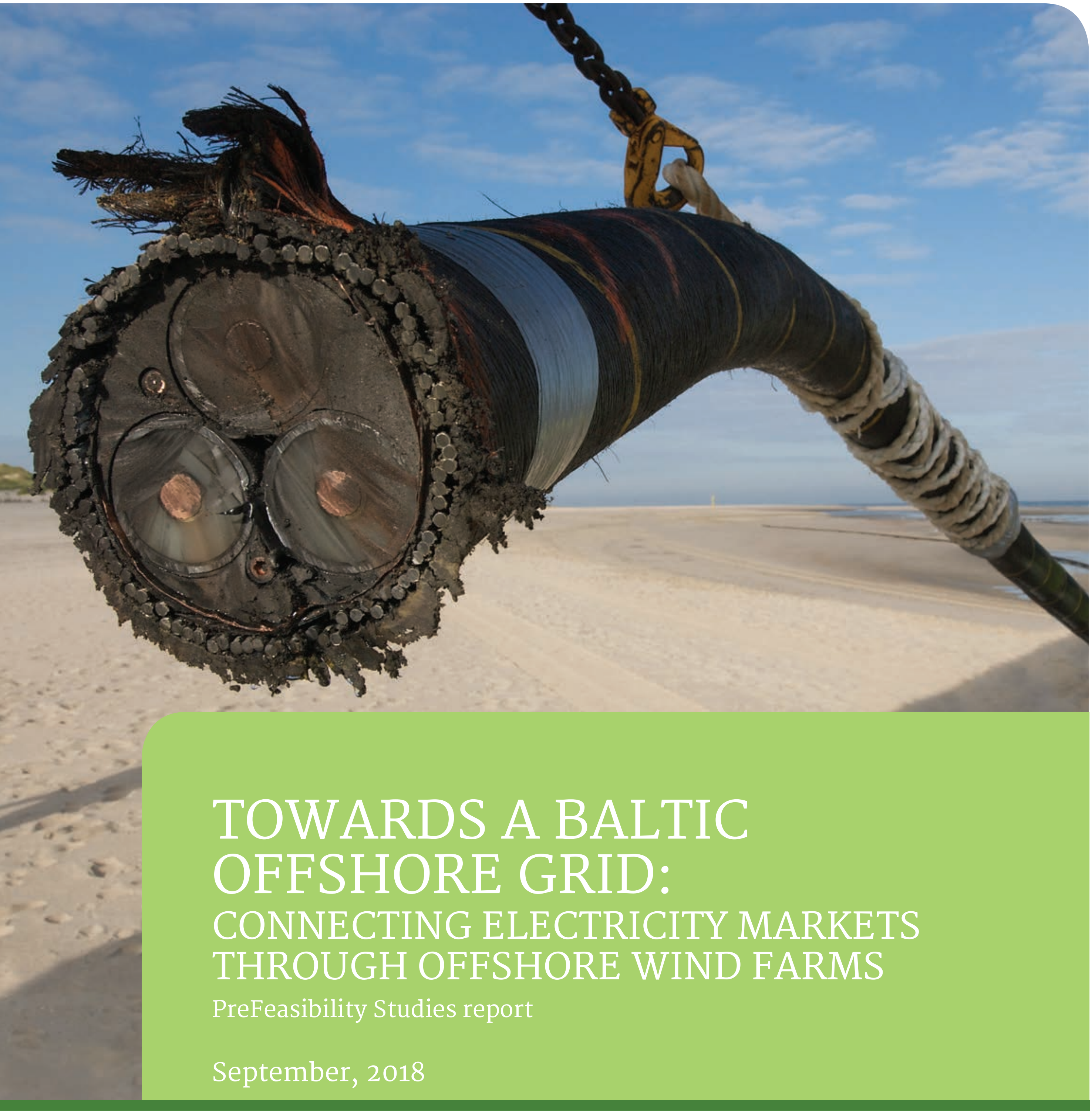
Baltic InteGrid

Integrated Baltic Offshore Wind Electricity Grid Development



TOWARDS A BALTIC OFFSHORE GRID:

CONNECTING ELECTRICITY MARKETS THROUGH OFFSHORE WIND FARMS

PreFeasibility Studies report

September, 2018

Interreg Baltic Sea Region

EUROPEAN UNION

EUROPEAN REGIONAL DEVELOPMENT FUND

Towards a Baltic Offshore Grid:
connecting electricity markets through offshore wind farms

PreFeasibility Studies report for Polish-Swedish-Lithuanian and German-Swedish-Danish interconnectors integrated with offshore wind farms

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Content

1. Executive Summary

This report was developed within the Baltic InteGrid project (www.baltic-integrid.eu) co-financed through the INTERREG Programme for the Baltic Sea Region in the financial perspective 2014-2020. It summarises the results of extensive PreFeasibility Studies performed for 2 cases:

- The **Case Study 1** assumes an electrical connection between **Poland, Sweden and Lithuania** integrated with planned offshore wind farms in these countries. Choice for such setup was dictated by several conditions:
  - significant number of OWF projects planned in the Polish Exclusive Economic Zone (EEZ),
  - some OWF projects, both in Polish and Swedish waters are planned just at the Polish-Swedish border, at the South Middle Bank,
  - potential connection to Lithuania was indicated by the Polish Transmission System Operator (TSO) in connection to the potential synchronisation of the Baltics,
  - there is an existing Polish-Swedish interconnector, SwePol Link, (established infrastructural corridor),
  - there is also an existing Swedish-Lithuanian interconnector, Nordbalt, (established infrastructural corridor).
- The **Case Study 2** assumes a connection between **Sweden, Germany,** and – for the High Offshore Wind Power (High OWP) build-out scenarios – **Denmark**. Reasons behind such choice were the following:
  - significant number of OWF projects have been realized and are planned in the German Baltic Sea (territorial waters and EEZ),
  - both Swedish and Danish OWF projects close to the German border are under consideration by several developers,
  - the Swedish and German TSOs, Svenska Kraftnät (SvK) and 50Hertz, are realizing an interconnector, called Hansa PowerBridge (planned commissioning 2025 or 2026). Furthermore, an additional interconnector between Sweden and Germany might have significant market potential and is according to the TYNDP already under consideration by the corresponding TSOs (Hanse PowerBridge II).

The analytical work conducted for the study included the following steps:

- Analysis of existing and planned OWF projects and infrastructure,
- Scenario development (6 scenarios per case study),
- Technical design,

- Spatial analysis,
- Environmental analysis,
- Cost-benefit analysis (CBA) – based on the ENTSO-E CBA methodology.

General conclusions:

- In general, the integration of wind farms and interconnectors with a high level of offshore wind deployment in a given area brings more benefits than costs. With low wind deployment the results are not unambiguous.
- The CBA for an integrated solution has to be performed on a case-by-case basis and is very much dependent on the level of offshore wind deployment in the analysed area and the level of integration. This applies especially to complex setups where protection systems, such as HVDC breakers, are required.
- In the case studies the system complexity increases from zero integration, over partial, to maximum integration. A higher transmission capacity and integration might bring higher flexibility in terms of avoiding OWP curtailment and higher maximum cross-border energy trade. Furthermore, a higher level of interconnection might open up new possibilities, like selling the generated electricity towards both markets and price zones. However, it requires a stronger cooperation between all involved parties and a longer development phase for the needed components, systems, codes and operations, not to mention the stakeholder co-operation.
- In the integrated scenarios one challenge is to deal with more sophisticated and costly security measures (DC breakers). Furthermore, the lack of commercial implementations significantly increases the uncertainty and thus costs for the highly-integrated solutions.
- The adequacy analysis for both cases proved that in all scenarios the system has enough capacity available, but higher integration provides the system with more flexibility with regard to the adequacy rate. The conclusions are true for all countries included in the case studies.
- In integrated systems (or the part of the system that is integrated) the DC cables have higher utilisation rates, since the capacity of the cable not used for exporting electricity from wind farms can be used for Cross-Border Energy Trade (CBET). However, the scenario of near-maximum infrastructure utilisation rate would require that one of the interconnected countries would always have a sufficiently high power demand and electricity price in relation to the other interconnected country(s).
- Spatial analysis shows that the number of landfalls may become a limiting factor for offshore wind development in some of the case study areas. Depending on the case study, the zero integration (radial connection of OWFs) scenarios assumes 6 times more landfall cables then in the corresponding maximum integration case. The potential conflicts may include onshore environmental protection areas but also dispersed and sometimes congested settlements and tourist activity in the seaside.

There is an immense potential for introducing a grid solution integrated with OWFs for Poland, Sweden and Lithuania

Case-specific conclusions:

- **Case Study 1** – there is an immense potential for introducing a grid solution integrated with OWFs for Poland, Sweden and Lithuania both for High and Low Offshore Wind Power (High/ Low OWP) scenarios.
  - For the High OWP build-out (assuming 11,2 GW for the whole study area) the partial integration scenario (Scenario 2a) is the most favourable. The design logic of this scenario is to connect OWFs close to shore (Slupsk Bank, Lithuanian and Swedish projects near the coast) radially with AC technology, and the wind farms far offshore (South Middle Bank on the Polish and Swedish side) would be integrated with the HVDC interconnectors.
    This type of design would need a fair level of cooperation for all projects and stakeholders

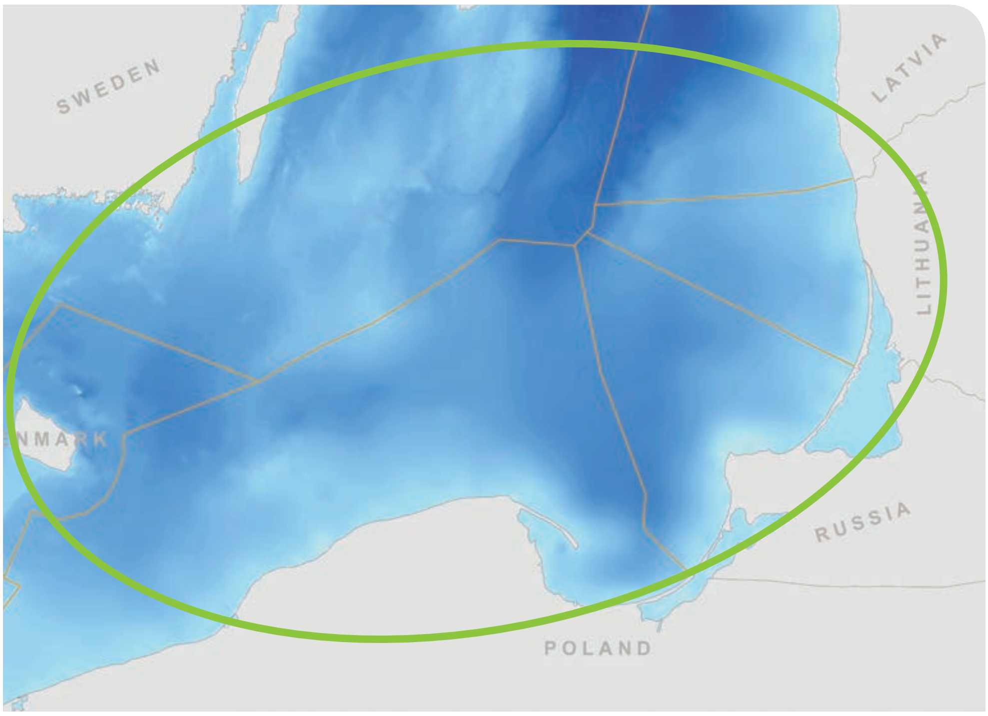

Figure 1
Case Study 1 Area

using the VSC-HVDC system. In return, the solution could provide higher flexibility, utilisation rates and cost sharing opportunities. The grid costs are lowest for the partial integration scenario – 2.96 billion EUR. The costs for the zero integration and the maximum integration scenarios are: 3.27 billion EUR and 3.50 billion EUR respectively. **Based on CBA analysis, compared to the base-case scenario (zero integration), the partial integration brings additional benefits of 0,36 billion EUR.**

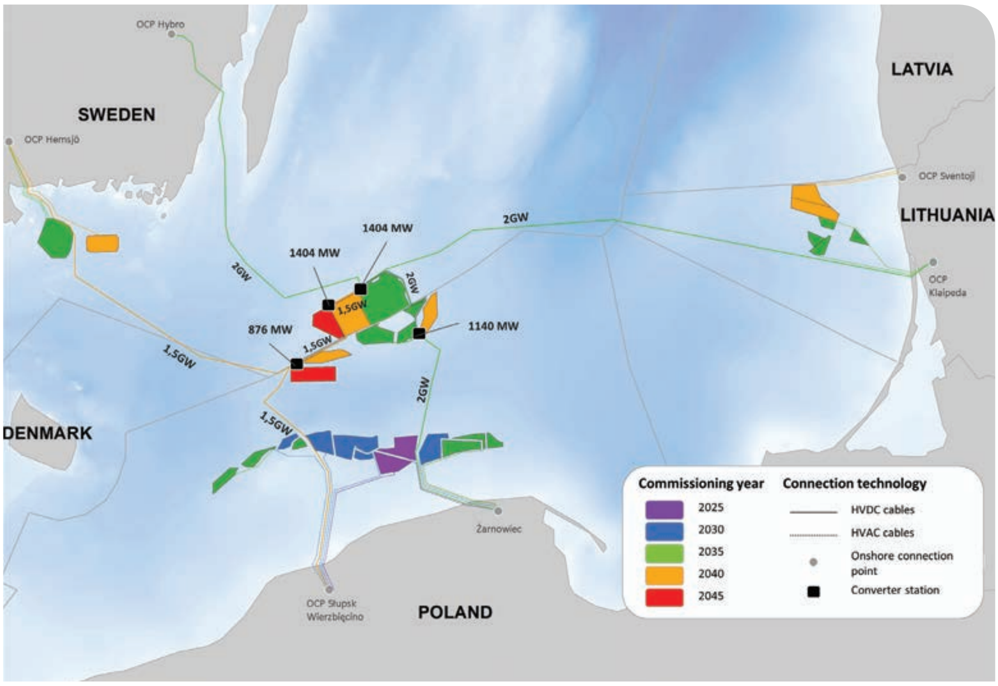

Figure 2
Case Study 1 – Scenario of High OWP/partial integration – schematic build-out

The partial integration scenario could depict the development of OWE in Poland and Sweden, where the most developed projects in Poland are planned to be connected radially. However, projects farther from shore, at Southern Middle Bank (both in Swedish and Polish waters), will be developed most likely after 2030 and could be connected in a more coordinated approach.

- **For the Low OWP build-out** (assuming 5,7 GW in the whole study area) the maximum integration scenario (Scenario 3b) is the most favourable. The key characteristic of this scenario can be summarised as high cooperation and planning requirement, technically challenging, flexible power flow routing, possibility for high utilisation rates, shorter total cable lengths and possibility to share costs. The grid costs are lowest for zero integration scenario – 1.40 billion EUR. The costs for the partial integration and the maximum integration scenarios are: 1.50 billion EUR and 1.47 billion EUR respectively. **Even though the costs for the maximum integration scenario are higher, the benefits surpass the costs and compared to the base-case scenario (zero integration), the additional benefits amount to 0.91 billion EUR.**

Analysis shows, that the grid solution integrated with OWFs is favourable provided that a critical mass of wind power is installed and integrated into the grid

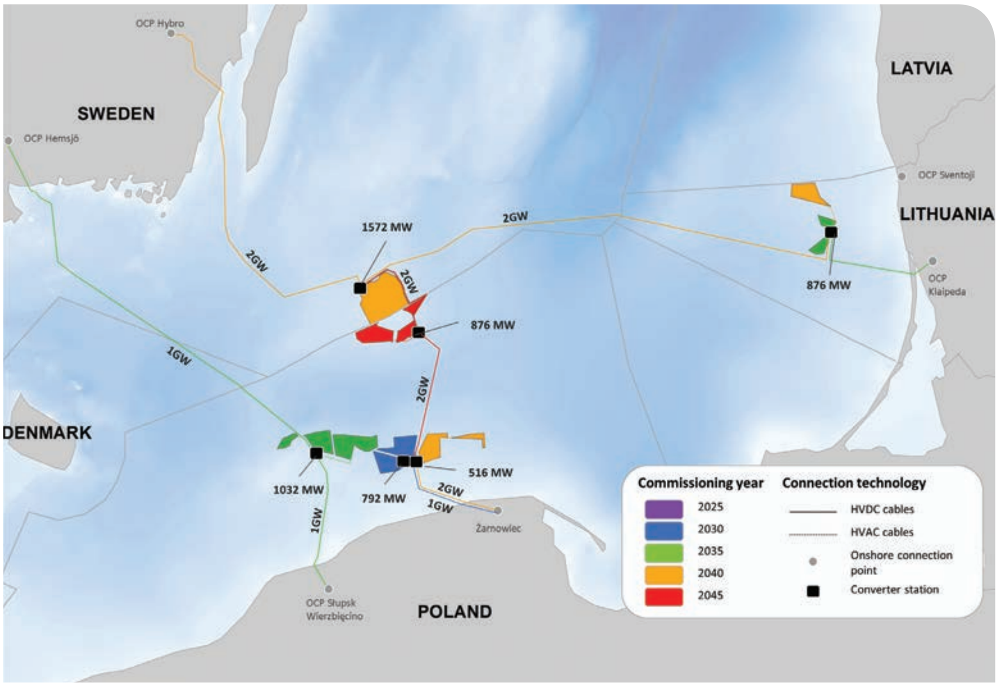

Figure 3
Case Study 1 – Scenario of Low OWP/maximum integration – schematic build-out

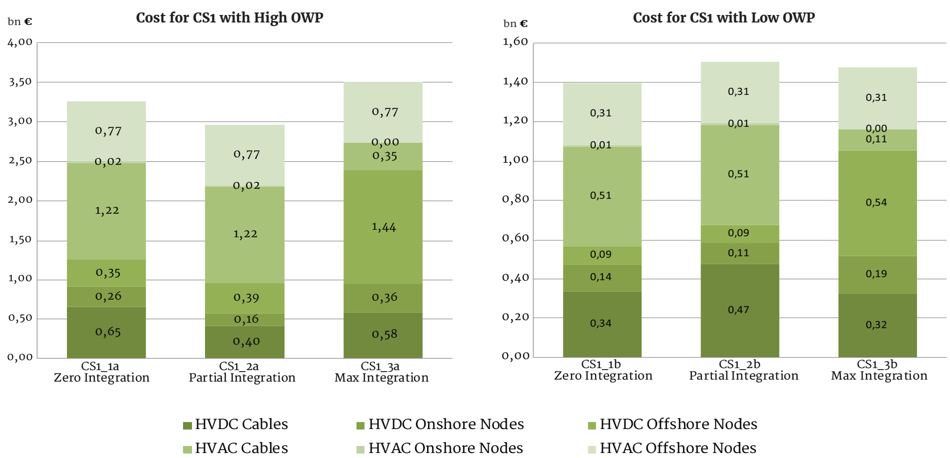

Figure 4
Cost structure for the Case Study 1 scenarios

- **Case Study 2** – analysis shows, that the grid solution integrated with OWFs is favourable provided that a critical mass of wind power is installed and integrated into the grid.
  - **For the High OWP build-out** (assuming 3.7 GW for the whole study area) the maximum integration scenario is the most favourable due to reduced costs. This approach however, requires large efforts to coordinate international energy infrastructure and sea use planning, extensive technological know-how regarding multi-terminal systems. The benefits of such a system could be high infrastructure utilisation rates and cost sharing opportunities. The grid costs are lowest for the maximum integration scenario – 1.32 billion EUR. The costs for the zero integration and the maximum integration scenarios are: 1.37 billion EUR and 1.75 billion EUR respectively. **Based on the CBA analysis, compared to the base-case scenario (zero integration), the additional benefits of the maximum integration amount to 1.81 billion EUR.**

Figure 5
Case Study 2 Area

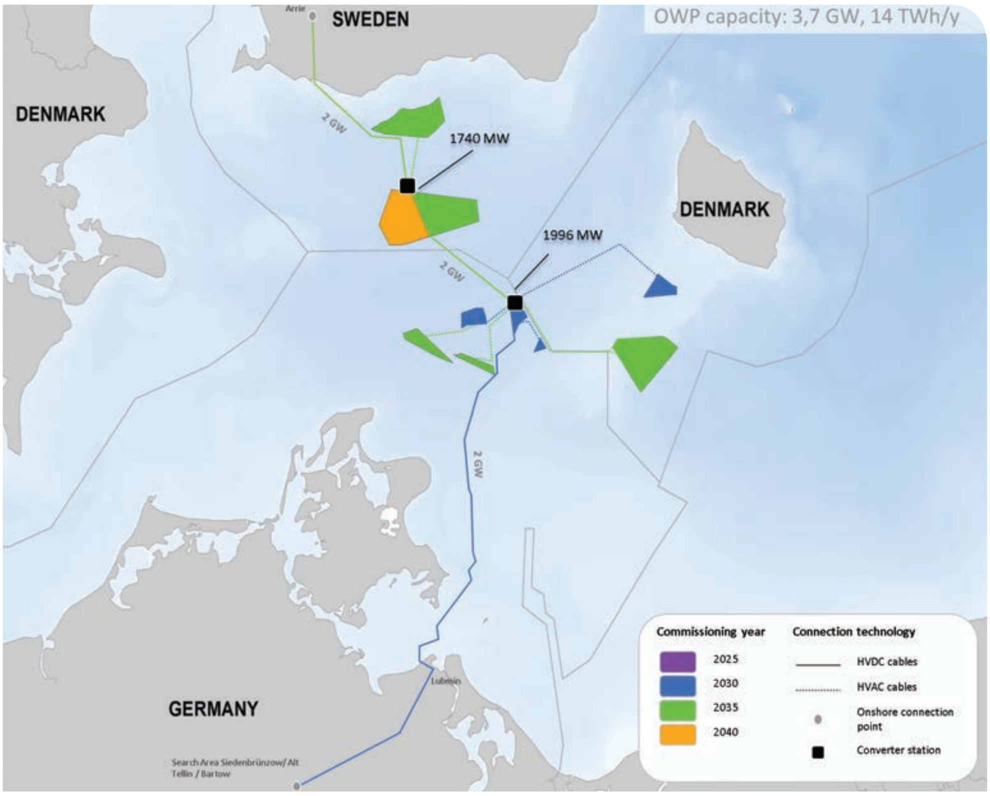

Figure 6
Case Study 2 – Scenario of High OWP/maximum integration – schematic build-out

- **For the Low OWP build-out** (assuming 1.9 GW) no extra benefit and no cost reduction can be observed for wind farm integration. The costs for each of the scenarios are: zero integration – 0.72 billion EUR; partial integration 0.76 billion EUR; maximum integration – 0.81 billion EUR. **Here, the zero integration scenario should be favoured. This means that all projects are connected radially to shore.**

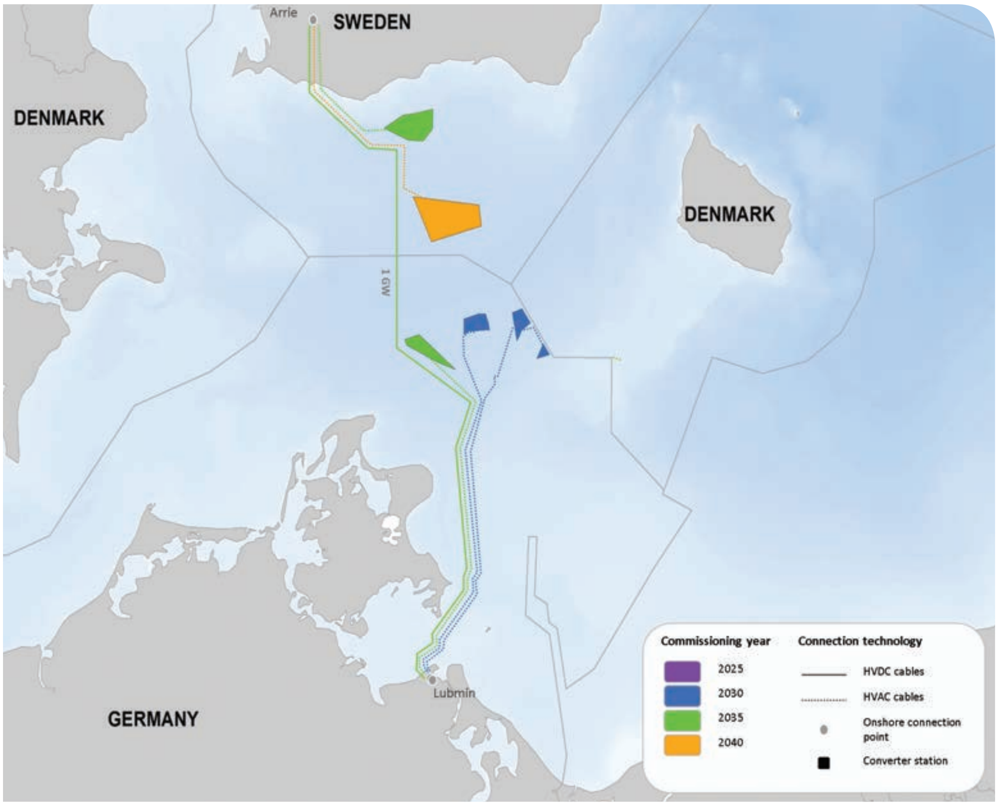

Figure 7
Case Study 2 – Scenario of Low OWP/zero integration – schematic build-out

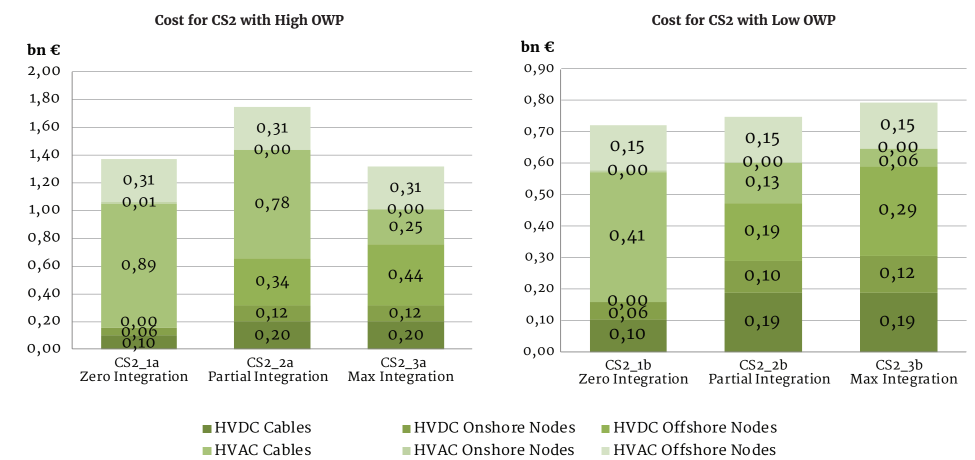

Figure 8
Cost structure for the Case Study 2 scenarios

Table 1 sums up which level of integration has been evaluated to be the most economic for each scenario. Within the case studies a higher level of integration is favorable together with a high utilization of offshore wind power.

Table 1   Summary showing the most economic scenarios for the case studies

	Case Study 1 (SE/PO/LT)	**Case Study 2 (DE/SE/DK)**
High OWP	Partial Integration	Maximum Integration
Low OWP	Maximum Integration	Zero Integration

However, there is no clear trend visible and extensive analysis (including a CBA and Cross-Border Cost Allocation) should be done for each project under consideration.

By Maciej Stryjecki, Fundacja na rzecz Energetyki Zrównoważonej

Photo: Fährhafen Sassnitz

2. Introduction

2.1. Goal and structure of the PreFeasibility Studies

This document includes the results of PreFeasibility Studies for two cases of interconnectors integrated with offshore wind farms (OWF):.

- Case study 1 includes a Polish-Swedish-Lithuanian Interconnector and
- Case Study 2 includes a German-Swedish interconnection with the possibility to connect offshore wind farms located in Denmark (off the coast of Bornholm).

The principal goal of the study is to answer the question whether an integrated approach in which offshore wind farms are connected to an interconnector, is feasible from technical, market, environmental and economic points of view

The principal goal of the study is to answer the question whether an integrated approach in which offshore wind farms are connected to an interconnector, is feasible from technical, market, environmental and economic points of view. In order to fulfil this goal, the aims of the PreFeasibility Studies are to:

- Compare a meshed grid approach and a radial approach for planned OWFs and interconnectors,
- Provide potential technical designs with general costs for different alternatives (the scenarios considered in the study),
- Facilitate flexible development of the transmission grid,
- Provide general spatial alternatives,
- Provide a comparison of the costs and benefits of different scenarios.

The following are **NOT** the purpose of the study:

- Provide final solutions – those will have to be the subject of a full feasibility study and design process,
- Provide a prognosis for offshore wind development in the region – the PreFeasibility Studies rather focus on how to connect projects already in the pipeline. Nevertheless, for each case study, 2 different development roadmaps are presented for comparative reasons,
- Propose final corridors and layouts – these are also subject to detailed analysis.

The document is structured in the following manner:

1. Background information on the countries involved in both case studies providing the general background situation and context for the study,
2. Methodology of the study (analogical for both case studies),
3. Case Study 1 description, including results and conclusions,
4. Case Study 2 description, including results and conclusions.

2.2. Description of the Case studies

The geographical scope of the case studies, as well as the choice of potential interconnection, was decided after performing an analysis of existing conditions:

- Areas with highest potential of offshore wind energy development and an existing pipeline of projects,
- Energy price differences in the region and potential electricity interconnections,
- Ten Year Network Development Plans,
- Potential synchronisation of the Baltics (requiring additional transboundary infrastructure).

The choice of potential connections was discussed with transmission system operators.

An analysis of planned OWF projects showed that the majority of projects under development are located in this southern part of the basin. Therefore, both case studies involve areas in the South Baltic Region. The choice of suitable case studies had to take into account potential OWFs that could be connected to an interconnector.

Case Study 1 assumes a connection between Poland, Sweden and Lithuania which was dictated by several conditions:

- A significant number of OWF projects planned in the Polish Exclusive Economic Zone,
- Some OWF projects, both in Polish and Swedish waters are planned just at the Polish-Swedish border, at the South Middle Bank,
- A potential connection to Lithuania was indicated by the Polish Transmission System Operator (TSO) in connection to the potential synchronisation of the Baltics,
- There is an existing Polish-Swedish interconnector: SwePol Link (established infrastructural corridor),
- There is also an existing Swedish-Lithuanian connection: Nordbalt (established infrastructural corridor).

Although a second Polish-Swedish connection was not directly included in the Ten Year Network Development Plan (TYNDP) 2016 as a project candidate, it has been described as having significant market potential due to price difference. Instead, in the TYNDP 2016, there is a Polish-Danish interconnection. However, due to the significant expected development of offshore wind farms in Poland and Sweden, and at a later stage in Lithuania, a Polish-Swedish-Lithuanian interconnection was eventually chosen for the Case Study.

Case Study 2 assumes a connection between Sweden, Germany, and – for the High Offshore Wind Power (High OWP) build-out scenarios – Denmark. Reasons behind such choice were the following:

- Significant number of OWF projects have been realized and are planned in the German Baltic Sea (territorial waters and EEZ),
- Swedish and Danish OWF projects close to the German border are under consideration by several project developers,
- The Swedish and German TSOs, Svenska Kraftnät (SvK) and 50Hertz, are realizing an interconnector, called Hansa PowerBridge (planned commissioning 2025 or 2026). Furthermore, an additional interconnector between Sweden and Germany might have significant market potential and is according to the TYNDP already under consideration by the corresponding TSOs (Hanse PowerBridge II).

2.3. About the Baltic InteGrid project

Baltic InteGrid "Integrated Baltic Offshore Wind Electricity Grid Development" is co-financed through the INTERREG Programme for the Baltic Sea Region in the financial perspective 2014-2020. The project's duration is fixed at 2016-2019.

The Baltic InteGrid project aims at contributing to sustainable electricity generation, the further integration of regional electricity markets, and security of the supply of electricity in the Baltic Sea Region by applying an integrated grid approach to optimise the potential and efficiency of offshore wind energy.

The Baltic InteGrid project contributes to the EU Strategy of the Baltic Sea Region and fits into this strategy, as the development of a Baltic Offshore Grid concept is a step towards the creation of a fully interconnected and integrated regional energy market, the implementation of a Baltic Energy Market Interconnection Plan (BEMIP) and the demonstration of coordinated OWF connection solutions.

The project pursues the objective of:

- Interconnection and integration of the regional market,
- Development and integration of energy markets,
- Improving the security of electricity supply,
- Fostering the diversification of energy sources, and therefore helping to reduce the emission of greenhouse gases,
- Contributing to considerable economic growth due to new business activities in the renewable energy and grid sectors.

During the project lifetime, the project partners from all eight EU Member States in the Baltic Sea Region are working in close cooperation with key stakeholders towards the following main outputs:

- The Baltic Offshore Grid Forum: The conference and communication platform of the project,
- A high-level concept for the Baltic Offshore Grid: A summary of the interdisciplinary research component of the project,
- Detailed case studies for two interconnection scenarios serving as components of the Baltic Grid Concept (the purpose of this document),
- Strategic recommendations.

The Ministry of Economics of the Republic of Latvia, acting as the Policy Area Coordinator for the Policy Area Energy (PA Energy) of the EU Strategy for the Baltic Sea Region (EUSBSR), accepted the project Baltic InteGrid as a Flagship Project under the EUSBSR.

