	14923529
OWFs surplus (MEUR)	268	267	380
Hours of redispatch	0	372	3074
Cost of redispatch (MEUR)	0	0.7	3.3

Then, considering the results from a nodal point of view for each electricity market arrangement:

Table 19. Market simulation of meshed hybrid asset: nodal results, small BZs market

Node	Average price[97] (€/MWh)	Revenues (MEUR)	Payments (MEUR)	Surplus producers (MEUR)	Surplus consumers (MEUR)	Hours null price	Average revenues[98] (€/MWh)
A	12.47	5908	5932	3975	3180036	0	12.90
B	33.34	18228	18615	12833	6722162	212	34.18
C	27.75	9403	9687	7348	5021326	0	30.40
A1	12.47	46.01	0	46.01	0	0	12.18
A2	17.90	43.46	0	43.46	0	180	11.51
B1	23.79	62.27	0	62.27	0	212	17.98
B2	18.59	41.69	0	41.69	0	228	12.37
C1	25.83	45.94	0	45.94	0	180	18.72
C2	17.19	28.20	0	28.20	0	207	11.51

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[97] Yearly nodal average price per period.

[98] Yearly nodal average revenues per generated energy.

Table 20. Market simulation of meshed hybrid asset: nodal results, single OBZ market

Node	Average price (€/MWh)	Revenues (MEUR)	Payments (MEUR)	Surplus producers (MEUR)	Surplus consumers (MEUR)	Hours null price	Average revenues (€/MWh)
A	12.46	5896	5928	3971	3180040	0	12.89
B	33.33	18275	18613	12831	6722164	212	34.21
C	27.74	9361	9684	7345	5021329	0	30.30
A1	18.81	51.63	0	51.63	0	0	13.67
A2	18.81	51.63	0	51.63	0	0	13.67
B1	18.81	47.06	0	47.06	0	0	13.59
B2	18.81	47.06	0	47.06	0	0	13.96
C1	18.81	34.79	0	34.79	0	0	14.18
C2	18.81	34.79	0	34.79	0	0	14.20

Table 21. Market simulation of meshed hybrid asset: nodal results, home market

Node	Average price (€/MWh)	Revenues (MEUR)	Payments (MEUR)	Surplus producers (MEUR)	Surplus consumers (MEUR)	Hours null price	Average revenues (€/MWh)
A	12.49	5899	5939	3981	3180029	0	12.90
B	33.31	18212	18605	12823	6722173	212	34.15
C	27.75	9424	9686	7347	5021327	0	30.37
A1	12.49	46.10	0	46.10	0	0	12.21
A2	12.49	46.10	0	46.10	0	0	12.21
B1	33.31	92.48	0	92.48	0	212	27.51
B2	33.31	92.48	0	92.48	0	212	28.38
C1	27.75	51.18	0	51.18	0	0	20.86
C2	27.75	51.18	0	51.18	0	0	20.89

Finally, some graphs from the results shown in the previous tables are attached.

