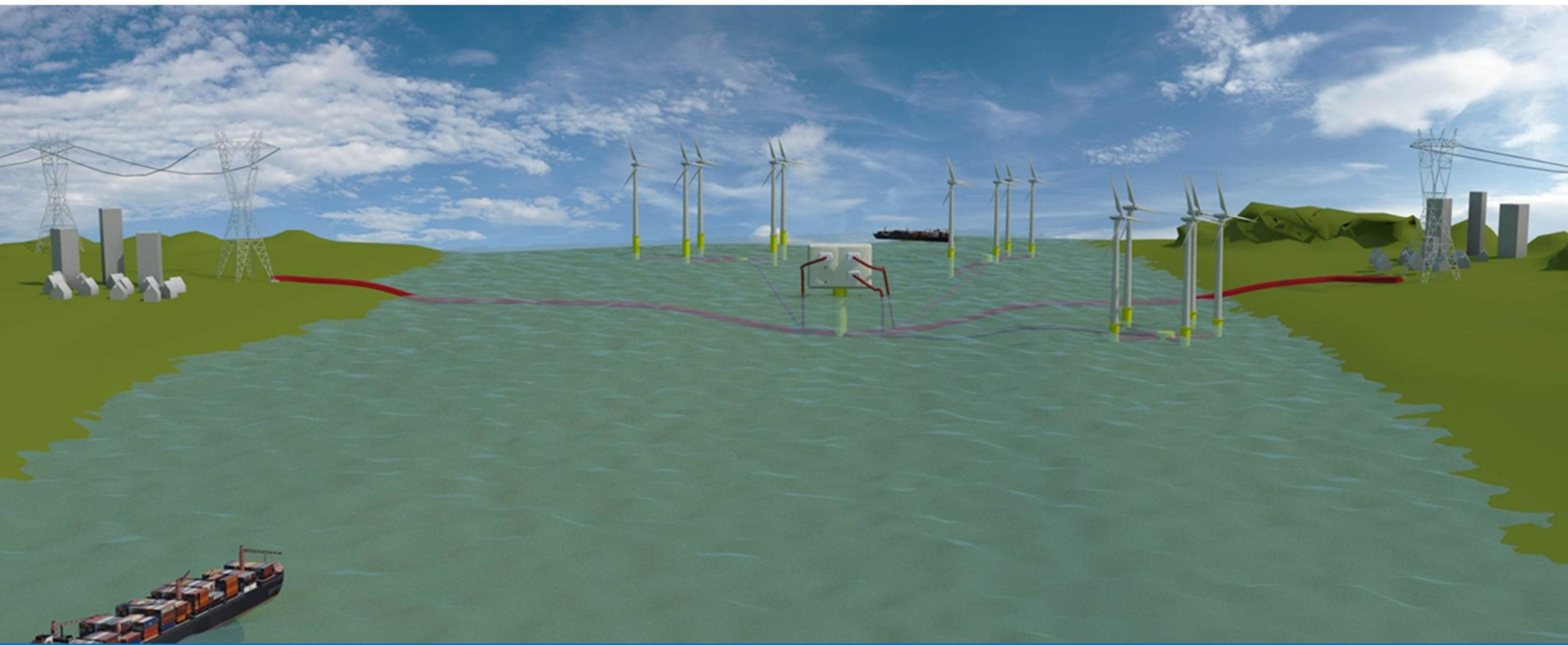

Synergies at Sea

Feasibility of a combined infrastructure for offshore wind and interconnection

Final report (public version)

Authors: Nuon/Vattenfall (leading Subproject 1), ECN, Delft University of Technology, University of Groningen, Royal HaskoningDHV and DC Offshore Energy

Date: 1 March 2017

Synergies at Sea is a consortium that investigates the feasibility of an innovative electricity infrastructure on the North Sea. The consortium examines technical solutions, (required) changes to international legislation and regulations and new financing models. The consortium consists of Nuon/Vattenfall, ECN, RoyalHaskoningDHV, Groningen Centre of Energy Law of the University of Groningen, Delft University of Technology, DC Offshore Energy and Energy Solutions, and is coordinated by Sweco Netherlands (previously Grontmij).

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TKI - Wind op Zee

Subproject 1: Interconnector

Nuon/Vattenfall (leading Subproject 1)

ECN

Delft University of Technology

University of Groningen

Royal HaskoningDHV

DC Offshore Energy

1 March 2017

Preface

This report is part of the project Synergies at Sea. Synergies at Sea is conducted by a consortium that examines technical solutions, necessary changes to international legislation and regulations and new financing models. The consortium comprises eight members: Nuon/Vattenfall, ECN, Royal HaskoningDHV, Groningen Centre of Energy Law of the University of Groningen, Delft University of Technology, DC Offshore Energy and Energy Solutions, and is coordinated by Sweco.

The Synergies at Sea project has started in 2013 and will be finished in 2016. It comprises the following sub-projects (SP's):

- SP1-S P1 UK-NL Interconnector: Feasibility and Design study on the Offshore Wind Interconnector
- SP2 New Financial Structures and Products
- SP3 Regulatory Framework
- SP4 Distributed Temperature Sensing
- SP5 Value Engineering

The research for Synergies at Sea is carried out within the scope of the Top Sector Energy. The Top Sector Knowledge and Innovation - Offshore Wind (TKI-WoZ) leads the research, innovation and implementation activities concerning off shore wind technology, for the industry (small and medium sized enterprises) in the Netherlands. The aim is an effective cost reduction of 40 % for offshore wind as well as reinforcing the economic activities in the Netherlands, ensuring the international leading position of the Dutch offshore wind sector. The current project is part of Research and Development (R&D) line 3 of TKI-WoZ "Internal electrical network and grid connection". This report is the final report of sub-project 1.

TKI-WoZ collaborates with Netherlands enterprise Agency from the Ministry of Economic Affairs

Executive summary

In this final report of Sub Project 1 of the Synergies at Sea project, the feasibility of an interconnection between the United Kingdom (UK) and the Netherlands (NL) via two planned offshore wind farms is assessed. This analysis concludes that 'integrated solutions', where wind farms are connected to an interconnector are technically feasible. In particular cases, integrated solutions lead to significant societal benefits compared to 'stand-alone solutions'. In such solutions, the same amount of offshore wind and interconnector capacity is installed, but connected directly to the land network, and not to the interconnector. It should be noted that these conclusions are based on the specific case of an interconnection between the UK and the Netherlands and can therefore not be generalized to other cases without further study.

Cost reductions would further increase the economic feasibility of an integrated offshore grid. However, industry is hesitant to undertake the required R&D efforts due to a lack of effective market demand. Therefore, it is essential that policy makers develop a clearer vision and create supportive legislation to accommodate the combination of wind farms and international transmission assets.

The main findings are:

1) Suitable technologies for integrated solutions already exist

Technologies required for combinations of offshore wind farms and interconnectors already exist on the market. These are based on High Voltage Alternating Current (HVAC) combined with High Voltage Direct Current (HVDC) point-to-point connections of up to 900 MW. HVDC connections, however, have higher power levels and small multi-terminal HVDC grids are close to market implementation.

2) Some integrated solutions are more beneficial than a stand-alone solution and a separate Interconnector

Two scenarios were found to be substantially more beneficial than the conventional alternative. Firstly, scenario **UK4** which consists of a 900 MW offshore wind farm in the UK connected to the Dutch grid through a 1200MW HVDC link. The second scenario is **UK-NL7** which consists of a 1200MW HVDC connection between a 900MW UK offshore wind farm to a 900MW Dutch offshore wind farm. Additional net benefits over the lifetime of M€ 200 to M€ 300 can be achieved in case these scenarios are chosen instead of the stand-alone alternative of a separate interconnector and wind farm connections. The determining factor is that the integrated solution requires less investment because the interconnection makes use of existing infrastructure of the wind farms. These cost savings outweigh the limitation of the trading revenues due to the combined use with offshore wind transmission.

As the stand-alone solution requires additional investments for onshore connection, although not considered in this study, the preferred integrated solutions will be more beneficial, relative to the stand-alone solution. The smaller need for onshore grid reinforcements saves scarce space and accelerates the realization of such infrastructure and the benefits that it generates.

3) *Existing regulation and legislation poses a barrier for realizing integrated solutions[1]*

Current legislation in both countries does not yet allow for the development of combined infrastructure for interconnection and wind farm connection and is, therefore, considered as a limiting factor for the development of an integrated offshore grid.

4) *Integrated solutions between the UK and NL are unlikely to be realized in NL before 2023*

Offshore wind power plants in the Netherlands will be developed at near-shore locations first. Therefore it is unlikely that combined infrastructure involving the UK and the Netherlands will be realized before 2023, although some scenarios proved to be economically feasible by then. In order to develop such combined infrastructure for post 2023 wind farms, this solution should already be incorporated in the tender regulations by 2019 and the decision to start with this adaptation should be taken as soon as possible. This will provide the necessary incentive to project developers to investigate the best options for interconnection and for suppliers to speed up their developments.

[1] The legal research analysed the existing legislation as it was up-to-date in Augustus 2014. Updates in legislation are included in the Comprehensive Summary, Regulatory analysis (§ 4) and conclusions (§ 7) of this report.

Comprehensive Summary

In this report, the feasibility of an interconnection between the United Kingdom (UK) and the Netherlands (NL) via two planned offshore wind farms on both sides of the border is assessed. The main conclusion is that this is technically feasible and in particular cases leads to significant societal benefits. It is therefore advised to take action to prepare for an offshore integrated grid. It should be noted that this conclusion is based on the specific case of an interconnection between the UK and the Netherlands and cannot, therefore, be generalized to other cases without further study.

Cost reductions would further increase the feasibility of connections. Manufacturers are, however, hesitant to undertake the required R&D efforts due to the lack of effective market demand. To accommodate the combination of wind farms and international transmission assets, legislation needs to be changed. The main technical options for offshore networks integrating interconnectors and offshore wind farms are discussed in the next paragraphs. This is followed by an analysis explaining a preference for some alternatives over others.

Grid topologies for integrating wind farms and interconnectors

The original idea of this study was to create an interconnection between the UK and the Netherlands through interconnecting two offshore wind farms at either side of UK-Dutch border. This topology, labelled **UK-NL** in Figure 1-1, requires only a cable circuit of 100km instead of 260km for a separate interconnector (IC) parallel to the existing BritNed cable, cf. **IC** in Figure 1-1. The term “Interconnecting link” **(IL)** is introduced here to explicitly stress the issue that is to be dealt with, that being the need for infrastructure to connect different countries via Offshore Wind Farms (OWFs). At the start of this project, such connection did not have a legal basis. However, under the current Dutch regulatory regime where TenneT TSO develops and operates the offshore transmission infrastructure, such connection can be classified as an Interconnector (between two TSOs: TenneT and the UK OFTO).

Two alternative topologies have been defined, **UK** and **NL**, which only require an interconnection through a single wind farm. In the **UK** topology, the UK wind farm is also connected to the Netherlands, while in the **NL** topology, the NL wind farm is connected to both sides. In the **UK** topology the IL follows a shorter route to the onshore connection point, resulting in a length of 110 km instead of 100 km + 35km. These solutions are considered to be less complicated than the UK-NL scenario in terms of planning and design.

These project scenarios **UK+NL**, **UK** and **NL** have been compared to a business-as-usual scenario **IC,** which has a separate Interconnector (IC), parallel to the existing BritNed link. A further break-down with respect to installed wind capacities, cable capacities and cable technologies defines a number of different scenarios.

All costs that can be directly related to different project alternatives, especially the additional investments needed to connect the offshore facilities to the onshore grid have been included in this analysis. The possible need for strengthening onshore transmission grids however has not been included in the analysis. Different network capacities, as well as different technology alternatives, e.g. Alternating Current (AC) versus Direct Current (DC), have been assessed. In total 13 alternative scenarios have been formulated based on the basic grid topologies, numbered **UK-NL1** to **UK-NL7**, **UK1** to **UK4** and **NL1** and **NL2**.

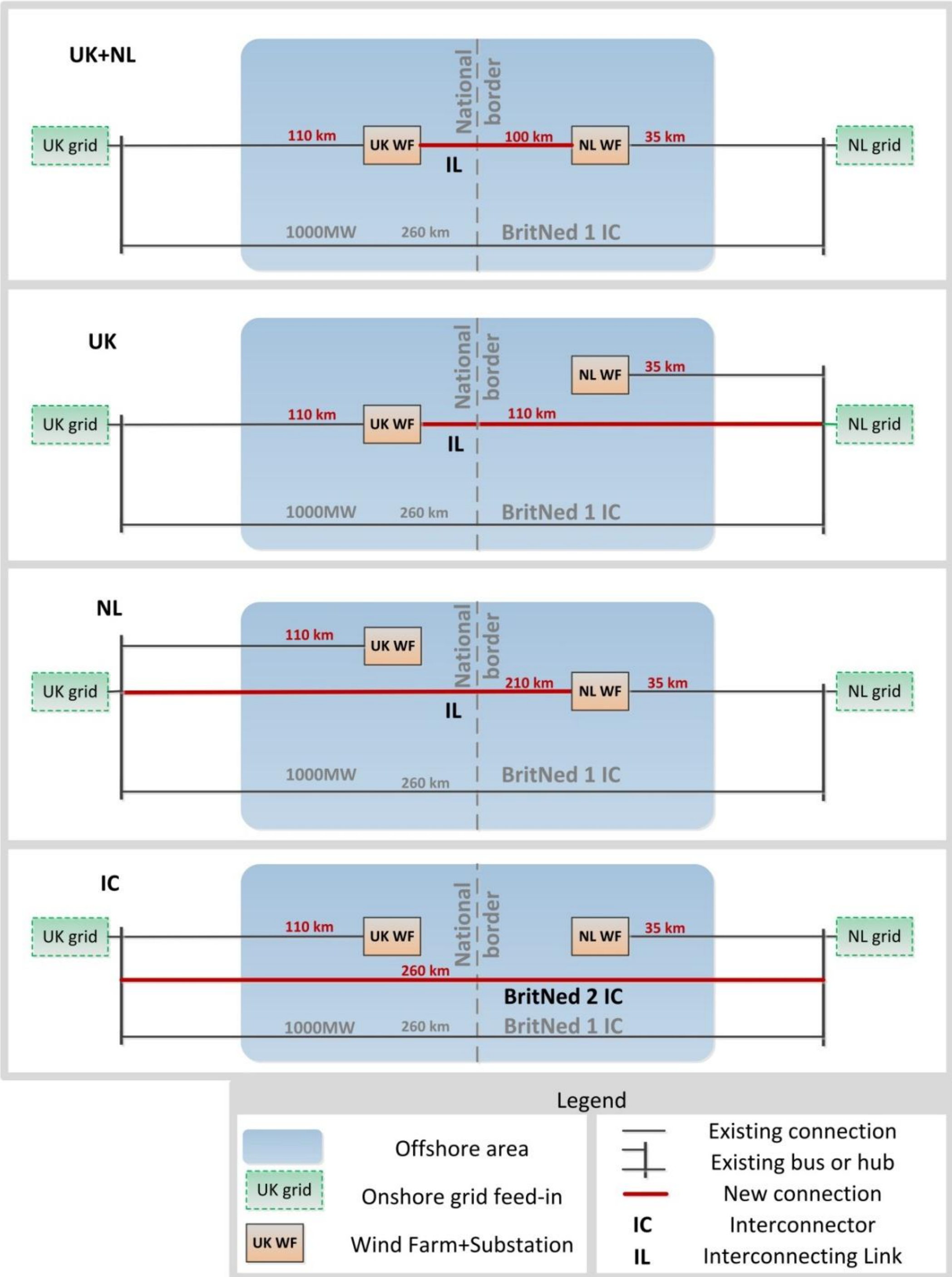

Figure 1-1: Basic grid topologies, where the red line represents the additional infrastructure

Some integrated solutions are more beneficial than a parallel Interconnector

In an economic analysis, the integrated solutions were compared with the business-as-usual scenario of a conventional solution of a parallel interconnector. This included all wind farms connected only to the country in whose exclusive economic zone or territorial sea the wind farm is located. This was analyzed both from the viewpoint of a private investor, owning the transport infrastructure, as well as from the viewpoint of society, in which the overall impact on consumers and producers of electricity are taken into account.

Two scenarios were found to be substantially beneficial for private investors as well as for society, cf. Figure 1-2:

1. UK4, consisting of a High Voltage Direct Current (HVDC) connection between a 900 MW wind farm in the UK to the Dutch grid.
2. UK-NL7, consisting of an HVDC connection between a 900 MW UK wind farm to a 900 MW Dutch wind farm.

The reason for this is that the additional revenues from electricity trade between the UK and the Netherlands are higher than the added costs for the interconnection via these wind farms. This leads to additional net societal benefits over the lifetime of M€ 102 for **UK4** and M€ 186 for **UK-NL7**, as well as sufficiently high benefits to a private investor. The alternative to building a parallel interconnector also showed to be beneficial, although less than the preferred integrated scenarios. The determining factor is that the integrated solutions require less investment because the interconnection makes use of existing infrastructure of the wind farms. These cost savings outweigh the limitation of the trading revenues due to the combined use with offshore wind transmission.

As the stand-alone solution requires additional investments for onshore connection, which have not been considered in this study, the preferred integrated solutions will even be more beneficial, relative to the stand-alone solution. The smaller need for onshore grid reinforcements also saves scarce space and accelerates the realization of such infrastructure and the benefits that it generates.