The Baltic InteGrid project is executed in a consortium of 14 project partners (PP) from all 8 EU Member States in the Baltic Sea Region:

PP 1 – Project Leader – Institute for Climate Protection, Energy and Mobility (Germany)

PP 2 – Foundation for Sustainable Energy (Poland)

PP 3 – Rostock Business and Technology Development (Germany)

PP 4 – Technical University of Denmark (Denmark)

PP 5 – Energy Agency for Southeast Sweden (Sweden)

PP 6 – Deutsche WindGuard GmbH (Germany)

PP 7 – Maritime Institute in Gdańsk (Poland)

PP 8 – German Offshore Wind Energy Foundation (Germany)

PP 9 – Latvian Association of Local and Regional Governments (Latvia)

PP 10 – Aalto University (Finland)

PP 11 – University of Tartu (Estonia)

PP 12 – Public Institution Coastal Research and Planning Institute (Lithuania)

PP 13 – Lund University (Sweden)

PP 14 – Aarhus University (Denmark)

In addition, the project consortium is supported by 35 Associated Organisations, which include, among others, Transmission System Operators from Poland, Lithuania, Germany, Denmark and Estonia, investors in the OWFs, enterprises, representatives of administrations from Germany, Lithuania and Latvia, as well as research and development agencies and institutions.

More information about the project and the consortium can be found at: www.baltic-integrid.eu.

Photo: EnBW

3. Background

3.1. European context

3.1.1. Policy and regulation

At the EU level, the **Energy Union** as a political strategy aims at:

- Achieving security of supply,
- Achieving an integrated EU energy market,
- Improving energy efficiency,
- Decarbonising the economy,
- Supporting breakthroughs in low-carbon and clean energy technologies.[1]

To this end, the EU is pursuing a strategy building on its 2030 Framework for Climate and Energy[2]. In November 2016, the Commission proposed the **Winter Package**, a new legislative package which, among other things, recasts legislation from the EU's 3rd energy package[3] and sets new rules for Agency for the Cooperation of Energy Regulators (ACER), the European energy regulator[4]. Among other factors, strengthening cross-border cooperation and enhancing interconnection between electricity systems is of great importance.[5]

Furthermore, in order to bring the EU internal energy market in the Baltic Sea Region forward and end energy isolation in this area, all partner countries and the Commission signed a Memorandum of Understanding for a **Baltic Energy Market Interconnection Plan (BEMIP)** initiative in 2009, which was updated in 2015.[6] The BEMIP aims at designing an integrated electricity and gas market in the Baltic Sea Region, among other ways, through the development of renewable energy infrastructure projects and interconnectors.[7] The BEMIP action plan 2015 defined concrete actions in the field of energy infrastructure, electricity markets, power generation, security of supply, energy efficiency and renewable energy and encompasses measures for the period until 2020.[8]

In this context, the **Baltic InteGrid** project aims at assessing the optimised potential of offshore wind energy in the Baltic Sea region by applying an approach in which OWFs are integrated with interconnectors. Baltic InteGrid is directly in line with the Energy Union's objectives, as it promotes not only the reinforcement and interconnection of electricity networks, but also fosters regional cooperation and regional energy security.

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1 European Commission, "Energy union and climate," Accessed August 8th, 2018. https://ec.europa.eu/commission/priorities/energy-union-and-climate_en.

2 European Commission, "Building the Energy Union" Accessed August 8th, 2018. https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/building-energy-union.

3 European Commission, "Commission proposes new rules for consumer centred clean energy transition" Accessed August 8th, 2018. https://ec.europa.eu/energy/en/news/commission-proposes-new-rules-consumer-centred-clean-energy-transition.

4 European Commission, "Clean Energy for All Europeans" Accessed August 8th, 2018. https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans.

5 Recast of Directive 2009/72/EC as proposed by COM(2016) 864 final/2, p. 7.

6 European Commission, "Baltic Energy Market Interconnection Plan" Accessed August 8th, 2018. https://ec.europa.eu/energy/en/topics/infrastructure/trans-european-networks-energy/baltic-energy-market-interconnection-plan.

7 European Commission, "Memorandum of Understanding on the Baltic Market Interconnection Plan. Brussels", 2009 Accessed August 8th, 2018. https://ec.europa.eu/energy/sites/ener/files/documents/2009_bemip_mou_signed.pdf.

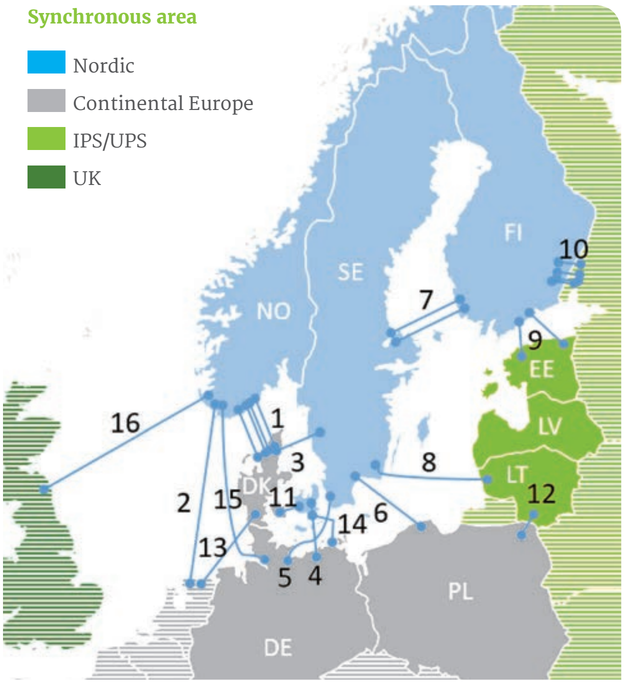
8 European Commission, "PA Energy – BEMIP Action Plan (for competitive, secure and sustainable energy)" Accessed August 8th, 2018. https://ec.europa.eu/energy/sites/ener/files/documents/BEMIP_Action_Plan_2015.pdf.

Internal
Energy Market

3.1.2. Internal Energy market

Development of a fully integrated internal energy market is one of the five key goals of the EU Energy Union. This chapter describes the general background of the electricity markets in the Baltic Sea Region. Within the region, there are three separate synchronous systems: the Nordic system, the Continental system, and the Baltic power system; the latter is synchronous with the IPS/UPS system (i.e. Russia and Belarus).

The BEMIP allowed the Baltic States to reach an **interconnection level of 23%**, making the region among the best interconnected in Europe.[9] Synchronising the Baltic electricity grid with the EU remains a challenge however. Currently, the Baltic States are still part of the Belarus-Russia-Estonia-Latvia-Lithuania ring (BRELL), and are aiming at synchronising with the European network by 2025.[10] As a result, the NordBalt link (connecting Sweden and Lithuania) and LitPol link (connecting Poland and Lithuania) were constructed. The synchronous areas are illustrated in Figure 9 below, notably Denmark is divided between two synchronous areas: Denmark-East, which is part of the Nordic system, and Denmark-West, which is part of the continental system.[11]



HVDC interconnections

Existing		
1.	Skagerrak 1-4	1600 MW
2.	Norned	700 MW
3.	Konti-Skan 1-2	680/740 MW
4.	Kontek	600 MW
5.	Baltic Cable	600 MW
6.	SwePol Link	600 MW
7.	Fenno-Skan 1-2	1200 MW
8.	NordBalt	700 MW
9.	Estlink 1-2	1000 MW
10.	Vyborg Link	350/1400 MW
11.	Storebaelt	600 MW
12.	LitPol Link	500 MW
Under Construction		
13.	Cobra (2018)	700 MW
14.	Kriegers Flak Combined Grid Solution (2019)	400 MW
15.	Nord Link (2020)	1400 MW
16.	Nord Sea Link (2021)	1400 MW

Figure 9
Synchronous Areas and HVDC interconnections of Baltic Sea Region
[Source: ENTSO-E]

Total annual electricity consumption in the Baltic Sea Region amounts to 1100 TWh, and half of it is consumed by Germany. The Nordic power system is dominated by hydropower with the additional sources being nuclear, Combined Heat and Power (CHP) (a large portion being based on wood waste), wind power, and a small but increasing share of solar. The hydropower sources are mainly located in Norway and northern Sweden whereas the nuclear power plants are located in southern Sweden and Finland (additional one is under construction). The international trade is usually leaning

9 European Commission, "Baltic Energy Market Interconnection Plan" Accessed August 8th, 2018. https://ec.europa.eu/energy/en/topics/infrastructure/trans-european-networks-energy/baltic-energy-market-interconnection-plan.

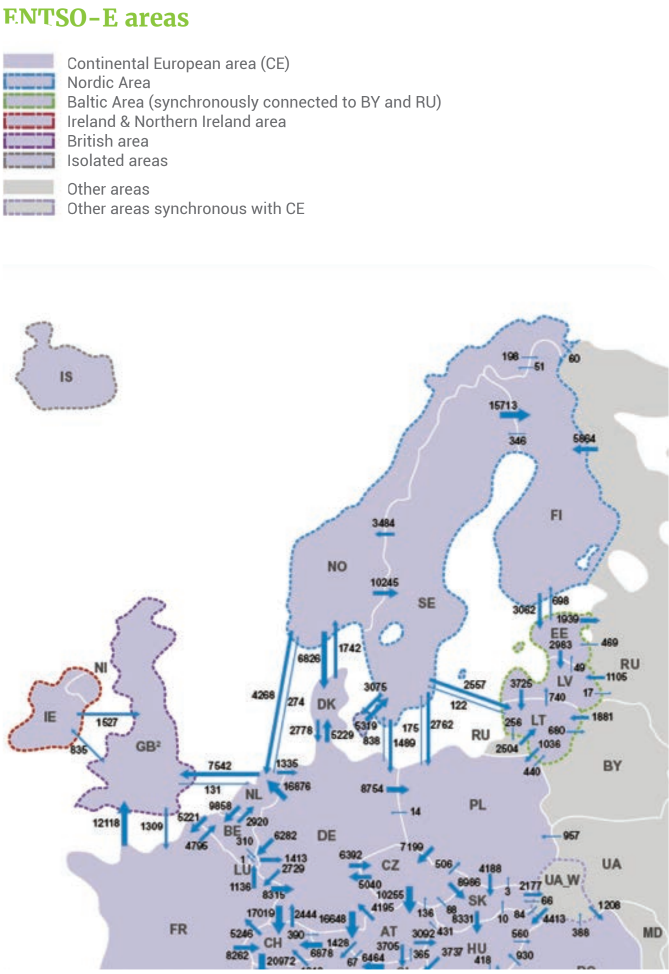
10 European Commission, "Country Report Lithuania 2018", Brussels: European Commission, 2018. Accessed August 8th, 2018. https://ec.europa.eu/info/sites/info/files/2018-european-semester-country-report-lithuania-en.pdf.

11 ENTSO-E, "Regional Investment Plan 2017. Regional Group Baltic Sea". Brussels: ENTSO-E, 2017.

towards energy export from the Nordic region in a normal year, however it is highly weather dependent. Sweden and Norway have a surplus of energy whereas Finland is a net electricity importer.

The continental part of the Baltic Sea is different. Thermal power dominates, except for Denmark which is dominated by wind power and other renewable energy sources (RES).

From the Baltic Sea Region countries, Denmark, Poland, Estonia and Latvia have a neutral annual power balance and Germany is a net exporter of electricity. Lithuania is currently operating with a large energy deficit. The trend for Lithuania and Denmark is towards dependency on imports in peak load situations.[12]



	Sum of imports¹	Sum of exports¹	Balance (imp-exp)
AT	28 156	19 434	8 722
BA	3 086	6 841	-3 755
BE	14 654	8 451	6 203
BG	4 570	10 930	-6 360
CH	33 477	29 052	4 425
CZ	13 815	24 787	-10 972
DE	27 023	80 767	-53 744
DK	15 130	9 839	5 291
EE	3 580	5 620	-2 040
ES	21 845	14 175	7 670
FI	22 473	3 459	19 014
FR	19 959	60 939	-40 980
GB²	21 187	2 275	18 912
GR	9 836	1 039	8 797
HR	12 398	6 057	6 341
HU	17 971	5 240	12 731
IE	835	1 527	-692
IT	43 133	6 236	36 897
LT	11 107	2 834	8 273
LU	7 728	1 414	6 314
LV	4 828	3 791	1 037
ME	2 909	2 609	300
MK	5 201	3 154	2 047
NL	24 195	19 009	5 186
NO	5 611	21 537	-15 926
PL	14 018	12 016	2 002
PT	4 616	9 702	-5 086
RO	2 296	7 311	-5 015
RS	5 559	7 880	-2 321
SE	17 045	29 080	-12035
SI	8 360	9 415	-1 055
SK	13 249	10 598	2 651
TR³	6 413	1 444	4 969
ENTSO-E	446 263	438 462	7 801

Physical flow values in GWh

Figure 10
Cross border physical energy flows (GWh) in the Baltic Sea Region in year 2016
[Source: ENTSO-E]

Energy prices

The energy prices in the Baltic Sea Region differ markedly with differences reaching over 10 EUR per MWh in comparison with continental Europe and Nordic countries (see Figure 11). The wholesale baseload prices for each quarter of 2017 are shown in the figure below. In general, the highest energy prices are found in Poland, although energy prices in Germany fluctuate significantly. The lowest energy prices are found in the Nordic region: Norway and Sweden.

12 ENTSO-E, "Regional Investment Plan 2017. Regional Group Baltic Sea". Brussels: ENTSO-E, 2017.

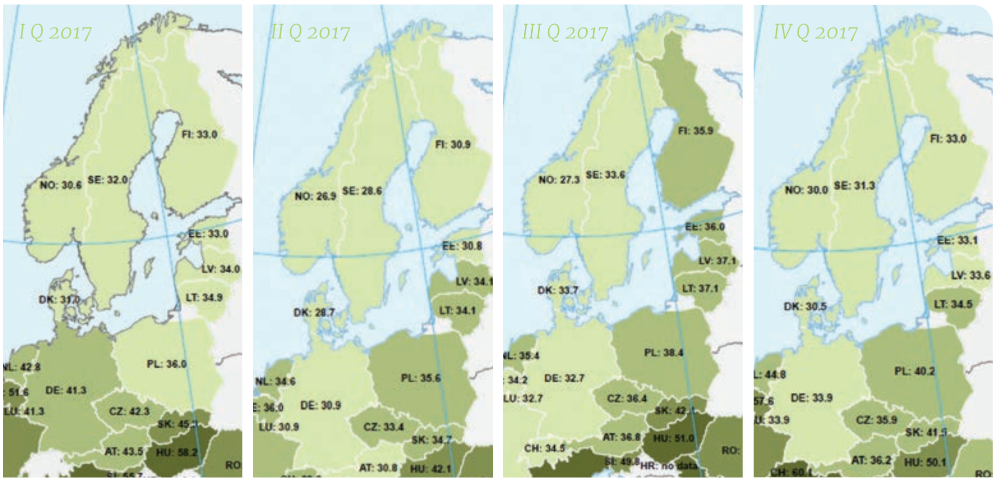


Figure 11
Wholesale baseload electricity prices in I – IV Quarters of 2017

[Source: European wholesale power exchange; EC DG Energy Quarterly Report on European Electricity Markets]

Interconnection capacity

Building a well-functioning integrated energy market requires a well-integrated electricity grid. To this end, the EU set out electricity interconnection targets between countries for 2020 and 2030 which are 10% and 15% respectively.

Table 2 Member States' interconnection levels in 2017 and 2020[13]

Country	Interconnection levels in 2017	Expected interconnection levels in 2020*
DE	9%	13%
DK	51%	59%
EE	63%	76%
FI	29%	19%
LT	88%	79%
LV	45%	75%
PL	4%**	9%
SE	26%	28%

** As assessed by TYNDP 2016 and ENTSO-E Vision 2020.*

*** The low interconnection level is caused in the major part by the uncontrolled flow of energy (loop-flows) which hinders the possibility of transnational exchange through existing interconnectors.*

The implementation of Projects of Common Interest (PCI) has led to increasing interconnection levels over the recent years. In order for a project to obtain a status of PCI it should be included in a Ten Year Network Development Plan (TYNDP) which is revised every two years. At the moment of writing of this report, the TYNDP 2018 was under preparation. TYNDP 2016 projects map is available below in Figure 12.

13 European Commission, "Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions. COM(2017) 718 final". Brussels: European Commission, 2017.

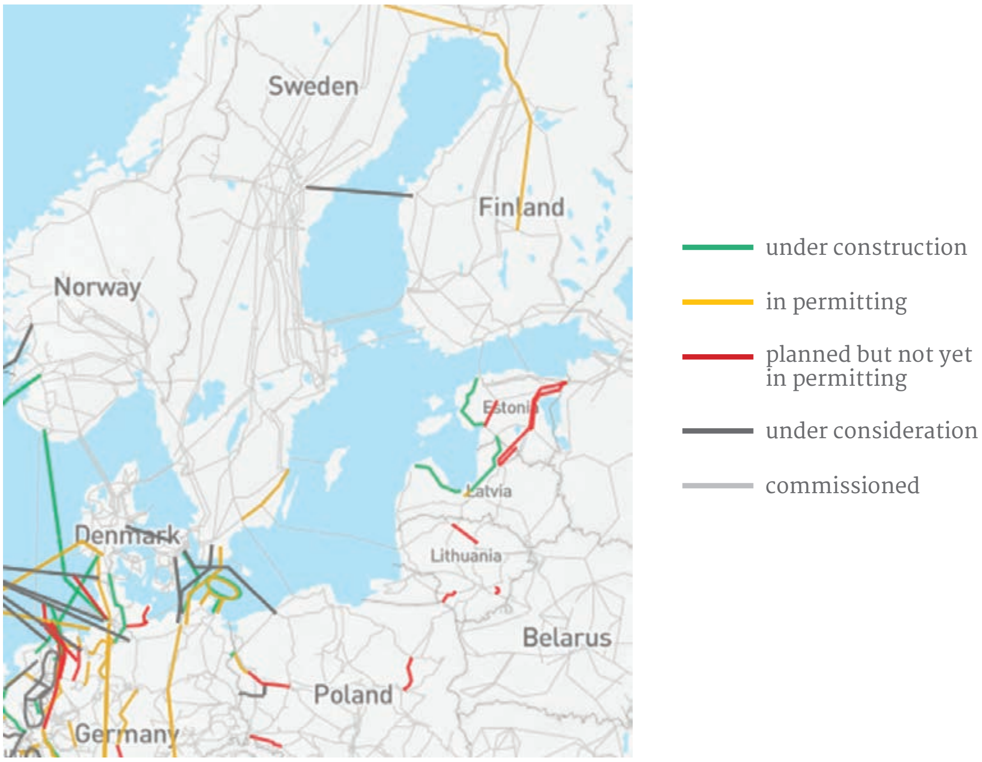


Figure 12
TYNDP Projects map[14]

It has to be noted that a second Polish-Swedish connection was considered but not included in the TYNDP 2016, as it showed potential benefits. However, the decision by SvK and PSE was not to nominate it as a new project candidate for inclusion in the TYNDP 2016. There are several reasons for this decision, and the most important is that there are already two new interconnectors between Sweden and Germany included in this Regional Investment Plan as well as one from Poland to Lithuania.[15]

The consultation of the TYNDP 2018 will be conducted between June and September 2018.

3.1.3. Maritime spatial planning

Spatial Planning

In 2014, Directive 2014/89/EU of the European Parliament and of the Council establishing a framework for maritime spatial planning was adopted. It sets out the requirement of Member States to establish their Maritime Spatial Plans (MSPs) by 31st of March 2021.

Currently, the MSPs are at varying stages of development and implementation in the Baltic countries. So far, only Germany has adopted a Marine plan targeting intensive offshore wind development and marine environmental protection goals, as well as traditional maritime uses such as shipping and fisheries. However, for many coastal countries, an additional driver for a MSP is the rapid increase in interest in the development of offshore renewable energy projects. Questions still remain whether MSPs can fulfil their anticipated benefits, including the ability to reduce spatial conflicts among traditional resource uses (e.g. fishing, shipping, tourism) and new ocean uses (e.g. OWE projects)[16].

14 ENTSO-E, "Project map" Accessed June 5th, 2018. http://tyndp.entsoe.eu/map/.
15 ENTSO-E, "Regional Investment Plan 2015 Baltic Sea Region". Brussels: ENTSO-E, 2015. Accessed June 5th, 2018. https://docstore.entsoe.eu/Documents/TYNDP%20documents/TYNDP%202016/rgips/Regional%20Investment%20Plan%202015%20-%20RG%20BS%20-%20Final.pdf.
16 Gopnik M. Et al, "Coming to the table: Early stakeholder engagement in marine spatial planning." Marine Policy 36, No. 5 (2012): p. 1139 – 1149.

*[NOTE]: Countries where MSP is in the process of being developed keep 2021 as the final deadline for releasing their final plans.

Table 3 Overview of MSP status in countries included in the study

Case study country	MSP status	MSP legal power	MSP role in terms of OWF	Allowed OWF areas
Sweden[17]	In the consultation stage (by October 2018)*	Non binding regional plans	OWF areas are not strictly defined by the plan. Project developer decide on the location of OWF	On a case by case basis
Germany[18]	In place	Binding MSP	Importance for the federal plan (EEZ), and guiding role for state waters	OWF areas are proposed in the MSP for EEZ. Yet, no strict exclusion of possibility for claiming other areas according to the EIA and avoiding conflicts with other uses
Denmark[19]	In development (1st draft by mid 2019. Final MSP plan 31.03.2021)	Non binding regional plans	MSP coordinates all marine uses, while planning and management of OWF is the responsibility of the Danish Energy Agency	Location depends on the size of the OWF; 4-20 km from the shore for smaller and beyond 15 km for large scale OWF
Poland[20]	In the consultation stage (1st draft released in June 2018)*	Currently available only non-binding pilot plans	MSP indicates suitable areas for OWF	Only in EEZ
Lithuania[21]	In place under the "Comprehensive Plan of the Republic of Lithuania", adopted in 2015	Binding MSP	MSP propose suitable areas, while the Ministry is responsible for detailed management	Beyond 20 m isoline

Market & Supply Chain

3.1.4. Supply chain

A detailed overview of the supply chain issues related to the grid development in the Baltic Sea is included in the publications developed under the Market & Supply Chain Working Group in the scope of Baltic InteGrid project[22]:

17 More information – Swedish Agency for Marine and Water Management (SWAM): www.havochvatten.se.
18 More information – EEZ MSP. Bundesamt für Seeschifffahrt und Hydrographie (BSH): www.bsh.de; territorial waters: www.ikzm-strategie.de.
19 More information – Danish Maritime Authority, Ministry of Business and Growth: www.dma.dk.
20 More information – Ministry of Maritime Economy and Inland Navigation: www.mgm.gov.pl, Maritime Office in Gdynia: www.umgdy.gov.pl.
21 More information – Ministry of the Environment: www.am.lt.
22 Publications developed within the Baltic InteGrid project will be published and availaible on the www.baltic-integrid.eu.

- Supply Chain Analysis, Overview for the Baltic Sea Region[23],
- "Assessment of Baltic hubs for offshore grid development"[24],
- "Baltic offshore grid SME business cases"[25].

Based on those publications a general state of the transmission system supply chain in the Baltic Sea Region is presented, including its adequacy and opportunities for new entrants.

There are just a few well established OWE transmission component suppliers in Europe, especially in the case of **export cables**. An increasing demand for export cables is forecast in the coming years; and interviews with major European cable suppliers[26] suggested that manufacturers stand ready to adjust their production capacities so that no bottlenecks occur. However, other interviewed companies stated that export cable production lines could become a bottleneck in the future since their capacities are restricted, particularly in the case of HVDC technology, which is increasingly in demand. Still, other, larger companies, e.g. from Asia, could enter the European market.

The market for subsea cables is dominated by a few multinational corporations. All of the companies that produced inter-array and export cables for the European market in 2016 have been in business for many years and are often large and well established multinational corporations. New market entrants would face extremely high costs in building a manufacturing plant, hiring skilled workers, buying specialised cable laying vessels and developing subsea cable expertise. Subsea cables are produced in extreme lengths to avoid large numbers of joints; thus, the production process differs greatly from onshore cables. Only specialised manufacturing plants can perform the necessary production steps.

The production of HVDC cables in particular comes (currently) with a larger number of risks than the production of HVAC cables. The HVDC technology is still a younger and less established technology. Thus potential setbacks – including financial loss – are more likely. The production of HVDC cables is therefore not a business case for small and medium sized companies.

The research and development of **converters, transformers, cables and protection equipment** is extremely cost-intensive and many additional factors such as employee training and education must be considered. Like the subsea cable market, the development and manufacturing of the components requires specialised facilities and a large worldwide network of experts and know-how. The market for VSC-HVDC is rather new and the technology is quite expensive. And the new technology has its risks that, for the most part, only large corporations can absorb.[27, 28] Offshore challenges such as extremely deep water, hostile weather conditions and a lack of shore-side infrastructure create further barriers to entry.[29]

The barriers to entry for companies entering the market for **offshore substation foundations** are different to the barriers to entry for the previously described products. The technology for foundations is less complex. New market entrants need to have a facility available where they can manufacture

23 Rostock Business, "Supply Chain Analysis, Overview for the Baltic Sea Region" A report for the Baltic InteGrid project (2018), Baltic InteGrid.
24 BVG Associates, "Assessment of Baltic hubs for offshore grid development." A report for the Baltic InteGrid project (2018). Baltic InteGrid.
25 BVG Associates, "Baltic offshore grid SME business cases". A report for the Baltic InteGrid project (2018). Baltic InteGrid.
26 Interviews by Elizabeth Côté and Julia Sandén. WindEurope Conference & Exhibition, Amsterdam, November 28-30, 2017.
27 Manager Magazin, "Deutschlands schwimmende Steckdose" Accessed August 8th, 2018 http://www.manager-magazin.de/unternehmen/energie/general-electric-jagt-siemens-bei-offshoe-windkraft-a-1158523-2.html.
28 Inwl, "Evaluation of active converters ".
29 The High Wind Challenge, "Reducing weather downtime in offshore wind turbine installation" http://www.highwindchallenge.com/2016/06/13/reducing-weather-downtime-in-offshore-wind-turbine-installation/.

very large and very heavy products. Additionally, they need direct water access to transport their products since road transport would be nearly impossible due to the high costs.[30] Larger companies might consider entering the market by creating a subsidiary and draw from expertise already existing in the field. An example is Steelwind Nordenham, which is part of the Dillinger Group, an established steel producer.[31]

Maintenance and repair service is the combination of all technical and administrative measures including management measures during the lifetime of a unit to maintain its safe and proper functioning. In offshore projects especially, the machines and equipment face extremely challenging environmental conditions. It is in the manufacturers' interest to have as little maintenance and repair work (especially in the early years of the project) as possible needed. Because of that, for offshore substations, most of the manufacturing companies offer maintenance and servicing solutions themselves, although it is quite common for these large companies to hire subcontractors for some of the maintenance and service tasks.

Figure 13 shows an exemplary grid connection timeline for the case of an 80 km export cable, status 2017. The durations for the different tasks include design, production, transportation and installation.

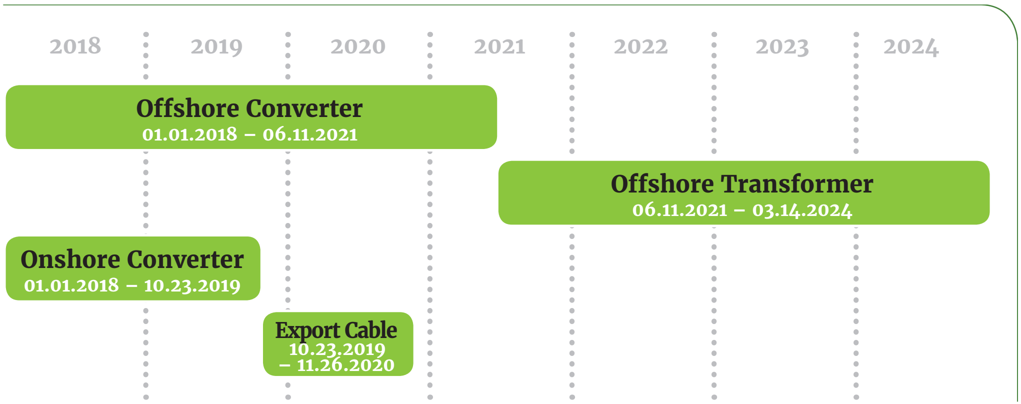


Figure 13
Overview of the erection timeline of an offshore transmission system
[Source: Baltic InteGrid – Supply Chain Analysis Overview for the Baltic Sea Region]

Environment & Society

3.1.5. Environment

The general characteristics of the Baltic Sea environment was presented in the chapter 6 of the Impact Mitigation Strategy for the Baltic Offshore Grid (IMS)[32], which is one of the publications developed within the Baltic InteGrid project. The characteristics mentioned above concern the whole of the Baltic Sea (including the parts covered by both case studies) and referred to the following aspects:

- Bathymetry, hydrography and water quality,
- Geological structure, surface sediments and contaminants,
- Climate and air quality,
- Benthic and pelagic habitats,

30 NWZ Online, "Nordenham: Steelwind-Ansiedlung versetzt Blexer in Hochstimmung" (2011) Accessed August 8th, 2018. https://mobil.nwzonline.de/wesermarsch/wirtschaft/nordenham-steelwind-ansiedlung-versetzt-blexer-in-hochstimmung_a_1,0,583171070.html
31 Steelwind Nordenham, "About us " Accessed August 8th, 2018. http://www.steelwind-nordenham.de/steelwind/unternehmen/wersindwir/index.shtml.en
32 J. Makowska; A. Marczak; M. Karlikowska; M.Wójcik; M. Trzaska, "Impact Mitigation Strategy for the Baltic Offshore Grid". Developed under Baltic InteGrid project, (2018). Baltic InteGrid.

- Fish,
- Marine mammals,
- Birds,
- Protected areas and Natura 2000 sites,
- Eutrophication,
- Underwater noise,
- Shipping and shipping lanes,
- Marine fisheries,
- Conventional weapons and chemical warfare,
- Mining areas.

For the description of the status of the Baltic Sea please refer to the IMS.


Photo: Arno Nym

Denmark

3.2. Country context

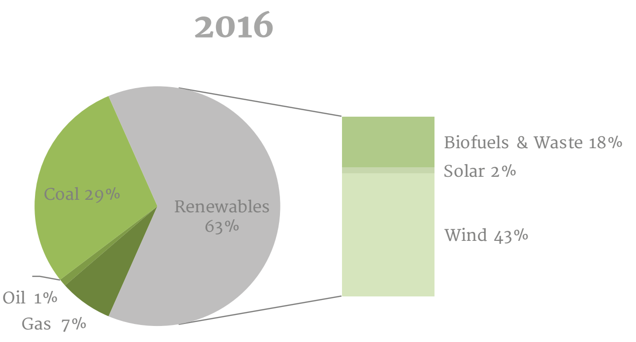
3.2.1. Denmark

[NOTE]: none of the case studies includes a connection to Denmark or Bornholm, however one of the scenarios inclu-des offshore wind farms located in Danish waters, which are connected to other countries.

Political goals for renewable energy and offshore wind

- Current target assumes at least 50% renewable energy for all supply by 2030.[33]
- '**Our Future Energy**' strategy introduced in 2011, sets a target of 100% of renewable energy by 2050 in the electricity, heat, industry and transport sectors.
- The Danish government plans a coal phase-out from plants and private boilers by 2030, as well as 100% of electricity and heat from renewable energy sources by 2035.
- The **2012 Energy Agreement** provides a roadmap for the development of energy demand and supply between 2012 and 2020, with a focus on the expansion of offshore wind so that renewables reach 70% of Danish electricity production by 2020 (of which 50% would come from wind)[34]. The Agreement notably implies that Kriegers Flak (600 MW) and Horns Rev (400 MW) would both be built before 2020, as well as an additional 500 MW of offshore wind near-coast and 1,800 MW onshore.[35]

Energy numbers



Electricity generation: 30.1 TWh (2016)

RES share (electricity): 63% (2016)

Electricity consumption per capita: 5,81 MWh/cap/annum (2016)

Figure 14
2016 Gross electricity generation in Denmark

[Source: International Energy Agency]

Offshore wind capacity installed

At the end of 2017, Denmark had 12 grid-connected offshore wind farms with 506 grid-connected turbines that had a total installed capacity of 1,266 MW.[36]

OWF grid connection and cost allocation

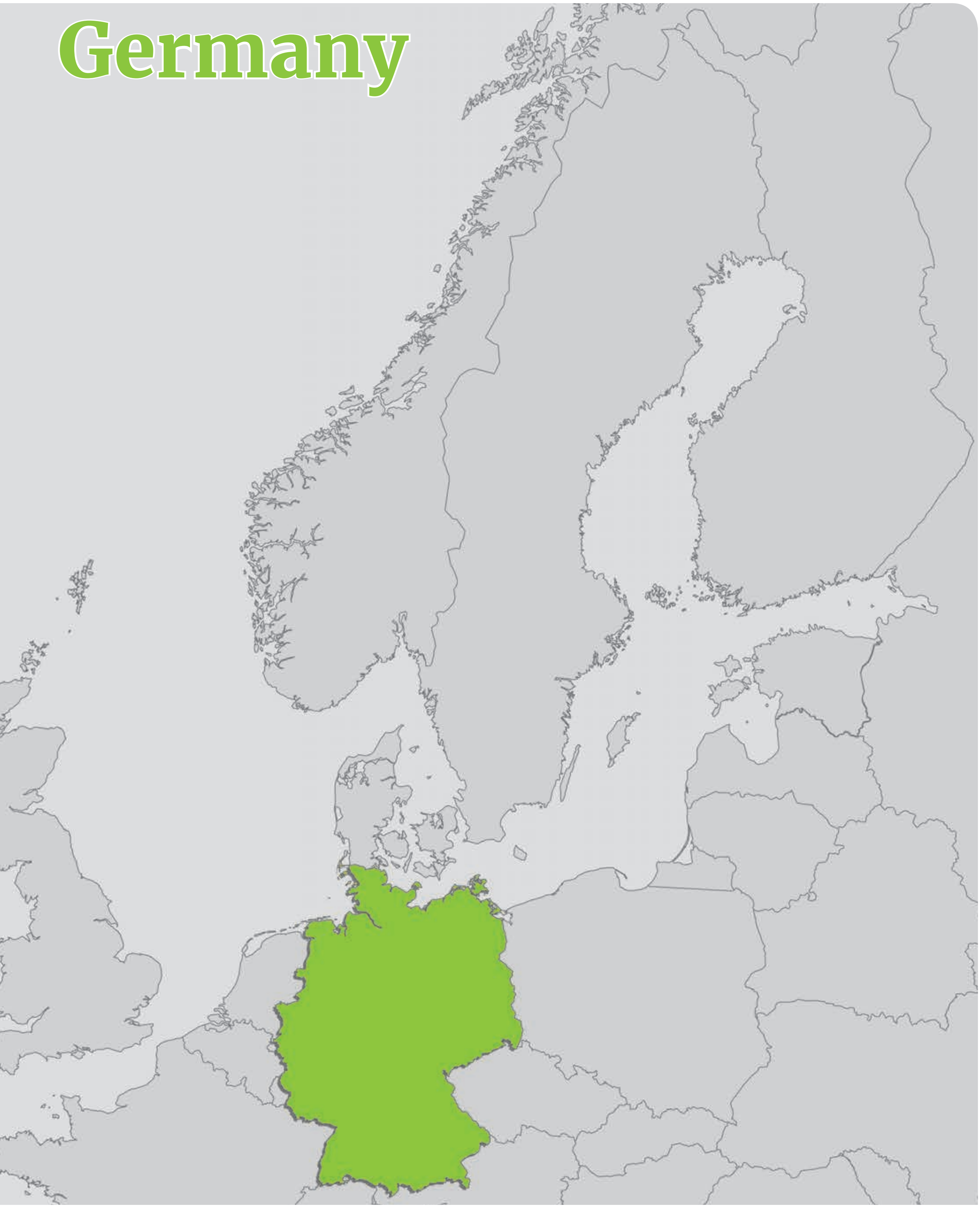
Connection costs are borne by the plant operator up to a near onshore connection point; additional costs are borne by the TSO. In those cases, charges are calculated to a theoretical point that might be closer than the physical connection point. In tendered, far-shore projects such as Kriegers Flak, the plant operator bears the costs only up to the offshore connection point at the AC transformer station.