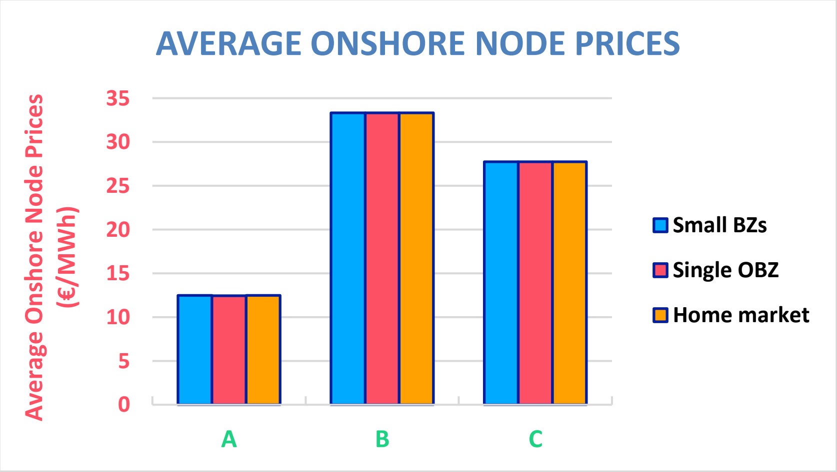

Figure 49. Market simulation of meshed hybrid asset: average onshore node prices

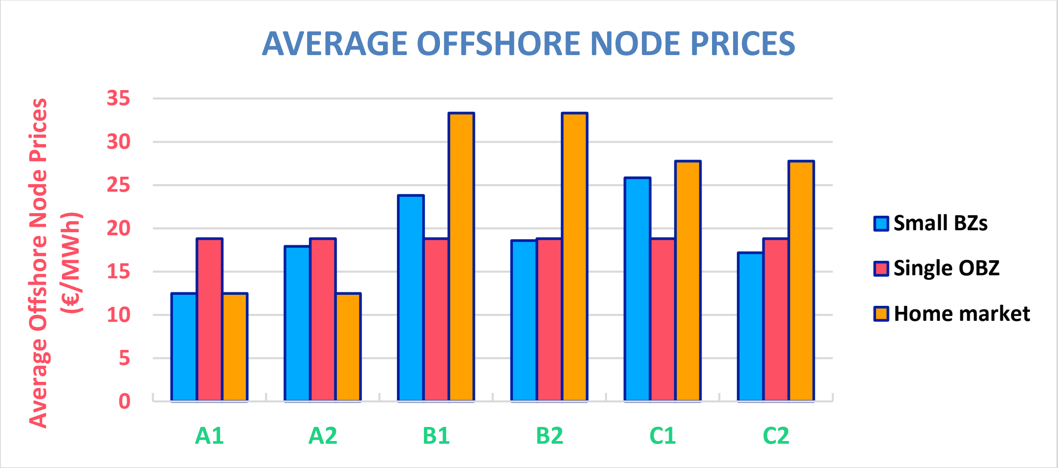

Figure 50. Market simulation of meshed hybrid asset: average offshore node prices

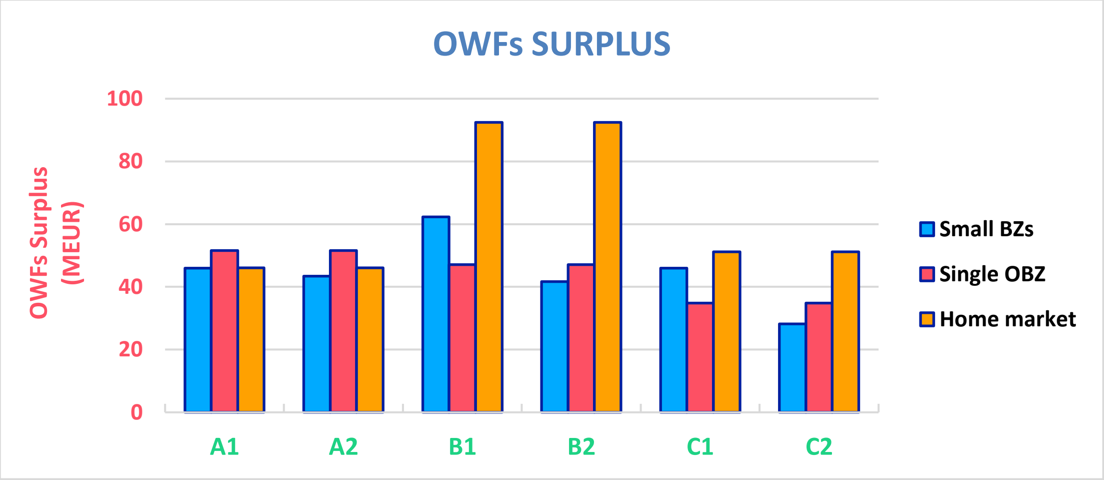

Figure 51. Market simulation of meshed hybrid asset: individual OWFs surplus

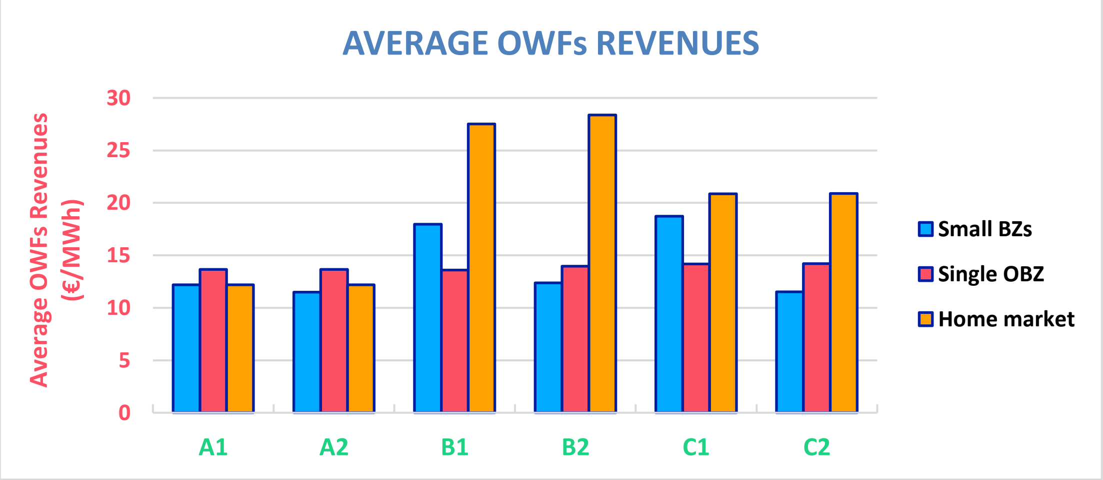

Figure 52. Market simulation of meshed hybrid asset: average individual OWFs revenues