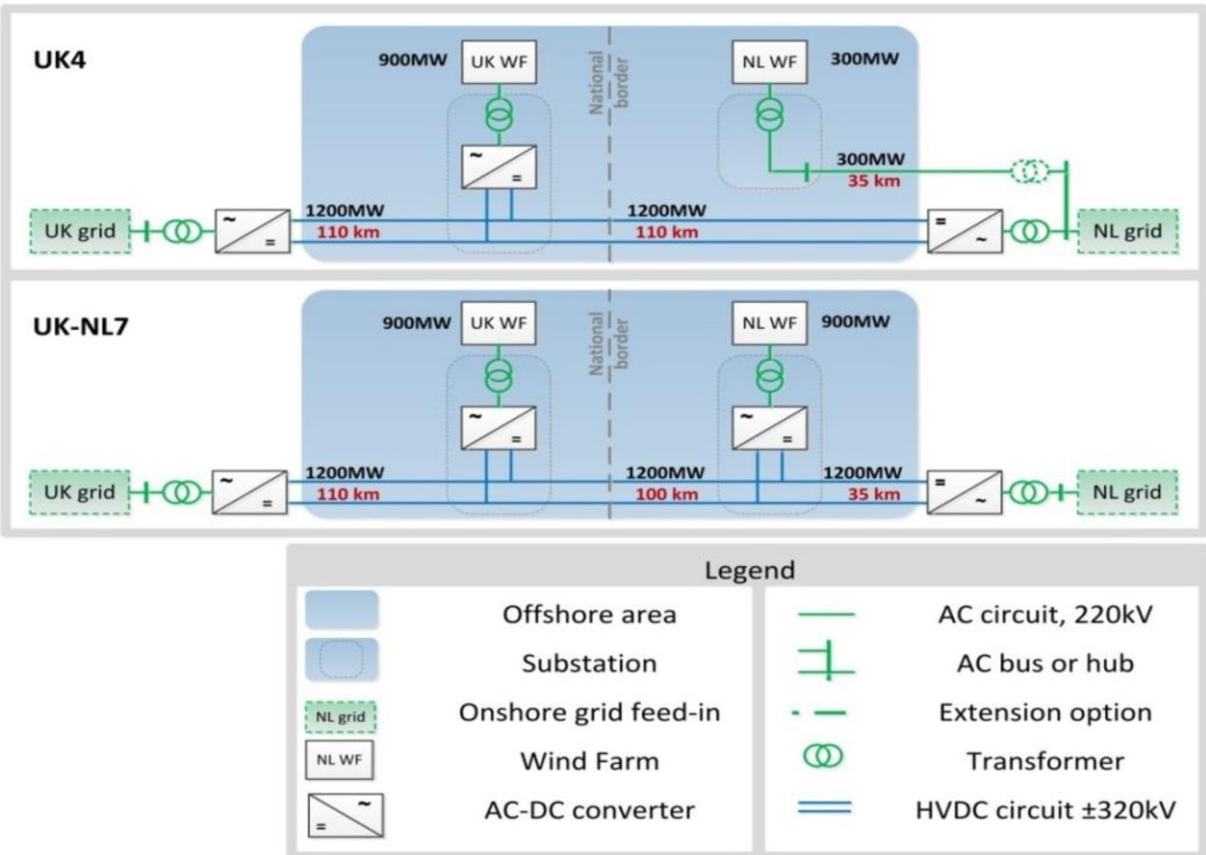

Figure 1-2: Two most attractive scenarios

Existing legislation poses a barrier for realizing integrated solutions[2]

In this study, it is found that the current legislation in both countries does not allow for the development of combined infrastructure for interconnection and wind farm connection. Therefore, the current legal framework is regarded as a limiting factor for the development of an integrated offshore grid. This slows down investments of industry to develop products in the HVDC market, which is required to reduce the current high costs and risks. This has a negative effect on parties' interested in considering this as an investment option.

Integrated solutions involving UK and NL are unlikely to be realized before 2023

Whether a particular scenario is feasible depends on the electricity market conditions on both sides of the connection, the costs related to the connection distance and technology. Integrated solutions are currently not included in the planned developments of wind farms in the Netherlands and the UK. Since the implementation plans in the Netherlands have a strong focus on developing near-shore areas first[3,4], it is unlikely that combined infrastructure involving the UK and the Netherlands will become economically feasible before 2023.

However, this study also shows that some scenarios after 2023 are feasible for both society and for the parties investing in the offshore infrastructure, even with the current state of technology. Besides this particular case, interconnecting other future wind farms between the UK and the Netherlands or between other countries may also be economically feasible. In particular connections between offshore wind farms in the Netherlands and Germany should be assessed at short notice from a bilateral or European perspective.

In order to develop such combined infrastructure for post 2023 wind farms, this solution should already be incorporated in the laws and regulations by 2019 and the decision to start with this adaptation should be taken as soon as possible. This will provide the necessary incentive to wind energy developers, TSOs and governments to investigate the best options for interconnection and to suppliers to speed up their developments.

Integrating offshore wind farms in interconnection infrastructure between UK and NL leads to various benefits

Main benefits of an integrated solution are:

- **Reduction of the Total Cost of Energy (TCoE)** by M€ 200 to M€ 300 over the lifetime of a 1200 MW link.
- **Strengthening of the electricity market by increased cross-border capacity.**
- **Reduction of balancing problems,** preventing additional costs for the Transmission System Operator (TSO) for integration of renewable energy.

These findings are in line with previous European studies like OffshoreGrid[5] and NorthSeaGrid[6] which also showed benefits of integrated solutions.

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[2] The legal research analysed the existing legislation as it was up-to-date in August 2014. Updates in legislation are included in the Comprehensive Summary, Regulatory analysis (§ 4) and conclusions (§ 7) of this report.
[3] https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/nieuws/2015/04/15/geplande-windparken-op-zee-in-beeld
[4] http://www.ser.nl/en/publications/publications/2013/energy-agreement-sustainable-growth.aspx
[5] http://www.offshoregrid.eu/
[6] http://www.northseagrid.info/

Other benefits are:

- **Limited expansion of the onshore grid connection capacity** in the countries is needed, as the connection capacity is available for wind energy anyway. This is a cost advantage and also enables development of additional cross-border capacity in cases when development of new interconnectors is not possible due to limited onshore connection capacity or space.
- **Increased availability and flexibility of the offshore transmission system**, which results in additional benefits for wind farm operators from yield increase, reduction of unbalance volumes and possibly lower costs for auxiliary power supplies (cf. section 3.6.2).
- **Extended European technological leadership** on HVDC point-to-point connections with this new application of integrated solutions. Favorable market perspectives will encourage further technology development, in particular, for offshore HVDC (as shown in section 3.2 of the main report).
- **Faster development of interconnection** through utilizing infrastructure already planned for offshore wind farm connection, while stand-alone solutions would require additional cable routes as well as onshore connection and transport capacity.

Main conclusions

- Both from a societal perspective as well as from a private investors' perspective, the analysis shows that in some scenarios the combined, or synergy solution, is preferred over individual connections of offshore wind farms and a conventional interconnector. This only applicable if the necessary legal barriers have been cleared.
- Technologies required for combinations of offshore wind and interconnectors, either already exist on the market (based on High Voltage Alternating Current (HVAC) combined with HVDC point-to-point connections up to 900 MW) or are close to market implementation (larger HVDC offshore connections and small multi-terminal HVDC grids).
- Technological developments are beneficial to obtain lower costs; currently these are hindered by regulatory barriers. Due to those barriers there is no market for offshore HVDC grids, with Offshore Wind Farm (OWF) feed-in and there is little incentive for suppliers to develop HVDC technology.
- From a regulatory perspective:
  - A combination of offshore wind farms and interconnection requires that electricity can be transported to either side of the border without impediments, i.e. without financial barriers with regard to subsidies. The national support schemes do not allow for feed-in of renewable energy over a direct cross-border connection between the offshore wind farm and a foreign grid. In order to be eligible for subsidizing, the electricity needs to be fed in on the national grid before the electricity is exported. After the amendment of the Dutch Electricity Act '98 in early 2016, both the British and Dutch offshore wind farms are connected to an offshore sub-station of their respective TSO.
  - Due to the principle of the non-discriminatory network access and the unbundling requirements, it is at this moment not possible to reserve network capacity on the interconnecting link or interconnector for the wind farm operator. It is mandatory, in order to make the synergy solution feasible, that the offshore wind farm operators

have a guaranteed and/or priority network access due to the higher value of offshore wind power compared to cross-border trade flows in electricity. If the offshore wind farm operators are not able to transport the produced electricity due to congestion on the interconnecting link, it would lead to damages for the wind farm operator, which under the current regime are not recoverable. This poses a serious barrier for the realization of integrated offshore infrastructure.

– This research has shown that, apart from the difference in national support schemes, other legislation in the Netherlands and the UK creates barriers for a wind farm interconnection combination. In the Netherlands, the *Elektriciteitswet 1998*[7] did not mention any obligation for the TSO to be involved in the development of offshore transmission infrastructure until additional legislation was adopted for offshore wind energy in 2015 and 2016[8]. Since 1 April 2016, TenneT TSO is responsible for developing and operating the offshore transmission system for connecting offshore wind farms to the Dutch onshore grid. In the UK, the primary focus of the Offshore Transmission Owner (OFTO)[9] regime is on the connection of offshore wind farms through radial connections. The regime discourages the inclusion of optionality in the design of the offshore substation by the developer of the offshore transmission system regardless of whether the OFTO-build of the generator-build model is applied. As these investments will not be done under the OFTO regime it is unsuitable for the combination of offshore wind farms with an Interconnector.

Recommendations

Short term: To allow connections between offshore wind farms in two countries

1) Solve the most important regulatory barriers.

   a. The responsible governments of the Netherlands and the UK should advise and facilitate the European Commission (EC) to adjust Regulation (EC) 714/2009[10] which deals with cross-border flows of electricity. The future regime should also include a framework for multi-terminal offshore grids in addition to the framework for point-to-point interconnectors. The envisaged regime should deal with matters such as unbundling and guaranteed i.e. priority access for the offshore wind farm operator(s). Due to the fact that an offshore grid including wind farms and interconnectors is a *sui generis* electrical system that is not regulated under the existing Regulation (EC) 714/2009, it is required that the European legislator designs a regime for this concept that provides legal certainty to the TSOs and wind farm developers This must be flexible enough to be applied to different situations i.e. different configurations of wind farms and interconnectors.

   b. The future Integrated Transmission Planning and Regulation (ITPR)[11] regime that is expected to replace the OFTO regime in the UK and should be designed in such way

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[7] http://wetten.overheid.nl/BWBR0009755/2016-04-01
[8] Wet windenergie op zee (Stb. 2015,261) and Wet tijdig realiseren doelstellingen Energieakkoord (Stb. 2016,116).
[9] https://www.ofgem.gov.uk/electricity/transmission-networks/offshore-transmission
[10] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009R0714&from=EN
[11] https://www.ofgem.gov.uk/publications-and-updates/integrated-transmission-planning-and-regulation-itpr-project-final-conclusions

that it allows for the application of the integrated synergy solution.

2) Assess the different alternatives: The opportunity to develop an integrated offshore grid is only an option until the development and planning of the offshore wind farms is done. As soon as the design of the substation and cable route is chosen this cannot be changed without (very) large extra costs. Therefore:

   a. On national level by member states (e.g. in the Netherlands: Ministry of Economic Affairs) it is recommended (to prevent missing opportunities), the performance of a study considering the viability of future cross-border point-to-point connections between wind farms zones (with a focus on the wind farms planned on short term. This should include all interconnecting link alternatives In particular: start looking into the realization of identified viable options in more detail.

   b. For the connections for which viability is likely, it is advised to consider implementing the *optionality* to connect an interconnector through an Offshore High Voltage Substation (OHVS) of future wind farms, or to connect a future wind farm to a newly developed interconnector. The assignment to take up the optionality in case of feasibility could, in NL, be given by the Ministry of Economic Affairs. There must also be preparation for appropriate incentives for the stakeholders at European and/or national level to develop and invest in an Interconnector-Wind Farm combination (ICWF).

Long term: To prepare for an integrated offshore grid

1. In addition to the modifications above, European legislation should be adapted to better facilitate the planning and coordination of offshore grid development. The study underlines that the development of an offshore grid in the North Sea requires a coordinated approach from the North Sea countries and the EC, taking into account the competence limits of the EC regarding the offshore EEZ.

2. National support schemes for offshore wind energy should be designed in such a way that it becomes irrelevant for a wind farm owner/operator to know what part of the generated electricity is flowing to either of the two (or more) countries. This includes the possibility of exporting the electricity from the wind farm directly to another member state without prior injection of the electricity in the domestic offshore transmission system.[12]

3. Although increasing the capacity and flexibility of cross-border transmission is already prioritized by the EC, more coordination is required to set up a number of concrete initiatives in order to realize these ambitions.

4. Regional initiatives should include offshore grid development, together with the required market reforms and technology development. This could be structured as follows:

   a. Consider, at the national level, involving the EC, the TSOs, other coastal member states ENTSO-E, NSCOGI and ACER, and other potential cross-border interconnecting links between wind farm development zones to decipher whether

[12] Examples of such a concept would be an UK offshore wind farm that is solely connected to the Dutch onshore transmission system and a Dutch offshore wind farm that is solely connected the UK onshore transmission system. These scenarios are not explored in this research as these would not include an interconnector and therefore would not be synergy solutions.

could be possible. This should be followed by a feasibility study for a number of selected cases. This ought to include an assessment of socio-economic costs and benefits and an analysis comparing the interests of different stakeholders, followed by an assessment of incentives and barriers.

b. Set up pilot projects with high level support to develop and demonstrate an ad-hoc regulatory regime. On the basis of these pilot projects, recommendations can be made to overcome the barriers identified under the previous item. Important factors are:

   i. The need to overcome the regulatory barriers as TSOs or private investors will not see ICWF as an option when it is unfeasible from a current regulatory point of view.

   ii. The vested interests of key actors (receiving congestions rents by TSOs, changes in consumer electricity prices, increased/decreased risks for the availability of a wind farm connection).

c. Align Research, Development and Demonstration (RD&D) activities at national and European level to tackle the identified barriers and to support long-term planning, development and innovation. The initiative for such a coordinated RD&D program has been taken by EERA NSON[13].

5. When the benefits of integrated solutions have been confirmed to result in sufficient value for society, it is recommended to establish a mechanism. An example of this is a follow-up of the Inter-TSO Compensation mechanism (ITC)[14] which would compensate for adverse economic effects in EU countries due to unevenly distributed costs and benefits. Removing this barrier of cost-benefit allocation will stimulate investments in these links.

6. Technology development support on HVDC is needed to obtain more mature and cost-effective solutions:

   a. Standardization of HVDC technology is needed for future compatibility of systems;

   b. Control and protection of (multi-terminal) HVDC;

   c. Upscaling of offshore HVDC offshore platform and cable capacity.

In their report “Fostering Investment in Cross-Border Energy Infrastructure in Europe” from April 2016, the High-Level Group on Energy Infrastructure in Europe made a number of recommendations[15], of which recommendations 2, 3 and 7 on cross-border projects, are well in line with this study.

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[13] North Sea Offshore and Storage Network (NSON) is an initiative within European Energy Research Alliance (EERA) Joint Program Wind for a co-operative European RD&D program targeting a transformation of the energy supply system by, among other means, a sustainable and well-coordinated grid extension and expansion on the European level. Core partners of NSON are: SINTEF (NO), Univ. of Strathclyde (UK), Fraunhofer IWES (DE), DTU (DK), University College Dublin (IRE) and ECN (NL), http://www.sintef.no/globalassets/project/deepwind2014/presentations/b/korpas_m_sintef.pdf

[14] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:250:0005:0011:EN:PDF

[15] Fostering Investment in Cross-Border Energy Infrastructure in Europe, page 21 https://www.ceps.eu/publications/fostering-investment-cross-border-energy-infrastructure-europe-report-high-level-group

Contents

Acronyms

AC Alternating Current.
ACER Agency for the Cooperation of Energy Regulators.
ACM Authority Consumer and Market.

CAPEX Capital Expenditures.
CAR Contractors All Risk.
CCC-CSC Capacitor-Commutated Current Source Converter.
CfD Contracts for Difference.
CoE Cost of Energy.
CSC Current Source Converter.

DC Direct Current.
DNB Dutch Central Bank.

EC European Commission.
ECB European Central Bank.
EERA European Energy Research Alliance.
EEZ Exclusive Economic Zone.
ENTSO-E European Network of Transmission System Operators for Electricity.
EU European Union.
EWG Energiewirtschaftsgesetz.

FC-CSC Forced-Commutated Current Source Converter.

GIS Gas-Insulated Switchgear.

HVAC High Voltage Alternating Current.
HVDC High Voltage Direct Current.

IC Interconnector.
ICWF Interconnector-Wind Farm combination.

IGBT Insulated-Gate Bipolar Transistor.
IL Interconnecting Link.
IRR Internal Rate of Return.
ITC Inter-TSO Compensation mechanism.
ITPR Integrated Transmission Planning and Regulation.

LCC Line-Commutated Converter.
LCC-CSC Line-Commutated Current Source Converter.
LCC-VSC Line-Commutated Voltage Source Converter.
LCoE Levelized Cost of Energy.
MMC Modular Multi-level Converter.
MTDC Multi Terminal Direct Current.
MV Medium Voltage.
MVdc Medium Voltage Direct Current.

NL the Netherlands.
NPV Net Present Value.
NSCOGI North Sea Countries Offshore Grid Initiative.
NSON North Sea Offshore and Storage Network.

O&M Operation and Management.
OFTO Offshore Transmission Owner.
OPEX Operational Expenditures.
OHVS Offshore Substation.
OWF Offshore Wind Farm.

PCI Project of Common Interest.

R&D Research and Development.
RD&D Research, Development and Demonstration.
ROC Renewables Obligation Certificate.