Transmission System Operator

In Denmark the grid is operated by the company Energinet (www.energinet.dk)

33 Danish Energy Agency, "Denmark's Energy and Climate Outlook 2017". Copenhagen: DEA, 2017. Accessed August 8th, 2018. https://ens.dk/sites/ens.dk/files/Analyser/denmarks_energy_and_climate_outlook_2017.pdf p. 21.
34 IRENA, "Denmark. Market overview". Accessed April 24th, 2018. https://www.irena.org/documentdownloads/publications/gwec_denmark.pdf.
35 IEA, "Danish Energy Agreement for 2012-2020". Accessed April 24th, 2018. https://www.iea.org/policiesandmeasures/pams/denmark/name-42441-en.php.
36 WindEurope, "The European offshore wind industry. Key trends and statistics 2017". WindEurope (2018). Accessed August 8th, 2018. https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2017.pdf, p. 18.

Germany

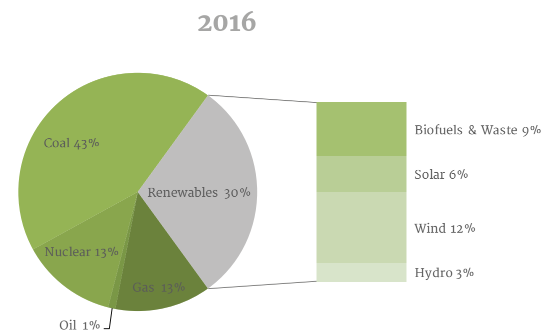


3.2.2. Germany

Political goals for renewable energy and offshore wind

- Development of renewable energy sources is at the heart of the German's **energy transition strategy, the so called Energiewende.**[37]
- The Renewable Energies Act[38] (EEG) sets targets for a share of renewable energy in the electricity mix of 40-45% by 2025, 55-60% by 2035 and at least 80% by 2050.[39] In order to achieve these targets, Germany aims at developing its offshore wind sector.
- Germany envisages an offshore wind installed capacity of 15 GW by 2030[40], of which 3.3 GW will expectedly be installed in the Baltic Sea[41]. Offshore wind energy production amounted to 17.9 TWh in 2017[42].

Energy numbers



Gross electricity generation: 654.8 TWh (2017) of which 17.9 TWh (2.8%) is generated by offshore wind energy

RES share (gross electricity generation): 33.3% (2017)

Electricity consumption per capita: 6.92 MWh/cap/annum (2016)

Figure 15
2016 Gross electricity generation in Germany

[Source: 2016 data International Energy Agency / 2017 data AG Energiebilanzen e.V.]

Offshore wind capacity installed

At the end of 2017, Germany had 5.4 GW of installed offshore wind capacity feeding into the grid – of which 692.3 MW were installed in the Baltic Sea.[43]

OWF grid connection

In Germany, the transmission system operator covers the connection costs from the offshore substation to the onshore grid connection point. The costs are financed through grid tariffs.

Transmission System Operator

In Germany, there are four transmission system operators, the one responsible for the Baltic Sea is the company 50Hertz Transmission GmbH (www.50hertz.com).

37 European Commission, "National action plans" Accessed April 24th, 2018. https://ec.europa.eu/energy/en/topics/renewable-energy/national-action-plans.
38 Erneuerbare-Energien-Gesetz vom 21. Juli 2014 (BGBl. I S. 1066), das zuletzt durch Artikel 1 des Gesetzes vom 17. Juli 2017 (BGBl. I S. 2532) geändert worden ist (EEG).
39 Sec. 1 par. 2 EEG.
40 Sec. 1 par. 2 (1) WindSeeG.
41 German Offshore Network Development Plan 2030 (O-NEP).
42 AGEB, "Wytwarzanie energii elektrycznej brutto w Niemczech od 1990 r.". Accessed August 8th, 2018. https://ag-energiebilanzen.de/index.php?article_id=29&fileName=20171221_brd_stromerzeugung1990-2017.pdf.
43 Deutsche WindGuard, "Status Des Offshore-Windenergieausbaus in Deutschland". Varel: Deutsche WindGuard. Accessed August 8th, 2018 http://www.windguard.de/veroeffentlichungen.html?file=files/cto_layout/img/unternehmen/veroeffentlichungen/2018/Status%20des%20Offshore-Windenergieausbaus%20in%20Deutschland%2C%20Gesamtjahr%202017.pdf.

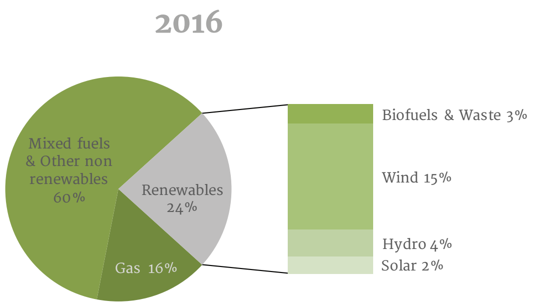
Lithuania

3.2.3. Lithuania

Political goals

- In recent years, Lithuania has diversified its energy mix and connected with other Member States in the region to strengthen its energy independence and security of supply. NordBalt, Estlink, and LitPol have led to a significant increase of the interconnection level, from 4% (2014) to 22% (2017), allowing the country to reach the EU interconnection target of 10%. Moreover, Lithuania achieved its renewable energy target of 23% for 2020 in 2014.
- On 13 June 2018, the Lithuanian Parliament officially adopted an ambitious National Energy Strategy which for a 45% renewables share of its electricity mix by 2030 and 100% by 2050.[51]

Energy numbers



Electricity generation: 4.3 TWh (2016)

Electricity demand: 12.5 TWh (2016)

Electricity consumption per capita: 4.11 MWh/cap/annum (2016)

RES share (electricity): 49% (2016)

Figure 16
2016 Gross electricity generation in Lithuania
[Source: International Energy Agency]

Offshore wind capacity installed

Several offshore wind farms are planned in Lithuanian waters, however no offshore wind farms have been installed yet.

OWF grid connection

The plant operator bears 40% of the connection costs. This also includes the costs incurred from reinforcing the onshore transmission grid (up to a threshold of 10% of the incurred costs).

Transmission System Operator

In Lithuania, the company responsible for the transmission grid is Litgrid (www.litgrid.eu).

51 Ministry of Energy of the Republic of Lithuania, "National energy independence strategy, executive summary – energy for competitive lithuania". 2018. Accessed August 8th, 2018. http://enmin.lrv.lt/uploads/enmin/documents/files/National_energy_independence_strategy_2018.pdf.

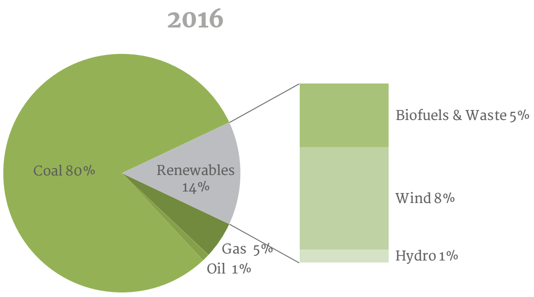
Poland

3.2.4. Poland

Political goals for renewable energy and offshore wind

- With its strategic Energy Policy of Poland until 2030 published in November 2009, the Polish government aims at developing methods in-line with the European Commission energy goals to enable the deployment of renewable energy sources, achieve energy security, reduce GHG emissions in the energy sector as well as observe the principles of sustainable development. It sets a renewable energy development target of a 15% share in final energy consumption by 2020.
- Furthermore, the Polish National Renewable Energy Action Plan published in 2010 shows the development of offshore wind energy as one key element for energy safety of Poland. However, the planned offshore wind capacity of 500 MW, which is set to be implemented by 2020, will not be achieved.

Energy numbers



Electricity generation: 165,8 TWh (2017)

RES share (electricity): 14% (2017)

Electricity consumption per capita: 4.11 MWh/cap/annum (2016)

Figure 17
2016 Gross electricity generation in Poland

[Source: 2016 data International Energy Agency/ 2017 data PSE S.A.]

Offshore wind capacity installed

Despite planning the development of many offshore wind farm projects, Poland has no installed offshore wind capacity yet.

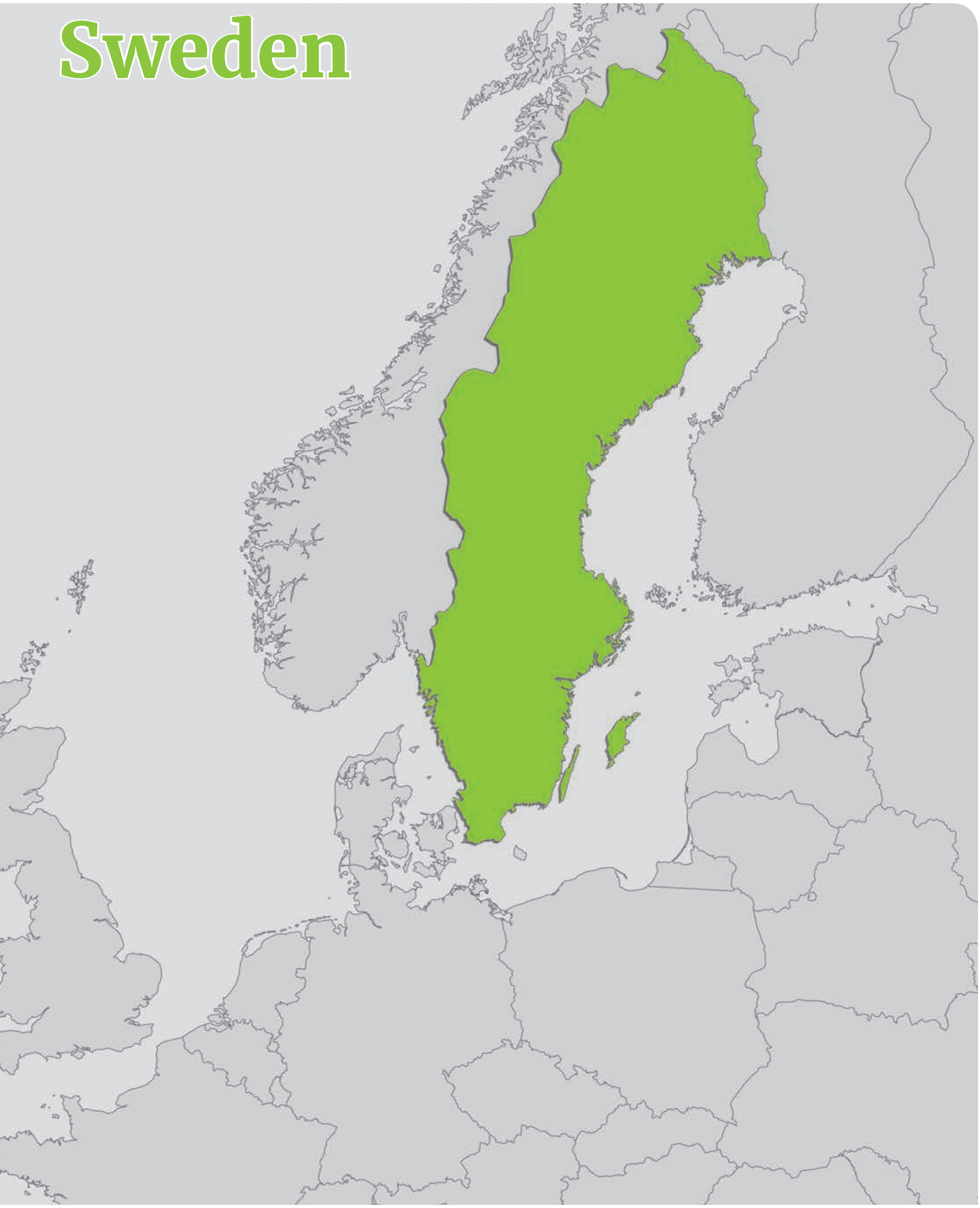
OWF grid connection

The OWF operator covers the investment expenditures to build the connection site, which contains the direct line, and extension or rebuilding costs for the substation (if necessary) where the connection takes place. The reinforcement and development of the existing network is performed by the TSO.

Transmission System Operator

In Poland, the company responsible for the transmission grid is Polskie Sieci Elektroenergetyczne S.A. (www.pse.pl).

Sweden

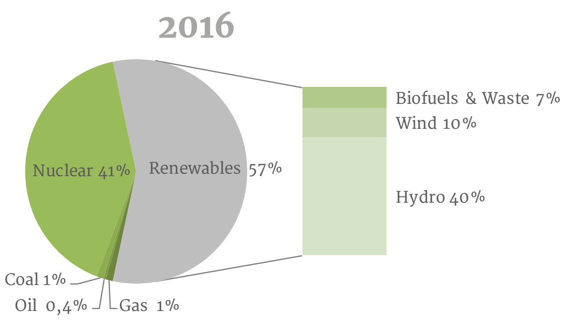


3.2.5. Sweden

Political goals

- The Swedish **National Renewable Energy Action Plan**[44] reflects the Swedish Parliament's decision to have at least 50% of total energy usage come from renewable energy sources by 2020.[45]
- Sweden reached its goal of 50% renewable energy in 2012, several years ahead of the originally planned 2020 schedule[46], and has set itself a target of 100% electricity production from renewable energy sources by 2040.[47]
- There are no binding strategic goals with reference to offshore wind development in Sweden. The Swedish government has however expressed its interest in developing the offshore wind energy market: in its budget proposition for 2017, the Swedish Government mentioned OWE on a few occasions,[48] whilst referring to the 2009 national framework where wind energy planning targets were set to 30 TWh by 2020 with 10 TWh of offshore wind energy.[49]

Energy numbers



Electricity generation: 154.8 TWh (2016)

RES share (electricity): 57% (2016)

Electricity consumption per capita: 13.79 MWh/cap/annum (2016)

Figure 18
2016 Gross electricity generation in Sweden

[Source: International Energy Agency]

Offshore wind capacity installed

Sweden had an offshore wind grid-connected installed capacity of 202 MW at the end of 2017, with 5 grid-connected wind farms and 86 grid-connected turbines.[50] Out of these, 10 turbines/30 MW are located in Lake Vänern.

OWF grid connection

Plant operators take the cost necessary to connect the OWF to the grid as well as grid expansion to the extent that is necessary for their use.

Transmission System Operator

In Sweden, the company responsible for the transmission grid is Svenska Kraftnät (www.svk.se).

44 European Commission, "National action plans". Accessed April 24th, 2018. https://ec.europa.eu/energy/en/topics/renewable-energy/national-action-plans.
45 European Commission, "National action plans". Accessed April 24th, 2018. https://ec.europa.eu/energy/en/topics/renewable-energy/national-action-plans.
46 Sweden.se, "Energy use in Sweden". Accessed April 24th, 2018 https://sweden.se/society/energy-use-in-sweden/.
47 Framework agreement between the Swedish Social Democratic Party, the Moderate Party, the Swedish Green Party, the Centre Party and the Christian Democrats, 10.06.2016. Available under: https://goo.gl/hxFfgs.
48 Regeringskansliet, "Budget proposition 2017, utgiftsområde 21 – Energi". Accessed April 24th, 2018 http://www.regeringen.se/rattsdokument/proposition/2016/09/prop.-2016171/.
49 European Commission, "National action plans". Accessed April 24th, 2018 https://ec.europa.eu/energy/en/topics/renewable-energy/national-action-plans.
50 WindEurope, "The European offshore wind industry. Key trends and statistics 2016". WindEurope. Accessed August 8th, 2018. https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2016.pdf.

Photo: Detlef Gehring, Eon-Netz

4. Methodology

4.1. Assumptions

- The study includes an analysis of two cases. The choice of the case studies was based on an investigation of existing and planned OWF and interconnection projects. The choice of cases in the study was based on the following analysis and inputs: the economic and spatial possibility of locating an interconnection, potential OWF projects, the projects identified in TYNDP, and consultation with TSOs.
- The area of the study was chosen separately for each case and includes the area around the investigated interconnections considered in the case study. Only OWF projects which are at a reasonable distance from the potential analysed interconnections were included in the study.
- The analysis applies a staging approach which comes in the form of snapshots of generation capacity at years 2025, 2030, 2035, 2040, 2045 (the same for both case studies). It is important to note that the uncertainty of project implementation with regard to the commissioning date, project location, size and technology etc. increases significantly after 2030/2035. Therefore, assumptions regarding project development had to be made.
- It is not the purpose of the study to try to predict the development of the OWFs in the Baltic Sea. Instead the study aims to provide potential design solutions, provided that OWF develops in the basin.
- The study is not a substitute for a proper feasibility study.
- This PreFeasibility Study is based on the following analytical steps which are described in greater details in the coming chapters:

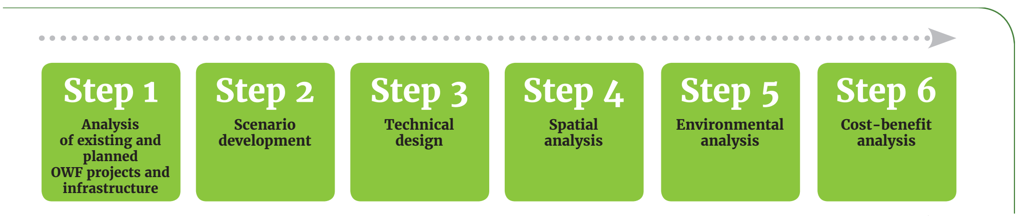


Figure 19 Analytical steps applied to the PreFeasibility Study

4.2. Step 1: Analysis of existing and planned OWF projects and infrastructure

Existing and planned OWFs and interconnectors in the study area were identified based on the database of projects developed within the Baltic InteGrid project. The database was based on the following inputs:

- Knowledge and expertise of partners in each Baltic Sea region country,
- Public information of national authorities,
- News releases,
- Consultation with stakeholders (OWF developers, TSOs),
- Online databases (e.g. 4cOffshore).

Figure 20 represents projects included in the database, at different levels of development.

As of May 2018, there were total of 1,794 MW of offshore wind farm capacity installed in the Baltic Sea, and further 427 MW were under construction. Based on the analysis executed within the Baltic InteGrid project the OWE potential for the Baltic Sea was estimated for over 9 GW until 2030 (upside scenario) and 35 GW until 2050.

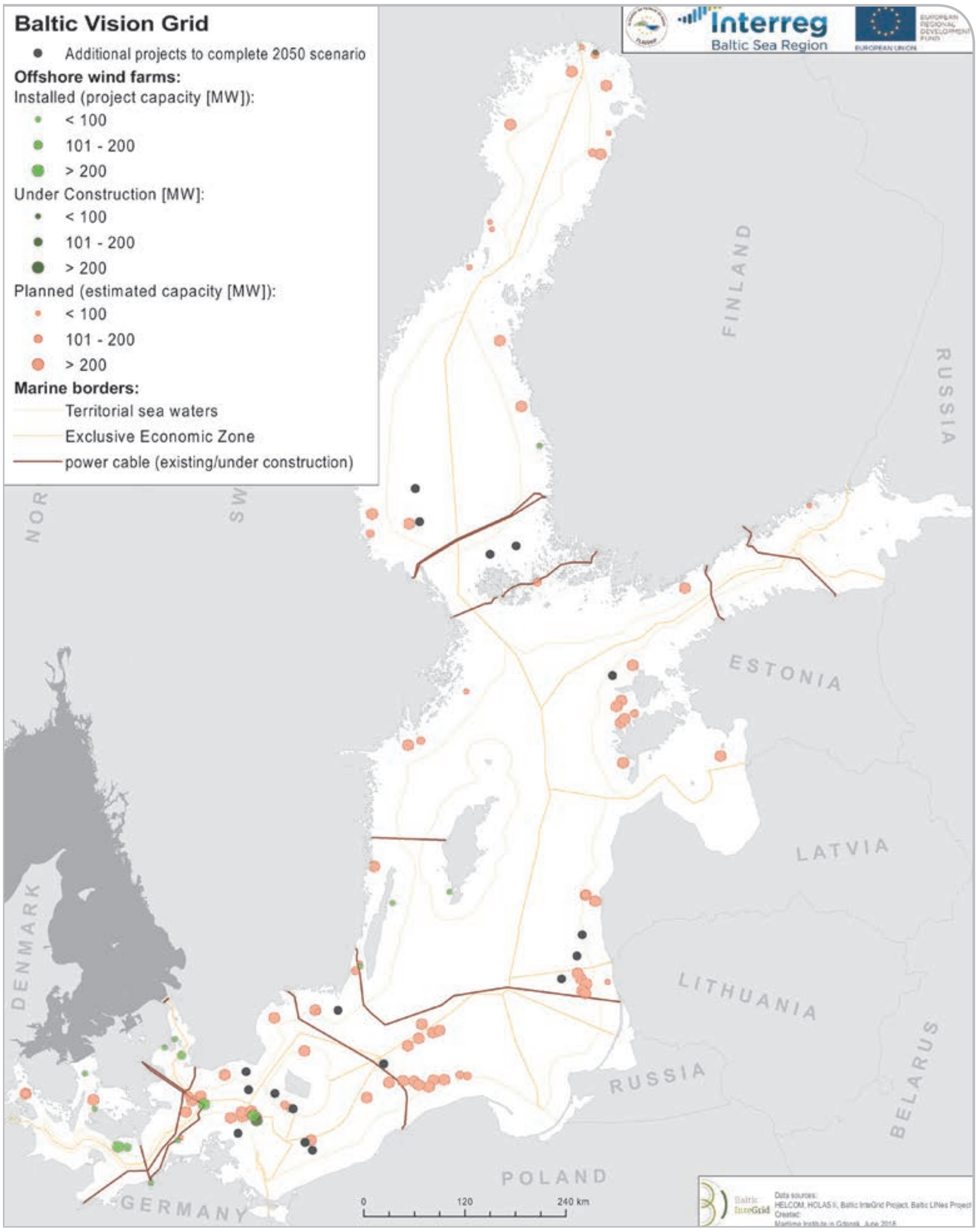


Figure 20
Map of existing and planned OWFs and interconnection projects in the Baltic Sea – status as of June 2018

[Source: Baltic InteGrid project – Maritime Institute in Gdańsk]

4.3. Step 2: Scenario development

A scenario analysis was performed for both case studies. It allowed the different solutions to be compared, and tackled the uncertainty related to OWF deployment in the case study area.

A total of 6 scenarios were developed for each case study. They were based on two variables:

- **Level of integration** – assumes different degrees to which the OWF projects are integrated with the analysed interconnections or with each other. This variable enables costs to be compared.
- **OWF development** – due to the high level of uncertainty regarding the level and speed of OWE development in the region, the scenario assumes two rates at which the OWE will develop in the study area.

4.3.1. Level of integration

The following levels of integration were assumed:

- **Zero Integration** – assumes no integration of OWFs with a planned interconnector. This means that interconnectors are developed independently from OWFs' export infrastructure. This acts as a baseline in the comparative analysis.
- **Partial Integration** – assumes partial integration of OWFs with interconnectors and development of the remaining OWFs in a radial manner.
- **Maximum Integration** – maximum integration of OWFs with interconnectors and/or other OWFs. Potential OWFs to be integrated should be identified as part of the scenario assumptions. This scenario acts as maximum case scenario in the comparative analysis.

4.3.2. OWF development

It is not possible to predict the exact future in terms of OWP build-out, especially when considering the long-time scope of 2025-2045 covered by the study. To better tackle this uncertainty, scenarios presenting different levels of OWF build-out were created. Also, it is important to note that predicting the correct OWP build-out of the Baltic Sea is not one of the objectives of the study. It is rather to evaluate if and how the recommended grid integration level depends on the amount of OWP in the system.

The scenarios assume High and Low OWF development which are based on the projects being considered in the study. For each OWF development (High and Low), a list of projects developed over time (in 5-year intervals) was identified:

- **High OWP –** assumes rapid development of offshore wind in the region and most of the projects planned are commenced within the PFS timeframe. Apart from projects with a high level of certainty of development (for example, projects already approved, with permits obtained, and paid for, or well advanced in the project development process), it also assumes projects with a lower level of certainty, or at the beginning of the planning process (e.g. projects not yet approved).
- **Low OWP –** the conservative approach in which projects develop at a slower pace and only projects with higher certainty and further in the development process are included.

To set up the OWF development (High and Low) the following steps were taken:

- Inventory and assessment of earlier proposed OWF projects in the study area, and alongside possible interconnections among the countries in the study,
- Addition of not yet proposed but feasible areas for future OWP development. OWFs added in this step are typically allocated at a later commissioning time step.
- Assessment of installed OWP capacity of each OWF, looking at:
  - commissioning time step,
  - wind resources,
  - proximity to neighbouring OWFs.

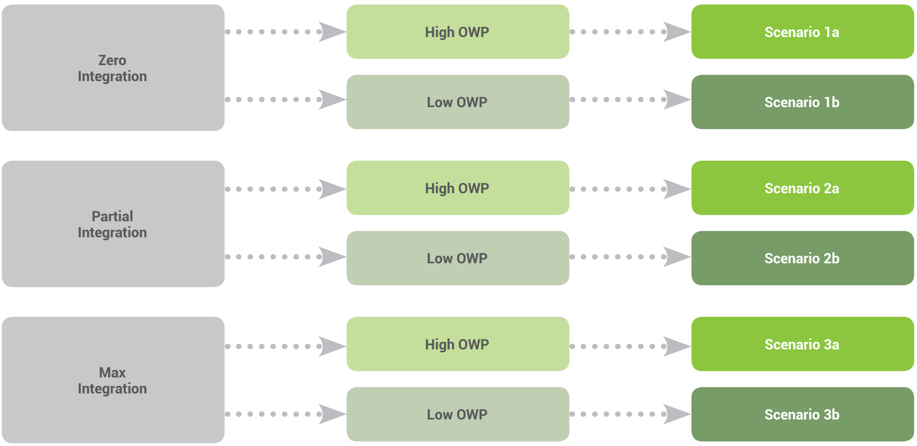


Figure 21
Diagram showing development of scenarios for analysis

4.4. Step 3: Technical design

Development of technical designs for both case studies was a very complex part of the study which was broken down to the following stages:

- Assessment of the installed wind power for each project included in the study,
- General grid assessment,
- Detailed system analysis.

Graph below presents the analytical process.

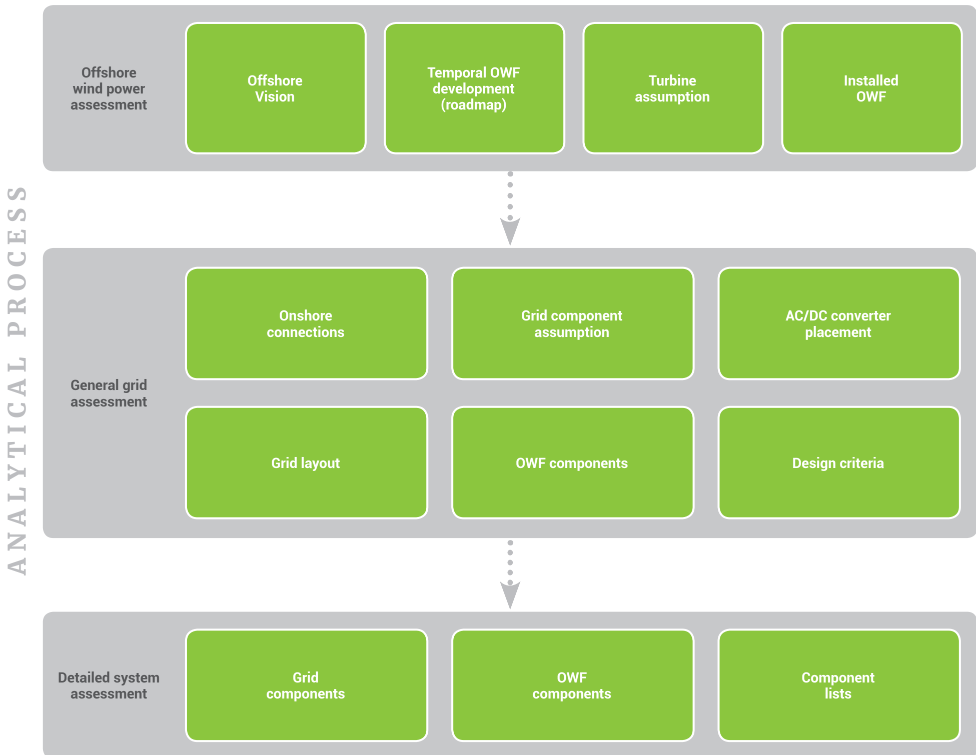


Figure 22
Analytical process applied for the development of technical design

4.5. Step 4: Spatial analysis

A spatial analysis was performed in parallel to the technical design development in order to provide optimal cable corridors and locations for offshore converter stations.

The spatial analysis included the following steps:

- Data collection,
- Constraint criteria development – separately for linear infrastructure (subsea cables) and offshore structures (converter stations). As a result, hard and soft spatial constraints were identified,
- Mapping of the constraints,
- Identification of optimal cable corridors and areas for location of electrical stations based on the general technical design.

The data collected were depicted on a map by applying different attributes to each data set, based on the constraint criteria from the previous step.

As a result, two conclusive maps depicting the constraints were created, separately for offshore linear infrastructure (subsea cables) and offshore structures (converter stations). The maps show all datasets overlapping each other. The level of constraint is depicted by applying a different level of transparency to each dataset, based on the constraint criteria. Hard constraints are represented as white objects (non-transparent), whereas soft constraints are represented in white but with a different level of transparency dependant on the level of the soft constraint (high/medium/low). In short, the whiter the area, the greater the constraint.

[NOTE]: It has to be noted that the data may not be complete due to the fact that not all datasets are publicly available. It is assumed that the data collected represent the best available knowledge. Nevertheless, a detailed analysis should be performed for the proper feasibility study stage.