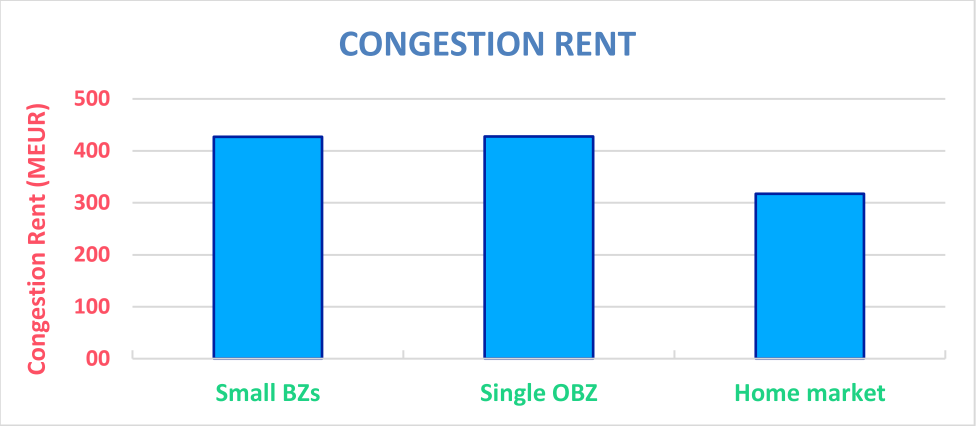

Figure 53. Market simulation of meshed hybrid asset: congestion rent

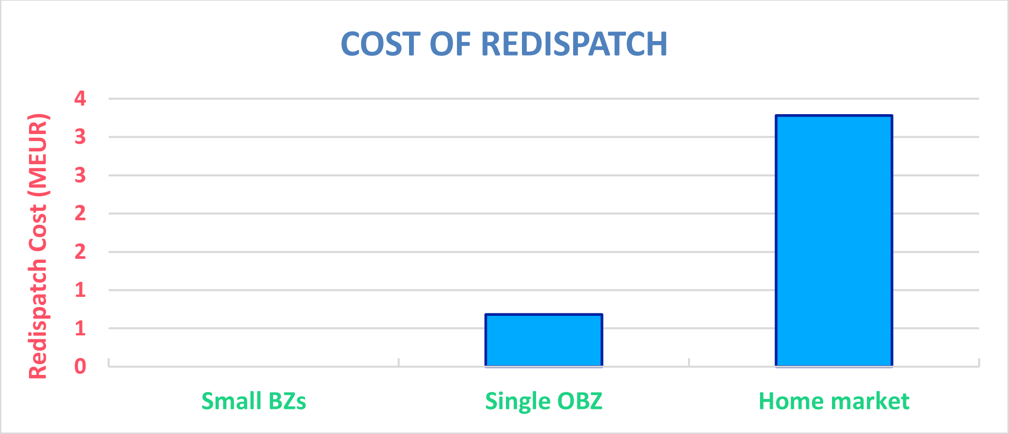

Figure 54. Market simulation of meshed hybrid asset: cost of redispatch

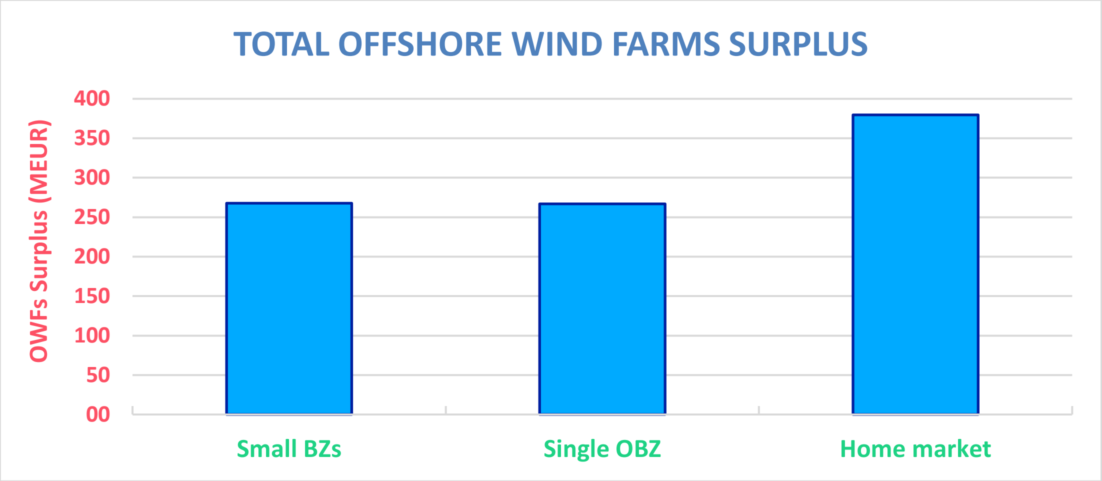

Figure 55. Market simulation of meshed hybrid asset: total OWFs surplus