SDE+ Stimuleringsregeling Duurzame Energieproductie
(Dutch national support scheme for renewable energy production).

TCoE Total Cost of Energy.

TEN-E Trans-European Energy Networks.
TFEU Treaty on the Functioning of the European Union.
TKI-WoZ Top Sector Knowledge and Innovation - Wind at Sea.
TSO Transmission System Operator.

UK United Kingdom.

VSC Voltage Source Converter.

WACC Weighted Average Cost of Capital.
WF Wind Farm.
WPP Wind Power Plant.

1. Introduction and background

1.1. Background

The electrical infrastructure connecting OWFs to the onshore grid represents a large share of the total costs of offshore wind and currently represents a significant risk in terms of insurance claims. With large scale integration of renewables the need for costly electricity transmission grid reinforcements arises, including transnational links to support an increase in cross-border electricity exchange. This is a pre-requisite to progress from individual national markets to a single European electricity market. These reinforcements together with the market integration will increase the efficiency of the European electricity system, leading to cost price and emission reductions. The benefits of more interconnection capacity between North Sea countries, e.g. between The Netherlands and the United Kingdom, has been identified in several grid studies[16,17].

By building interconnections between offshore wind farms in different countries, the offshore electrical infrastructure can be used both for wind power export and for cross-border trade. The average load of dedicated offshore wind grid infrastructure, which is typically 40 % to 50 %, offers room for additional electricity transport and thereby more efficient utilization. Electricity can be traded to neighboring countries via the same infrastructure and for the offshore wind farms there is a redundant connection to shore. For beneficial connections this leads to a lower energy price in Europe and could lead to a higher turnover of the wind farm and lower risk of power loss, reducing the needed amount of government support for offshore wind. In some cases cost savings can be obtained in the design and realization phase from combining cabling routes and reducing the number of offshore platforms and converter stations.

Realization of such novel grid concept needs both technological innovations and an improved regulatory framework. To obtain an optimized design and efficient utilization of the wind farm connections an integral approach is needed focusing beyond the boundaries of a single wind farm.

1.2. Objectives

The project *Synergies at Sea*, sub-project Interconnector has studied the feasibility of a specific case, namely combining offshore wind farms with an interconnection between the UK and the Netherlands Figure 1-1. This feasibility study aims to deliver:

1. A statement on feasibility and the conceptual design of a specific case involving two offshore wind farms and interconnection capacity between the UK and the Netherlands;
2. An overview of important technical and regulatory barriers relevant to the case study and to other future offshore grids to which offshore wind farms will be connected.

The feasibility study addresses the main technical design trade-offs as well as the business case evaluation from an investor's perspective, the expected socio-economic benefits and the regulatory and legal implications.

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[16] OffshoreGrid. *Offshore Electricity Grid Infrastructure in Europe*. 2011. u r l: http://www.offshoregrid.eu/images/FinalReport/offshoregrid_fullfinalreport.pdf

[17] NSCOGI. *Final report*. 2012. url: http://www.benelux.int/nl/kernthemas/energie/nscogi-2012-report/

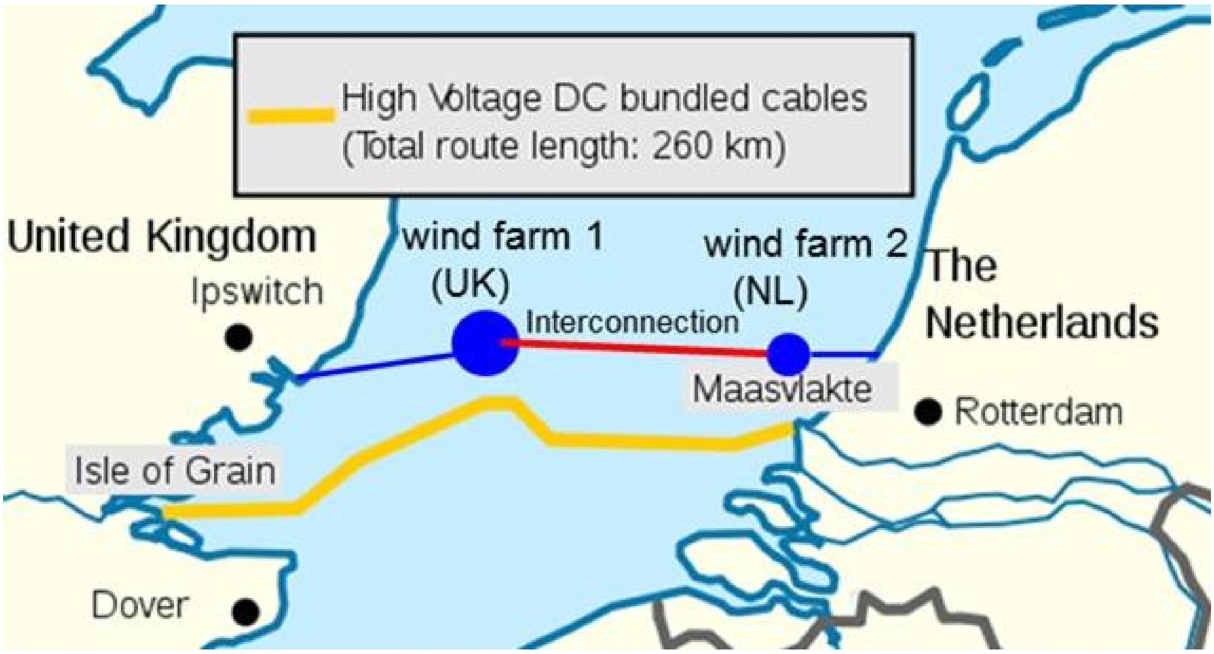

Figure 1-1: An example of two planned wind farms in the UK and the Netherlands and a possible inter- connection between these wind farms to illustrate the concept of integrating two functions: off-shore wind energy generation and interconnection of neighboring countries.

1.3. Scope

This study is different from earlier, more general or conceptual studies, in the sense that it focusses on a particular case involving two planned offshore wind farms and strengthening of the existing limited interconnection capacity between the UK and the Netherlands. The time horizon for the feasibility assessment has been set to 2020 as the year in which the investment decision has to be made. This would mean that the realization should be possible before 2023, which is stated as the ultimate date for the Netherlands to achieve their 16% renewables target. However, issues and developments beyond this time horizon are also identified and discussed. These will be studied in detail within R&D projects on technology and legal framework which are ongoing within the Synergies at Sea consortium.

In the study three particular approaches have been applied which were implemented as separate work streams:

Regulatory/Legal

This work stream involves a legal/regulatory feasibility assessment to determine whether the existing legal/regulatory framework can accommodate cross-border integrated offshore electricity infrastructure development. The legal/regulatory framework consists of different legal rules from three different levels. First, a review of EU legislation and British and Dutch legislation relevant for offshore wind energy development and interconnection is conducted.

The relevant pieces of EU legislation are Directive[18] 2009/72/EC concerning common rules for the internal market in electricity, Regulation[19] (EC) No 714/2009 on conditions for access

[18] In EU law, directives set out general rules to be transferred into national law by each country as they deem

to the network for cross-border exchanges in electricity, and Directive 2009/28/EC on the promotion of the use of energy from renewable sources. The primary pieces of national legislation are the British Electricity Act 1989 and the Dutch Electricity Act 1998.

Secondly, six selected scenarios for cross-border integrated offshore electricity infrastructure are assessed vis-à-vis the existing legal framework. This assessment determines the extent to which the current legal framework accommodates such scenarios or creates legal problems for development.

Technical

The aim of the technical feasibility study is to determine the possible grid topologies and applicable technologies and secondly, to estimate the involved costs and assess the performance. For the grid design, different combinations of HVDC and HVAC technologies in a multi-terminal topology have been considered. This requires innovative solutions, in particular for multi-terminal HVDC systems. For the evaluation, it is a challenge to combine these new solutions with existing ones, based on proven technologies.

A technical review has been conducted to get an overview of the available technologies and their applicability and to understand the numerous options for the technical implementation. In the first project phase a long-list of technical scenarios has been made, from which a short-list is selected for further evaluation with respect to costs and performance and a final selection from an integral feasibility assessment. The feasibility study also identifies and elaborates on issues for further research in the subsequent phase of the sub-project Interconnector within Synergies at Sea. Two main topics that have already been defined are

1. design optimization, including control and protection schemes,
2. R&D of dedicated power-electronic converters.

Thirdly, the technical work stream interacts with the other work streams to integrate the results, for instance by providing cost and transmission losses estimates.

Socio-economic analysis and Business Models

In this work stream the socio-economic effects of the concept are investigated. The benefits for the main stakeholder categories are quantified from a national perspective based on analysis with the European electricity market model COMPETES. This includes the aspects of integration into the Power Markets of the UK and the Netherlands, taking into account their position in the other European markets.

Parallel to the analysis from a national economic perspective, a business case has been defined and analyzed from the perspective of a private investor in the interconnecting link. In both analyses, exactly the same assumptions regarding costs and other inputs have been applied. The business case is limited to costs and benefits of the interconnecting link. In the national economic analysis, cost and benefits for all stakeholders are included, notably for other electricity producers and the impact on consumers. These different perspectives provide answers for different stakeholders: is an interconnecting link desirable for the national economy, and is it a feasible investment for a private party?

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appropriate.

[19] In EU law, a regulation is similar to a national law with the difference that it is applicable in all EU countries.

1.4. **Report outline**

This Final Report presents the preliminary research findings on the feasibility of integrating offshore wind farms with interconnectors. Furthermore, this report also describes potential deviations and hurdles for the Synergies at Sea sub-project 1: Interconnector. This project was granted a subsidy as part of the TKI Wind op Zee program.

In chapter 2 the main research questions are presented. Most of the analytical work is divided over three work streams which are described respectively in chapter 3 (Technical solutions to integrate offshore wind farms with interconnectors), chapter 4 (Regulatory issues) and chapters 5 and 6 (Socio-economic findings).

2. Methodology

This section presents the chosen research method. The process is shown in the simplified process diagram in Figure 2-1.

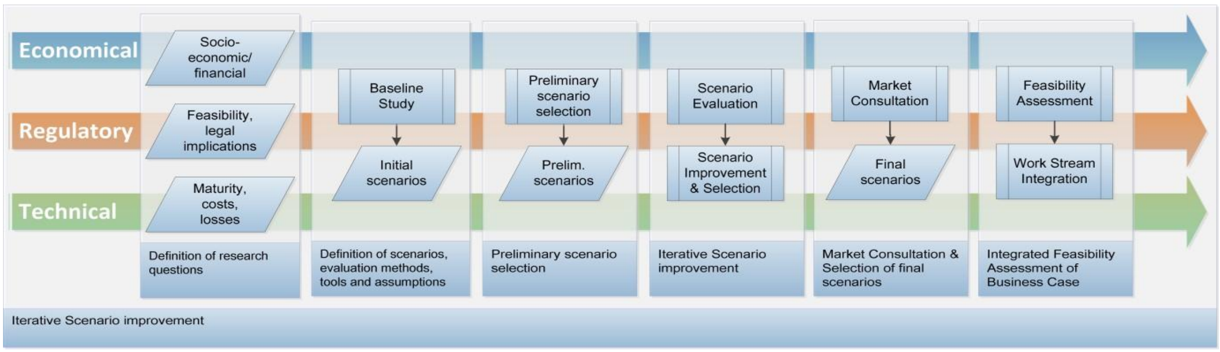

Figure 2-1 Simplified process diagram of the chosen research method.

The research questions presented in the next subsection have been elaborated in different work streams: Economical, Regulatory and Technical. In order to obtain a final feasibility assessment, the results of these work streams have been integrated. The work streams share a common set of scenarios and evaluation criteria. The scenario definition, evaluation and selection followed an iterative approach, because of the many different design choices that can be made, e.g. on the topology and power ratings in the offshore grid. After a first evaluation round better founded design choices could be made and the number of scenarios for the final feasibility assessment was reduced. In the course of the project other scenarios have been added in order to study the sensitivity of specific parameters.

As a part of the process a market consultation has been conducted in order to test the approach, e.g. the assumptions regarding the available technologies, the relevance of the selected scenarios and a first check of the preliminary feasibility assessment.

2.1. Research questions

2.1.1. General

In order to assess the feasibility of interconnecting offshore wind farms in the UK and the Netherlands first a number of possible solutions should be identified, which are then evaluated and iteratively improved. The central questions in this process are:

Which feasible solutions exist for an IC/OWF combination between UK and NL?

What is the potential effect on the cost price of offshore wind energy?

2.1.2. Decision making process for investment in IC/OWF combination

An important aspect of the feasibility of a particular concept is to take into account what are the different perspectives of the decision making actors for the realization of that concept.

Therefore in this study the following question needs to be asked:

Under what circumstances will these actors decide to invest in an interconnection/wind farm combination?

In general, TSOs are responsible for investments in and operation of transmission assets. Until today TSOs have been the only investors in interconnectors in Europe. However, private investors are allowed to invest in exempted[20] interconnectors, e.g. BritNed is an exempted cable, invested in by a (semi) private company, BritNed Development Limited (a joint venture owned by TenneT and National Grid). However, an interconnector/wind farm combination is a more complex situation in which at least part of the asset is owned by private investors (both under the OFTO and in the current Dutch legislation, the transmission asset is owned by private parties). Therefore there might be other ways in which, and reasons why, the interconnecting link[21] can be owned by a private party.

Therefore, an interconnector, or an Interconnecting Link, might be operated and owned and invested in by two types of actors, which are (1) the TSO and (2) a private investor. For both groups of actors the feasibility in terms of a *positive investment decision* will be determined:

> *Is the IC/WF combination technically, economically, and regulatory feasible from the perspective of both actors?*

To answer this research question the feasibility study will investigate the decision making processes for different resulting business cases from the viewpoints of both actors.

Public investor (TSO)

In case of an investment with public money the decision will be driven by societal benefits. Therefore the decision making processes of these actors will be described for both the UK and NL and the feasibility in terms of *will the investment be made*? is determined. For an investment with public money in a certain connection it is assumed that this connection will be regulated. Most likely, these decisions will be based on the following criteria:

> *Are there sufficient societal benefits to justify an investment?*
>
> *Is the setting of tariffs for the regulated line for both trade as well as wind energy transmission sufficient[22] to cover the investments?*

Private investor

In case of a private investment in an international connection (sometimes called a *merchant line*) the decision is driven by the business case of the investment.

> *Is it sufficiently viable from a financial point of view?*
>
> *Taking into account the business model and required return in relation to the risks involved*

For a wind farm owner:

> *What are the additional benefits of the combined solution (like reduced risk due to a redundant grid connection)?*

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[20] A *regulated* cable is built and exploited exclusively by TSOs. From the Dutch side only TenneT can invest in this cable based on a regulated tariff scheme, like for example is the case for the NorNed interconnector. An *exempted cable*, like the BritNed interconnector, allows investments from other parties than TSOs.

[21] Interconnecting link is the term which is used here to explicitly stress the issue that we are dealing with infrastructure for connecting different countries, via OWF, which does not yet has sufficient legal basis.

[22] Note that for a regulated line, benefits to society are the principle criterion to base a go/no-go decision on. The investment costs are covered by tariff (increases) primarily born by all customers obtaining electricity from the transmission grid, not limited to only those directly involved in trade over the interconnector.

Business cases

For the legal status of the connection different options are considered:

1. Interconnecting link between two wind farms as a part of the asset (so-called, exempted line, owned by one or more commercial companies);
2. A regulated cable as part of the TSO grid;
3. A hybrid form in which the TSO (partly) takes over the line after a certain time. In each of these cases the main questions are:

Is it legally possible?

What are the possible business models?

Is it economically viable?

The following enabling factors need to be fulfilled:

- Regulatory enablement
- Technical enablement

Final goal

The final goal of this study is to determine the potential cost price reduction for offshore wind energy when applying this concept of integrating interconnectors with wind farm connections. Most likely benefit allocation will be dependent on who is the investor, owner and operator of (a part of) the assets involved. For the private investor's perspective a solid minimum profit margin for the Interconnecting Link has been determined and the with this the additional profit for the wind farms has been determined.

The research (sub-)questions are applied for the various project scenarios which are compared with the base case scenario (a separate interconnection and separate wind farm grid connections). The research questions for the different work streams are discussed in the following paragraphs.

2.1.3. Technical work stream

The technical realization of an interconnecting link is a highly complex project, which requires a thorough understanding of the available transmission technologies and their main technical bottlenecks. Its complexity is further corroborated by the fact that such a link does not yet exist worldwide and therefore no experience exists yet. The main technical research questions that arise are the following:

Which grid layout is most suitable and which is the most suitable capacity and power transmission technology for each part?

Which are the critical design parameters that determine the feasibility of the project? Which are the trade-offs that need to be optimized for the final grid design?

Which innovations are essential to realize a cost-effective and reliable grid design and which innovations can provide significant technical or economic benefits?

What are the estimated costs and performance of the different technical solutions?

It becomes apparent that the technical feasibility study has two main objectives: firstly, to determine the possible grid topologies and applicable technologies and secondly, to estimate the involved costs and assess the performance. The third research question, related to design optimization, will be addressed in next phase of the project, whereas the fourth question provides guidance in the relevance of further research.

In chapter 3, the main technical issues related to the transmission technologies and their applications are briefly presented and an overview is provided of the technical challenges that require further research. In-depth information on each of the presented topics is provided in Appendix B.

2.1.4. Economy /business case work stream

The research questions for the Economic Feasibility Analysis are as follows.

First: the allocation of costs and benefits for the main stakeholders. One of these is the wind farm developer. Another major stakeholder is the owner of the transmission infrastructure. With the perspective of society also the consequences for consumers and for other producers than the wind farm owners have been taken into account.

Is an interconnection in combination with wind farm export financially viable for an investor?