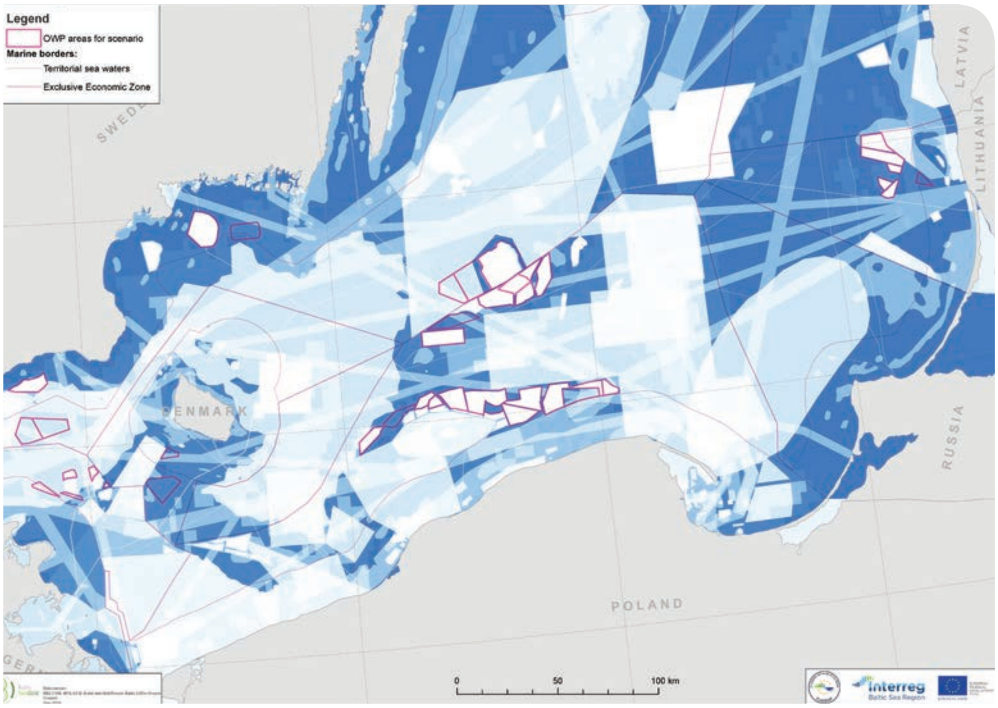


Figure 23
Map presenting constraints for linear infrastructure

[source: Baltic InteGrid project – Maritime Institute in Gdańsk]

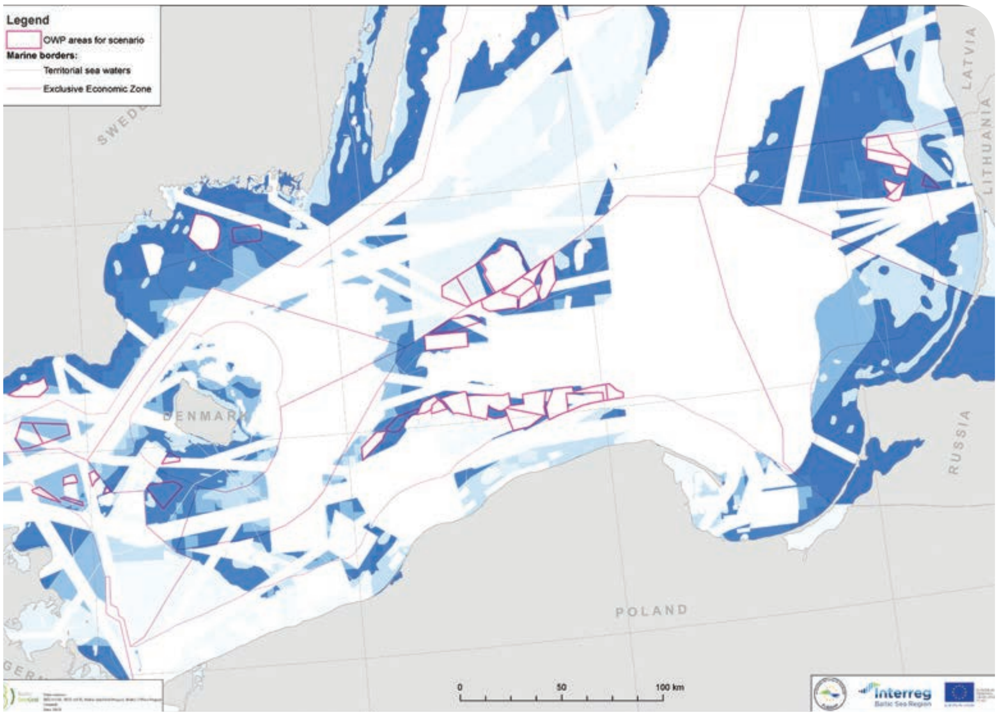


Figure 24
Map presenting constraints for offshore substations

[Source: Baltic InteGrid project – Maritime Institute in Gdańsk]

4.6. Step 5: Environmental analysis

All scenarios were analysed in terms of potential significant impacts on the environment and other sea users. The environmental analysis was performed (only for grid components i.e. offshore stations, cables, landfalls etc.) based on the information included in the Impact Mitigation Strategy for the Baltic Offshore Grid (IMS)[52] developed within the Baltic InteGrid project.

The analysis included the following steps:

- Analysis of the general characteristics of the Baltic Sea,
- Analysis of potential impacts of the case studies based on the matrix presented in the Impact Mitigation Strategy,
- Analysis of protected areas which might be affected by the development of the components included in the case studies,
- Analysis of the impact of the offshore grid development on other sea users.

It is important to note that the environmental analysis was indicative only and each investment in the transmission grid should undergo proper environmental impact assessment based on environmental surveys.

4.7. Step 6: Cost-benefit analysis

The examination of the costs and benefits of different design options for an integrated offshore grid is based on case study scenarios in a disaggregated manner and brought together in an overall

52 J. Makowska; A. Marczak; M. Karlikowska; M.Wójcik; M. Trzaska, "Impact Mitigation Strategy for the Baltic Offshore Grid". Developed under the Baltic InteGrid project, (2018). Baltic InteGrid.

Cost Benefit Analysis (CBA). A CBA is a systematic approach to estimate the strengths and weaknesses of different variants of projects or investments. It answers the question of whether the benefits of an investment option outweigh its costs. For very large projects with a long-term time horizon, the cost-benefit analysis has to deal with a raised complexity and higher uncertainty of all parts of the benefits and costs. A variety of assumptions has to be made, such as for the development of the energy market, for commodity prices, or for future political decisions. One main challenge is the monetisation of benefits, which is only possible to a limited extent.

The CBA methodology applied here is based on the ENTSO-E CBA methodology[53], which provides criteria for the assessment of costs and benefits of European transmission projects. The proposed set of indicators has been adapted to fit the reduced complexity of a result-oriented CBA[54]. The core indicators are the socio-economic welfare and the project expenditures. These indicators are fully monetarised and weighed against each other. Additional indicators evaluate a transmission system's security of supply. The costs and benefits are analysed in two separate models: a market model to evaluate the socio-economic welfare of the various scenarios as well as their individual security of supply, and a linear cost model to calculate a project's capital (CAPEX) and operational expenditures (OPEX). All cash flows are discounted to the base year 2017 with a discount rate of 4 percent, as suggested by ENTSO-E. The following figure presents an overview of the general approach, details of the two models are presented in the subsequent sections.

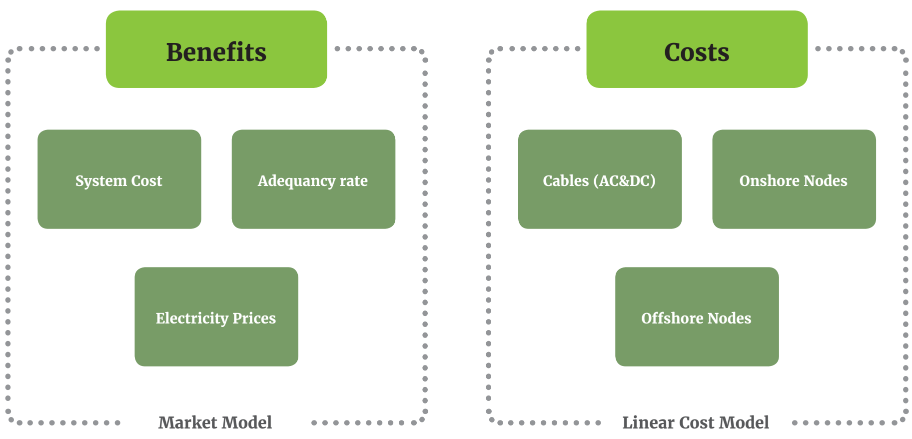


Figure 25
Approach to the cost-benefit analysis

This CBA can be understood as a comparative CBA that does not evaluate whether a certain scenario is beneficial or not. Instead, the analysis compares the scenarios with different degrees of grid integration to each other to evaluate the additional benefits and costs of increased integration. For each of the combinations of study region (Case Study 1 and Case Study 2) and offshore wind installation (Low OWP and High OWP), the zero integration scenario is set as a baseline. The following figure illustrates this approach for case study 1 with high offshore wind installation.

53 ENTSO-E, "ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects, Version for ACER official opinion". Brussels: ENTSO-E 29 July 2016.
54 Meeus, L.; von der Fehr, N.; Azevedo, I.; He, X.; Olmos, L.; Glachant, J., "Cost Benefit Analysis in the Context of the Energy Infrastructure Package". Firenze: European University Institute (2013).

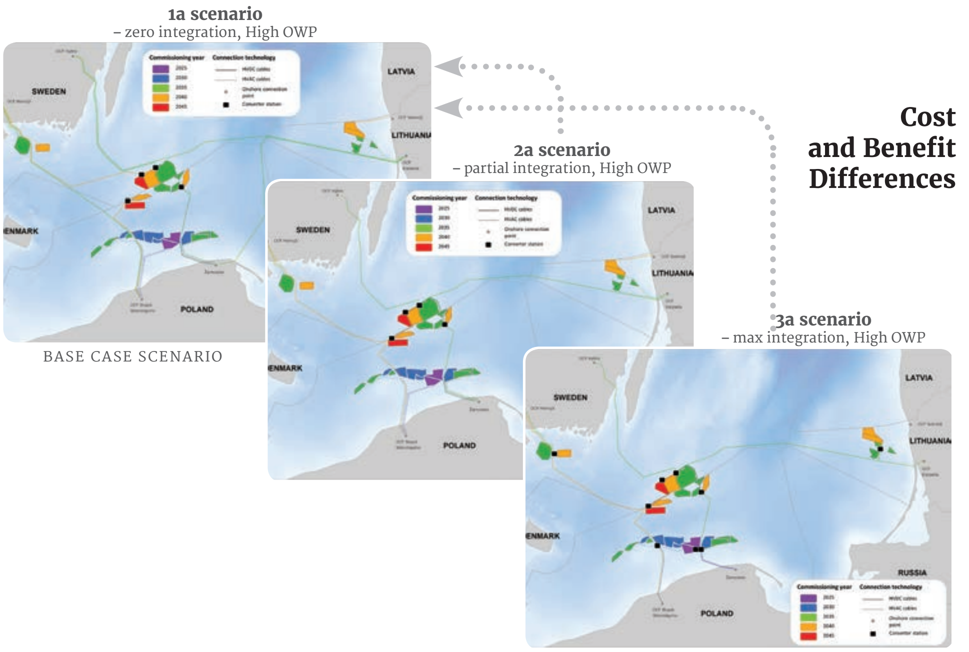


Figure 26
Schematic illustration of the cost-benefit analysis as a comparison to the base case scenario

4.7.1. Benefits

To determine the benefits of additional integration between offshore wind farms and the interconnections between market areas, the dynamic investment and dispatch model dynELMOD[55] is used, thereby identifying the benefits from the market side. The model determines cost effective investments into generation capacities, storages and interconnectors for Europe until 2050. Further information on assumptions and methodology are described in “Cost-Benefit Analysis for an Integrated Offshore Grid in the Baltic Sea – Comparison of different levels of grid integration based on case studies” developed by Deutsche Windguard and IKEM.[56]

4.7.2. Adequacy

The adequacy of generation capacity per market area was analysed. This is determined by cumulating all available generation capacity in each region and its neighbours. Generation capacities from neighbouring countries are only considered if there is enough capacity on the respective interconnector.

4.7.3. Costs

The cost assumptions for far future projects are always subject to high uncertainty. This is especially the case if new technology such as HVDC components are used. For the cost evaluation, a linear cost model (LCM) is used. The LCM assumes cost parameters for branches and nodes (electrical stations). Branch costs cover cables and associated construction costs. Node costs cover the total cost for converters or transformers, respectively, plus the platform cost if it is an offshore node. The LCM can thus be applied to any electrical HVDC transmission infrastructure layout.

55 Gerbaulet C., Lorenz, C., "dynELMOD: A Dynamic Investment and Dispatch Model for the Future European Electricity Market: DIW Berlin Data Documentation 88". Berlin, Germany (2017).
56 Wallasch A.K., Bormann R., Künne T. Gerbaulet C., Weinhold R. "Cost-Benefit Analysis for an Integrated Offshore Grid in the Baltic Sea. Comparison of different levels of grid integration based on case studies". Germany (2018).

5. Case study 1 – Poland-Sweden-Lithuania

5.1. Case study description

5.1.1. Geographic area with interfaces

The geographical scope of this case study covers the south-east part of the Baltic Sea. This includes waters enclosed partly by the Swedish and Polish waters and the total area of the Lithuanian waters.

In the case study area, two banks mainly stand out in their potential to accommodate significant numbers of clustered OWFs. The Southern Middle Bank is located in a centred position, divided by the Polish and Swedish EEZ border. The bank provides approximately 2000 km^2 of waters with depths shallower than 40 m. Both Swedish and Polish draft maritime spatial plans have been presented to develop OWFs in this location.

Southwards from the Southern Middle Bank, the Słupsk Bank can be found within the Polish EEZ. This bank houses a Natura 2000 area, but outside of this protected zone, it provides substantial areas of shallow water depths suitable for OWP.

Many wind farms have already been suggested around this area. An advantage is the moderate distance to shore which is often a 25-40 km direct route from the proposed OWFs to shore.

Also, at decent distances from the Lithuanian coastline, significant areas can be found with the same characteristics. The national authorities have pointed out zones here reserved for renewable energy extraction.

This particular corner of the Baltic Sea has the advantage of large areas of favourable water depths for offshore wind power on bottom fixed foundations. Since the body of unobstructed water is among the largest of the Baltic Sea, this results in a good wind resource. In addition, most of the offshore wind farm projects currently being developed, especially in Polish waters, are within this area.

The geographical scope of this case study was chosen based on the assumption to connect Lithuanian, Polish and Swedish electricity systems via potential OWP clusters.

5.1.2. High and Low OWP development, including power densities

Figure 27
Map of PL-SE-LT case study area

Not all previously proposed or possible OWFs in the case study area are included in the High OWP development roadmap. The reason for this is that not all possible wind farm positions fill the criteria of being located along the general direction of country-to-country interconnections. For any given OWF to be included in the case study, it needs to make reasonable sense to integrate this wind farm to the DC grid through the maximum integrated approach. As a result, the potential of OWFs in the countries included in the cases may be higher than that shown in the study.

The following conditions were taken into account when identifying projects for High/Low OWP development:

Polish waters:

- In the High OWP development, projects with valid but also expired location permits were included in the study. Projects with connection agreements signed are developed first.
- In the Low OWP development, only projects with valid location permits were considered, and the build-out of OWFs is pushed out further in time.
- Provisions from the current environmental permits and location permits (including the 500 m inward buffer clear of OWF structures) were included.
- A 2 km buffer around the Nature 2000 area "Ławica Słupska" clear of OWF structures (based on the first environmental decision) was applied.

Swedish waters:

- In the High OWP development, projects with ongoing permits and possible (but not yet started permit process) are included.
- The extended areas (orange and red) around South Middle Bank are classified as Natura 2000 areas. However, in Sweden it is possible to obtain a permit for a wind farm according to the Swedish Environmental Protection Agency. It´s very much up to the presented project solution within the Environmental Impact Assessment done by the wind farm developer.
- In the Low OWP development, only one existing project at South Middle Bank is included that most likely will be built depending on upcoming new grid connection regulations and the electricity price level in Sweden.

Lithuanian waters:

- In the High OWP build-out projects which obtained a positive environmental decision, and which are undergoing environmental impact assessment were included. For some of the projects. onshore grid reinforcement would be required.
- In the Low OWP build-out, only the so called "1st priority sites" were included which are most probable in terms of realisation and do not require additional grid reinforcement.

The maps below present High and Low OWP development included in the Case Study. The colour scheme applied to the projects shows the period in which the project is to be commenced.

Power densities are given in the maps.

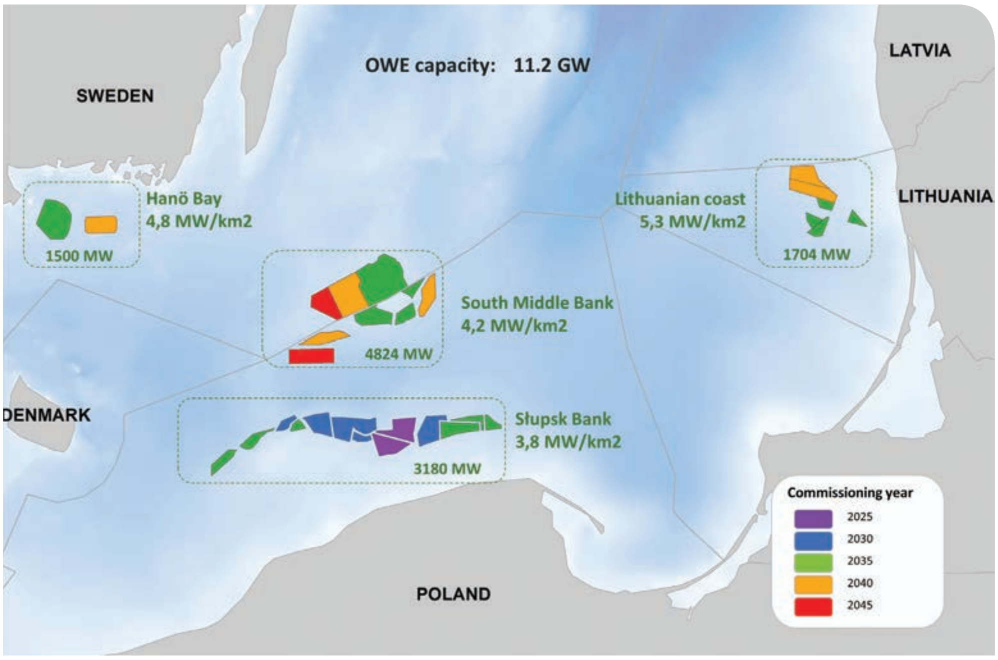
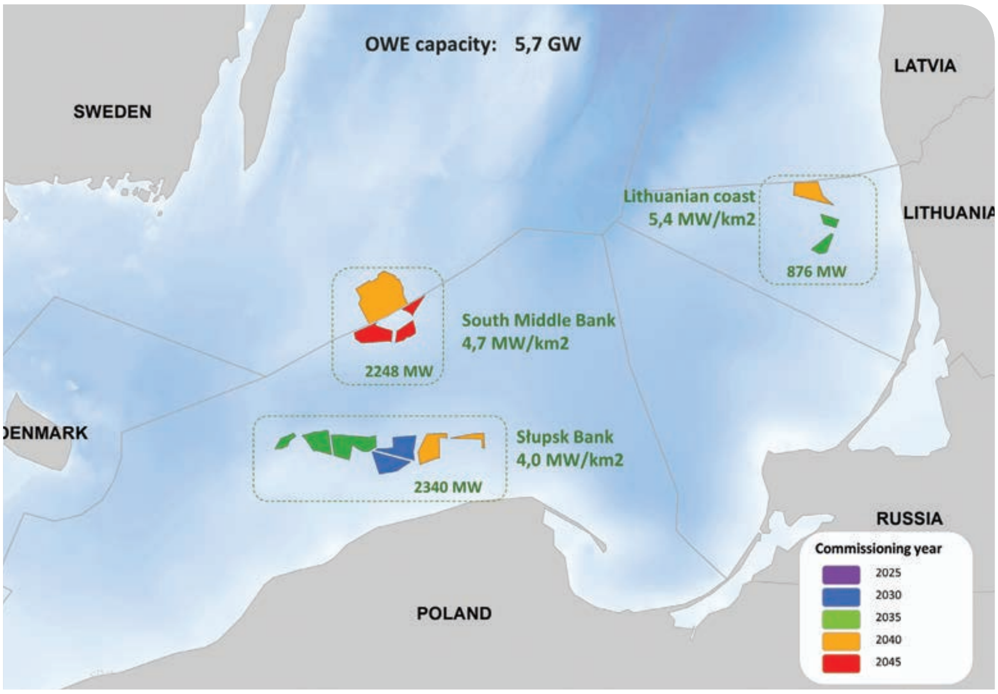


Figure 28
Map presenting the High OWP development vision, displaying installed OWP capacity and chosen power density per cluster

Case Study



[NOTE]: only offshore wind projects relevant to Case Study 1 are included in this map. For example, in the western part of Poland there are projects planned that are not part of the case study

Figure 29
Map showing the Low OWP development vision, displaying installed OWP capacity and chosen power density per cluster.

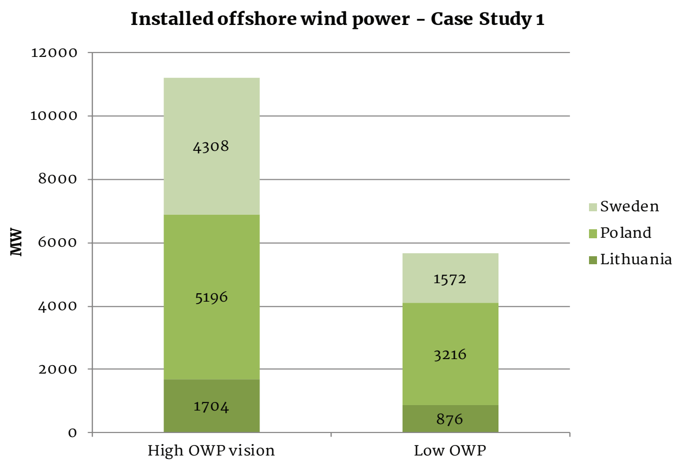


Figure 30
Installed offshore wind power High/Low OWP–Case Study 1

5.1.3. Onshore connection points

All onshore connection points chosen for this case study are based on the current conditions of the grid locations, and the potential for future synergies (i.e. for energy storage).

Over the time of the case study, it is obvious that all of the presented onshore connection points and the surrounding onshore high-voltage grid will need substantial upgrades to accommodate the suggested future power flows.

5.2. Scenario presentation

5.2.1. Scenario 1a – Zero integration Scenario – High OWP development

This scenario represents a low technical and coordination complexity. Most of the projects, whether an OWF or a cross-border interconnector, are planned and built separately. The only few projects that require coordination are the OWFs located around the Southern Middle Bank. These projects are far from the closest onshore connection point (longer than a 120 km cable route). This is why these OWP projects are clustered together and the power is aggregated between numerous OWFs to be transmitted to shore.

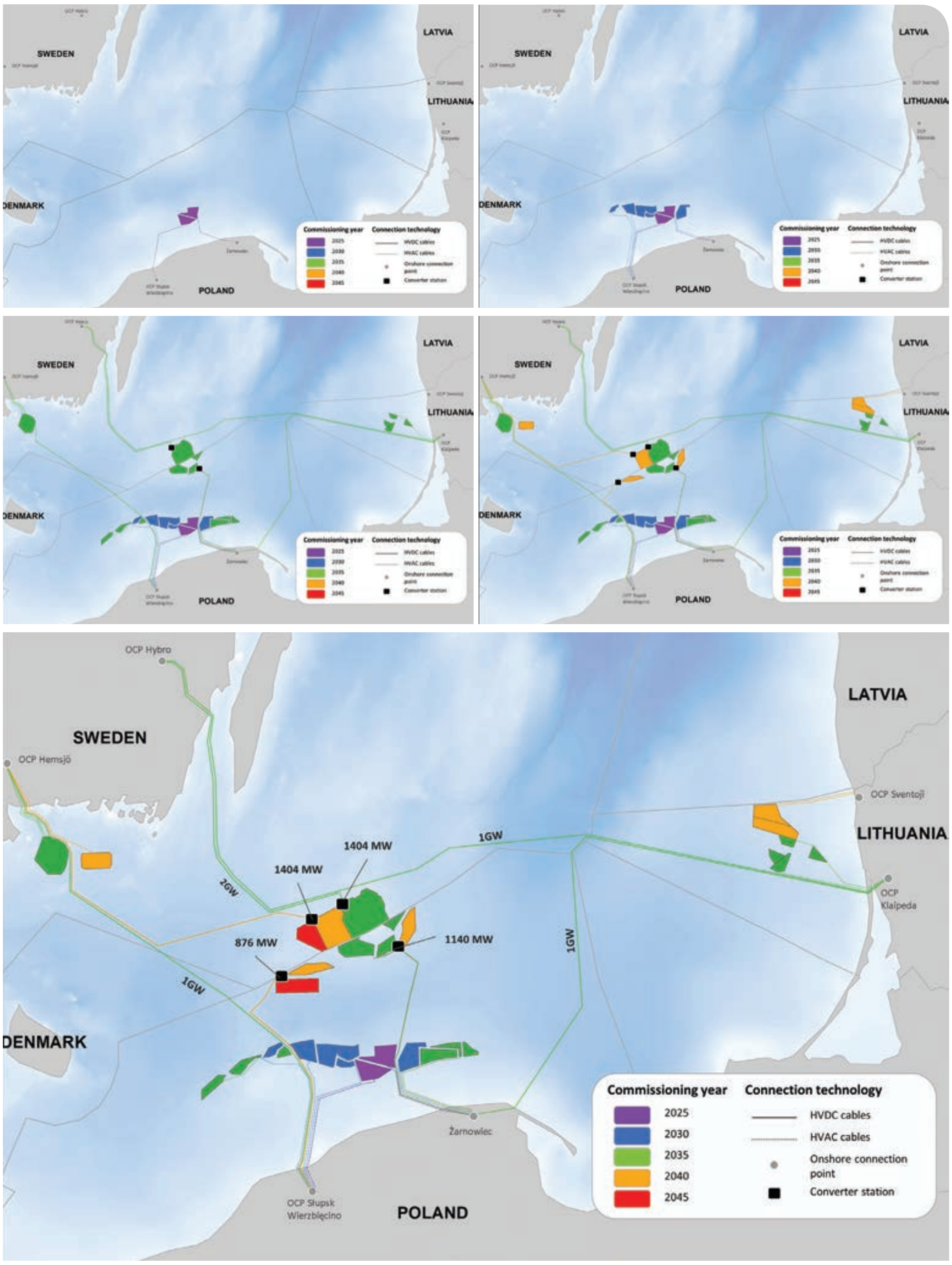


Figure 31
Case Study 1 – Scenario 1a schematic build-out

Case Study

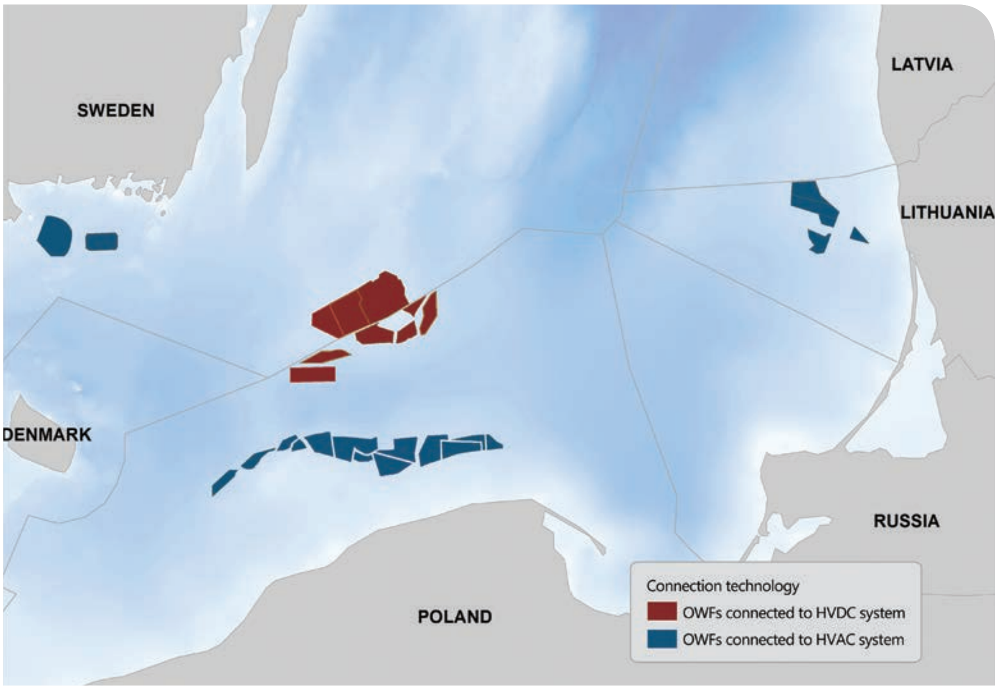


Figure 32
Case Study 1 – Scenario 1a
OWF connection technology

Advantages	Disadvantages
Low complexity, Business-as-usual, low cooperation, relatively low biggest fault potential (1.4 GW)	Parallel cables, larger sea use, higher environmental impact, “low”/different flexibility/redundancy, low infrastructure utilisation rate

Scenario summary

This scenario highlights the advantages and disadvantages of keeping the interconnectors and OWP separate. At a technical level, this scenario only implements system topologies and technologies commercially used today. Regarding component ratings, an incremental upgrade of today's voltage levels and power ratings is assumed. When it comes to the need for coordination, this only applies to the OWF developments far from shore where DC technology is assumed to be the most cost effective. In this scenario, there is no need for specific DC protection equipment (e.g. DC breakers), which can be an advantage. A disadvantage is that if a link fails, there are no alternative routes for either OWP or energy trading to be rerouted through.

With the approach of zero integration, OWFs and interconnectors can for the most part be developed independent of each other. Looking towards the needed infrastructure, a longer total cable length will be needed due to the situation of many parallel cables. In this scenario, TSOs will have total control over the interconnectors since they all are built point-to-point. This means they can continue their trade on them like business-as-usual.

5.2.2. Scenario 1b – Zero integration – Low OWP development

The second scenario builds on the same principle of zero integration, just as with the previous scenario. However, the difference is the assumption of an overall lower and slower OWP build-out in the case study region. The total installed wind power amounts to 5.7 GW and the Cross-Border Energy Trade (CBET) capacity is kept at 1 GW between all countries. The greatest OWP build-out will take place at the Slupsk bank and the Southern Middle Bank in this scenario. The only coordination required between projects is for the clustered OWP at the South Middle Bank, where multiple OWFs are aggregated to the same converter station. Scenario 1b is characterised by a high number of parallel cables and a low required synchronisation between OWF projects and interconnectors.

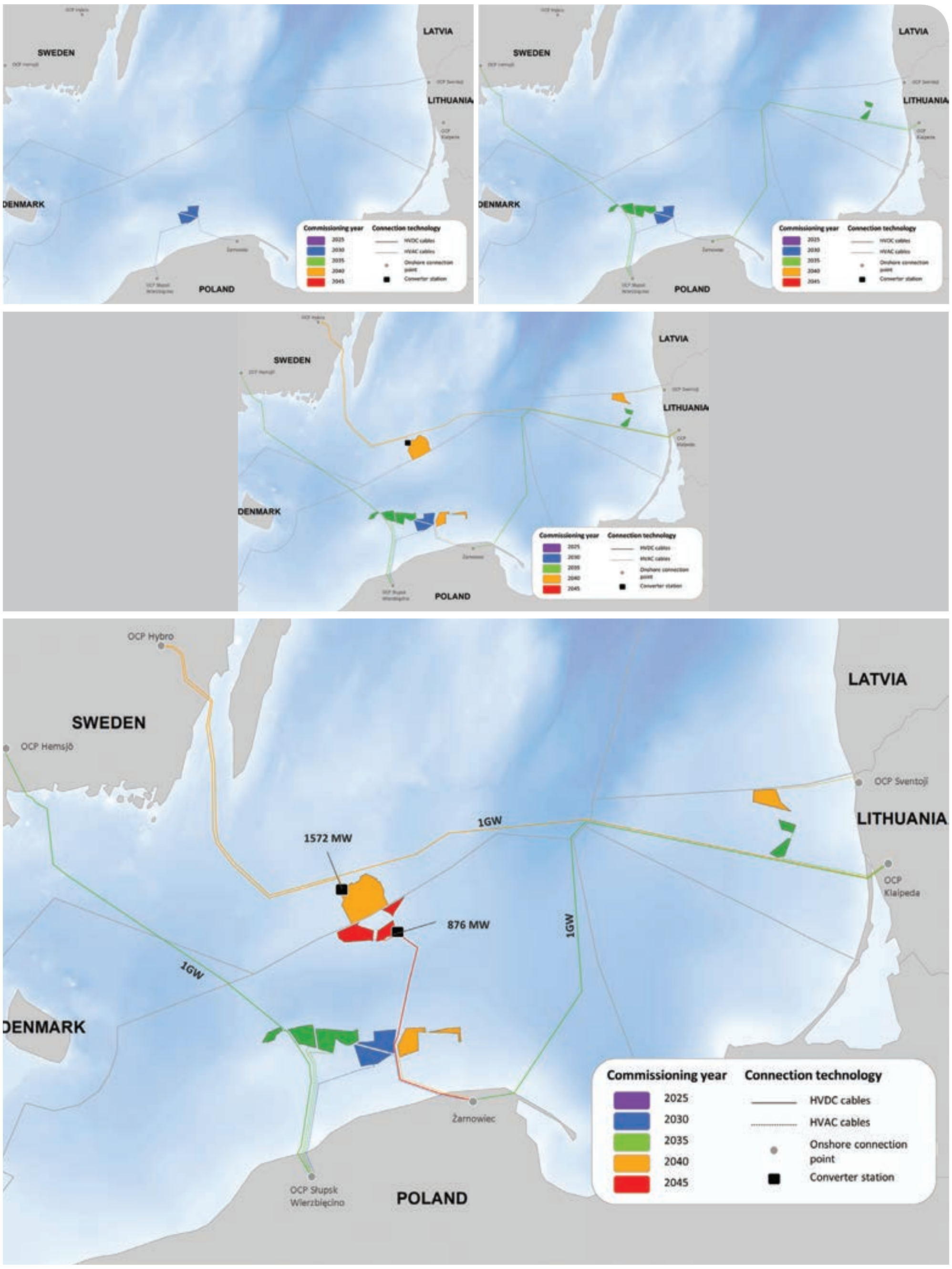


Figure 33
Case Study 1 – Scenario 1b schematic build-out

Case Study

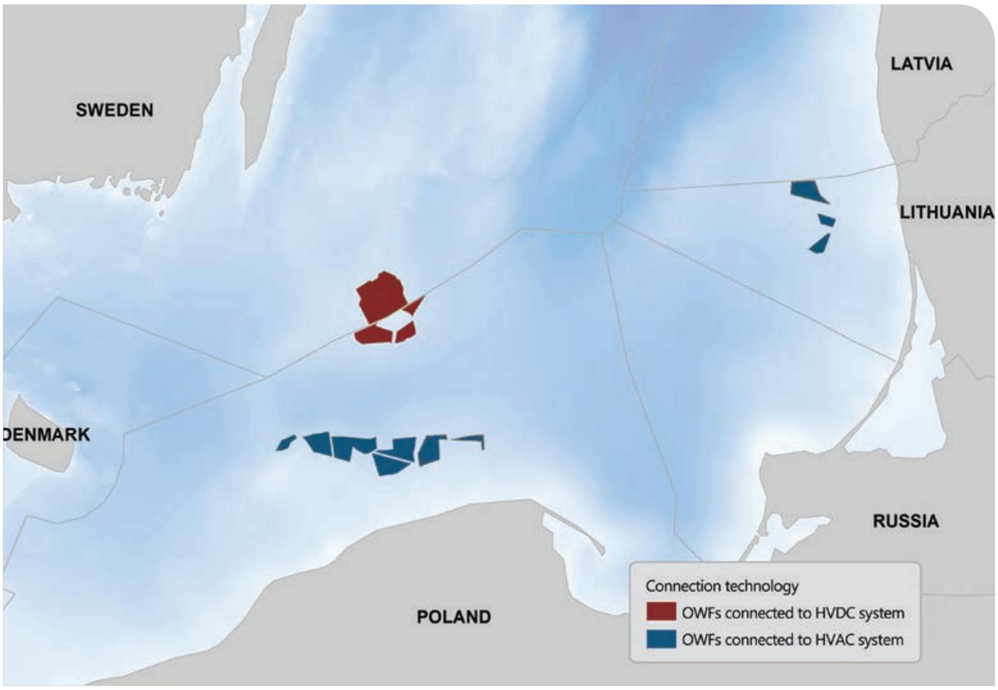


Figure 34
Case Study 1 – Scenario 1b
OWF connection technology

Advantages	Disadvantages
Low complexity, Business-as-usual, low cooperation, no DC protection system needed, biggest fault potential (1.57 GW)	Parallel cables, larger sea use, higher environmental impact, "low"/different flexibility/redundancy, low infrastructure utilisation rate

Scenario summary

Scenario 1b is in many respects very similar to scenario 1a, correlating with the design similarities. Due to the independent development approach of the zero integrated design, the level of OWP build-out only changes the results of the technical analysis slightly.

Like in the previous scenario, the unsynchronised build-out approach leads to a less technically challenging set-up, with no interdependencies between OWP development and interconnectors. However, the result is generally longer total cable routes, low levels of redundancy and a utilisation rate of the farm-to-shore links that is set by the OWP's capacity factor.

5.2.3. Scenario 2a – Partial integration – High OWP development

The scenario presents the possibility of a hybrid system, incorporating both radial and integrated OWF connections. The design logic of this scenario is to connect OWFs close to shore radially with AC technology, and the wind farms far offshore would be integrated with the HVDC interconnectors. This type of design would need a fair level of cooperation for all projects and stakeholders using the VSC-HVDC system. In return, the solution could provide higher flexibility, utilisation rates and cost sharing opportunities.

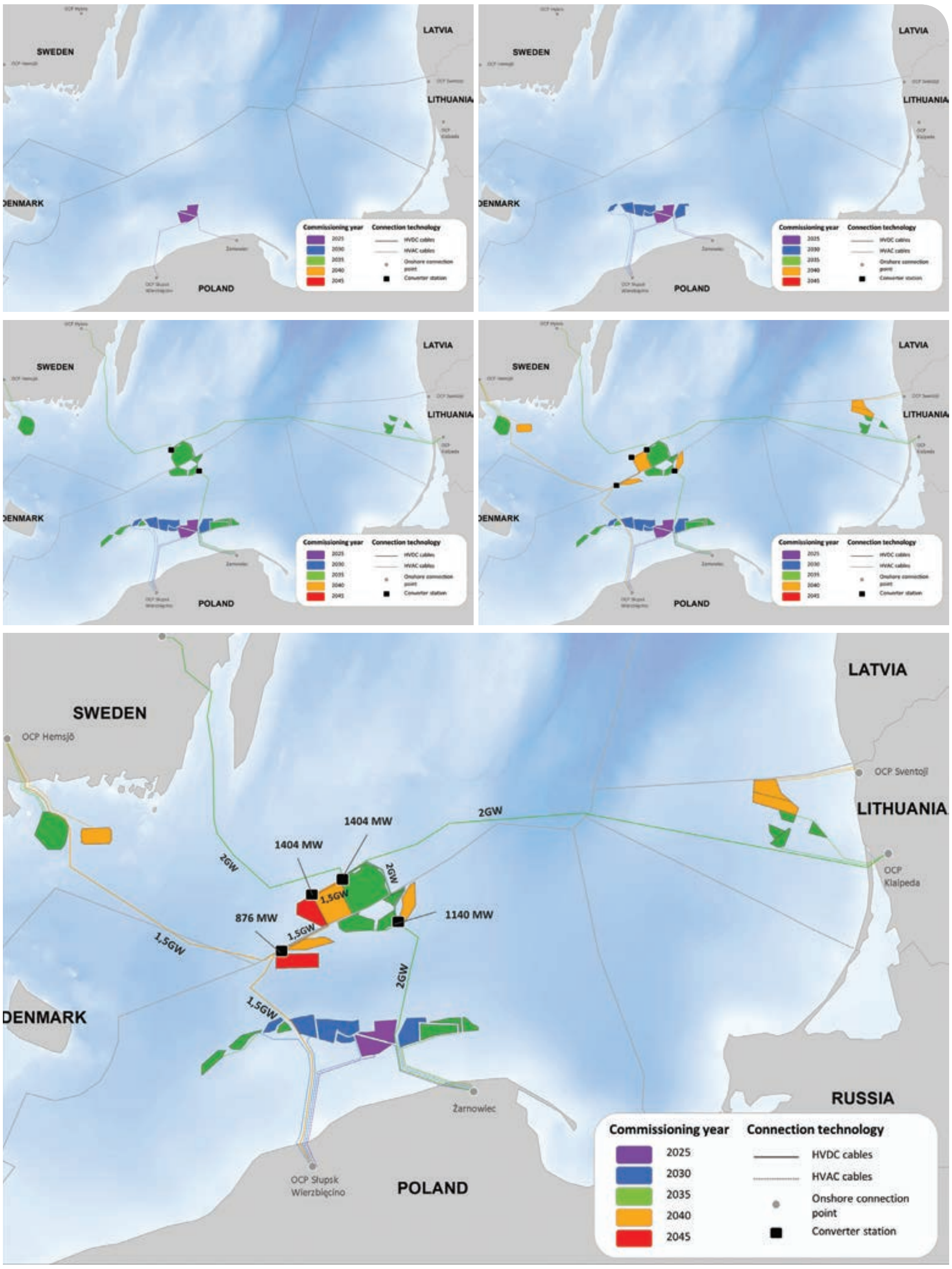


Figure 35
Case Study 1 – Scenario 2a schematic build-out

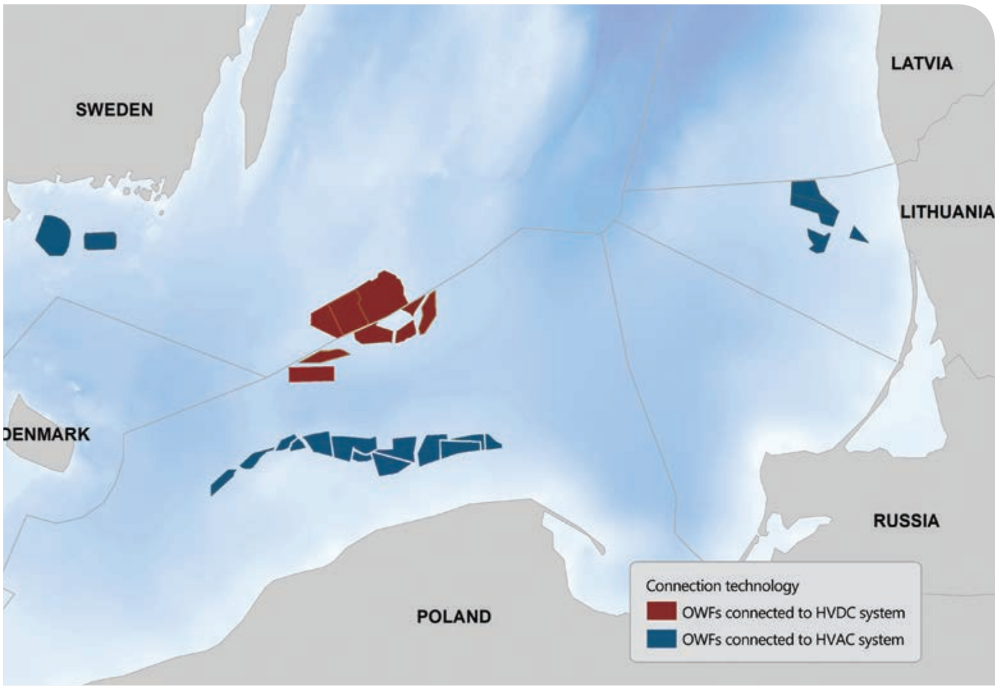


Figure 36
Case Study 1 – Scenario 2a
OWF connection technology

Advantages

Less parallel infrastructure then in zero integration, Business-as-usual for AC, higher infrastructure utilisation rate, higher flexibility/redundancy

Disadvantages

Need for cooperation of OWP and TSOs, substantial sea use, DC protection system needed, relatively higher biggest fault potential (2 GW)

Scenario summary

Scenario 2a shows an example of how to interlink OWFs far from shore and interconnectors in a HVDC grid. Naturally, this calls for a high level of co-operation between OWP developers and TSOs, which could very well lead to longer planning horizons. The upside is that the development of OWP in the South Middle Bank will take place after 2030.

Cooperation is not only a precondition up until installation of the system, but also during the operation phase. The energy trading patterns for such a system will have to take the current OWP generation into consideration. With that said, the maximum trading capacity will be higher, since the ratings of the links are dictated by the installed OWP. On the down side, a higher rating of the links inevitably leads to a bigger possible fault.

When it comes to the technical complexity and novelty of the scenario, a new topology, compared to today, is introduced. However, the time step of the first interconnected DC grid is set to 2035. This makes available a significant 15 years of development and piloting before implementation in the Baltic Sea. Additionally, some level of DC protection (minimum one DC-breaker) will most probably have to be implemented in such a system.

5.2.4. Scenario 2b – Partial integration – Low OWP development

Scenario 2b uses the same design approach as 2a, but with a limited OWP build-out schedule. Only OWP far from shore will be connected into the multi-terminal VSC-HVDC system. In this variant of the partial integrated case, it becomes apparent that not only OWFs but also interconnectors can be connected radially. Similar to the previous scenario, this approach tries to strike a balance between technical and organisational complexity, economic feasibility and power flow flexibility.

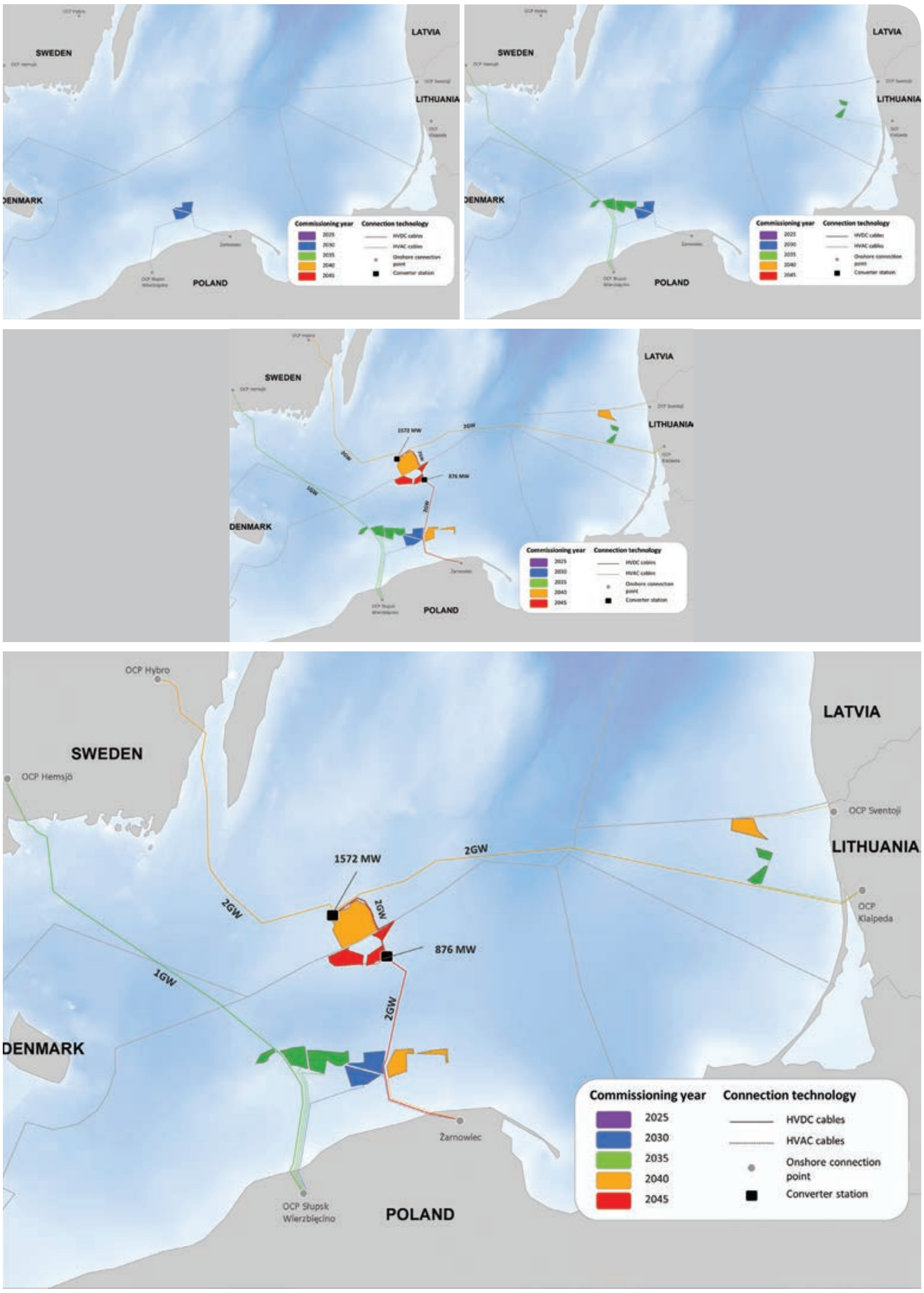


Figure 37
Case Study 1 – Scenario 2b schematic build-out

Case Study

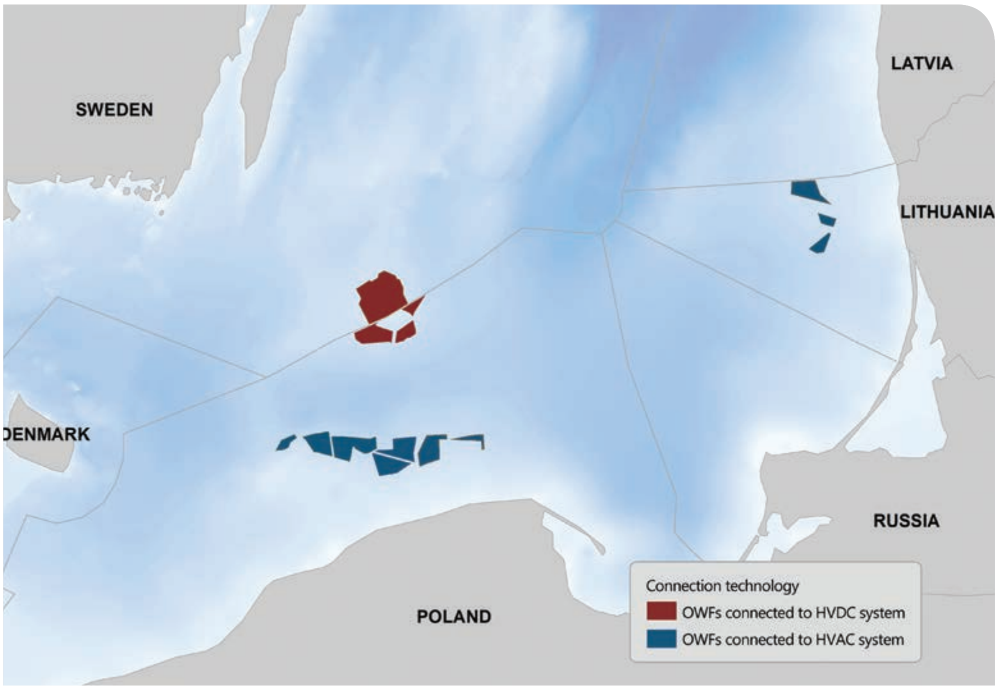


Figure 38
Case Study 1 – Scenario 2b
OWF connection technology

Advantages

Less parallel infrastructure,
higher infrastructure utilisation rate,
higher flexibility/redundancy,
DC protection system may not be needed

Disadvantages

Need for cooperation of OWP and TSOs,
still substantial sea use,
relatively high biggest
fault potential (2 GW)

Scenario summary

This scenario shows an example of integrating some OWFs into the interconnecting DC grid, while other farms are connected radially with AC technology. Generally, the OWFs relatively close to shore are the ones where the additional value of DC grid integration is the lowest. It is assumed that a radial connection with AC technology is the preferred choice here.

To maintain a high level of interconnection capacity between Sweden and Poland, a radial interconnector is needed. This shows the hybrid character of this scenario, both for OWP interconnection and for traditional vs. grid integrated interconnectors. The approach of having two separate links or "DC systems" can be seen as an advantage from an operational point of view, when taking the risk of faults into account.

Due to the rather "small" DC system with "only" 5 nodes, it is assumed that no additional DC protection components are needed.

5.2.5. Scenario 3a – Maximum integration – High OWP development

This introduces the concept of full integration of OWP into the border-crossing VSC-HVDC system. The conditions for this approach are large efforts for international energy and sea use planning, extensive technological know-how regarding multi-terminal VSC-HVDC systems and the availability of an economically attractive HVDC security toolbox. The benefits of such a system could be maximum flexibility of power flow, high infrastructure utilisation rates and cost sharing opportunities.

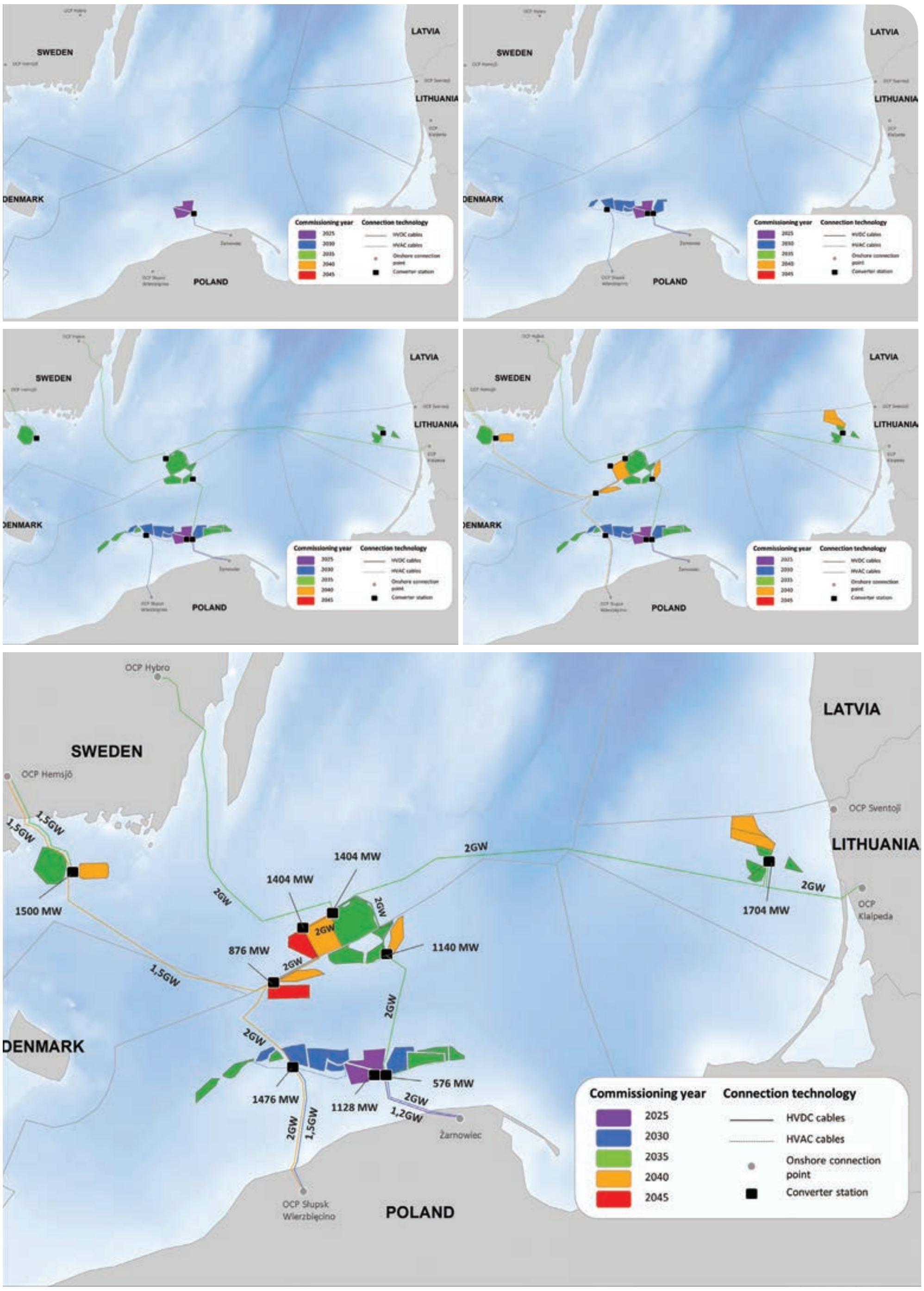


Figure 39
Case Study 1 – Scenario 3a schematic build-out

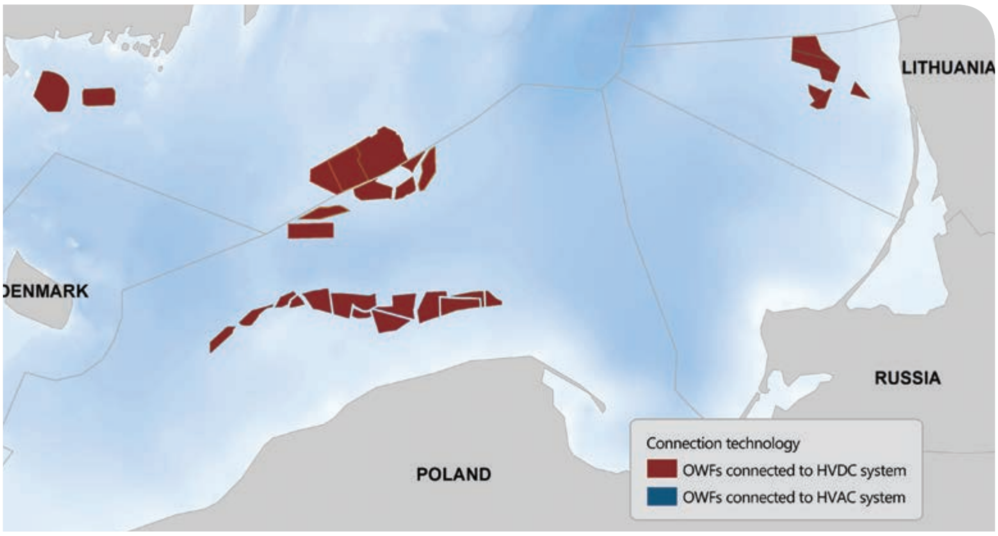


Figure 40
Case Study 1 – Scenario 3a
OWF connection technology

Advantages	Disadvantages
Minimum parallel infrastructure, highest infrastructure utilisation rate, highest flexibility/redundancy	Need for cooperation of OWP and TSOs, DC protection system needed, relatively big fault potential (2 GW)

Scenario summary

Scenario 3a displays the fully integrated version of the case study. All OWFs are connected to the offshore DC grid. This leads to a significant number of converter stations, as well as at least one converter station with a suboptimal rating. A cluster area with a wide spread of commissioning time steps (more than two steps), like the cluster closest to the Żarnowiec onshore connection point, leads in this case to a station rating of 516 MW. This would most probably constitute an economically unfavourable rating for a DC converter. If a fully integrated approach would be decided on, it would be important to align the commissioning years of all OWFs within the same area.

It is important to note the heavy and early cooperation of nations, TSOs and OWP developers in order to obtain maximum integration in the case study area. Basically, all aspects and details around the integrated grid would have to be researched well before the connection of the first OWFs up until 2025. This would apply to the technical specifications for the components, modularity options for future extension, grid codes, security standards, etc. but also for energy market, maritime spatial planning, policy, regulation and political issues. Assuming that DC-DC transformers do not turn out to become a viable option during the time period of the case study, engaging in the maximum integrated grid earlier, with a lower DC voltage, leads to a “lock in” at this voltage level. This might or might not be a problem during the time scope of the case study, since the step-in voltage of 525 kV is already rather high.

A DC grid incorporating these high levels of GWs would need the implementation of DC protection equipment at a number of nodes in the system.

Although the presented layout erases the presence of any parallel AC and DC cables, there will be parallel DC cables routes. The reason is the design criteria allowing over-investment in infrastructure over only one additional time step (for example: the cluster close to Żarnowiec), and the chosen cable rating limit (for example: the connection to Hemsjö).

Regarding redundancy, this scenario shows the highest level of OWP export security. All connected OWFs will have at least two routes of export to rely on. When it comes to the security of supply of CBET, there is only a slight increase to the maximum trading capacity in scenario 3a compared to scenario 2a.

5.2.6. Scenario 3b – Maximum integration – Low OWP development

This scenario shows the same principles of maximum integration as in scenario 3a, but with a lower amount of OWP built in the area. The VSC-HVDC system in scenario 3b extends to individual branches of multi-terminal VSC-HVDC systems. Similar to scenario 2b, this can be valued as an aspect increasing overall system reliability. The key characteristic of this scenario can be summarised as high cooperation and planning requirement, technically challenging, flexible power flow routing, the possibility for high utilisation rates, shorter total cable lengths and the possibility to share costs.

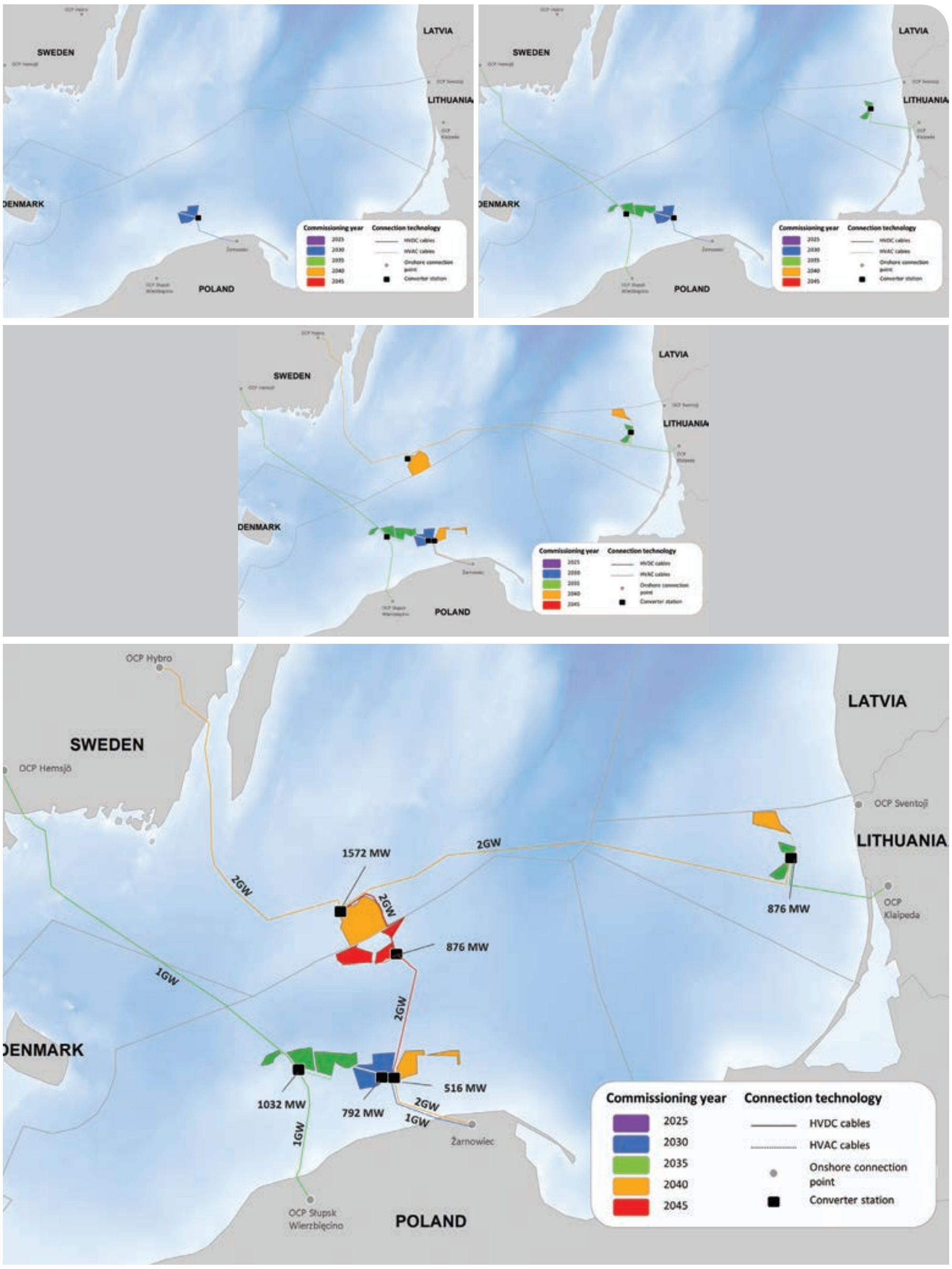


Figure 41
Case Study 1 – Scenario 3b schematic build-out

Case Study

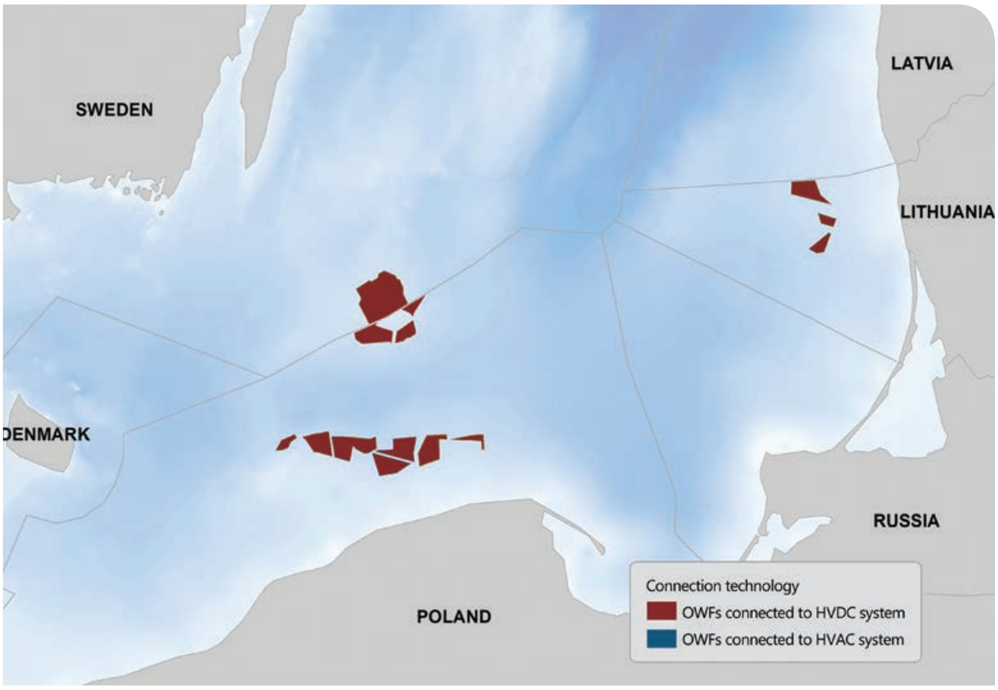


Figure 42
Case Study 1 – Scenario 3b
OWF connection technology

Advantages

Minimum parallel infrastructure, highest infrastructure utilisation rate, highest flexibility/redundancy.

Disadvantages

Need for cooperation of OWP and TSOs, DC protection system may be needed, relatively big fault potential (2 GW)

Scenario summary

This scenario shares many of the advantages and disadvantages discussed in scenario 3a. This design requires relatively many converter stations in relation to the connected OWP. This can in part be traced back to four offshore converters rated below 1 GW. Again, this is dependent on the specific case study and doesn't have to be the case in a different geographic area, or just with different time step allocations of the same OWFs. An interesting characteristic of this scenario design is the emergence of two individual branches of the DC grid. These systems can function rather independently from each other, which could be seen as a safer operation overall system. If one branch experiences a fault and has to be shut down, the other one could continue its operation unaffected. After the immediate instance of the fault, the surviving branch could, to the largest possible extent, try to compensate the power flow in order to minimise the changes to the overall system.