What are the costs and benefits for each of these major stakeholders of the different alternatives in integrating offshore wind with interconnection?

Secondly: a European perspective:

What are the societal benefits from European perspective of the proposed offshore grid with connected wind farms between NL and UK?

How does this solution increase the cross-border trade and the integration of offshore wind energy in the market?

Are the developed offshore grid concept and the innovations applicable for other countries around the North Sea?

2.1.5. Regulatory work stream

The research questions for the regulatory work stream are as follows:

What is the existing legal framework concerning offshore wind energy development and interconnection?

How does this framework facilitate or obstruct the realization of cross-border integrated offshore electrical infrastructure?

These main research questions can be divided in to a number of sub-questions:

What is the current legal framework at the level of the European Union legislation?
What is the current legal framework in the Netherlands?

What is the current legal framework in the UK?

What are the legal obstacles at EU and national level, for a TSO or a private investor (like the wind farm owner), preventing the realization of cross-border integrated offshore electrical infrastructure?

What are possible solutions at EU/national level to remove these legal obstacles?

2.2. **Definition of scenarios**

In Appendix A all scenarios used in the study can be found. In the project four basic grid topologies for interconnection have been considered for connecting offshore wind farms in the UK and the Netherlands, named **UK-NL** (connect UK wind farms with NL wind farms), UK (connect UK wind farms with the Netherlands) , **NL** (connect NL wind farms with the UK) and **IC** (an additional interconnector between the UK and the Netherlands). The baseline for the calculation of costs and benefits as well as for the technical and regulatory evaluation in the project is the situation in which no new wind farms are connected and the interconnection capacity between the Netherlands and the UK is limited to the existing BritNed interconnection (*BritNed1*). The **IC** scenario is the business as usual case in which additional offshore wind farms are only connected to one country, and additional interconnection capacity results from an additional 1200 MW interconnector between the UK and The Netherlands (*BritNed2*). It is used to compare the different Interconnecting Link (**UK-NL**, **UK** and **NL**) scenarios with a conventional interconnector.

In topology **UK-NL**, an Interconnecting Link (IL) between the two offshore Wind Power Plants (WPPs) is constructed. The term "Interconnecting link" **(IL)** is introduced here to explicitly stress the issue that we are dealing with infrastructure for connecting different countries via OWFs, which does not yet has sufficient legal basis, as explained in section 4.2.1. It enables cross-border trade via both WPP export links. It requires relatively little investment for additional cables. In topology **UK**, an IL is built between the UK WPP and the Dutch grid. The Dutch WPP remains connected to the Dutch onshore grid with a separate export cable. The third option, **NL**, is an IL from the UK grid directly to the Dutch WPP. This topology is a mirror of topology **UK** but with different values for the WPP capacity and the distance to shore. The grid topologies are shown schematically in Figure 2-2. The black parts represent the infrastructure that is assumed to be: the existing BritNed1 interconnector, and the export lines of the planned WPPs. The dark red line represents the new transmission line that enables cross-border trade: either an IL, or a conventional interconnector.

These topologies form the basis for both the market scenarios and technical scenarios. For the market scenarios the rated capacities of the WPPs and the different line segments need to be defined. The technical scenarios also require definition of specific technologies for transmission as well as a basic design, i.e. component types and ratings locations and how these are connected and operated. An overview of the scenarios is presented in Appendix A.

2.3. **Evaluation of scenarios**

The chosen scenarios and their evaluation are presented per work stream in the following sections where the modelling assumptions are also explained.

The capital costs and transmission losses resulting from the technical scenario evaluations are inputs for the economic analysis. For comparison reasons care has been taken to apply the same cost basis for the different economic assessments. To evaluate and compare the private investor's perspective and the socio-economic perspective, assumptions have been aligned. The different work streams have been combined to an integrated feasibility statement. The outcome of the feasibility study also serves as starting point for further research within the Synergies at Sea project on technology and regulatory issues.

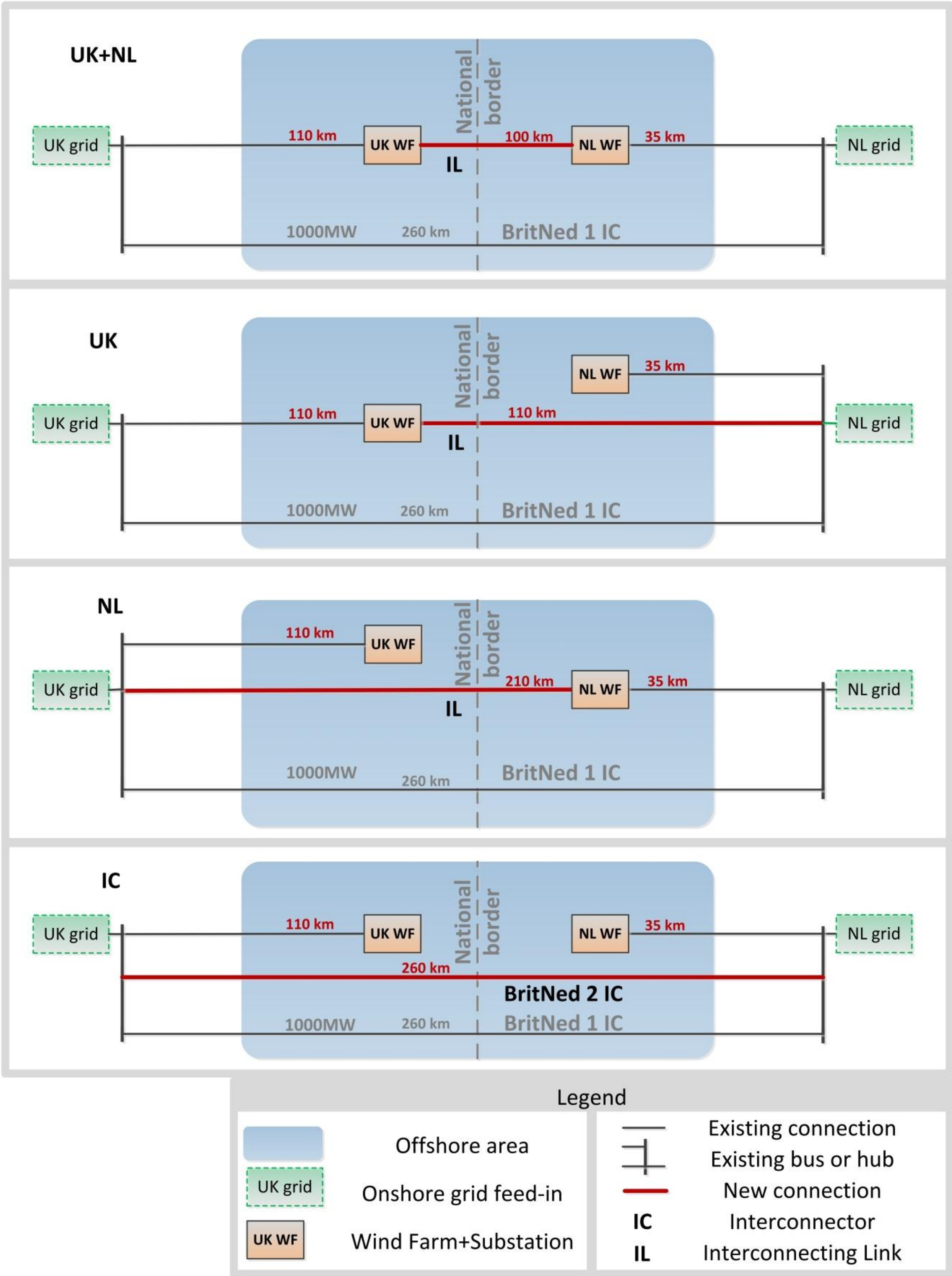

Figure 2-2: Basic grid topologies used in this study.

3. Technology selection and analysis

For each market scenario one or more technical implementations have been selected and evaluated with respect to costs, losses and availability. In the following paragraph the possible technologies are characterized and evaluated, resulting in a selection of scenarios.

3.1. Technology selection approach

As a starting point, a long-list of proposed technical solutions has been made for each of the market scenarios. The first selection of technologies to be applied in the scenario evaluation was based on an extensive technology review, see B.1. Therefore this review has assessed the maturity of each technology, the suitability for this particular case and to compare in costs and risk levels. Second outcome was that a number of innovations have been identified, which are either required or promising for certain technical solutions.

The technology maturity and outlook of technological innovations have been listed in three categories, namely: *currently available on the market*, *available in 2020* and *available after 2020*. This means that the first two categories provide technologies that are considered in the feasibility study. The middle category will get most attention from industry, while the longer term will be the focus of the technical R&D track within the project.

The summary of the technical review in the following paragraph covers both High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC) technologies, with Multi Terminal Direct Current (MTDC) as a special case of HVDC. The background is that the NL and UK grid are not synchronized, so a conversion to DC is required somewhere in the connection for decoupling the two grids. This means application of an AC/DC/AC conversion using two separate substations. This is because a back-to-back AC/DC/AC converter would need an HVAC connection for the total length, which is considered not feasible.

For all offshore AC/DC converters, Voltage Source Converter (VSC) technology is chosen, whereas classical Line-Commutated Current Source Converters (LCC-CSCs) are not feasible offshore, because of their huge footprint, their limited control capability and their requirement for a strong AC-grid. In the future, Forced-Commutated Current Source Converters (FC-CSCs) might be an alternative.

Based on the discussed characteristics a first selection of technical solutions has been made, which still leaves a considerable number of possible solutions. Therefore a detailed assessment has been conducted to quantify costs, performance and technical reliability as the basis for further selection.

3.2. Maturity level of available technologies and technical challenges

In this section the maturity level of the technologies associated with the HVAC and HVDC trans- mission systems is presented and the main technical challenges that require further research are described.

In general, minimizing the HVAC cabling length offshore in favor of HVDC cabling seems profitable as cable costs are lower as well as the losses. However, connecting the offshore wind farms to HVDC requires offshore converter substations, which are far more expensive than HVAC offshore substations of comparable rating. Moreover, connecting both offshore wind farms via HVDC requires a multi-terminal HVDC grid. Control and protection of such a grid solution is yet to be demonstrated. Another aspect is that the applicable power ratings differ with the chosen technology and connection distance.

In the technical review these pros and cons per technology option have been inventoried and weighed in a systematic way, starting with currently available technologies, near future developments and post-2020 development needs.

3.2.1. Transmission system technologies - currently available

The transmission system technologies which are currently available on the market are presented in Table 3-1.

Table 3-1 Status of critical high voltage transmission technologies currently available on the market and developments expected before 2020

Technology	Current status	Developments expected before 2020
HVAC submarine cables	Max. distance without mid-point compensation: 110 km (140 km possible) for 220 kV, 300 MW to 350 MW)	Increase max. (dynamic) rating beyond 400 MVA for 200 kV; Increased voltage rating: 420 kV; reduced (armoring) losses
HVAC mid-point reactive power compensation	Readily available for existing platform designs. Design for 700 MW, 220 kV platform with optional mid-point compensation presented by TenneT TSO	Gain practical experience with long HVAC cables, midpoint compensation, voltage control
VSC converters	MMC max. ratings: ±640 kV, 2430 MW (bipolar) ±320 kV, 900 MW (offshore)	Increased power ratings, improved fault blocking and fast recovery schemes
VSC offshore platforms	HVDC offshore platforms rated around 900 MW, ±300 kV	Offshore platform design for 1200 MW VSC and beyond
HVDC Cables	XLPE cables: 660 MW, 320 kV Mass impregnated (MI) cables: 1000 MW, 500 kV	Apply recently presented 525 kV XLPE cables in VSC system
LCC-CSC, LCC-based (multi-terminal) HVDC networks	Maximum rating for 12-pulse stations: 7200 MW@ ±800 kV. Offshore interconnectors up to± 500 kV, 2500 MW, incl. multi-terminal systems.	N/A as LCC technology is unsuitable for offshore installation due to its large footprint and poor controllability, see post-2020 developments on hybrid systems

HVAC cable technology

HVAC transmission technology has been used in most offshore wind energy projects up to date. This is because it is an already established technology and it is easier to achieve higher voltages by means of a transformer. Additionally, generating electricity via three-phase synchronous generators is easier, cheaper and more efficient than using HVDC converters for the power conversion.

However, it is not possible to use HVAC transmission technology in a transmission system when an asynchronous connection is required, as is the case between the UK and the Dutch grids. Moreover, HVAC transmission systems present high losses when long underground or submarine cables are involved. The active power transmission capability of AC (submarine) cables decreases sharply with distance because of the large reactive power production, resulting in high needs for reactive power compensation. Most of the HVAC-based projects have a transmission voltage of 133 kV or 150 kV. The wind farms Anholt (Denmark) and

NorthWind (Belgium) are the first to make use of HVAC cables with a rated voltage of 220 kV. To present the level of maturity of the cables technology on this aspect, the maximum transferrable power is presented in Figure 3-1 as a function of transmission distance for different AC and DC submarine cables.

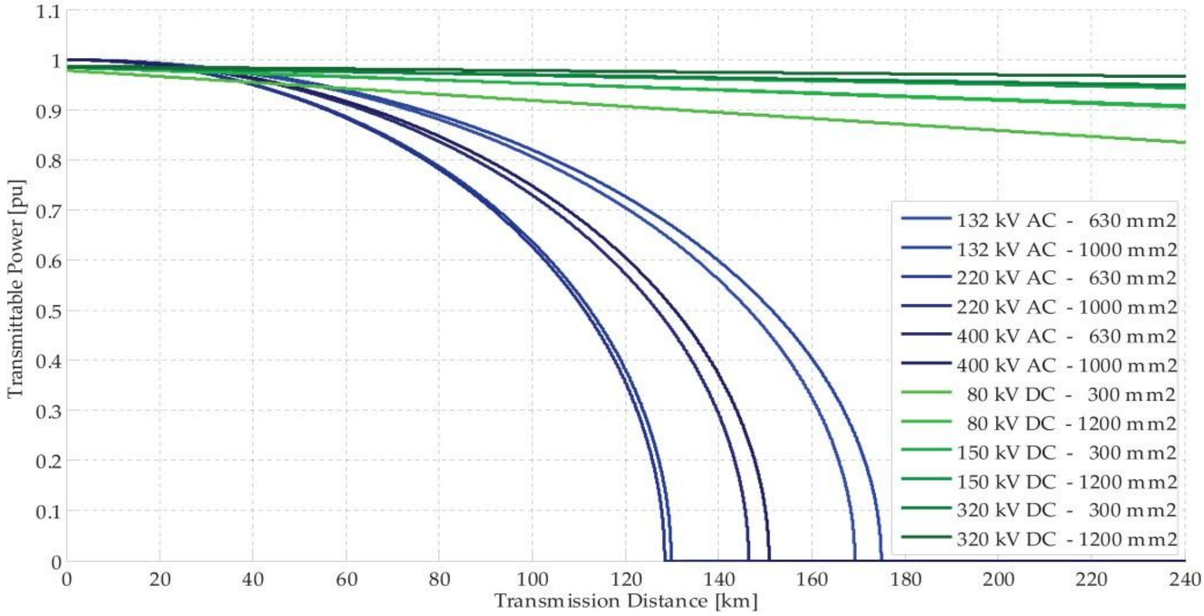

Figure 3-1: Maximum transferrable power as a function of transmission distance for AC and DC submarine cables.

As a result, there is the need for reactive power compensation at both line ends or even at the mid-point, which increases the capital costs, especially in offshore applications. So far, Transmission System Operators (TSOs) have considered HVAC technology for connections of 300 MW at 220 kV up to a distance of 110 km without mid-point reactive power compensation. Moreover, to assist the connection of higher power transmission over the same distance more cables can be connected in parallel, as was the case for the Gemini wind farm, for which 2 export cables were used to transfer 600 MW over 110 km. Although higher power levels can be transferred with only one export cable, e.g. the Anholt offshore wind farm has a capacity of 399,5 MW, the transmission distance remains a limitation.

A distance of 140 km is claimed to be possible by increasing the insulation thickness. However, in this case there is a trade-off between the cable capacitance, which decreases due to increased insulation thickness, and the cable rating, which also decreases because of worse heat transfer from conductor to sheath. Moreover, it has to be noted that as the voltage rating of the cables increases their power transfer capability increases as well, whereas the distance the power can be transferred without mid-point compensation decreases due to the increased reactive power production, leading to increased losses as well as higher switching currents.

In Figure 3-2, a schematic overview of the cost comparison between AC and DC systems is given based on the transmission distance. The break-even-distance is much smaller for submarine cables (typically about 100 km) than for an overhead line transmission (approximately 700 km), while at the same time it depends on several factors, such as power rating, reactive power demand of AC cables, loss evaluation among others. As a result, an analysis must be made for each individual case.

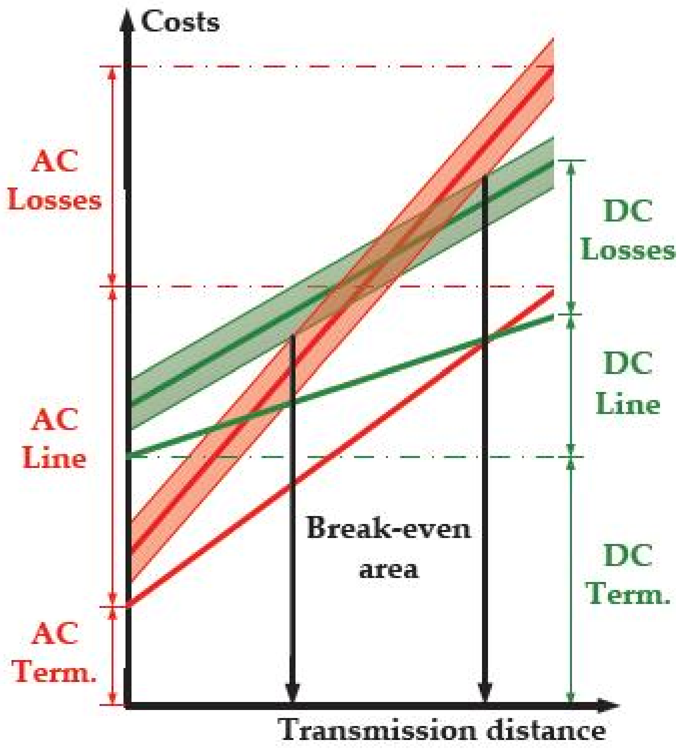

Figure 3-2: Cost comparison between HVAC and HVDC transmission systems.