5.3. Conclusions

5.3.1. Comparison of Scenarios

Table 4 Comparison of technical parameters for all scenarios – Case Study 1

Parameter	High OWP			Low OWP			Unit
	1a – Zero Integration	2a – Partial Integration	3a – Max Integration	1b – Zero Integration	2b – Partial Integration	3b – Max Integration	
OWP via DC	4.8	4.8	11.2	2.4	2.4	5.7	GW
OWP via AC	6.4	6.4	0	3.2	3.2	0	GW
CBET capacity LT-PL	1	2	2	1	2	2	GW
CBET capacity LT-SE	1	2	2	1	2	2	GW
CBET capacity PL-SE	1	3.5	3.5	1	3	3	GW
Full trade capacity	2035	2040	2040	2040	2045	2045	
Onshore converters	10	5	8	8	8	6	units
Offshore converters	4	4	9	2	2	6	units
Total number of converters	14	9	17	10	10	12	units
Total offshore converter power	4.9	4.9	11.2	2.5	2.5	5.7	GW
Total onshore converter power	10.9	9.0	13.7	8.5	8.0	9.0	GW
Total DC cable length	3,283	1,979	2,378	2,641	1,793	1,942	km
Offshore transformers	26	26	26	12	12	12	units
Total offshore AC transformer power	12.4	12.4	12.4	6.2	6.2	6.2	GW
Onshore AC transformers	15	15	0	7	7	0	units
Total onshore AC transformer power	7.11	7.11	0	3.54	3.54	0	GW
Total AC export cable length	1,073	1,073	354	506	506	138	km
Total conductor weight	14,720 Al (36,820 Cu)	17,590 Al (43,990 Cu)	18,740 Al (46,840 Cu)	10,350 Al (25,890 Cu)	13,800 Al (34,510 Cu)	12,930 Al (32,320 Cu)	tonnes

5.3.2. Technical design

System complexity

- When going from low to high interconnection levels, the technical complexity of the system increases. System complexity could bring both higher flexibility in terms of avoiding OWP curtailment and higher maximum CBET rates. Also, it can bring an OWF the flexibility to directly sell the generated electricity to two or more countries/markets/price zones (depending on the electricity market architecture). On the other hand, it could require a longer development phase of the needed components, systems, codes and routines, not to mention stakeholder co-operation.
- In integrated scenarios, the challenge is the need for more sophisticated security measures. If DC breakers remain the only alternative to secure a highly branched grid (many OCPs within the same interlinked system) and the costs of these components remain high, the cost of greater system flexibility could outweigh the benefits.
- In high integration, the flexibility of the system increases. It is important to note that the term flexibility, as used in this technical section, refers to a system-wide flexibility with the focus on

reaching multiple energy markets (or energy prices) and the power flow re-routing possibilities in the case of a fault. However, the term flexibility does not refer to, for example, a TSO being able to trade any level of power independently from the current OWP generation in the system. An example would be the zero integrated case, where from a TSO's point of view, it would have the flexibility to trade up to the rated power, at any hour, over a traditionally connected OCP-to-OCP interconnector.

- If both OWP and CBET will use the same DC links, it must be clearly analysed how such a communication and prioritisation system should work.
- These conclusions are equally valid for Low OWP.

Infrastructure utilisation rate

- The utilisation rate of a traditional export cable is limited to the OWFs capacity factor. For future OWFs in the Baltic Sea, it is reasonable to assume a capacity factor close to 50%. For an integrated system (or the part of a system that is integrated) the possibility arises to reach a higher utilisation rate, since the available capacity could be used for CBET. However, the scenario of a near-maximum infrastructure utilisation rate would require that one of the interconnected countries would always have a high enough power demand and electricity price in relation to the other interconnected country(s).

DC breakers

- The DC breakers are only considered in partial and maximum integration scenarios High OWP and in the maximum integration in Low OWP.
- If the DC grid in the integrated scenarios is protected with DC breakers, following the same approach as in an AC grid, this would result in a high number of breakers. For the partially integrated case (2a) the number of DC breakers would be 15, and for the maximum integrated case (3a) the corresponding number would be 33 units.
- A more economically reasonable alternative, which herein is also claimed to be technically satisfactory when it comes to DC protection, is the approach using regional HVDC grids. A regional HVDC grid is limited to a maximum number of nodes. It is proposed that these grids typically house a maximum of 5 nodes and with a maximum power rating according to the onshore connection point requirements. An additional criterion for the regional HVDC grid is that all included converters are of the modular multilevel converter (MMC) type. With this type of flexible power control, and with the comparably inexpensive off-load DC switch gear in every grid node, DC breakers could be avoided or considerably reduced.
- Two or more regional HVDC grids can be interconnected to form a bigger HVDC grid. This method is needed for both integrated scenarios: 2a (High OWP, partial integration) and 3a (High OWP, maximum integration), due to the included number of converters (nodes). For the interface between regional HVDC grids, DC breakers are proposed as the protection equipment of choice.
- For scenario 2a, one DC breaker is proposed, and for scenario 3a, three units are proposed.

Dimensioning fault

- The dimensioning fault is related to the N-1 criteria in AC-systems meaning that the system should endure a failure on the largest component in the AC-system. In the Nordic system this is 1450 MW related to the largest nuclear reactor block in Sweden. In Poland and Germany the dimensioning fault is higher, about 2000 MW, due to the larger interconnected AC-system. In the case studies it was assumed that the dimensional fault in the interfaces to countries included in the study will be 2000 MW after 2030. This means that DC breakers are needed when more than 2000 MW in total is connected to one nation from the same DC-system.

- Only the zero integrated case has a different outcome regarding the dimensioning fault. The reason for this is not necessarily the integration level per se, but the different design criteria used for the three system designs. In the partial and maximum integration case, the system is designed with over-capacity. This was done to increase system resilience, with the notion that the extra added capacity can be used for CBET. Also, it was viewed to be beneficial from an economical and practical point of view, to have fewer differently rated converter stations.
- The partial and maximum integrated scenarios could have been designed without this extra resilience capacity. In normal operation, the system functionalities would be the same, other than that the maximum CBET would be the same as the full OWP generation of the integrated wind farms.
- These conclusions are equally valid for Low OWP.

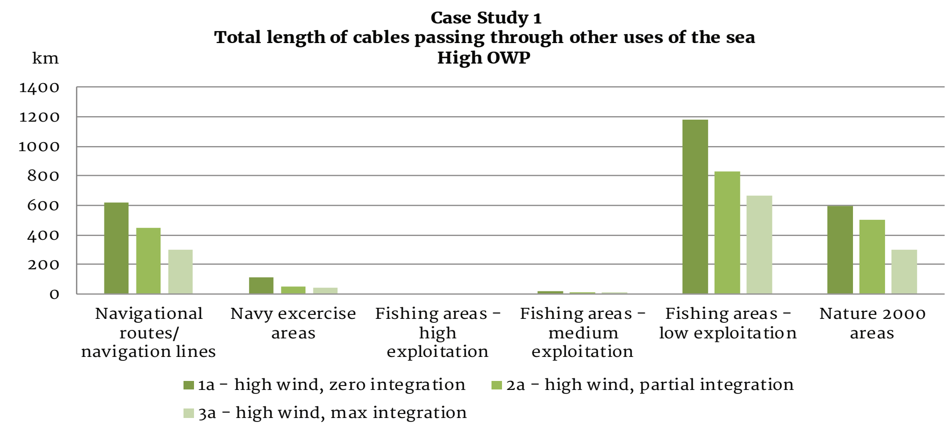
Cross-Border Energy Trade potential

- Two scenarios including some level of integration provide a far greater infrastructure capacity for potential trade. However, as discussed before, the capacity has to be shared with the OWP generation.
- The scenarios 2a, 3a and 3b provide greater infrastructure capacity for potential trade. However, this capacity has to be shared with the OWP generation. The forecasting models for wind generation offshore are getting better and better. Offshore wind generation can be forecasted but not planned. The CBET potential of such a system therefore fluctuates. However, carbon-neutral offshore wind energy should be granted priority grid excess over additional trading capacity.
- These conclusions are equally valid for Low OWP.

5.3.3. Spatial analysis

- In both the High and Low OWP scenarios, maximum integration is most favourable in terms of potential spatial conflicts due to the lower number of cable corridors.
- Potential overlappings occur with the following sea uses: navigational routes, fishing areas and environmental protection areas.
- In none of the scenarios, the cables cross areas with a high priority for fisheries (based on HELCOM/VMS data – areas with over 450 h of fishing effort using bottom-contacting fishing gear). Some sections of the cables do cross the areas with a medium priority for fisheries (areas between 150 – 450 h/a of fishing effort bottom-contacting fishing gear). The majority of the cables run through areas with low interest for fisheries (below 150 h/a fishing effort).
- In both High and Low OWP scenarios, there are substantially more crossings of linear infrastructure, than in the partial and maximum integration scenarios. In Low OWP scenarios the lowest number of crossings is in the partial integration scenario.
- The number of landfalls may become a limiting factor. The zero integration scenario assumes 3 times more cables then maximum integration. For example, for the zero integration with High OWP there are 25 cable landfalls (in all countries and for all onshore connections points), whereas in maximum integration there are only 8 landings. The potential conflicts may include onshore environmental protection areas, but also dispersed and sometimes congested settlements and tourist activity at the seaside.
- Potential mitigation measures will have to be applied in terms of potential navigational route crossings and areas with a medium value for fisheries (e.g. cable burial, concrete mattresses, establishment of safety zones, avoiding open-trench landfall).

Case Study



[NOTE]: the analysis includes data that was openly available for analysis. Spatial analysis should be further investigated based on data and contacts with the relevant authorities.

Figure 43
Total length of cables passing through other uses of the sea; High OWP scenarios – Case Study 1

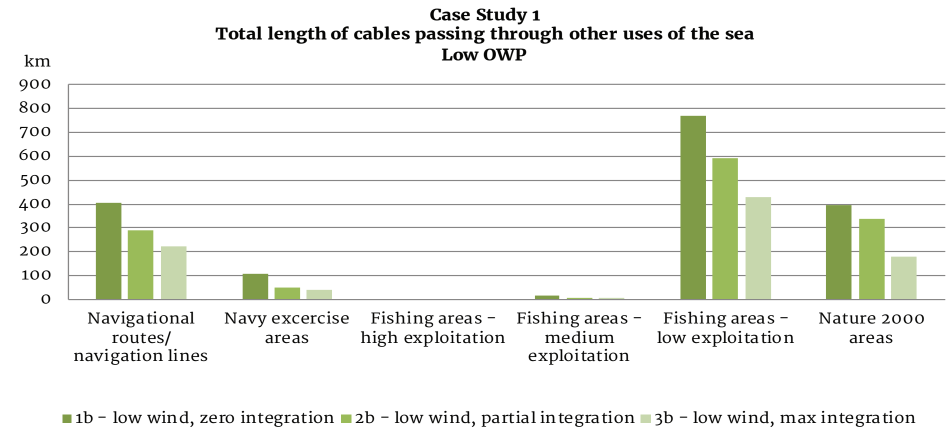


Figure 44
Total length of cables passing through other uses of the sea; Low OWP scenarios – Case Study 1

5.3.4. Environmental analysis

Most of the identified impacts (related to the transmission system components) are expected to occur only on a local scale with the exception of underwater noise emissions during the installation of the offshore foundations for converter stations. The noise emission can be detectable even on a regional scale. Nevertheless, the most detrimental effect on marine animals caused by underwater noise such as fatal injuries (fish) or a permanent change of the hearing threshold (fish and mammals) is expected to be spatially limited and to occur at a relatively close distance to the source of the noise. It is also possible to apply mitigation measures such as bubble curtains and ramping-up of noise to scare off potential animals.

It is not expected that development of the transmission infrastructure could have a significant effect on the environment in general, especially as none of its technical elements (offshore cables and converter/transformer stations) are qualified according to the EIA Directive as projects which are likely to have significant effects on the environment.

5.3.5. Cost-Benefit analysis

Benefits – results

- Case Study 1 shows very small differences in total system costs between partial and high integration, however a more prominent cost reduction appears in the Low OWP scenario.
- The lower system costs (higher benefits) in the integrated scenario are caused by reduced investments in interconnectors. The increased integration allows for more flexibility in transport, which is why less interconnector capacity is needed.
- The adequacy analysis shows that in all scenarios the system has enough capacity available, but higher integration provides the system with more flexibility with regards to the adequacy rate. The conclusions are true for all countries included in the Case Study. The detailed results are shown below as differences between the zero integration scenario and the partial and maximum integration scenarios. In the following graphs, the differences in overall system costs for the different scenarios and results related to system adequacy are shown.

The main results regarding the differences between overall system costs for each scenario are shown in the graphs below. The graphs show the overall costs for the different scenarios.[57]

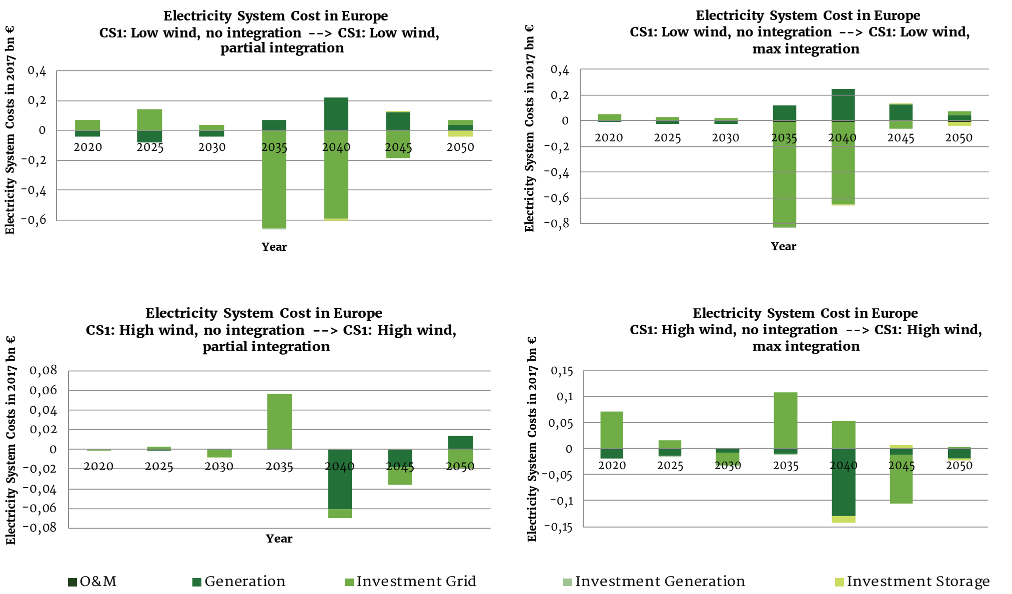


Figure 45
Electricity System Cost in Europe – Case Study 1

Costs – results

- A higher level of scenario integration leads to a shorter combined cable length of AC and DC cables. As the total cable length decreases, the total conductor volume increases. What can be stated at this point is that installation costs are rather closely related to total installed cable length.
- The smallest number of converter stations (onshore plus offshore) are needed in the partially integrated scenario. This could translate to an important advantage, since the cost of converter stations and their installation, is a substantial part of the final investment cost. It should be

57 System costs reflect the cost of optimal investment and generation decision based on the scenario specific data. The figures present the comparison between the base case (zero integration) and a partial or high integration case however also implies that benefits that come from the infrastructure that is already available in the base case, like additional interconnector capacities, are not captured. The difference between the zero integration and higher levels of integration allow to specifically see if the changed topology allows for different outcomes that are directly related to the respective change in topology and wind farm development and therefore directly reflect additional benefits.

remembered that an offshore converter station is more expensive than an onshore one.

- For High OWP, the lowest total costs occur for the partial integration scenario. This is due to a significant reduction in HVDC cable cost and HVDC onshore converter station (node) cost because of a more efficient grid layout. These cost reductions overcompensate the cost of one DC breaker.
- In the maximum integration scenario, HVAC grid infrastructure is largely substituted by HVDC lines, which leads to a decrease in HVAC costs but also to a significant increase in HVDC costs, especially for additional offshore nodes that also, in some nodes, include DC breakers. These two effects total to an overall cost increase.
- For Low OWP, the total costs for the different degrees of integration are on a comparable level. The lowest costs are associated with the zero integration scenario. The cost increase for the maximum integration scenario only amounts to 7%, although it is characterised by a completely different cost structure that is dominated by HVDC offshore node costs.
- No significant cost trend can be seen for an increasing degree of integration. This results from the very case specific scenario choices and the fact that the scenarios are designed in a way that keeps the interconnecting capacity between countries at comparable levels.

The primary output of the LCM are the cost structures of the previously defined scenarios. The following figures illustrate the cost structure of the various scenarios.

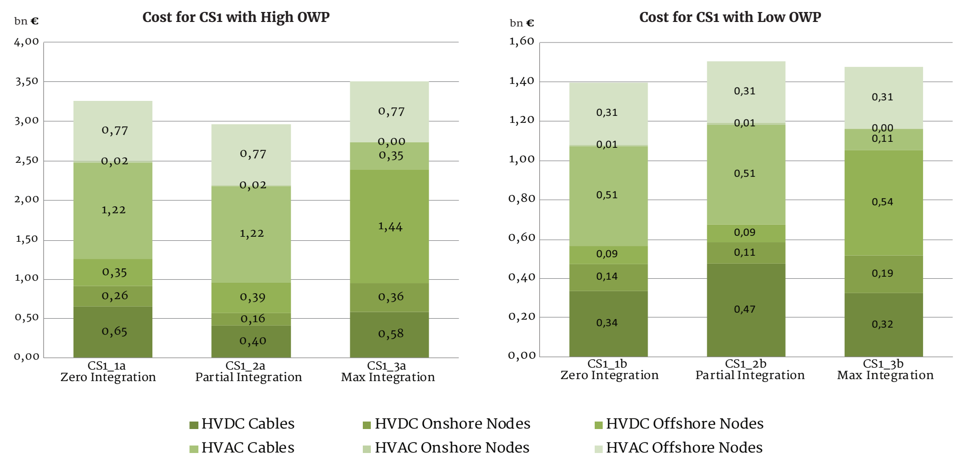


Figure 46
Cost structure for the scenarios in Case Study 1

Weighing the Costs and Benefits

- For Case Study 1 with High OWP, the **partial integration** case is the **most favourable.** The partial integration case has both lower costs and brings additional benefits compared to the baseline scenario. A higher degree of integration leads to an extra benefit but also to higher costs. Therefore the maximum integration case is the least favourable here.
  The partial integration scenario could depict the development of OWE in Poland and Sweden, where the most developed projects in Poland are planned to be connected radially. However, projects farther from shore, at Southern Middle Bank (both in Swedish and Polish waters), will be developed most likely after 2030 and could be connected in a more coordinated approach.
- This picture changes for the case of Low OWP. Increased integration leads to an increase in benefit that overcompensates for the associated additional costs. In this case, **the maximum integration** scenario is the **most favourable**.

The costs and benefits are provided as net present values and can be weighed against each other. The following tables summarise the output of the two models.

Table 5 Summary of Cost-Benefit Analysis – Case Study 1

CS1 (PL, SE, LT)			
High Offshore Wind Power		Low Offshore Wind Power	
Partial Integration	Max Integration	Partial Integration	Max Integration
CS1_2a – CS1_1a	CS1_3a – CS1_1a	CS1_2b – CS1_1b	CS1_3b – CS1_1b
Benefit (higher is better)			
0.06 bn€	0.09 bn€	0.92 bn€	0.99 bn€
Cost (lower is better)			
-0.30 bn€	0.24 bn€	0.11 bn€	0.08 bn€
Benefit – Cost (higher is better)			
0.36 bn€	-0.15 bn€	0.81 bn€	**0.91 bn€**

Table 6 Summary showing the most economic scenarios

	Case Study 1 (SE/PO/LT)
High OWP	Partial Integration
Low OWP	Maximum Integration

Photo: tom def

Havvindparken Sheringham Shoal (Foto Harald PettersenStatoil) by NHD-INFO under CC BY 2.0 licence

6. Case study 2 – Germany-Sweden-Denmark

6.1. Case study 2 description

6.1.1. Geographic area with interfaces

The second case study is located in the south-western part of the Baltic Sea – mainly within the Arkona Basin – close to the border triangle between Sweden, Germany and Denmark. The case study area includes Swedish, German, and – for the high offshore wind scenarios – Danish waters (the area west of Bornholm). Most of the case study area lays within the Arkona Basin. The maximum water depth in the basin is around 50 meters. In the west, the Arkona Basin is bounded by the elevation of Kriegers Flak (Please note that Kriegers Flak is not part of the case study). The Arkona Basin is connected with the Bornholm Basin in the north-east and adjoined by the Rønne Bank in the east. South-west of the Rønne Bank, the Adler Ground can be found.

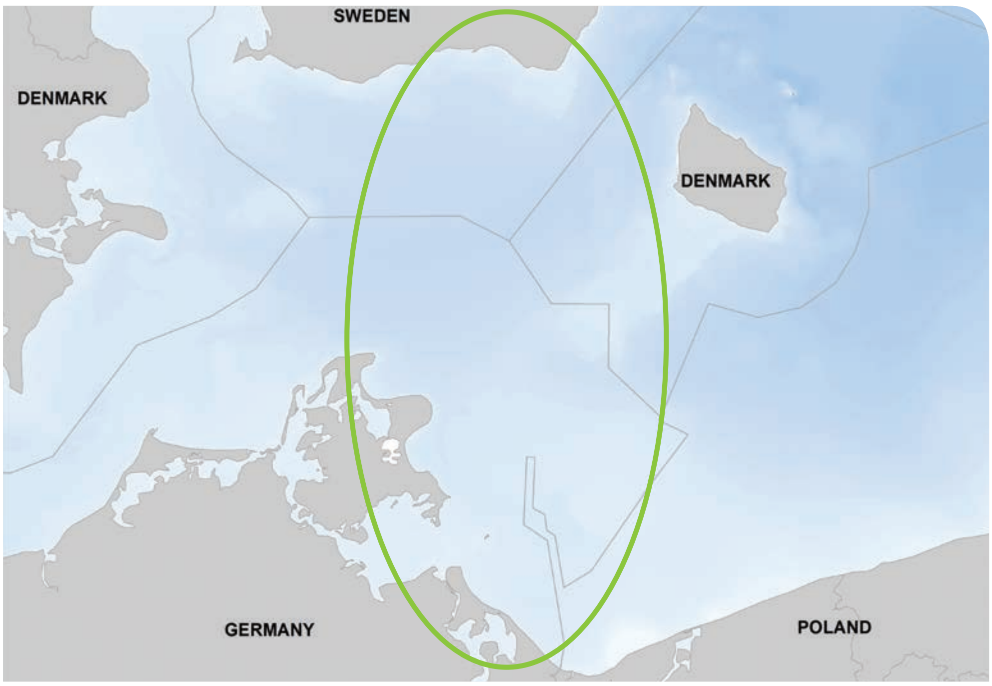


Figure 47
Case Study 2 Area

The Swedish part of case study 2 includes an area south of Skåne County in the Arkona Basin.

The German part of the case study 2 area is located north-east of the island of Rügen. In that area, certain clusters are reserved for the development of offshore wind energy – cluster 1 and 2 in the German EEZ, cluster 4 in the territorial waters of the state of Mecklenburg-Vorpommern. In contrast to all of the other considered areas within the two case studies, there are already several offshore wind farms constructed in the German waters. Currently, there are two offshore wind parks (i.e.Wikinger, Arkona Becken Südost) located in the German part of the case study area, but they are not part of the case study, since they have already been build. The same is true for the offshore wind farms that will be built until 2026 (see Infobox Germany).

Please note, that there are further OWFs in the German Baltic Sea (EnBW Baltic 1 & 2), but these OWFs are not part of the case study area and located in clusters 3 and 6 (see Figure 48).

Figure 48
Offshore Wind Energy Clusters in German Baltic Sea
[Source: Bedarfsermittlung 2017-2030, Bestätigung Offshore-Netzentwicklungsplan]

The Danish part of Case Study 2 is an area west of the island of Bornholm on the Rønne Bank. This area has relatively shallow waters and good, stable wind conditions – ideal conditions for the development of offshore wind (see Figure 47).

6.1.2. High and Low OWP development including power densities

Predicting the offshore wind build out in the Case Study 2 area underlies high uncertainty. Within the Swedish and Danish waters of the case study area, only preliminary considerations for the development of offshore wind energy have been undertaken. In contrast, in Germany there is a goal of installing roughly 3 GW by 2030 in the German Baltic waters. The High OWP roadmap for Case Study 2 can be thought of as a visionary timeline for the case study area (see Figure 52). The Low OWP roadmap constitutes more of an estimated baseline for the development in the covered area (see Figure 53).

Within the Case Study 2 area, it is assumed that Sweden will install 1,740 MW of offshore wind by 2045 in the High OWP build-out scenarios, and 948 MW for the Low OWP build-out scenarios. In the Swedish waters, the build-out is concentrated in the Swedish EEZ south of Skåne County.

For Germany, it is assumed that by 2030 there will be roughly 3 GW installed in the German Baltic waters. This includes projects within and outside the discussed case study area. Within the Case Study area, a build-out between 2030 and 2045 of 1,132 MW for the High OWP roadmap and 928 MW in the Low OWP roadmap is assumed. It deserves particular attention that the build-out in this study was assumed prior to the announcement of Germany's last offshore tender. The exact results of the tender were not expectable: three projects within the Baltic Sea were awarded – two in the EEZ and one in the territorial waters with in the state of Mecklenburg-Vorpommern. Therefore, the case study does not depict the actual build-out within the German waters. However, the results of the case study (e.g. the cost-benefit analysis) would most likely only change slightly, if the case study were adjusted to the actual situation.

INFOBOX: GERMANY

In the German Baltic Sea, there are currently 4 offshore windfarms installed: EnBW Baltic 1 (48.3 MW), EnBW Baltic 2 (288 MW), Wikinger (353.5 MW), and Arkona (384 MW, under construction). Please note that EnBW Baltic 1 and EnBW Baltic 2 do not lay within the the case study area (see Figure 39).

Further OWFs will be built between 2021 and 2025. On 27 April 2018, the results of Germany's second offshore wind tender were published. Three projects within the Baltic Sea have been awarded – two in the German EEZ and one in the territorial waters of Mecklenburg-Vorpommern. The two awarded projects, Baltic Eagle (476 MW) and Wikinger Süd (10 MW), are being developed by Iberdrola Renovables Deutschland GmbH. The project within the territorial waters, Arcadis Ost (247 MW, Cluster 4) has been planned by KNK Wind GmbH (350 MW). These three projects add up to a total volume of around 865 MW that will be built between 2021 and 2025 (see maps below).

Figure 49
Offshore Wind Build-out in Germany's Baltic EEZ and territorial waters

Figure 50
Offshore Wind Build-out and planned projects until 2025 in Germany's Baltic EEZ and territorial waters

Taking the existing and awarded projects into consideration, Germany will have 1.9 GW installed in the Baltic Sea by 2025 (see Figure 42). The national offshore grid development plan 2030 (Version 2017) assumes a buildout of just above 3 GW by 2030.

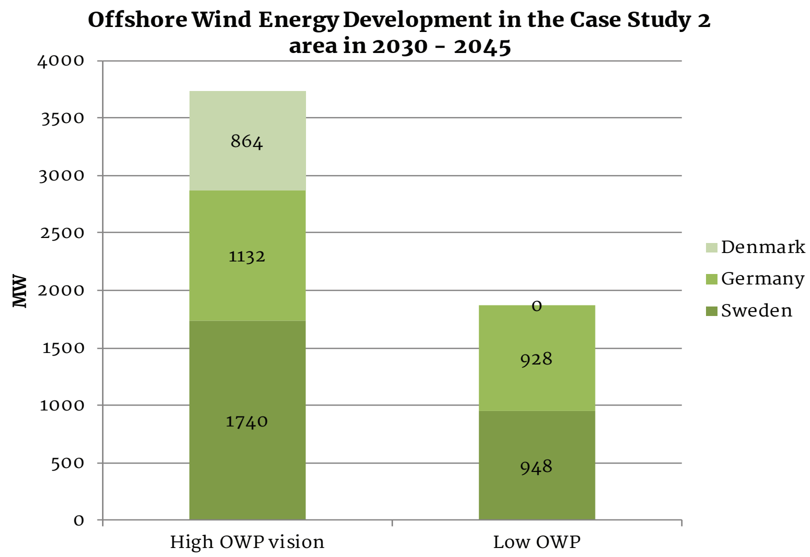


Figure 51
Installed offshore wind power High/Low OWP build-out – Case Study 2

For Denmark, 864 MW of offshore wind development is considered within the High OWP build-out scenario. The development will be south-west of the island of Bornholm. As mentioned before, this area offers good wind conditions and shallow waters. Furthermore, this area has been discussed for the development of offshore wind energy several times by the Danish Energy Agency. For the Low OWP build-out scenario, no offshore wind development is foreseen within the Danish part of the case study area.

The offshore wind farm power densities in Case Study 2 vary between Sweden, Germany and Denmark significantly. In Germany, the current Bundesfachplan-Offshore (BFO) 2016/2017 conducted by the national authority BSH is assuming a power density of about 14 MW/km² for project applications.58 This energy density is derived from the assumption of two 7 MW wind turbines per km². Currently, the average power density for authorised and applied projects in the German Baltic Sea is around 10,9 MW/km².59 The regulatory regime in Germany incentivised high power densities. The fixed feed-in tariffs made high-energy yields attractive for project developers. In contrast, the Danish system awards projects that offer the lowest price per kilowatt hour. Thus, the objective in Germany is currently a high power density, whereas in Denmark it is a low LCOE (lower power densities). Nevertheless, within the case study reasonable power densities for each geographic area were identified (see Figure 52).

58 BSH, " Bundesfachplan Offshore für die deutsche ausschließliche Wirtschaftszone der Nordsee 2016/2017 und Umweltbericht". Hamburg: BSH, 2017. Accessed August 8th, 2018. https://www.offshore-stiftung.de/sites/offshorelink.de/files/documents/BFO_Nordsee_2016_2017.pdf, p. 20.

59 Ibid.

Case Study

[NOTE]: Only offshore wind projects relevant to Case Study 2 are included in Figure 52 and Figure 53. In Germany, there are projects installed and under development that are not part of this Case Study.

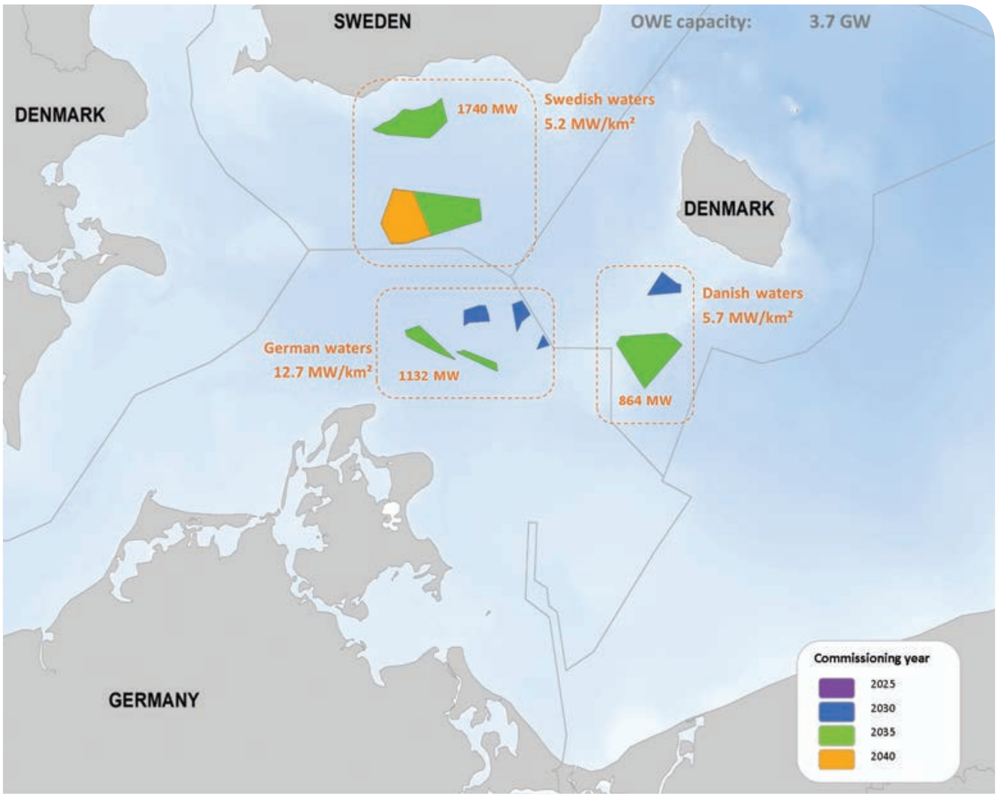


Figure 52
Map presenting the High OWP development vision, displaying installed OWP capacity and chosen power density per cluster.

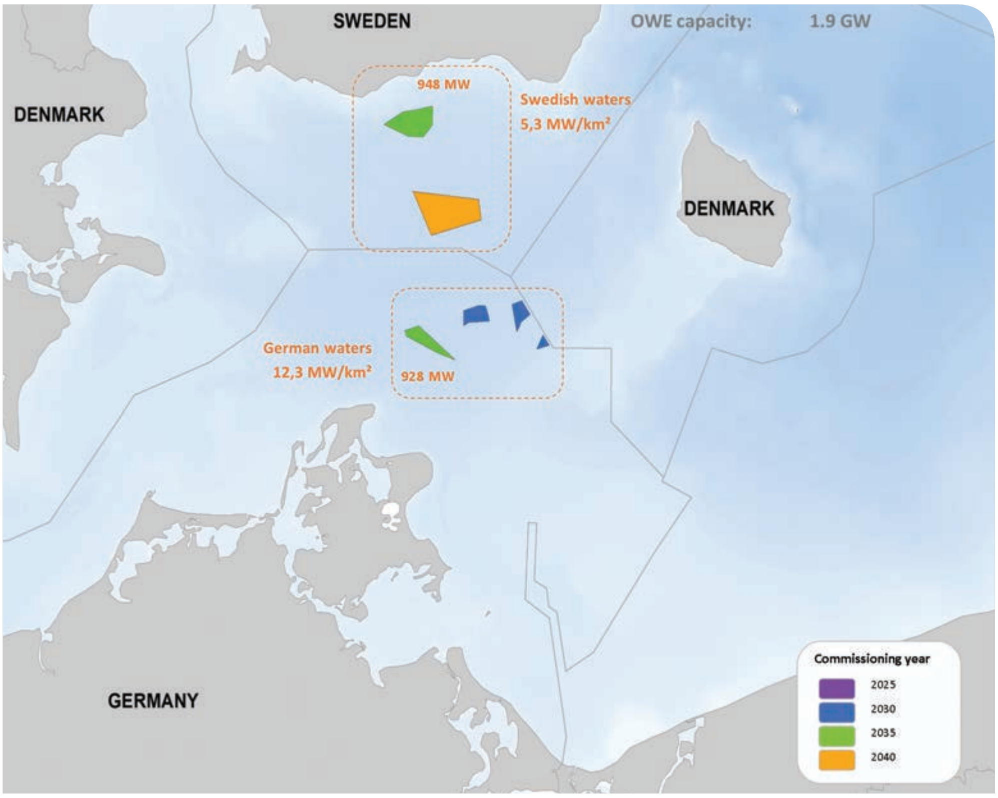


Figure 53
Map presenting the Low OWP development vision, displaying installed OWP capacity and chosen power density per cluster.

6.2. Scenario presentation

6.2.1. Scenario 1a – Zero integration Scenario – High OWP development

The first scenario incorporates a high level of OWP and with zero integration between electrical infrastructure for OWP and cross-border energy trade. This scenario represents a low technical and coordination complexity. In this scenario, most of the projects, whether an OWF or interconnector, are planned and built separately. It is assumed that all OWFs are connected via AC, since it appears to be the most cost-efficient solution for the respective conditions (e.g. distances to shore).

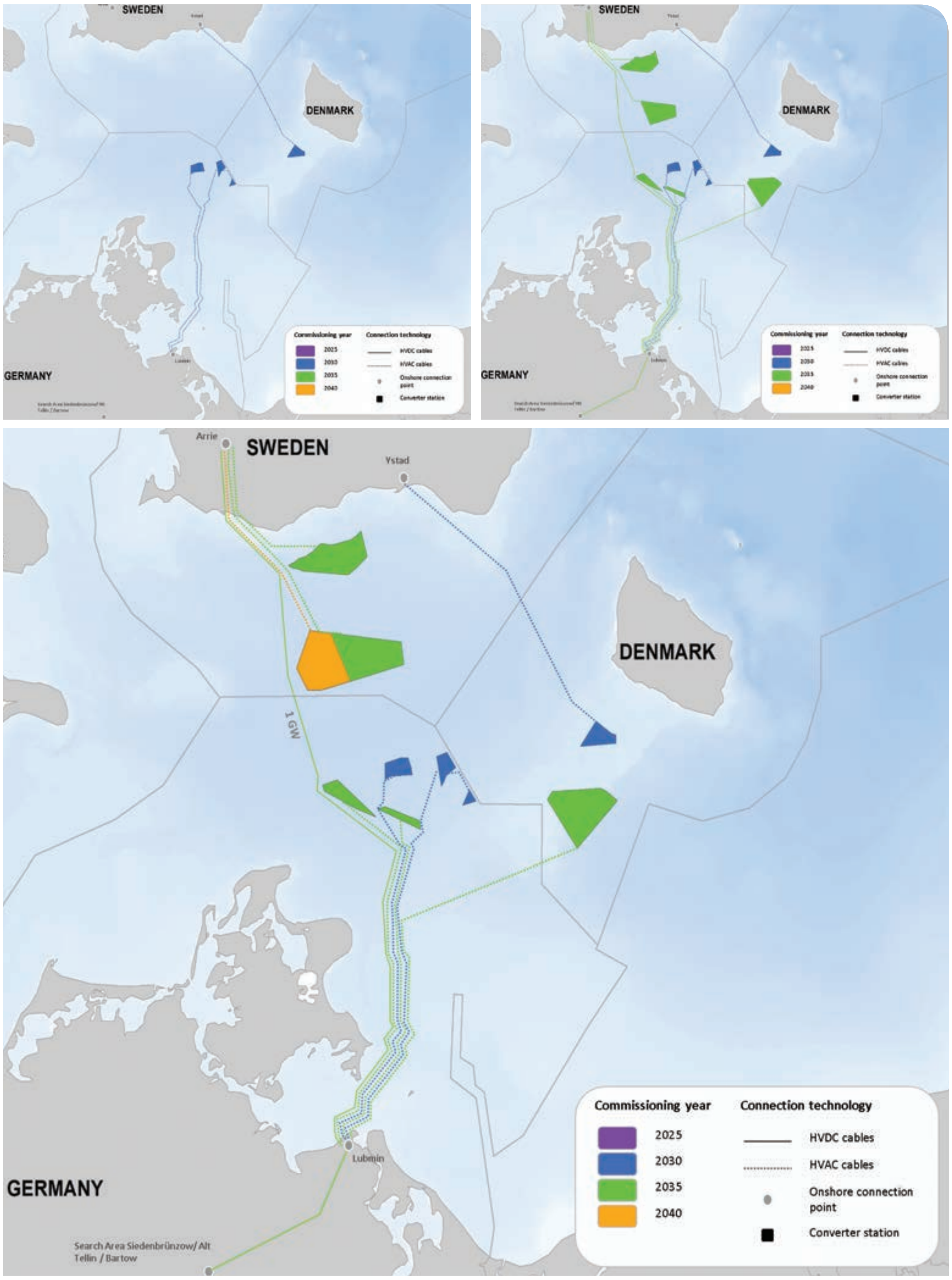


Figure 54
Case Study 2 – Scenario 1a schematic build-out

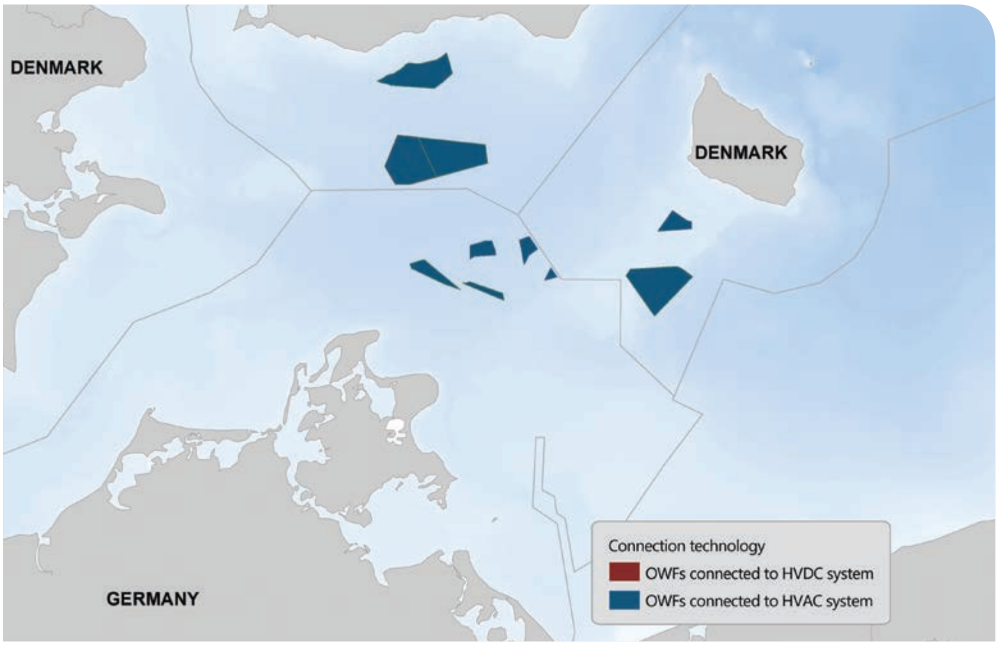


Figure 55
Case Study 2 – Scenario 1a
OWF connection technology

Advantages

Low complexity, Business-as-usual, low cooperation between offshore windfarm developers and TSOs.

Disadvantages

Parallel cables, larger sea use, higher environmental impact, "low"/different flexibility/redundancy, low infrastructure utilisation rate

Scenario summary

This scenario highlights the advantages and disadvantages of keeping the two systems for CBET and OWP separate. At a technical level, this scenario only implements system topologies and technology commercially used today. Offshore wind farms in this scenario are connected via AC technology. Thus, there is no need for relatively expensive DC technology (e.g. DC protection equipment), which can be an (cost) advantage. One disadvantage is that when a link fails, there are no alternative routes for either OWP or energy trading to be rerouted through. Furthermore, with the 2GW of additional transmission power some reinforcement will be needed in the German and Sweden onshore grids, independent of where the connection point will be.

With this zero integration approach, which is basically being practised today, OWFs and interconnectors can for the most part be developed independent of each other. However, more cables – both in quantity and length – are needed to exploit the offshore wind in that manner. In contrast, no HVDC technology is needed for the connection of the offshore wind farms to shore. Furthermore, in this scenario, the TSOs will have total control over the interconnector since, it is being build point-to-point from Sweden to Germany.

6.2.2. Scenario 1b – Zero integration – Low OWP development

This scenario builds on the same principle of zero integration, just as with the scenario 1a. However, the difference is the assumption of an overall lower and slower OWP build-out in the case study region. The total installed wind power amounts to 1.9 GW and the CBET capacity is kept at 1 GW between Sweden and Germany. Between the years 2025 and 2040, the OWP build-out in the case study area will be nearly equal in Germany and Sweden. It is assumed that both countries will develop slightly over 900 MW of offshore wind capacity. However, this development will occur faster in Germany. For Denmark, there is no offshore wind capacity planned within the case study area (area west of Bornholm). All offshore wind projects will be connected radially to shore – no coordination is required between the offshore projects. As in scenario 1a, it is assumed that all OWFs are connected via AC, since it is the most cost efficient solution for the respective distances to shore. Compared to scenario 1a, the argument for AC technology is even stronger, since there is less aggregated power in this scenario – for example in the German waters.

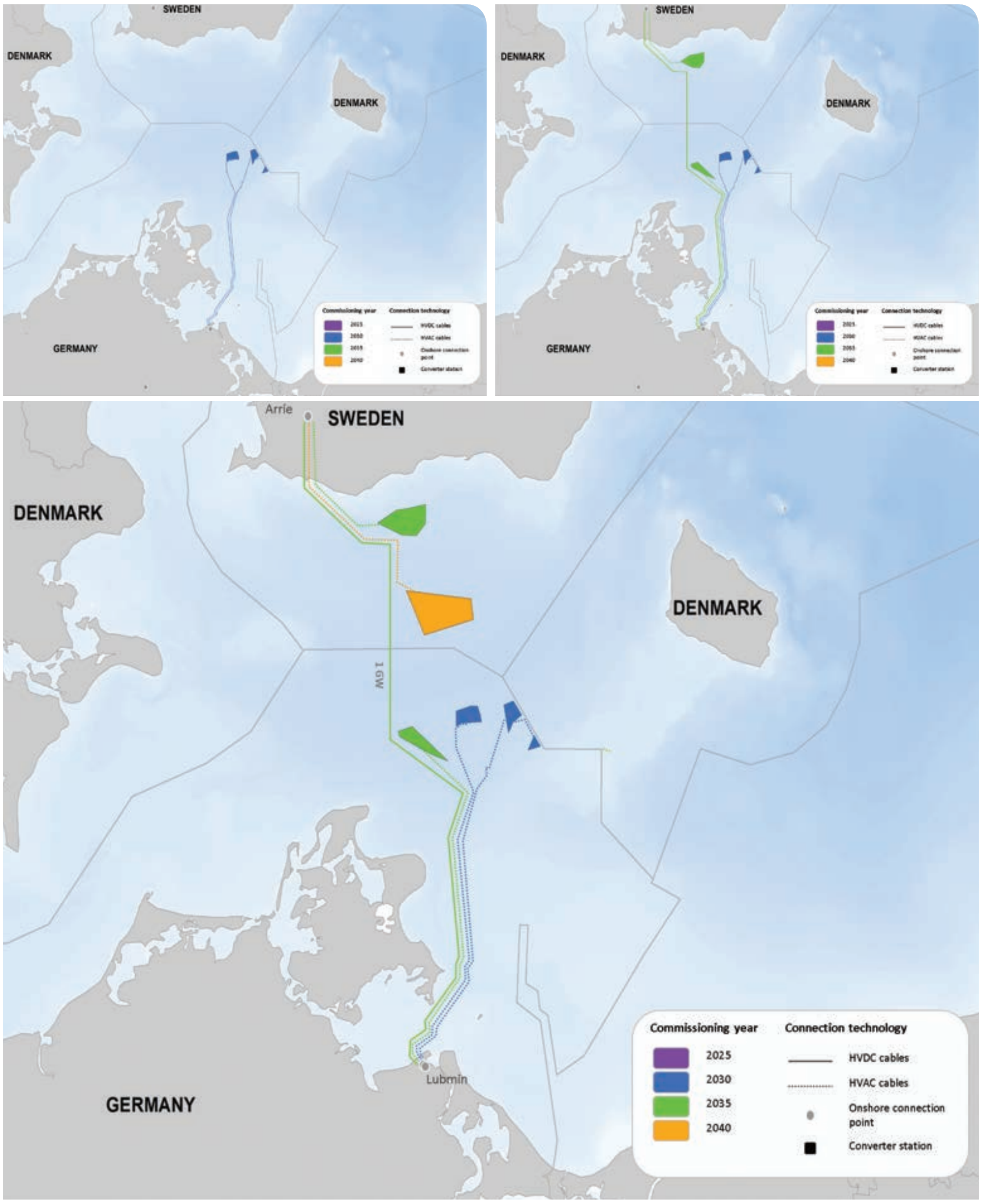


Figure 56
Case Study 2 – Scenario 1b schematic build-out

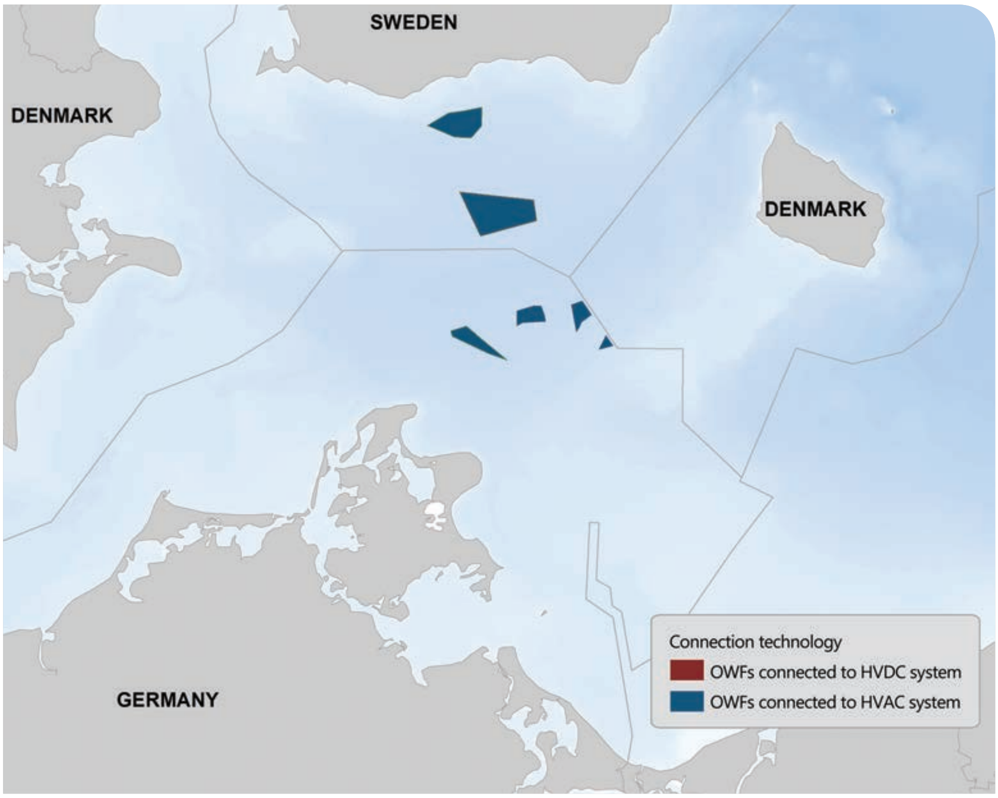


Figure 57
Case Study 2 – Scenario 1b
OWF connection technology

Advantages	Disadvantages
Low complexity, Business-as-usual, low cooperation between investor and TSO required.	Parallel cables, larger sea use, higher environmental impact, “low”/different flexibility/redundancy, low infrastructure utilisation rate

Scenario summary

Scenario 1b is in many respects very similar to scenario 1a, correlating with the design similarities. Due to the independent development approach of the zero integrated design, the level of OWP build-out only changes the results of the technical analysis slightly.

The uncoordinated build-out leads to a less technically challenging set-up, with no interdependencies between OWF development and interconnectors. However, the result is longer total cable routes, low levels of redundancy and an utilisation rate of the farm-to-shore links that is set by the OWP's capacity factor.

6.2.3. Scenario 2a – Partial integration – High OWP development

The scenario presents the possibility of a partial integrated system, incorporating both radial and integrated OWF connections. The design logic of this scenario is to connect OWFs close to each other with HVDC interconnectors and the OWFs that are further spread out via AC technology. However, the exception in scenario 2a is the Danish OWFs south-west of Bornholm. These OWFs are also connected to the HVDC converter, since they cannot be connected (for various reasons) to Bornholm. This partial integrated design would need a fair level of cooperation from all projects and stakeholders using the HVDC system. In return, the solution could provide higher flexibility, utilisation rates and cost sharing opportunities.

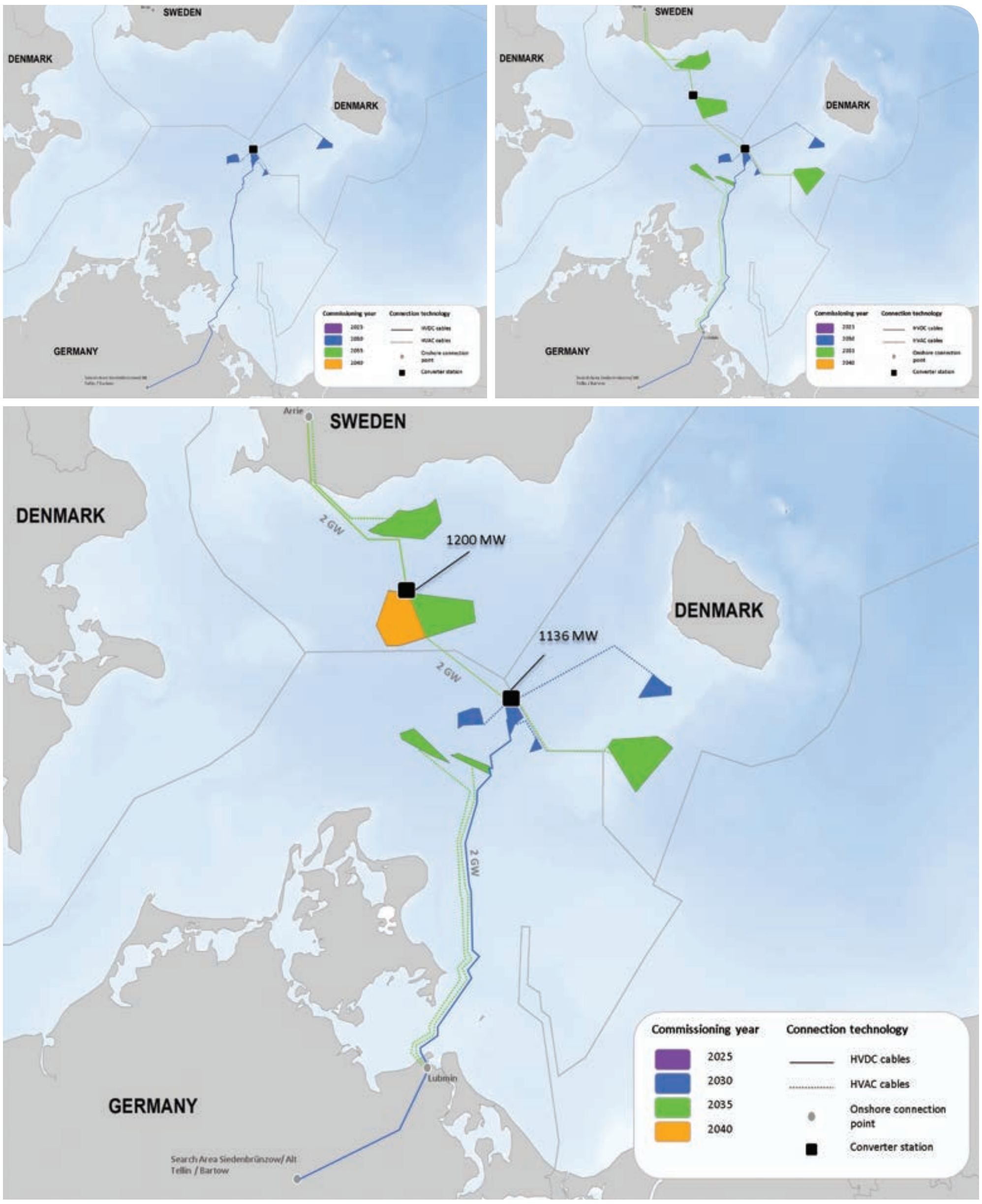


Figure 58
Case Study 2 – Scenario 2a schematic build-out

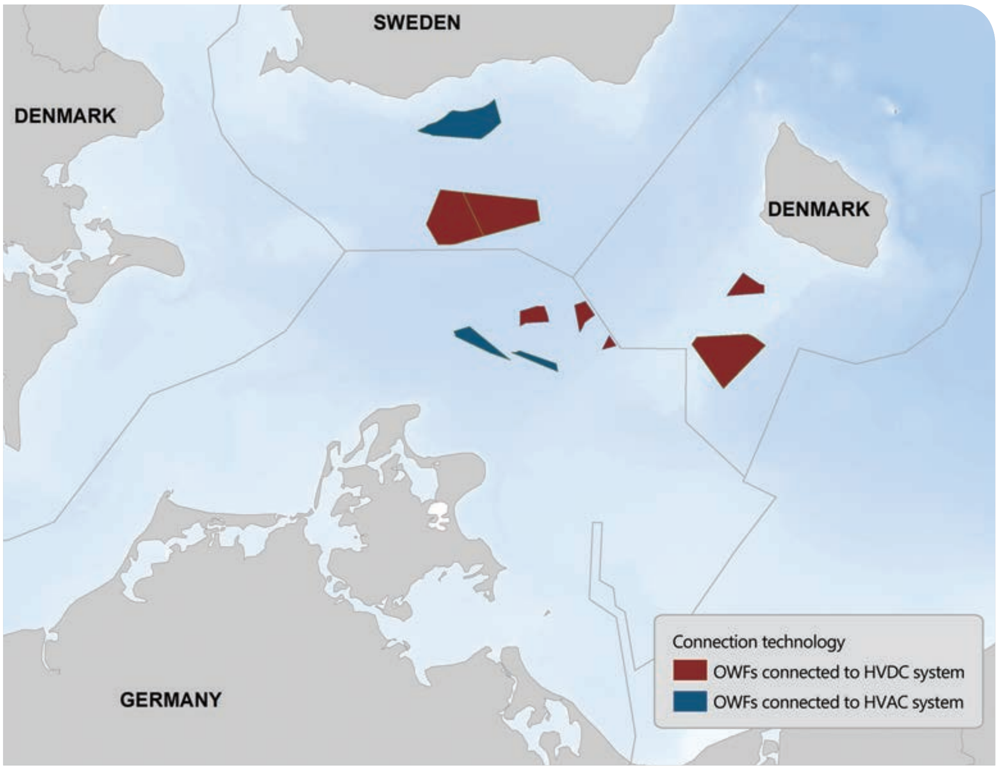


Figure 59
Case Study 2 – Scenario 2a
OWF connection technology

Advantages

Less parallel infrastructure than the zero integration scenario, Business-as-usual for AC, higher infrastructure utilisation rate than the zero integration scenario, higher flexibility/redundancy

Disadvantages

Need for cooperation between OWP developers and TSOs, still substantial sea use, relatively higher biggest fault potential (2 GW)

Scenario summary

Scenario 2a displays an example of how to interlink OWFs relatively far from shore and interconnectors in a DC grid. Naturally, this calls for a high level of co-operation between OWP developers and TSOs, which could very well lead to longer planning horizons. Cooperation is not only a precondition up until installation of the system, but also during the operation phase. The energy trading patterns for such a system will have to take the current OWP generation into consideration. With that said, compared to Scenario 1a, the maximum trading capacity is increased, since the rating of the links are dictated by the installed OWP. On the down side, a higher rating of the links inevitably leads to a bigger possible fault.

When it comes to the technical complexity and novelty of the scenario, a new topology, compared to today, is introduced. However, the time step of the first interconnected DC grid is set to 2035. This makes available a sizeable 15 years of development and piloting before implementation in the Baltic Sea. For this system, no DC-breakers are necessary. If a DC fault occurs, the system will go down for a short period, disconnect the faulted part and restart quickly.

6.2.4. Scenario 2b – Partial integration – Low OWP development

Scenario 2b uses the same design approach as 2a, but with a limited OWP build-out schedule. Only OWP far from the grid connection point will be integrated into the multi-terminal VSC-HVDC system. Similar to scenario 2a, this approach tries to strike a balance between technical and organisational complexity, economic feasibility and power flow flexibility.

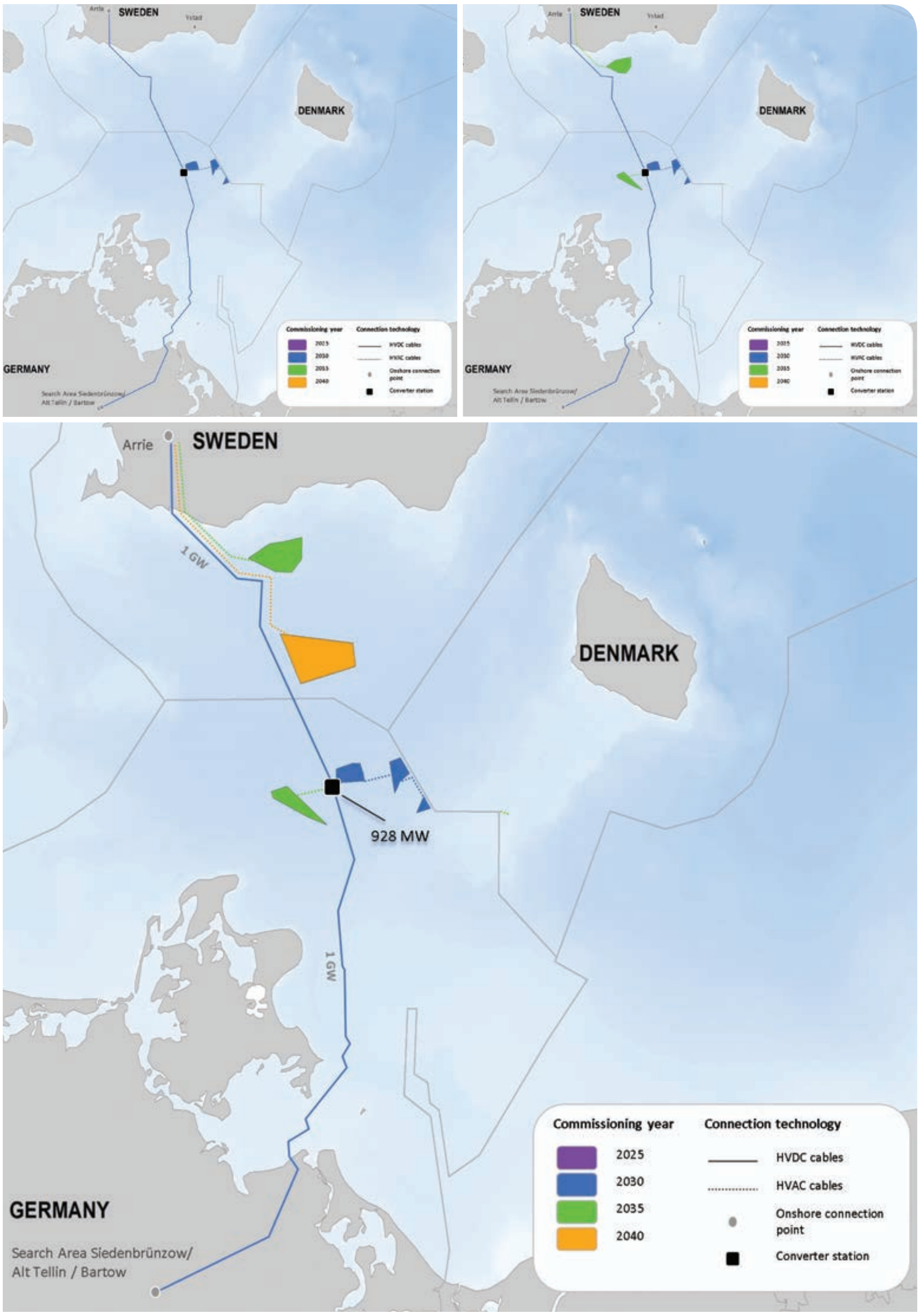


Figure 60
Case Study 2 – Scenario 2b schematic build-out

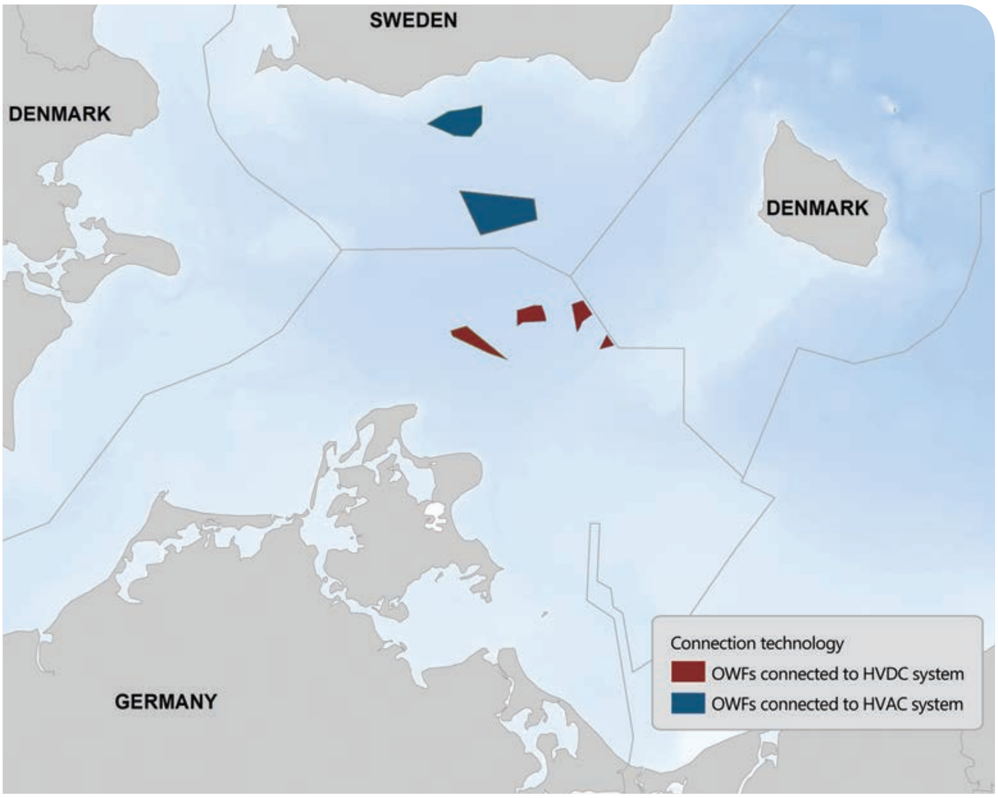


Figure 61
Case Study 2 – Scenario 2b
OWF connection technology

Advantages	Disadvantages
Less parallel infrastructure than zero integration, Business-as-usual for AC, a higher infrastructure utilisation rate than the zero integration scenario, higher flexibility/redundancy. Also fewer onshore connection points, only one DC cable that can be connected further inland, if needed, to reach a stronger point.	Need for cooperation of OWP and TSOs, still substantial sea use.

Scenario summary

Like its more ambiguous counterpart, scenario 2a, this scenario shows an example of integrating some OWFs into the interconnecting DC grid, while other farms are connected radially with AC technology. Generally, the OWFs relatively close to shore are the ones where the additional value of DC grid integration is the lowest. It is assumed that a radial connection with AC technology is the preferred choice here.

6.2.5. Scenario 3a – Maximum integration – High OWP development

This scenario introduces the concept of full OWP integration into the border-crossing VSC-HVDC system. The conditions for this approach are large efforts for international energy and sea use planning and extensive technological know-how regarding multi-terminal systems. The benefits of such a system could be high infrastructure utilisation rates and cost sharing opportunities.