HVDC

In comparison to HVAC, HVDC systems have lower losses at higher power levels and transmission lengths and the transmission distance is not limited by voltage stability issues. However, their maturity for offshore applications is still low and thus, more field experience needs to be built up and also research is required on improving HVDC technologies.

Up to now, there are only eight offshore HVDC projects in place, under construction or com- missioned, as shown in Table 3-2. This fact shows that manufacturers experience with offshore systems is limited and the available technology is yet to be improved. Moreover, it has to be noted that Germany is the only country which is building offshore wind projects connected to shore through HVDC technology. In all the projects mentioned there are no offshore hubs, i.e. each offshore converter station is directly connected to shore via an independent HVDC cable. Another noteworthy fact is that out of 8 projects, four different voltage levels (150, 250, 300 and 320 kV) are used. This shows the high need for standardization on the way towards multi-terminal HVDC networks.

To enable the connection between the traditional AC grids and DC transmission projects an interface is needed. There are two main HVDC converter technologies that play this role: the Current Source Converters (CSCs) and the Voltage Source Converters (VSCs).

Voltage Source Converter (VSC)

VSC stations involve the use of fully-controllable switches, usually Insulated-Gate Bipolar Transistors (IGBTs), at high switching frequencies, giving the advantage of independent active and reactive power control. VSC-HVDC transmission systems can reach up to ±640 kV and 2430 MW in bipolar applications. Although these ratings are lower than for HVDC Classic, the converter stations are highly modular and can be connected in many different configurations. However, it has to be noted that for offshore applications, the converter platforms pose the most stringent constraints. More specifically, so far only 900 MW offshore platforms are available, whereas 1200 MW platforms whilst technically feasible are yet expected to become commercially available.

Table 3-2: HVDC offshore converter stations

Project	**Client**	**Yard**	**Capacity [MW]**	**Mean distance to shore [km]**	**Status**
BorWin alpha	ABB	Heerema	400	95.5	In operation
beta	Siemens	Nordic yards	800	126.5	installed
DolWin alpha	ABB	Heerema	800	52	Installed
Beta	ABB	Drydocks	924	45	Installed
gamma	Alstom	Nordic yards	900	83	tender closed
HelWin alpha	Siemens	Nordic yards	576	57	Installed
Beta	Siemens	Nordic yards	690	85	Under construction
SylWin alpha	Siemens	Nordic yards	864	69	Installed

Contrary to Line-Commutated Current Source Converter (LCC-CSC), the high controllability of VSCs makes the realization of large Multi Terminal Direct Current (MTDC) networks feasible. More specifically, in the investigated network, VSC technology is possible for all the involved stations as there is no limitation in their use. However, the main disadvantage of VSC stations is their vulnerability to DC faults. Namely, due to the use of IGBTs in the converter valves, the converters are not able to block developing fault currents from the AC grids to the DC network. Up to now, protection in point-to-point connections has been achieved through AC breakers.

However, as the DC fault dynamics are very fast (2 ms to 5 ms) and the modern Gas-Insulated Switchgear (GIS) AC breakers interruption time is approximately 100 ms, the whole system needs to shut down in case of a DC fault in one line, before operation can be resumed. Protection plays an important role especially in multi-terminal systems. As a result, special attention is paid to this subject in this report when multi-terminal networks are discussed.

Regarding VSC technology, the two-level configuration is the most straightforward and has been widely used in the past. However, since 2003 when the Modular Multi-level Converter (MMC) concept was introduced, all the main manufacturers have adjusted their production lines accordingly. The multi-level concept is easily adjustable facilitating transmission of high power at high voltage levels, while at the same time synthesizing a high quality sinusoidal voltage waveform by incrementally switching a high number of voltage levels, thus lowering the filtering requirements. Table 3-3 indicates that the trend in future VSC-HVDC installations is to employ the MMC for power transmission and grid connection of OWFs.

Based on the main HVDC manufacturers, there is no real limitation on the size of the MMC converters, as their levels can increase accordingly to facilitate higher power transmission at higher DC voltage levels. Currently the maximum number of levels installed on a multilevel modular converter platform is 380.

Table 3-3: Overview of selected VSC-HVDC projects

Installation	Year	Manufacturer	Power [MW]	Converter Topology
Gotland	1999	ABB	50	2-level
Murray link	2002	ABB	220	3-level
Estlink	2006	ABB	350	2-level
BorWin 1(OWF)	2009	ABB	400	2-level
Trans Bay Cable	2010	Siemens	400	MMC
BorWin 2 (OWF)	2013	Siemens	800	MMC
HelWin 1 (OWF)	2013	Siemens	576	MMC
DolWin 1 (OWF)	2013	ABB	800	MMC
SylWin 1 (OWF)	2013	Siemens	864	MMC
South-West link	2014	Alstom	1440	MMC
HelWin 2 (OWF)	2014	Siemens	800	MMC
DolWin 2 (OWF)	2015	ABB	900	MMC

However, the main limitation comes from other parameters. An important restriction stems from the power level limit the TSOs set for disconnecting at once in case there is a fault in the system. More specifically, National Grid determines 1320 MW as the normal limit, whereas 1800 MW can be considered as the limit for infrequent disconnections. Moreover, especially in offshore applications the volume of the converter platform is a critical parameter for the project cost. The size of platforms is mainly determined by the insulation levels and the clearance distances, whereas the bigger the platform the less is the number of available crane ships that can handle offshore platform installations. Finally, it has to be mentioned that the power level of the converters is also imposed by the maximum current capability of the cables involved, e.g. XLPE have a maximum current rating of 1500 A at 320 kV. In the future, HVDC cables with a rating of 2 kA at 600 kV are expected.

In the Appendix the different MMC concepts are presented for the three biggest HVDC manufacturers (ABB, Alstom, Siemens). Regarding the converters power transfer capability, manufacturers argue that higher voltages and current ratings can be achieved with the existing semiconductor devices, simply by arranging them properly in series and in parallel, due to the modularity of the converter schemes. Moreover, it resulted from the market consultations that an increase in the current ratings of the converters from 1500 A to 2000 A is to be expected in 2016. This development in combination with the fact that ±500 kV links are currently possible will lead to an increase in the power that can be delivered by HVDC networks. In cases where two different onshore grids are connected via an HVDC interconnector, or in case of a combined OWF/IC infrastructure, the power trade margin will increase, resulting in higher socio-economic benefits. Furthermore, considering bulk power transfer, a hybrid connection of Line-Commutated Converter (LCC)-based onshore terminals and VSC-based OWF stations is a highly challenging R&D option for future HVDC grid plans, as it can facilitate the high power trade between countries, while at the same time it can connect OWFs to the shore via the same infrastructure. In this way, such a connection reduces the number of converter stations, the length of the employed cables and subsequently the overall installation costs.

Regarding the HVDC converter technology, it has to be noted that as there is not a lot of experience in the operation of MMC converters there is the need for more R&D regarding their reliability. More specifically, the response of MMC converters to DC faults needs to be investigated in depth. The very fast transients that develop during a contingency are likely to disturb the operation of the converters even after a DC fault is cleared. Therefore, several aspects need to be investigated, such as the maximum allowed number of switches or modules that can be off operation without affecting the converter performance. Moreover, different control techniques of the converters and the MTDC network need to be compared in order to alleviate the fault impact and allow a fast post-fault recovery of the system. Finally, as the losses of MMC converters (especially full-bridge-based MMC) are higher than the LCC equivalents, mainly due to their switching behavior, research should focus on the improvement of their power quality, the optimal switching frequency and different converter schemes, which employ less semiconductor devices. In this way costs could be brought down and reliability could increase.

HVDC cables

The main limitations in power ratings of transmission system projects are placed by the involved cables, as well as by the weight and size of the offshore substations. More specifically, Mass Impregnated (MI) cables can currently transfer up to 660 MW per pole at 500 kV. In the near future, a rating of 1500 MW per cable at 600 kV to 650 kV is achievable, based on the ENTSO-E *Offshore Transmission Technology report*. On the other hand, XLPE extruded cables are currently limited to a current rating of 1500 A at 320 kV and can only be used in VSC-based connections due to their inherent susceptibility to field polarity reversal. Based on the market consultations, new cables are expected within the next 5 years which could accommodate 2 kA at 600 kV.

From the aforementioned figures, it can be concluded that there is high need for R&D in the cable market and that the improvements in the cable section can significantly influence the future of HVDC connections. Currently there are five main manufacturers in Europe that can produce and deliver submarine cable systems of the required ratings for HVDC projects, namely ABB, General Cable, Nexans, NKT Cables and Prysmian. Therefore, it has to be taken into account that due to the limited number of manufacturers, an increase in cable demand in the near future is possible to lead to a significant increase in the system delivery time. This is an important parameter in the design of grids, which needs to be accounted for.

VSC Offshore Platforms

Another important aspect for offshore applications is the offshore platforms required for the converters and the associated equipment. As converter power ratings increase so does the platform size and weight. Currently offshore platforms for HVDC systems weigh up to 4000 tonnes and this figure is expected to rise. However, there is already a lot of experience in offshore platform construction from the oil and gas industry. The market consultations showed a preference for more but smaller platforms instead of a sole big platform, in order to increase the flexibility of the system, as well as to bring down the installation costs due to the limited number of crane vessels that can facilitate the installation of big platforms. Currently, VSC offshore platforms have a maximum power rating of 900 MW at ±320 kV.

Current Source Converter (CSC): Line-Commutated

A CSC station can be either Line-Commutated (LCC-CSC) or Forced-Commutated (FC-CSC). LCC-CSC, often referred to as HVDC Classic, is a mature technology that is used in most of the HVDC systems in operation nowadays. Most HVDC Classic transmission systems have distances between 180 to 1000km, with voltages between 500 to 1000 kV and power ratings between 500 to 2500 MW.

The HVDC Classic technology is undisputed when it comes to bulk electric power transmission and ratings up to 7.2 GW are possible using 1600 kV transmission systems, known as ultra-high voltage (UHVDC), such as the transmission link between Jinping and Sunan, which is being constructed in China and when finished will be the largest DC transmission system worldwide.

However, out of more than 140 HVDC projects worldwide, only two are known for having more than two terminals: the Hydro-Québec New England scheme, in Canada; and the SACOI scheme, between Italy and France. As power-flow reversal in LCC-CSC-based connections is achieved through DC voltage polarity changes, the realization of MTDC networks using only LCC-CSC is difficult because it involves high-level coordination between the converters.

Furthermore, LCC-CSC stations have low inherent controllability due to the use of thyristor technology. As was the case with mercury-arc valves, it is only possible to control the moment when thyristor valves turn on, but not when they turn off. The thyristor conduction has to be stopped externally by the AC network, which is why this type of HVDC converter is also known as line-commutated converter.

The fact that HVDC Classic is line-commutated means it can control its active power flow but it always consumes reactive power. Moreover, depending on the thyristors firing angle, the reactive power compensation can be circa 50 % to 60 % of the converter rated power. Hence, HVDC Classic transmission systems require strong AC networks and capacitor banks capable of providing the necessary reactive power, for proper converter operation, and thus, LCC-HVDC would be difficult to use for connection of offshore wind farms to the grid, as wind farms represent weak grids. As a result, in the investigated network, HVDC Classic would only be possible at the onshore stations of the two involved grids.

Conclusions

- For all of the modelled scenarios that include point-to-point HVDC combined with HVAC, the required technologies are available on the market, although the rated power level for offshore HVDC applied thus far is 900 MW.
- For applying point-to-point HVDC links up to 1200 MW new offshore platform designs are needed, which are expected to be available on the market before 2020, provided there is sufficient market demand. The same holds for power ratings beyond 1200 MW, but this also requires higher HVDC cable voltage ratings.
- Extending this power level combined with higher voltages is expected to have a significant impact on the CoE. Secondly, cost reductions are expected before 2020 by increased competition, standardized voltage levels, reduced converter losses and increased reliability.
- For extending the connection distance of HVAC mid-point compensation is already foreseen as an option in HVAC offshore platform designs and will be available on the market before 2018. Control and protection of long HVAC (meshed) offshore grids needs attention, however no fundamental problems are expected.
- Although the largest market for interconnectors is based on LCC technology, its application is not suitable for offshore applications. Combining onshore LCC (or other CSC technology) with offshore VSC technology is not considered before 2020.

3.2.2. Transmission Technologies - available on the market in 2020

In this section, the most important transmission technology developments expected in the market until 2020 are presented. Table 3-4 gives an overview of the main technologies, their current status and the necessary developments.

Table 3-4: Status of critical HVDC transmission technologies available on the market in 2020

Technology	Current status	Developments needed
MTDC VSC-based networks	Demonstration projects: Nanao (3-terminal) Zhoushan (5-terminal)	Power flow control, protection and fast recovery schemes (in relatively small systems using AC-breakers)
DC fault protection: DC-circuit breaker	Demonstration at industrial scale: ABB Hybrid (interruption time: 2 ms to 5 ms, tested at 3.1 kA, 320 kV) Alstom breaker (interruption time <5.5 ms, tested at 5,2 kA, 160 kV)	Market introduction and full-scale application
DC fault protection: handled by converter		Market introduction and full-scale application

Multi-terminal DC network (MTDC)

It is a fact that out of more than 140 HVDC projects in the world until 2013 only two of these were multi-terminal, i.e. involving the interconnection of more than two terminals, which are LCC-based (SACOI, Quebec-New England). This happens as the operation of a classic LCC-HVDC station in an MTDC network is difficult, because power-flow reversal involves polarity changes through mechanical switches and high level of coordination between the converters.

On the other hand, the high controllability of the VSC technology facilitates large MTDC net- works. In the past year, China announced two multi-terminal VSC-based projects. The world's first three-terminal VSC-based system was put in operation on December 19th 2013, which brings the wind power generated on the Nanao island to the AC grid of the mainland in Guangdong through a 32 km combination of HVDC land cables, overhead lines and subsea cables. The voltage level used is ±160 kV and the power levels of the three stations are 200, 100, 50 MW. SEPRI (Electric Power Research Institute, China Southern Power Grid) is technically responsible for the project, while multiple Chinese domestic suppliers were involved: three different VSC HVDC valve suppliers (Rongxin power electronic Ltd, XD Group, Nanrui relay Co. Ltd), two different HVDC land/sea cable suppliers and three different control & protection system/equipment suppliers (Institute of Electrical Engineering XD Group, Rongxin power electronic Ltd, Sifang relay protection Co. Ltd). DNV-GL was also involved in the commissioning of the project. This pilot project was followed by the commissioning of the world's first five-terminal system at ±200 kV connecting the Zhejiang Zhoushan Islands and covering a total distance of 134 km. The power levels of the stations are 400, 300, 100, 100, 100 MW. C-EPRI was the main supplier of the HVDC technology in this project.

However, there are still several aspects that need to be considered to realize large-scale MTDC networks. These include protection of those systems and power flow control and station coordination.

Control

The control of a VSC-based MTDC network is not as straightforward as in HVAC systems. The stations need to coordinate with each other through communication systems (e.g. fiber optics, satellite communication) and be controlled according to the necessary power flow. This can be done either via Distributed Voltage Control techniques (all onshore stations control the DC voltage level at their DC output) or via Single Converter Voltage Control (one station controls the DC voltage level of the systems and all other stations control directly the active power they inject to the MTDC network). Both these methods have been extensively studied for different operational conditions. However, as the only VSC-based MTDC systems currently in place are two new Chinese pilot projects, not sufficient information is published on the way these systems are controlled and the reliability and robustness of the aforementioned control methods in real applications. The main challenge in the control of such systems is the stabilization of the system against changes and disturbances in the network. In this perspective, communication delays and possible loss of information should be accounted for when managing the network. Therefore, the system control should not depend only on the communication of each station with a centralized remote controller. On the contrary, a more distributed control strategy based on local level controllers should be adopted, as well as a control approach that spans at different hierarchical levels.

DC Fault Protection

A VSC-based MTDC system is vulnerable to DC faults, as DC breakers and appropriate systems for the fast fault detection are not yet widely available to handle DC contingencies. ABB and Alstom have announced new HVDC breaker technologies that are tested for the voltage and power levels of their HVDC stations which are commercial products. Although, a prototype of the new hybrid HVDC breaker of ABB was presented in Hannover Messe 2014, this technology has not yet been tested at full-power level. The operation limit of the breaker is 1000 MW at 320 kV and can achieve breaking times of 2 ms to 5 ms. This limit is mainly set by the specially designed mechanical disconnector. On the other hand, Siemens is considering two different protection schemes, without the need for additional DC breakers. The selection of the protection scheme depends on the type of MMC converters used in each case and on the size and complexity of the complete dc-circuit. The two protection schemes can be summarized as follows:

Non-selective

Half-bridge MMC converters have no DC fault current blockage capability. Therefore, in case a DC fault occurs in the system, the whole HVDC grid needs to be de-energized by opening the breakers on the AC side. As soon as the DC fault is resolved the breakers are closed and the system can be re-energized within a time frame of minutes.

Selective

In case full-bridge MMC technology is employed, the fault current can be driven to zero by blocking the IGBT valves of the converter and in combination with fast mechanical disconnectors the faulty line can be selectively isolated within 100 ms. Although this is usually fast enough for the connection to the European grid, it should be checked whether this also holds for the UK grid connection.

It has to be noted that the time frame within which the DC fault needs to be isolated depends highly on the value of each line in the system and also the maximum allowable power level that can be disconnected at once in the grid. Currently this value is 1800 MW for the UK grid (National Grid) and 3000 MW for the ENTSO-E Continental Europe area (including the Netherlands). As a result, the protection need has to be estimated for each system individually and it is not necessary that every line in a multi-terminal system needs to be protected by a DC breaker. It is generally believed that there is no need for protection in systems with less than four interconnected terminals. Moreover, there is also the concept of creating protection zones within a highly meshed grid with the use of breakers to avoid a fault in one zone affecting the rest of the system, so that operation can continue through the remaining interconnected stations. It is expected that, for the same ratings, the footprint of a half-bridge MMC converter with a DC breaker will be the same as for a full-bridge MMC converter with a fast DC disconnector.

To sum up, as most of these concepts remain in research level, it cannot be predicted when components, such as HVDC breakers, will be commercially available, for the required power and voltage levels, at reasonable costs and therefore, research is needed on new protection concepts. Finally, it is very important to study the effect of losing a line/connection for a certain period of time on the operation of the rest of the system and the way the line can be re-energized, after a DC fault is resolved, without creating dangerous transients on the healthy lines.

Conclusions

- Small multi-terminal HVDC networks with limited power ratings could be realized before 2020 using fast AC-circuit breakers only and simple control schemes.
- Improved DC-fault blocking and recovery, either inside the converters or by separate DC- breakers offer improved reliability and less stability issues in the connected grids. Applying these will enable (extension to) larger power levels and more complex MTDC grids.

3.2.3. Transmission Technologies - after 2020

In this section, the transmission technology concepts are discussed, which have high research potential and are expected to play a role in the transmission systems in the future.

Table 3-5: Status of critical high voltage transmission technologies, developments after 2020

Technology	Current status	Developments needed
Hybrid Line-Commutated Voltage Source Converter (LCC-VSC) connection	Both converter technologies exist, but no combination has been proposed so far	New control and protection schemes. Market demand and business models, e.g. retrofitting of existing interconnectors.
FC-CSC converters	Medium Voltage Applications (up to 4,2 kV) (AC Motor Drives)	R&D on converter concepts and control and application in (hybrid) HVDC systems
Large-scale meshed offshore grid	Concepts, tested in down-scaled in laboratory	Market development as well as establishment of a common regional/ European regulatory framework for development and exploitation
DC hubs	No market demand at the moment. The concept has been included in ISLES study.	Development of concepts and applications, evt. combining different functions. Testing and designing at industrial scale

Hybrid CSC-VSC connection

Several studies have investigated the possibility of a hybrid LCC/VSC connection, where on- shore Classical HVDC CSC/LCC converters are combined with offshore VSC stations. The hybrid Configuration is claimed to combine advantages of both technologies, HVDC Classic and VSC, resulting in a more reliable power supply. Moreover, many already implemented interconnectors are based on LCC-CSC technology, whereas VSC is the only HVDC technology that can facilitate the grid access of offshore wind farms. This fact brings the concept of hybrid CSC-VSC connections to the fore. It has to be noted that the market consultations showed that there is currently no market demand for such a connection, as any alterations to the business case of the existing interconnectors are ruled out. However, for combining wind farms and bulk power transfer in a future HVDC offshore grid, a hybrid connection is a highly challenging research topic and its potential should not be excluded from future HVDC grid plans.

A case of hybrid CSC-VSC interconnection in the presented system could only come as a result of the use of VSC stations for the connection of the wind farms to the HVDC grid, while the onshore stations would use the CSC technology for bulk power transmission, resulting in a four-terminal hybrid HVDC network. The main disadvantage of a hybrid CSC-VSC connection is that the power can only flow in one direction not facilitating fast changes in power direction. This happens since CSC requires the reversal of the DC voltage for power flow reversal, while keeping the DC current unchanged, whereas VSC requires the opposite. Consequently, before reversing the power, the operation needs to be interrupted and the system needs to get totally de-energized. This is an essential drawback because in most of the interconnecting links the power should flow in either direction according to the level of supply and demand for electricity in the associated electricity markets.

Another drawback is that the CSC technology reaches power ratings up to 8000 MW while the VSC stations currently have values of circa 2000 MW. Therefore, the use of a VSC station on one end of the DC line along with a CSC station on the other end can limit the power rating of the HVDC system. However, in the case of a CSC-based interconnector and one VSC connecting a wind farm to the multi-terminal system, the VSC power rating does not affect the power that can be transferred / traded between the onshore grids.

At the moment, there is no interest in this concept from the manufacturers' point of view, as there is no market demand. However, it is considered to be technically possible especially with the use of full-bridge MMC converters and thus, it is not excluded in the present feasibility study. In case such a connection was to be made, changes in the existing control and protection techniques would be needed and the problem of black-start capability on a hybrid line would need to be solved. Finally, as full-bridge converters are expected in the market in 2015, the hybrid CSC-VSC connection could be realized within the next five years. An overview of the existing market solutions on MMC converters and their basic functionality is presented in B.1, section 2.3.1.

CSC: Forced-Commutated

To improve the limited controllability of LCC-CSC stations and to and mitigate stability issues when connected to weak grids, several converter concepts have been proposed. These are referred to as forced-commutated CSC converters (FC-CSC). One concept includes the use of capacitors to stipulate the thyristor switching. These converters are known as capacitor- commutated converters (Capacitor-Commutated Current Source

Converter (CCC-CSC)). How- ever, their controllability remains limited compared to converters based on fully-controllable switches. In another proposed option, fully controllable switch valves are used in series with diodes to increase the controllability of the converter stations. So far, CSCs have found industry applications in medium voltage AC motor drives, i.e. up to 4500 V. However, FC-CSC does not exist yet for high voltage applications and it comprises a challenge from the converter technology point of view.

Large-scale meshed grids

As already mentioned in section 3.2.2, a main challenge moving towards highly meshed HVDC grids will be their protection. The lack of DC breakers becomes more prominent when the power involved in a grid is higher than the maximum level allowed to be disconnected at once from each of the connected onshore grids (1320 MW to 1800 MW for UK; 3000 MW for ENTSO-E Continental Europe). As a result, the need for DC breakers to section the system into different protection areas is prominent.

In the coming three years, the three main HVDC manufacturers in Europe, namely ABB, Alstom Grid and Siemens, are expected to apply their protection solutions in full-scale lab experiments or pilot projects to gain more practical experience. This area offers high potential for research that could result into less costly commercial solutions. More specifically, more research is needed on fast selective DC fault detection methods, their accuracy and the communication means between different breaker controllers to ensure coordinated action. Moreover, due to the lack of a proven technology, new breaker designs need to be investigated and compared on the basis of their conduction losses during normal operation and their response to transients, such as the energy absorption time and the fault current interruption time. Multi-objective optimization schemes could be applied to optimize the sizing of the breaker components. Finally, coordination of DC protection systems with corresponding AC protection systems needs to be investigated to ensure that fault on either side of the grid have limited impact on the other side.

DC Hubs

Small HVDC networks involving up to five terminals are believed to be possible with the existing technologies. However, as more point-to-point HVDC projects are proposed or are under construction, the lack of standardization in the utilized equipment and in the used voltage and power levels will eventually lead to significant problems moving towards the realization of a highly meshed North Sea Transnational Grid. In this case, already established projects that operate at different voltage levels would need to get interconnected with similar future projects on the DC side. Therefore, there is the research opportunity to study the solution of a DC interface to achieve this transition from DC point-to-point connections to DC grids.

The role of an interface could be played by multi-port dc-dc converter stations which can be either placed onshore or offshore and will be able to accommodate the interconnection of HVDC projects. These multi-port converters are called DC hubs and could operate as offshore DC plugs. The main advantage of these hubs is the interconnection possibility of different HVDC projects that operate at different voltage and power levels, as well as the reduction of costs resulting from the placing of additional converters as soon as a new HVDC project is realized. These could additionally have a modularity capability so that they could be further extended depending on the amount of projects that need to be interconnected as elaborated in the North Sea Transnational Grid project[23]. Moreover, such DC hubs could enable the interconnection of more highly meshed grids to each other leading to the realization of a European Supergrid as this is envisioned as the future in transmission systems by several entities, such as the Friends of the Supergrid[24] (FOSG) association, the Mainstream Renewable Power development company and others.

Moving towards MTDC grids, the implementation of a DC hub could enable the optimization of the cost allocation within a DC grid, as different DC line sections with cables at different voltage levels could be chosen depending on the power level of the interconnected station. These would in turn be connected to the main HVDC line via a DC hub. This is a reason why dc-dc converters are considered to become an essential part of future DC grids and are thus, taken into account by many work groups consisting of manufacturers, TSOs and educational institutions, which are working towards the standardization of offshore HVDC grids.

Another reason to consider DC hubs is that as DC grids evolve, the need for DC collection grids in offshore wind farms will increase. DC collection grids could boost the efficiency of the grid, due to the lower number of conversion steps, as well as the grid stability, as AC resonance-related problems would be avoided. In this case, offshore wind turbines would be connected to a medium-voltage DC collection grid, which in turn would connect to the main HVDC network through a dc-dc converter (dc hub). This scheme is estimated to reduce the transmission losses by more than 10 % compared to an offshore AC grid with single point-to-point VSC-based HVDC connection, based on Alstom Grid calculations. However, the major benefit stems from the improved stability of the network. Nevertheless, DC hub schemes that have been theoretically proposed have the capability of isolating faults on any of the DC terminals, not allowing contingencies to propagate to the whole network. Therefore, the Synergies at Sea project provides an excellent R&D opportunity for the realization of such a DC hub, by developing and testing a down-scaled converter within the technical work stream, which will be part of the technical work stream, phase 2 of this subproject Interconnector.

Although currently there is no market demand, dc-dc converters are expected to play a significant role in the expansion of early HVDC networks. Currently, TSOs expect that HVDC systems will be built in steps, starting small but with the possibility of future interconnections involving different TSOs and manufacturers. Therefore, as long as there is no standardization of equipment in place and even so, as long as all the projects are not operated at a common voltage, there will be the need for DC voltage transformation, in case future interconnection is necessary. This would give more flexibility to the system designer to optimize the use of assets, such as cables. At the moment, there is no active interest from the main manufacturers, as there is no need for this technology in MTDC networks with a small number of terminals. However, it remains an area of prominent R&D interest as in the future large networks with many different voltage levels are expected to be developed. More specifically, a detailed design and comparison of different options is necessary, such as the dc-ac-dc one, where DC voltage is inverted first to AC at high frequency and then it is rectified to dc.

In this case, a transformer which offers galvanic isolation is used and optimization of the losses against the size of the AC equipment is needed. Another scheme involves direct dc-dc conversion with an amplification circuit in between the back-to-back converters, which on one

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[23] www.nstg-project.nl
[24] http://www.friendsofthesupergrid.eu/

hand increases the design and control complexity, whereas on the other hand it can minimize size requirements. In the design of a dc-dc converter the most important parameters that need to be taken into account are reliability, operating losses, footprint, control strategy for each of the involved converter parts and costs. Finally, it should be investigated whether such a device could provide protection functions, by isolating different parts of the grid.

Conclusions

- More complex and larger MTDC networks require advanced control and protection schemes, including improved DC-fault blocking and recovery, either inside the converters or by separate DC-breakers, which need to be demonstrated at full-scale. For these large networks the market demand (OWPP export, cross-border trade) should be clear in advance and the different national and international legal and support schemes should enable its construction and exploitation.
- Hybrid HVDC networks (based on VSC and CSC technology) are not yet considered by industry, but may offer the advantage of high power levels at lower costs and lower losses (LCC) as well as improved controllability and fault protection, especially with FC-CSC.
- Like hybrid networks DC hubs are also not considered by the market stakeholders. The additional flexibility in HVDC grid modular design, e.g. combining different HVDC and Medium Voltage Direct Current (MVdc) voltages, improved control and protection, should be made clear from R&D.

3.2.4. R&D

Based on the previous analysis, two main areas of interest were identified for further research within Phase 2 of Subproject 1 Interconnector of the TKI-WoZ consortium. These areas are:

1. Multi-objective optimization of the MMC converter design within an MTDC network;
2. Design of a multi-port DC hub, as integral part of the interconnecting link.

Regarding the modeling of the converters, although real application converters consist of a very high number of sub-modules per phase arm, modeling of the converters in the literature only considers a small number of levels due to the high computational needs. The average or switching models used to approximate the full-scale converter (>200 levels) rarely include more than five levels. For certain analyses, this might be sufficient, as they provide the proof-of-concept for control methods and basic dynamic studies. However, the level of reliability of converters (e.g. the maximum number of sub-modules per phase arm which can fail without affecting the operation of the converter) as well as the losses and the thermal management of a full-scale converter cannot be approximated so easily. Therefore, a new MMC simulation model will be studied, which is based on the analytical expressions that govern the dynamic operation of the converter and which take into account the real specifications of the components. This will be implemented using a programming language such as C++, which will decrease the computational time of the models.

Moreover, based on the literature review, two control methods were identified as the most promising for control of MMC: the adaptive, fault-tolerant control method and the model predictive control method. These two methods will be applied and compared based on the response of the control to abnormal behavior, the converter efficiency and their accuracy.

MMC design is a complex task which has several parameters that need to be accounted for. The large number of sub-modules, semiconductors, capacitors, arm reactors, gate-drive systems makes the design highly challenging. During the design phase, both normal and abnormal behavior should be taken into account and specifications should be made to achieve the highest level of performance in both stages. As a result, many design trade-offs appear which need to be optimized. In the recent past, multi-objective optimization techniques were applied for power electronic circuits design. This appears to be very promising as many different parameters can be optimized at the same time for different purposes, providing the system designer with a range of optimized solutions according to the respective needs. However, multi-objective optimization has not yet been applied in the field of HVDC components. As a result, there is a great potential for innovative approaches.

Regarding DC hubs, although several dc-dc converter designs have already been studied, in this work a novel scheme will be investigated, based on the MMC technology, which has multiple ports and can, thus, accommodate the interconnection of more than two systems which operate at different voltage levels. This tapping technique can be used to connect not only OWFs to HVDC interconnectors but also different DC links to each other. In this study, more modular concepts in multi-terminal networks will enable the expansion of offshore grids in the future and thus, dc-dc converters are expected to play an important role in grid developments.

In order to study the impact of DC hubs in multi-terminal networks, specific steps need to be taken. Firstly, the voltage and power level of the tapping and specifications such as conversion stages will be defined. Secondly, a detailed analytical model for a modular DC hub based on the MMC technology will be developed and the model will be incorporated and simulated into the multi-terminal HVDC network model. Finally, the operation of dc-dc converters as DC breakers will also be investigated for the isolation of healthy grid parts from faulty DC lines. In all the steps, the efficiency, thermal management and response to contingency cases of the dedicated converter will be studied.

3.2.5. Risk assessment of HVDC

Since its introduction, HVDC has only been used in a small number of offshore projects. More specifically, Germany is currently the only country using HVDC technology for the connection of offshore wind farms to the shore. Moreover, from the five installed offshore converter platforms (Borwin 1, Helwin 1, Borwin 2, Dolwin 1, Sylwin 1), only Borwin 1 was given to operation in 2013 and the other four await further testing. As a result, the experience from the use of HVDC offshore is limited. However, useful conclusions can be drawn and the risks associated with HVDC investments can be identified.

There are two main categories of risks associated with HVDC projects: the risks in the planning and construction phase and the risks in the commissioning and operational phase. The first category mainly refers to risks related to project delays, whereas the latter is related with the failure of equipment, including the transformer, power converter and cables.

Considering the risks in the planning and construction phase, there are three major bottlenecks. As far as the offshore converter stations are concerned, there are only three big suppliers in the European market, which increases the delivery time to 30 to 50 months. Moreover, the cable suppliers are few and it is often that shortages occur. Finally, only a few vessels are available with the ability to install converter stations heavier than 10 000 tonnes.

The aforementioned reasons, along with the challenging nature of the new technologies, have led to major delays in the planned HVDC projects. Those delays result in penalties and fines for the manufacturers. For example, it is worth to note that delays have already cost Siemens 800 M€. According to Tim Dawidowsky, CEO of Siemens Transmission Solutions, contracts had included overly optimistic construction times for HVDC grid connections, of a little as 33 months, when five years were more realistic for a fully certified project with bad-weather buffer (two years engineering, two years manufacturing and fabrication, and one year installation and commissioning). Helwin 1, which is the first HVDC station of Siemens, is running behind schedule for more than a year and the company already had to pay 500 M€ in additional costs and penalties. Moreover, cables are also presenting problems, as the enormous amounts of cables required have led to production bottlenecks[25]. Siemens also had problems with the cables in the case of Sylwin 1 project, as a cable originally destined for the project was lost in an incident in the Mediterranean Sea in July 2014. ABB was then requested to step in and help to support the project schedule[26].

According to TenneT, only two of its nine current offshore connection projects - Borwin 2 and Helwin 1 - are behind schedule and it is working with Siemens, the contractor for these two projects, to find ways of speeding up work in other areas to reduce delays[27]. However, it has to be noted that since the beginning of the very optimistic German plans for a huge expansion of offshore wind, TenneT had problems meeting the production deadlines and was faced with lawsuit from RWE to compensate losses caused by delays[28]. Apart from planning risks, there are also operational risks related to the immaturity of the technology which can lead to further delays. ABB currently experiences problems with the Dolwin 1 converter. The initial testing failed in late 2014 and the commissioning was moved to 2015, running several months behind schedule[29].