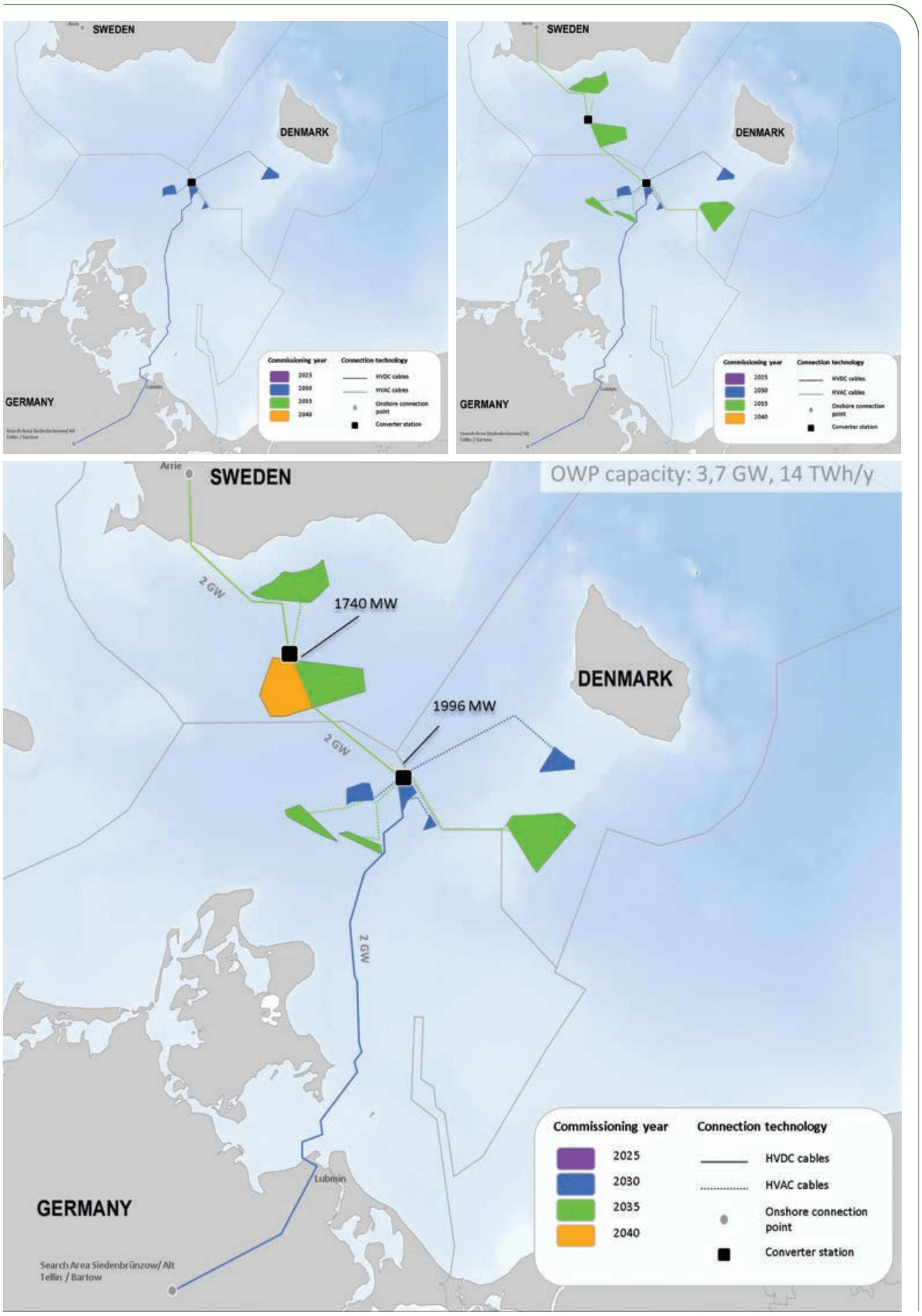


Figure 62
Case Study 2 – Scenario 3a schematic build-out

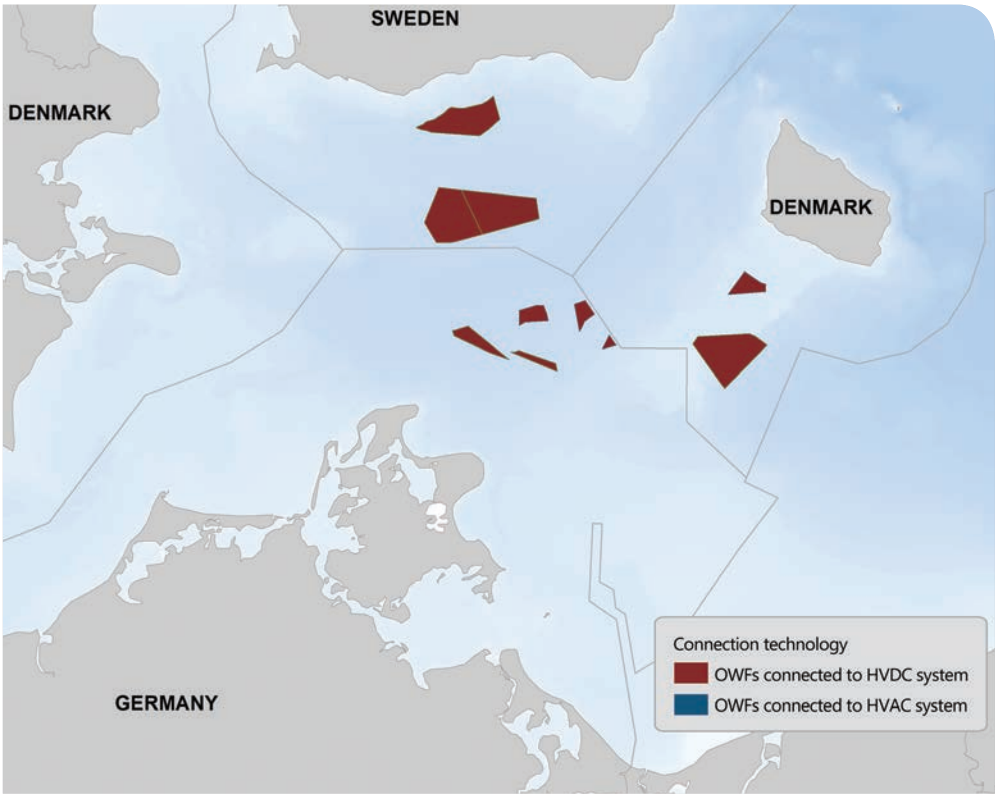


Figure 63
Case Study 2 – Scenario 3a
OWF connection technology

Advantages

Minimum parallel infrastructure, highest infrastructure utilisation rate, highest flexibility/redundancy. There is generally less sea use and environmental impact.

Disadvantages

Need for strong cooperation between offshore wind developers and TSOs.

Scenario summary

Scenario 3a displays the fully integrated version of the case study. All OWFs are connected to the offshore DC grid. This leads to an offshore system with two offshore HVDC converter stations.

It is important to note that the significant and early cooperation of nations, TSOs and OWP developers is needed in order to obtain maximum integration in the case study area. Basically, all aspects and details around the integrated DC link would have to be researched well before the connection of the first OWFs up until 2030. This would apply to technical specifications for components, modularity options for future extensions, grid codes, security standards etc. but also for the energy market, maritime spatial planning, policy, regulation and political issues. Regarding redundancy this scenario shows a high level of OWP export security. For example, if the wind power is less than 2 GW (depending on the wind speed), there will be an alternative route if a DC links fails and all of the wind power can be exported.

6.2.6. Scenario 3b – Maximum integration – LOW OWP development

This scenario shows the same principles of maximum integration, but with a lower amount of OWP built in the area. The key characteristic of this scenario can be summarised as high cooperation and planning requirements, technically challenging, the possibility for high utilisation rates, shorter total cable lengths and the possibility to share costs.

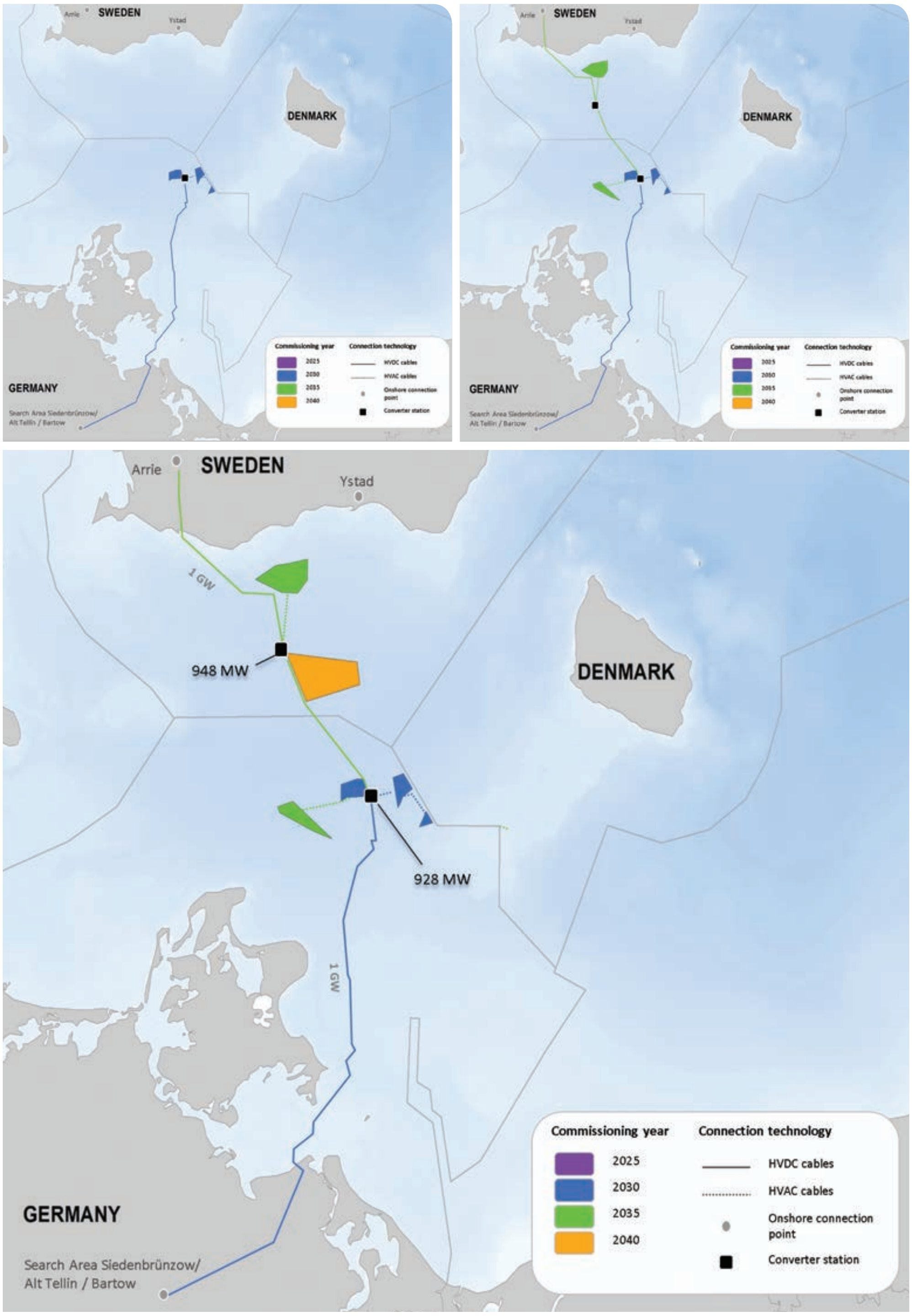


Figure 64
Case Study 2 – Scenario 3b schematic build-out

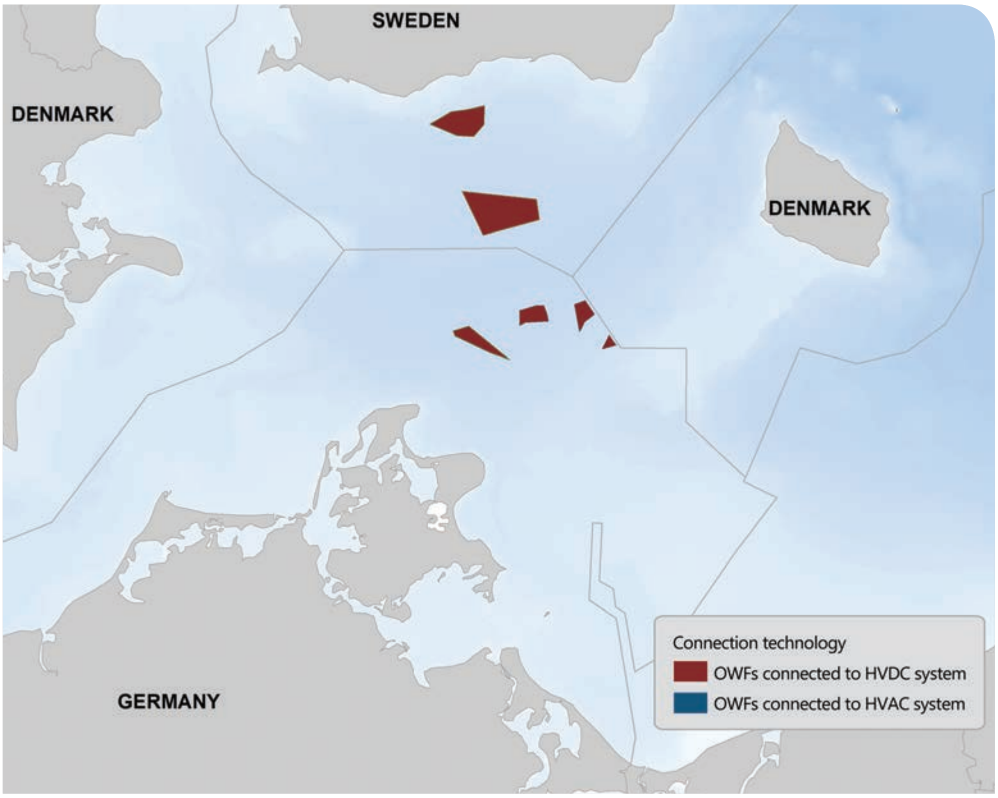


Figure 65
Case Study 2 – Scenario 3b
OWF connection technology

Advantages	Disadvantages
Minimum parallel infrastructure, highest infrastructure utilisation rate, minimum sea use and environmental impact.	Need for significant cooperation of OWP and TSOs, relatively higher biggest fault potential (1 GW)

Scenario summary

This scenario shares many of the advantages and disadvantages discussed for scenario 3a. It shows how several OWFs could be integrated into an interconnecting DC link interconnecting DC grid. As for scenario 3a, there is a high level of cooperation between all stakeholders necessary. However, there are also clear benefits for this scenario like the efficient use of marine space.

This scenario shows a high level of OWP export security. In scenario 3b, there will always be at least two alternative export routes even if wind power is at its max of 1.9 GW.

6.3. Conclusions

6.3.1. Comparison of Scenarios

Table 7 Comparison of technical parameters for all scenarios – Case Study 2

Parameter	High OWP			Low OWP			Unit
	1a – Zero Integration	2a – Partial Integration	3a – Max Integration	1b – Zero Integration	2b – Partial Integration	3b – Max Integration	
OWP via DC	0.00	1.20	3.70	0.00	0.95	1.90	GW
OWP via AC	3.70	2.50	0.00	1.90	0.95	0.00	GW
CBET capacity DE-SE	1	2	2	1	1	2	GW
Full trade capacity	2035	2040	2040	2035	2035	2040	
Onshore converters	2	2	2	2	2	2	units
Offshore converters	0	2	2	0	1	2	units
Total number of converters	2	4	4	2	3	4	units
Total offshore converter power	0.0	2.6	4.0	0.0	1.0	2.0	GW
Total onshore converter power	2.0	4.0	4.0	2.0	2.0	4.0	GW
Total DC cable length	450	485	485	465	451	462	km
Offshore transformers	10	10	10	5	5	5	units
Total offshore AC transformer power	4.1	4.1	4.1	2.0	2.0	2.0	GW
Onshore AC transformers	10	3	0	5	2	0	units
Total onshore AC transformer power	4.1	1.3	0.0	2.0	1.0	0.0	GW
Total AC export cable length	535	735	243	413	141	58	km
Total conductor weight	14,720 Al (36,820 Cu)	17,590 Al (43,990 Cu)	18,740 Al (46,840 Cu)	10,350 Al (25,890 Cu)	13,800 Al (34,510 Cu)	12,930 Al (32,320 Cu)	tonnes

6.3.2. Technical design

System complexity

- The system complexity increases from zero through partial to maximum integration level. A higher capacity and integration might bring higher flexibility in terms of avoiding OWP curtailment and higher maximum CBET rates. Furthermore, a higher level of interconnection might open up new possibilities, such as selling the generated electricity in both markets and price zones.
- With higher complexity, a longer development phase of the system is likely. For example, the technical set-up is more complex and needs stronger cooperation between the involved parties (e.g. TSOs, manufactures) thus a longer development phase is needed.

Infrastructure utilisation rate

- The utilisation rate of a traditional export cable is limited to the OWF's capacity factor. For future OWFs in the Baltic Sea, it is reasonable to assume a capacity factor close to 50%. For an integrated system (or the part of the system that is integrated), the possibility arises to reach a higher utilisation rate, since the available capacity could be used for CBET. However, the scenario of a near-maximum infrastructure utilisation rate would require one of the interconnected countries to always have a high enough power demand and electricity price in relation to the other interconnected country.

DC breakers

Case study 2 is planned without DC breakers.

Dimensioning fault

- The dimensioning fault is related to the N-1 criteria in AC-systems meaning that the system should endure a failure on the largest component in the AC-system. In the Nordic system this is 1450 MW related to the largest nuclear reactor block in Sweden. In Poland and Germany the dimensioning fault is higher, about 2000 MW, due to the larger interconnected AC-system. In the case studies it was assumed that the dimensional fault in the interfaces to countries included in the study will be 2000 MW after 2030. This means that DC breakers are needed when more than 2000 MW in total is connected to one nation from the same DC-system.

Cross-Border Energy Trade potential

Scenarios 2a, 3a and 3b provide greater infrastructure capacity for potential trade. However, this capacity has to be shared with the OWP generation. The forecasting models for wind generation offshore are getting better and better. Offshore wind generation can be forecasted but not planned. The CBET potential of such a system therefore fluctuates. However, carbon-neutral offshore wind energy should be granted priority grid excess over additional trading capacity.

6.3.3. Spatial analysis

- In both the High and Low OWP scenarios, maximum integration is most favourable in terms of potential spatial conflicts due to the lower number of cable corridors.
- Even partial integration would bring a significant reduction of potential spatial conflicts. There is a big difference between zero integration and partial integration, but a much smaller difference when going from partial integration to maximum integration.
- Potential overlappings occur with the following sea uses: navigational routes, fishing areas and environmental protection areas.
- In none of the scenarios, the cables cross areas with a high priority for fisheries (based on HELCOM/VMS data – areas with over 450 h of fishing effort using bottom-contacting fishing gear). Some sections of the cables do cross the areas with a medium priority for fisheries (areas between 150 – 450 h/a of fishing effort bottom-contacting fishing gear). The majority of the cables run through areas with low interest for fisheries (below 150 h/a fishing effort).
- In both High and Low OWP scenarios, there are substantially more crossings of linear infrastructure, than in the partial and maximum integration scenarios.
- The number of landfalls may become a limiting factor. In this case study, maximum integration assumes 6 times less cables and landfalls (High OWP) than in zero integration. The potential conflicts may include onshore environmental protection areas, but also dispersed and sometimes congested settlements and tourist activity at the seaside.

[NOTE]: the analysis includes data that is openly available for analysis. Spatial analysis should be further investigated based on data and contacts with the relevant authorities.

- Potential mitigation measures will have to be applied in terms of potential navigational route crossings and areas with a high value for fisheries (e.g. cable burial, concrete mattresses, establishment of safety zones, avoiding open-trench landfall). One of the scenarios (1a – zero integration, High OWP) crosses a traffic separation scheme (TSS), which may require deeper burial than with other navigational routes.

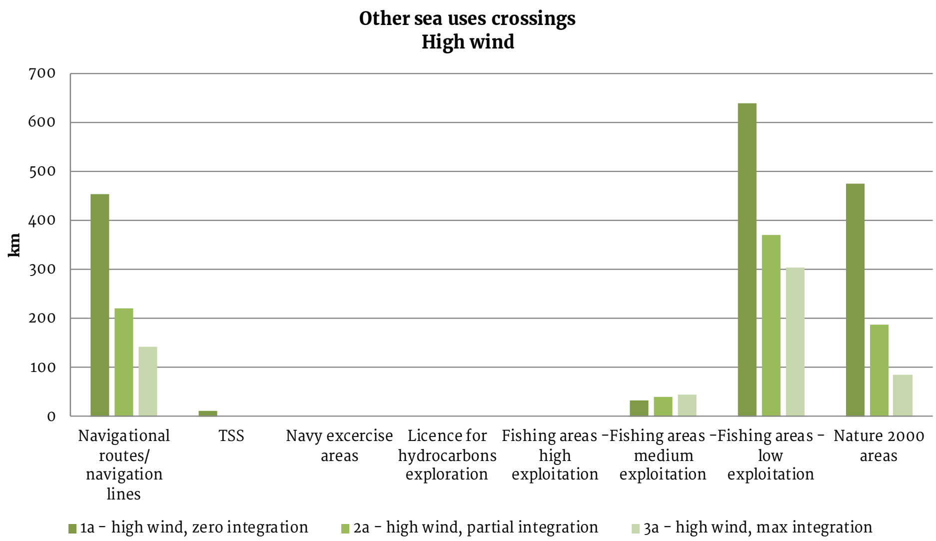


Figure 66
Total length of cables passing through other uses of the sea; High OWP scenarios – Case Study 2

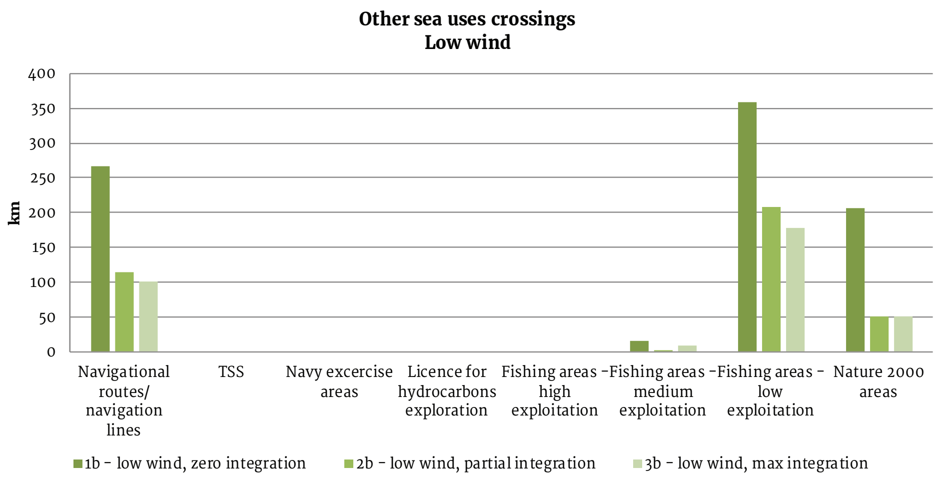


Figure 67
Total length of cables passing through other uses of the sea; Low OWP scenarios – Case Study 2

6.3.4. Environmental analysis

Most of the identified impacts are expected to occur only on a local scale with the exception of underwater noise emissions during the installation of the offshore foundations. The noise emission can be detectable even on a regional scale. Nevertheless, the most detrimental effect on marine animals caused by underwater noise such as fatal injuries (fish) or a permanent change of the hearing threshold (fish and mammals) is expected to be spatially limited and to occur at a relatively close distance to the source of the noise. It is also possible to apply mitigation measures such as bubble curtains and ramping-up of noise to scare off potential animals.

It is not expected that development of the transmission infrastructure could have a significant effect on the environment in general, especially as none of its technical elements (offshore cables and converter/transformer stations) are qualified according to the EIA Directive as projects which are likely to have significant effects on the environment.

6.3.5. Cost-Benefit analysis

Benefits – results

- In High OWP scenarios, the partial and maximum integration show lower system costs (higher benefits) in comparison to the baseline – zero integration scenario, by 1.83 billion EUR for partial integration and 1.76 billion EUR for maximum integration.
- Increased integration leads to an increase in transmission flexibility. Therefore, less additional interconnector capacity is needed. In Low OWP scenarios, system costs are comparable in all scenarios.
- The adequacy analysis shows that in all scenarios, the system has enough capacity available, but higher integration provides the system with more flexibility with regards to the adequacy rate. The conclusions are true for all countries included in the Case Study.

The main results regarding the differences between overall system costs for each scenario are shown in the graphs below. The graphs show the overall costs for the different scenarios.[60]

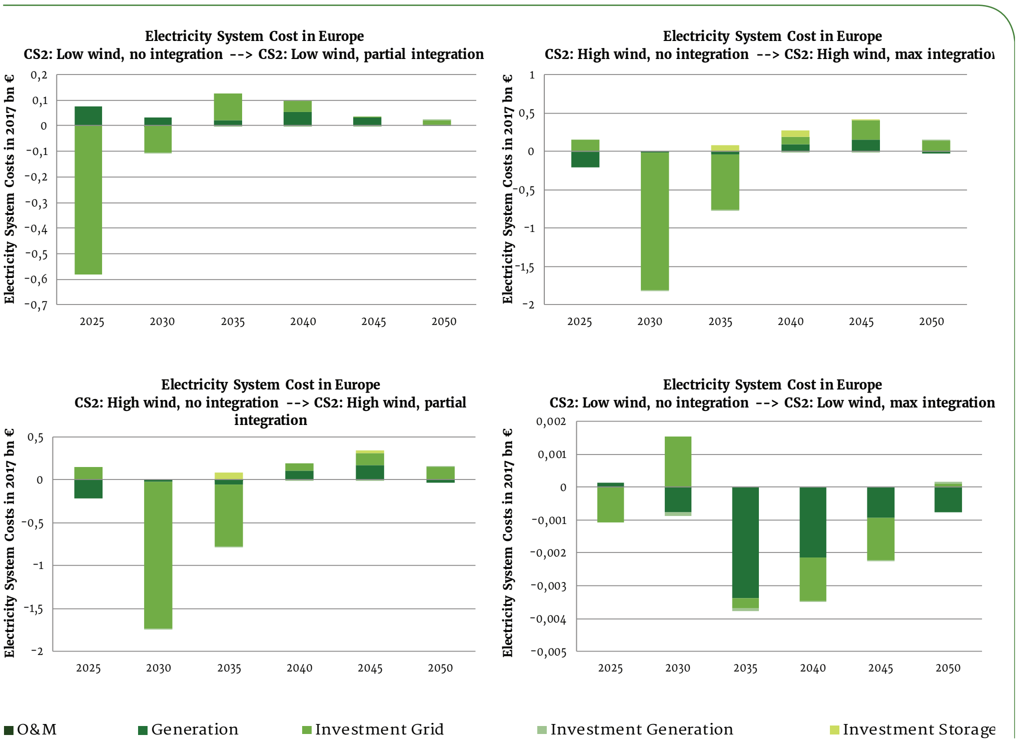


Figure 68
Electricity System Cost in Europe – Case Study 2

60 System costs reflect the cost of optimal investment and generation decision based on the scenario specific data. The figures present the comparison between the base case (zero integration) and a partial or high integration case however also implies that benefits that come from the infrastructure that is already available in the base case, like additional interconnector capacities, are not captured. The difference between the zero integration and higher levels of integration allow to specifically see if the changed topology allows for different outcomes that are directly related to the respective change in topology and wind farm development and therefore directly reflect additional benefits.

Costs – results

- A higher level of scenario integration leads to a shorter combined cable length of AC and DC cables. As the total cable length decreases, the total conductor volume increases. What can be stated at this point is that the installation costs are rather closely related to total installed cable length.
- For the partial and maximum integrated scenarios, four converter stations (onshore plus offshore) are needed. For the zero integration, only 2 converters are needed. These converters are only necessary for the DC link (Interconnector) between Sweden and Germany. Since the cost of offshore converters are a substantial part of the investment costs, this is a cost advantage of the zero integrated scenario.
- The zero integration scenario and High OWP is characterised by high HVAC costs, which are mainly cable costs.
- A significant cost increase can be seen for the partial integration scenario, where the increase in HVDC costs overcompensates for the cost reduction in HVAC cable costs, because of the addition of HVDC offshore nodes (converter stations).
- In the maximum integration case, HVAC cable costs can be reduced dramatically due to an efficient wind farm clustering. This results in a total cost decrease that makes the maximum integration case the least costly one.
- In the Low OWP scenarios, the total cost differences are low for the different degrees of integration. Because of the high costs that are associated with HVDC offshore nodes required to integrate the offshore wind farms, the substitution of HVAC infrastructure by HVDC technology results in a moderate cost increase for both the partial and the maximum integration cases. Here again, the zero integration case is the least expensive one.
- No significant cost trend can be seen for an increasing degree of integration. This results from the very case specific scenario choices and the fact that the scenarios are designed in a way that keeps the interconnecting capacity between countries at comparable levels.

The primary output of the LCM are the cost structures of the previously defined scenarios. The following figures illustrate the cost structure of the various scenarios.

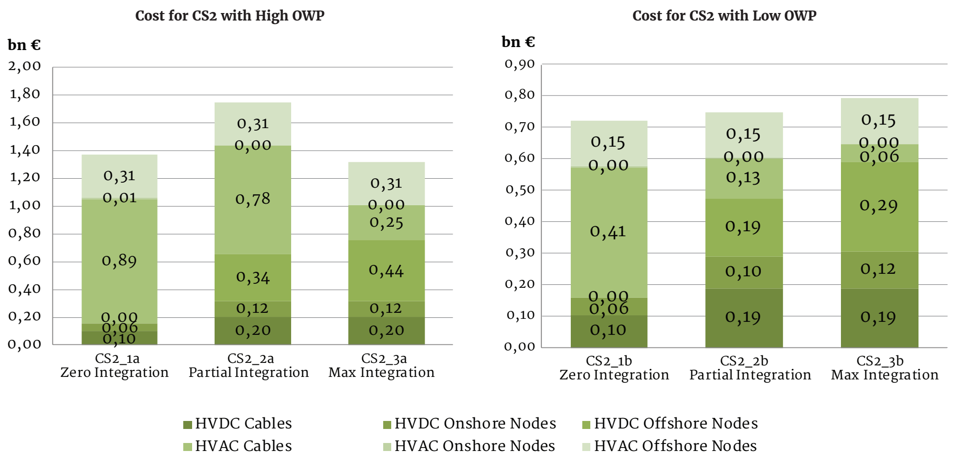


Figure 69
Cost structure for scenarios in Case Study 2

Weighing Costs and Benefits

- In the High OWP scenarios, a significant benefit increase can be seen for the partial integration scenario, which is slightly reduced for the maximum integration scenario due to the higher utilisation of interconnectors by the offshore wind power. Still, the maximum integration case is the favoured one because it has the lowest total costs.

- In the Low OWP scenarios, no extra benefit and no cost reduction can be observed for wind farm integration. Here, the zero integration scenario should be favoured.
- For the overall result, no distinct trend can be seen for an increasing level of integration. This is because of the scenario choice that was made with the premise to keep the total exchange capacity between neighbouring countries constant. A higher degree of wind farm integration seems to make more sense for scenarios with high offshore wind capacity.
- In the Low OWP, the overall results favour the zero integration scenario. However, an additional benefit that is not fully monetarised, such as the security of supply, could shift for the decision towards a higher level of integration.

The costs and benefits are provided as net present values and can be weighed against each other. The following tables summarise the output of the two models.

Table 8 Summary of Cost-Benefit Analysis – Case Study 2

CS2 (DE, SE, DK)			
High Offshore Wind Power		Low Offshore Wind Power	
Partial Integration	Max Integration	Partial Integration	Max Integration
CS2_2a – CS2_1a	CS2_3a – CS2_1a	CS2_2b – CS2_1b	CS2_3b – CS2_1b
Benefit (higher is better)			
1.83 bn€	1.76 bn€	-0.03 bn€	-0.01 bn€
Cost (lower is better)			
0.38 bn€	-0.05 bn€	0.03 bn€	0.07 bn€
Benefit – Cost (higher is better)			
1.45 bn€	**1.81 bn€**	-0.06 bn€	-0.08 bn€

Table 9 Summary showing the most economic scenarios

	Case Study 2 (DE/SE/DK)
High OWP	Maximum Integration
Low OWP	Zero Integration

Photo: Detlef Gehring, EnBW

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Abbreviations

Al	Aluminium
AO	Associated Organisation
AC	Alternating Current
ACER	Agency for the Cooperation of Energy Regulators
BEMIP	Baltic Energy Market Interconnection Plan
BSH	German Federal Maritime and Hydrographic Agency
CAPEX	Capital expenditure
CBA	Cost-Benefit Analysis
CBET	Cross Border Energy Trade
CHP	Combined Heat and Power
CS1/CS2	Case Study 1/Case Study 2
Cu	Copper
DC	Direct Current
DE	Germany
DK	Denmark
EEA	Environmental Energy Agency
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
EUSBSR	EU Strategy for the Baltic Sea Region
GoA	Group of Activities
GW	Gigawatt
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IMS	Impact Mitigation Strategy for the Baltic Offshore Grid
LCM	Linear Cost Model
LCOE	Levelised Cost of Energy
LT	Lithuania
MMC	Modular Multilevel Converter
MW	Megawatt
NGO	Non-Governmental Organisation
NTC	Net Transfer Capacity
OCP	Offshore Connection Point
OPEX	Operational expenditure
OWE	Offshore Wind Energy
OWF	Offshore Wind Farm
OWP	Offshore Wind Power
O&M	Operations & Maintenance
PCI	Project of Common Interest
PFS	Pre-Feasibility Study
PL	Poland
PP	Project Partner
RES	Renewable Energy Sources
SE	Sweden
SME	Small and Medium Enterprises
SMB	South Middle Bank
SvK	Svenska Kraftnät, Swedish transmission system operator
TSO	Transmission System Operator
TSS	Traffic Separation Scheme
TYNDP	Ten Year Network Development Plan
VSC-HVDC	Voltage Source Converters High Voltage Direct Current
VMS	Vessel Monitoring System
WP	Work Package

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