Furthermore, major problems appeared related to the commissioning and operation of the first installed converter platform Borwin 1, which connects the Bard Offshore 1 wind farm to the German onshore grid. The Bard Offshore 1 wind farm was opened in August 2013. It is the first commercial wind power plant on the high seas, around 100 km off the German North Sea coast. At the beginning of the year, there were frequent technical problems with the converter substation. In late March, a smoldering fire occurred on the substation and caused preliminary failure of the system. Then, engineers tried once again to bring the wind farm online, but they were met with failure as *wild current* fried filters at the offshore converter station after just a few hours. The fire was finally extinguished when the network connection system was switched off, according to TenneT. After five unplanned outages since the beginning of 2014, the BorWin1 cable system connecting the 400 MW Bard Offshore 1 wind farm to shore suffered another outage of several hours on 1 June due to problems with the seawater system. The project has now been delayed more than one year and the lost power is valued at 340 M€[30].

A first step towards the alleviation of the risks associated with offshore HVDC technologies was made by a joint industry project, including ABB, Alstom Grid, DNV GL, DONG Energy,

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[25] Source: http://www.modernpowersystems.com/features/featurenavigating-the-north-sea-learning-curve-4359059/

[26] Source: http://www.offshorewind.biz/2014/10/28/tennet-to-connect-butendiek-owf-to-sylwin-alpha-with-abbs-cable/

[27] Source: ehttp://www.spiegel.de/international/germany/german-offshore-wind-offensive-plagued-by-problems-a-852728-2.html

[28] Source: http://www.offshorewind.biz/2012/03/04/germanys-green-energy-revolution-faces-risk/

[29] Source: http://www.offshorewind.biz/2014/10/21/trianel-wind-farm-borkum-commissioning-pushed-to-2015/

[30] Source: http://www.windpoweroffshore.com/article/1297004/bard-1-transmission-problems-continue and http://www.offshorewind.biz/2014/06/23/bard-offshore-1-wind-farm-remains-out-of-operation/

Elia, Europacable, Scottish Power, Statkraft, Statnett, Statoil, SvenskaKraftnät and Vattenfall, which developed and proposed a practice on technology qualification of offshore HVDC technologies. The new practice is based on the methodology developed by DNV GL for technology qualification, which has been used extensively for managing technology risks in the oil and gas industry. Namely, technology qualification is a method to test that technical equipment will operate within specified limits with an acceptable level of confidence, both for suppliers and buyers of the relevant equipment[31]. Although this practice means an important step towards the risk reduction of HVDC investments, more targeted steps are necessary in the near future.

For more complex offshore networks, either combining HVDC and HVAC or MTDC, risks are even higher, as no practical experience exists. Before actually constructing such networks, the technical design as well as the operation principles should be elaborated and tested. Related to the studied interconnecting Link, the UK offshore HVDC platform design and operation could be made suitable for later connection to an IL.

3.2.6. Conclusion

Most of the technologies for the realization of future offshore grids appear to be in place. However, up to now, any proposed multi-terminal network is supplier specific, which results in a limited number of choices which limits the flexibility and the modularity of existing and future systems.

Standardizing a number of main characteristics such as voltage levels, platform capacities is needed to increase market size for the manufacturers, and reduce the costs of offshore networks. At the moment CIGRE and CENELEC are the only European groups working towards defining DC grid standards.

3.3. **Selected technical scenarios**

3.3.1. Power ratings

Starting from the basic grid topologies, in total 13 scenarios with interconnected OWFs plus two with a parallel interconnector have been defined. This is considered a fair representation of the many possible combinations for topologies, technologies and rated capacities.

Figure 3-3 provides an overview of the selection process, starting from a relatively small interconnecting capacity of 300 MW, based on the power rating of a single 220 kV HVAC circuit. The wind farm capacities were rounded as multiples of 300 MW, as closely linked to the planned wind farms Beaufort (NL) and East Anglia One (UK). These are presented in Figure 3-3 in the column "Initial scenarios".

[31] Source: http://www.offshorewind.biz/2014/09/18/dnv-gl-recommends-practice-for-offshore-\gls{hvdc}-systems/

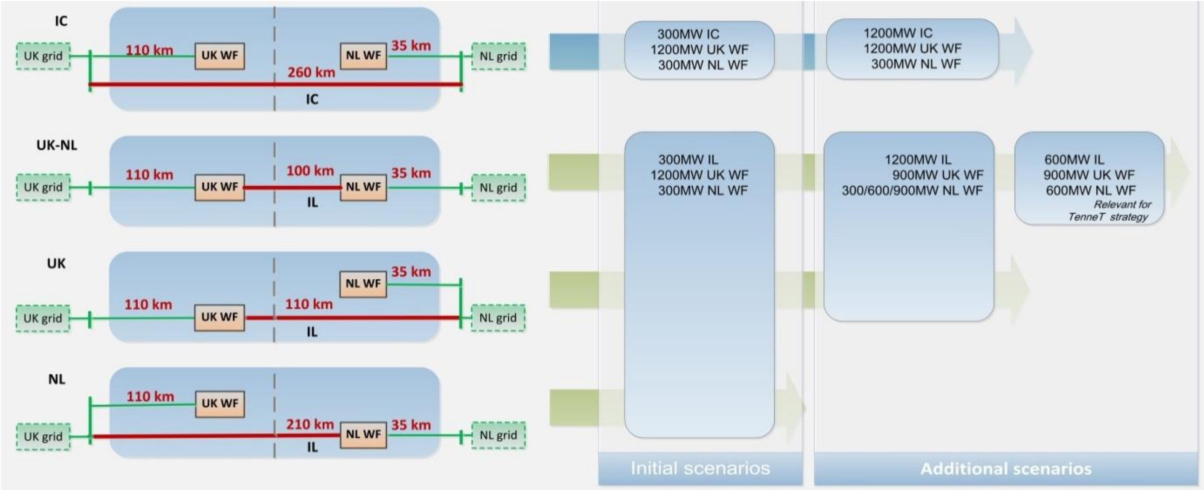

Figure 3-3: Overview of scenario topologies and capacities.

For the relatively small power rating of 300 MW for the interconnection the installation costs dominate the total costs per MW. Choosing cables with higher power ratings or even parallel cables will result in relatively lower installation costs and therefore promises to be more economical. Increasing the capacity of the interconnecting link also leaves more reserve capacity for cross- border trade, which may also help to improve the economic feasibility. Therefore a set of “Additional scenarios” with higher power ratings for the interconnection, up to the current available maximum rating of 1200 MW, has been defined.

Also the wind farm capacities have been varied to investigate the dependency to these parameters. For HVDC connected wind farms 900 MW is chosen, as this is the closest to the current ratings of the German offshore HVDC substations. At the NL side multiples of 300 MW have been chosen, based on the current maximum HVAC (220 kV) cable capacity.

Table 3-6 shows the connection capacities to shore. The differences in costs for the onshore substations have been calculated. Cost effects for the onshore grid and land use have not been included.

Table 3-6: Overview of required additional connection capacities to shore per scenario in MW.

Scenario	IC/IL [MW]	WF UK [MW]	WF UK [MW]	To UK {MW]	To NL [MW]	To UK+NL [MW]
IC300	300	1200	300	300	300	600
IC1200	1200	1200	300	1200	1200	2400
UK-NL1, UK-NL4	300	1200	300	0	900	900
UK1, UK2	300	1200	300	0	1200	1200
NL1, NL2	300	1200	300	300	0	300
UK-NL2	600	900	600	0	0	0
UK-NL5	1200	900	300	300	900	1200
UK-NL3,UK-NL6	1200	900	600	300	600	900
UK-NL7	1200	900	900	300	300	600
UK4	1200	900	300	300	1200	1500
UK3	1200	1200	300	0	1200	1200

One of the selected scenarios for topology **UK-NL**, is a 600 MW interconnecting link and a 600 MW OWF in the NL, all with HVAC technology. The reason is that the chosen power level and technology closely matches with the technical concept that is proposed by TenneT TSO to connect the OWFs planned in the Dutch EEZ.

For detailed schemes of the scenarios, see Figure A-2, Figure A-3 and Figure A-4 of Appendix A

3.3.2. Technology choices

A first selection of the technical scenarios has been made based on two criteria, which have been evaluated in the project team, mainly using expert judgement, see also the interim report:

C1 Expected costs

C2 Technical maturity, meaning that the technical solution can be realized in 2020

The Capital Expenditures (CAPEX) are the main cost factor, while Operation and Maintenance (O&M) costs for offshore equipment remain highly uncertain and should not be underestimated, referring to OWF Operational Expenditures (OPEX) which contribute about 20 % to 40 % to the Levelized Cost of Energy (LCoE). The two criteria are linked, as maturity usually regarded as less risky, which lowers financing costs and often also inherits lower O&M costs.

One of the main trade-offs has been to apply mature HVAC transmission technology preferably, while longer distances and higher power ratings require HVDC to limit transmission losses. For small ratings of 300 MW the HVAC option is considered technically feasible, while for the second set of scenarios with higher line ratings several HVAC variants have been discarded.

As said, because of the non-synchronous grids at least one HVDC line section between the NL and UK grid is required. For the project scenarios this means the inclusion of at least one HVDC offshore VSC converter, which is very costly. First solution is then to apply HVAC technology for the IL, which doesn’t need additional converter stations, as in **UK-NL1**. Second solution is locating the extra converter station onshore, as is in **UK2**, the costs for the offshore stations are reduced. When HVDC transmission technology is applied exclusively the two onshore and two offshore converter stations are required in multi-terminal configuration, where the size of the offshore converters is determined by the Offshore Wind Farm (OWF) power rating. Which technologies are technically feasible and which are optimal in terms of costs and benefits is likely to depend heavily on the actual distances and OWF capacities.

In terms of technical maturity the multi-terminal HVDC solutions based on VSC technology are less mature, although considered feasible, especially in case of relatively small power ratings when protection can be realized using fast AC breakers. Hybrid HVDC grids based on both Current Source Converters and Voltage Source Converters need longer development time and have therefore not been considered in this feasibility study.

3.4. Scenario modelling

The naming convention for the scenarios is explained in Table 3-7. The different scenarios have seven unique line segments, with distances and capacities are specified in Table 3-8.

Table 3-7: Studied scenarios with selected topology, capacities and technologies

Scenario label	Figure	Interconnection				UK-WF				NL-WF			
		IC/IL	IC/IL Capacity [MW]	Distance [km]	Technology	WF Capacity [MW]	Link Capacity [MW]	Distance [km]	Technology	WF Capacity [MW]	Link Capacity [MW]	Distance [km]	Technology
UK-NL1	1a	IL	300	100	AC	1200	1200	110	DC	300	300	35	AC
UK-NL2	1b	IL	600	100	AC	900	900	110	DC	600	600	35	AC
UK-NL3	1c	IL	1200	100	AC	900	1200	110	DC	600	1200	35	AC
UK-NL4	1d	IL	300	100	DC	1200	1200	110	DC	300	300	35	DC
UK-NL5	1e	IL	1200	100	DC	900	1200	110	DC	300	1200	35	DC
UK-NL6	1e	IL	1200	100	DC	900	1200	110	DC	600	1200	35	DC
UK-NL7	1e	IL	1200	100	DC	900	1200	110	DC	900	1200	35	DC
UK1	2a	IL	300	110	AC	1200	1200	110	DC	300	300	35	AC
UK2	2b	IL	300	110	DC	1200	1200	110	DC	300	300	35	AC
UK3	2c	IL	1200	110	DC	1200	1200	110	DC	300	300	35	AC
UK4	2d	IL	1200	110	DC	900	1200	110	DC	300	300	35	AC
NL1	2e	IL	300	210	DC	1200	1200	110	AC	300	300	35	AC
NL2	2f	IL	300	210	DC	1200	1200	110	DC	300	300	35	AC
IC300	3a	IC	300	260	DC	1200	1200	110	DC	300	300	35	AC
IC1200	3b	IC	1200	260	DC	1200	1200	110	DC	300	300	35	AC

1) Topologies: UK-NL = Interconnecting Link (IL) between UK and NK wind farms
UK = IL between UK wind farm and NL-grid
NL = IL between NL WF and UK-grid
IC = parallel Interconnector (IC) between UK-grid and NL-grid

2) The grid connection capacity of wind farms connected to an IL is chosen as the maximum of the nominal WF capacity and the IL capacity

3) Technology: AC = 220kVac, 300MW per cable system
DC = 320kVdc cable system in bipolar or symmetric monopole config.

Table 3-8: Line lengths and capacities

Line segm.	Market scenarios	Length offshore [km][1]	Length onshore [km][1]	Rated capacity [MVA][2]	Comment
Line 1	**IC,UK+NL, UK, NL**	73	34	1200	From East Anglia One project description
Line 2	**IC,UK+NL, UK, NL**	35.5	0	300	From Beaufort project description
Line 3	**IC,UK+NL, UK, NL**	260	0	1000	From BritNed 1 project description
Line 4	**IC**	260	0	1200[3]	Assumed same distance as BritNed 1
Line 5	**UK+NL**	100	0	300	Estimate, shortest route between WFs
Line 6	**UK**	110	0	300	Estimate, shortest route to Maasvlakte (NL)
Line 7	**NL**	173	34	300	Estimate, distances of lines 1 and 5 added

Notes:
1) Actual cable lengths might be longer, which can be critical for long HVAC lines.
2) Initial choice that may be optimized later in the project.
3) For comparing **IC** and Project scenarios a scenario **IC300** has been calculated in which a 300MVA interconnector has been modeled.

The scenario modelling and evaluation described here addresses research question 3 and limited to stationary performance and costs. The modelling and evaluation is done in the ECN model EeFarm-II with the use of power flows resulting from the COMPETES model from ECN Policy Studies. The process of modelling, which is described in Appendix B, holds specification of the scenarios, defining assumptions, specifying components and inputs power flows, model implementation choices and defining the processing of results.

3.5. **Results**

For each of the technical scenarios the investment costs have been calculated. These figures have been used as input for the economic analysis. The investment costs per scenario are presented in Figure 3-4. The total costs are subdivided in the costs of connecting the wind farms to the respective countries (in blue) and the additional costs for realizing the interconnection (in pink). The wind farm related costs include the offshore platform, transmission transformer(s), reactive power compensation and eventual AC/DC converter station. The Medium Voltage (MV) collection grid and the wind turbines are excluded. Furthermore, the costs for additional onshore connection capacity have been included, but possible need for strengthening onshore transmission grids has not been included. The cases **IC1200** and **IC300** require additional strengthening of onshore grids compared to the integrated scenarios. The main order in the presented scenarios is the increasing rated power of the interconnecting link and the basic topologies. The different base investments are directly related to the installed wind farm sizes.

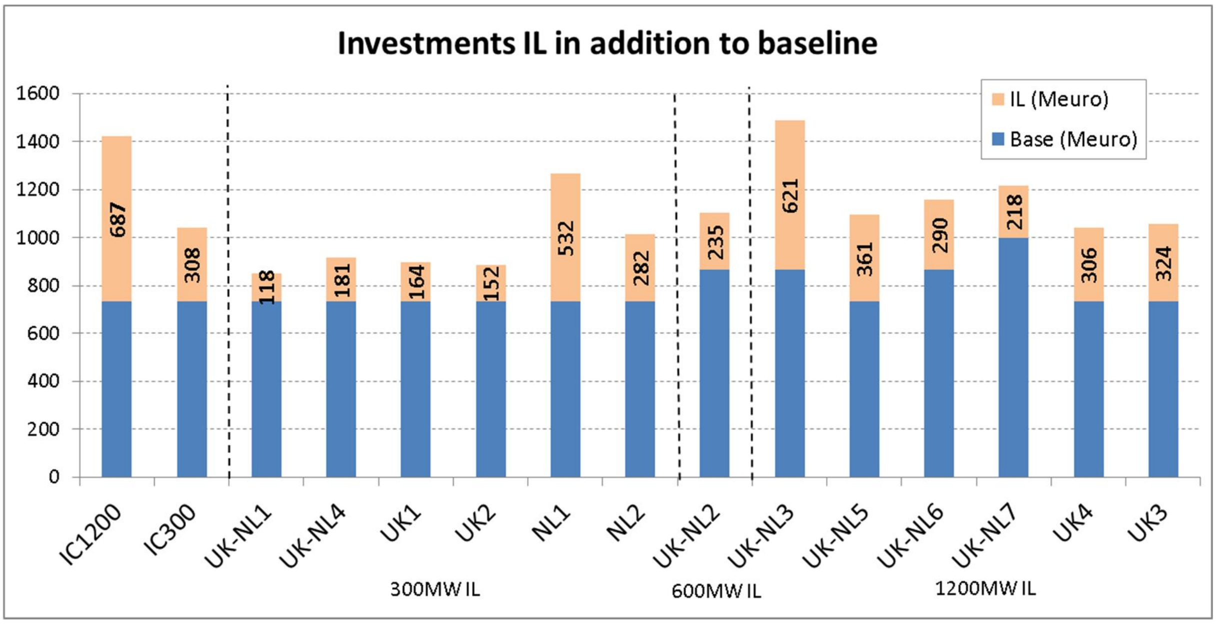

Figure 3-4: Overview of investment costs per scenario.

In order to formulate conclusions on preferred scenarios, more information is required than only these costs. The different grid topologies, as well as the choice of the rated capacities and the technologies determine the amount of energy that can be transported, which is shown in Figure 3-5.

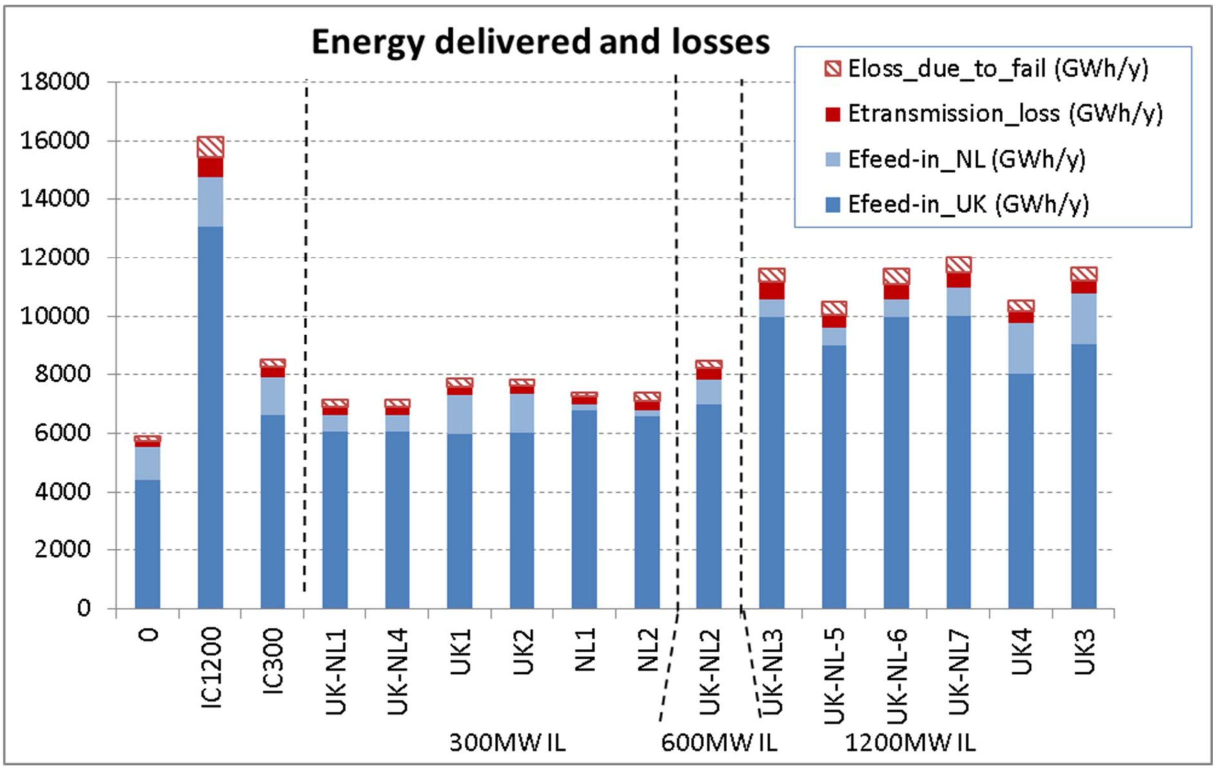

Figure 3-5: Transported energy and losses per scenario.

3.6. **Discussion**

3.6.1. Costs

By looking at subsets of comparable scenarios, e.g. same topology or rated capacities, some observations are presented below. These need to be combined with the technology risks as well as the economic and regulatory evaluation.

Comparing the costs for the different solutions involving a 300 MW IL/IC, cf. Figure 3-4, the scenarios **UK-NL1** and **UK-NL4** with an IL between the WPPs and **UK1** and **UK2** with an IL from the UK-WPP to the NL-grid have lower capital costs than case **IC300**. On the other hand, NL1 has a much higher investment cost (more than 300 M€ higher) than the scenario **IC300**.

The cost difference between the 1200 MW and 300 MW interconnector, cf. scenario **IC1200** and **IC300**, is roughly a factor two, which is much less than the factor four in the capacity. As expected also in the business case analysis the **IC1200** case of a conventional interconnector is financially more attractive (has a substantially higher Internal Rate of Return) than the 300 MW interconnector of **IC300**.

The cases **NL1** and **NL2** with an IL between the UK-grid and the NL-WPP are considerably more expensive than the **UK-NL** and **UK** topologies, due to the longer IL needed. It also shows that for the 1200 MW UK-WPP an HVAC solution NL1 is far more expensive than an HVDC solution and is therefore this topology has been discarded in further analyses.

For creating a 300 MW IL the HVAC variant **UK-NL1** is the least expensive one, although the relative differences with other scenarios **UK-NL4**, **UK1** and **UK2** are relatively small. For both 600 and 1200 MW power ratings the costs differences between HVAC and HVDC options are much more significant.

Looking at scenarios with a 1200 MW IL, Figure 3-6 shows significant cost differences for different topologies. Both IL scenarios need roughly about half of the additional investments of a separate interconnector. Furthermore, the Scenario **UK4** is not only less expensive than **UK-NL5**, but also has higher available trading capacity.

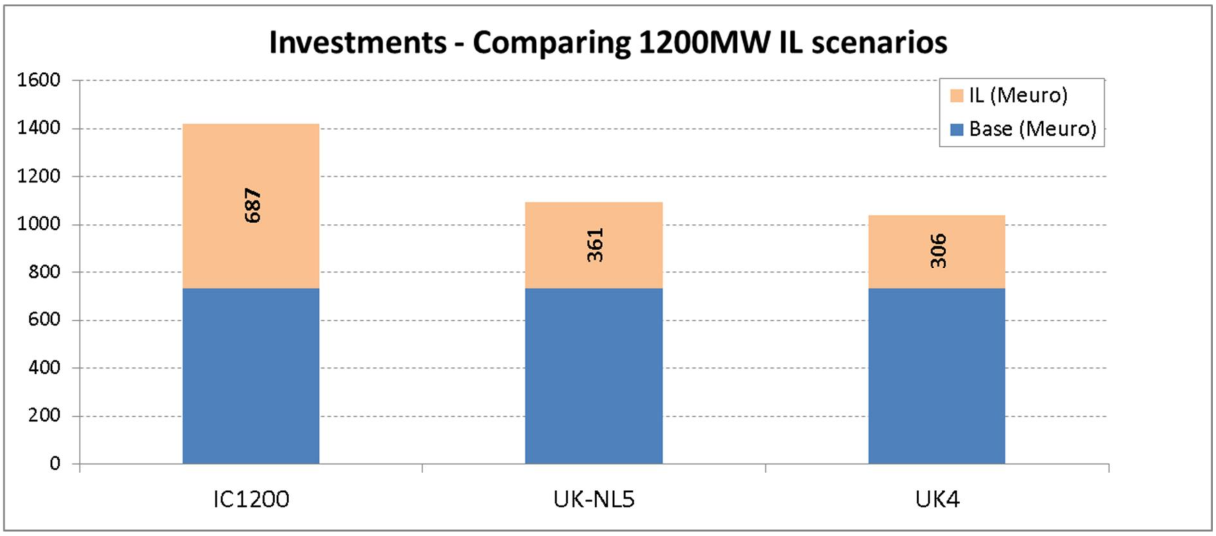

Figure 3-6: Investment costs per scenario comparing 1200 MW HVDC IL scenarios.

Figure 3-7 shows three IL variants for the same WPP rated power and topology. Scenario **UK-NL2** is an HVAC implementation that aligns best with the planned HVAC offshore grid in the Netherlands. Upgrading the HVAC 600 MW IL to 1200 MW **UK-NL3** shows more than a doubling of the additional costs. A comparable HVDC 1200 MW IL **UK-NL6** can be built at relatively small extra costs compared to the 600 MW IL of **UK-NL2**.

When considering alternative grid topologies (not shown in this figure) scenario **UK4** with a separate HVAC WPP connection to the Dutch grid and a 1200MW HVDC IL, also shows relatively modest additional costs, although the separate connection to the NL grid requires more space for an extra landfall and an HVDC substation.

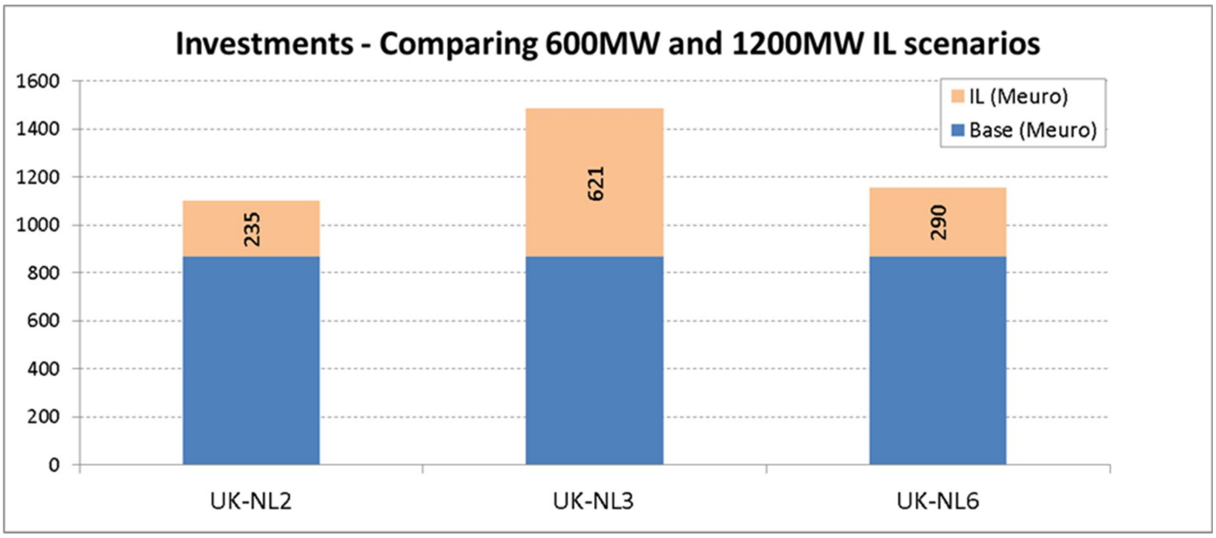

Figure 3-7: Investment costs per scenario comparing 600 MW and 1200 MW scenarios.

Figure 3-8 shows that additional investment costs for and IL (pink) decrease with an increasing WPP rated capacity at the Dutch side of 300MW, 600MW and 900MW, while obviously the total investments increase. The reason is that looking at the total investments, the largest part of the additional investments is already included in the grid connection of the WPPs. Upgrading the connection capacity the power rating of the IL requires smaller investments in case of a larger WPPs.

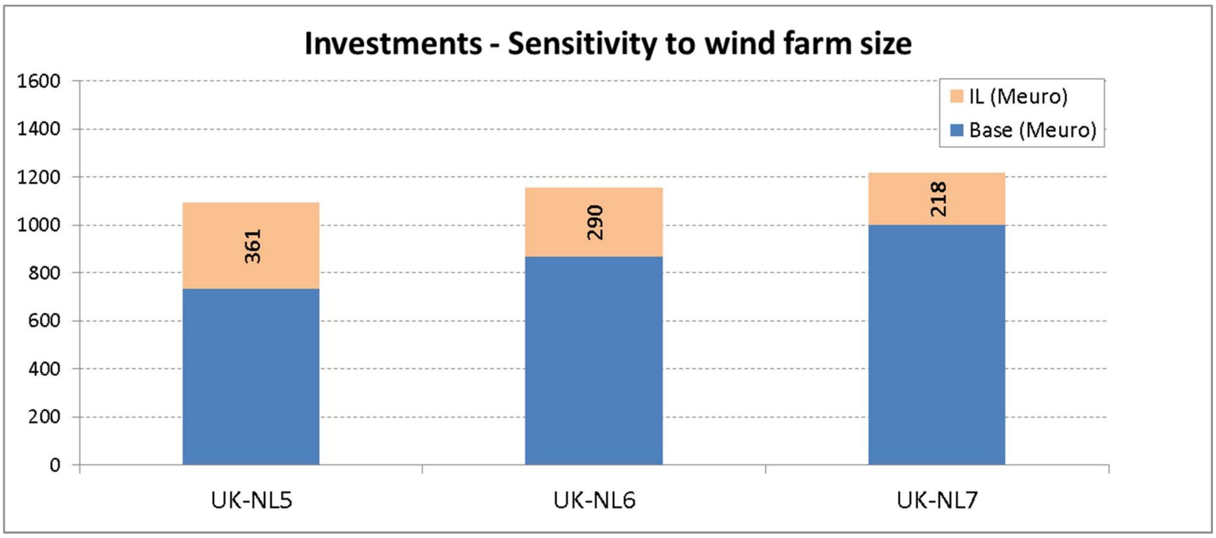

Figure 3-8: Investment costs per scenario sensitivity to WPP size.

3.6.2. Losses

For each of the technical scenarios the energy transmission losses and energy losses due to expected unavailability have been calculated. These loss figures have been used as input for the economic analysis. In Figure 3-5 the 300 MW IL scenarios already showed the dominant effect of the topology on the transported amount of energy. The available transport capacity is most limited for and IL between the two WPPs, i.e. topology **UK-NL**, while for a parallel connection for the Dutch WPP provides the largest energy transport. The increase in WPP size from 300 MW to 600 MW in the three scenarios **UK-NL5**, **UK-NL6**, **UK-NL7** shows a larger increase in transported energy than the increase from 600 MW to 900 MW, because of the limited transport capacity of 1200 MW to the Dutch grid.

The energy transported towards the Netherlands is small compared to the energy transported towards the UK, even in the line section between the WF_NL and NL_grid. This is an outcome of the market model which calculated higher energy production costs in the UK, resulting in power flows towards the UK.

The magnitude of the transmission losses and the losses due to failure in most scenarios are comparable. Although both lead to energy production loss, the influence on the cross-border trade differs, because of two reasons:

1. the relative transmission losses depend on the actual level of the power flow and
2. the transmission losses require extra power to be produced for cross-border trade, which lowers the revenues.

The effect is that it adds an offset to the price difference required to trade at a certain power level. Therefore the transmission losses serve as input to the market study. The transmission losses for solutions involving long distance HVAC lines are relatively high, while parallel HVAC lines result in lower failure losses due to the effect of redundancy.

In Figure 3-9, the losses (solid red bars) show variations in the range of 1 %, where the highest losses can be seen for a separate interconnector (**IC300** and **IC1200** scenarios), Long HVAC lines (Scenarios **NL1**, **UK-NL2**, **UK-NL3**) and a 1200 MW IL in between the two WPPs. Figure 3-9 also shows the lost energy due to component unavailability due to failure and maintenance (in blue). The third data series *Efail_rel_red* shows failure-related losses in case when the energy flow follows an alternative path in case in case a connection to shore fails. In the second series *Efail_rel_org* this alternative path has not been considered. The 300 MW IL shows a marginal improvement (lowering) of the lost energy because of the extra redundancy from the IL. For the 600 MW and 1200 MW IL this effect is more significant (i.e. it more than halves the amount of energy lost due to failure).

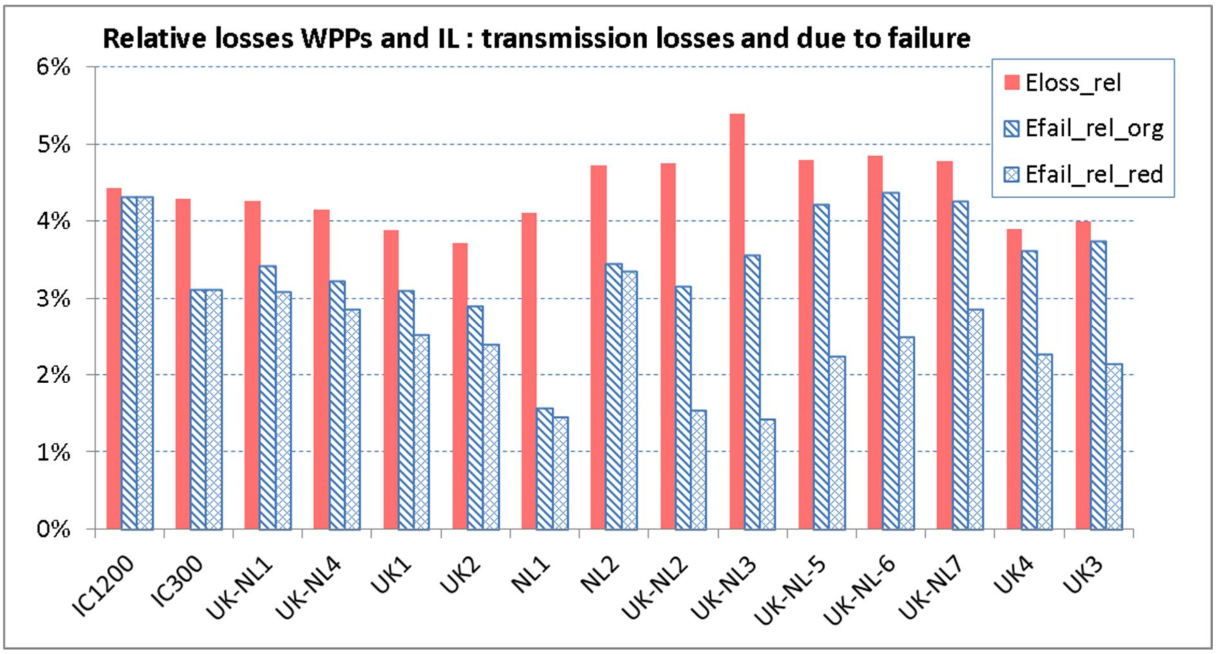

Figure 3-9: Overall relative losses per scenario: transmission and due to component failure.

Figure 3-10, shows the lost energy that can be attributed to the wind farm production. The dashed lines represent the relative energy losses without the extra redundancy from the interconnection, which for the UK WPP is much higher than from the NL WPP, due to the HVDC connection and the longer transmission distance. For the UK WPP the interconnection leads to a decrease in lost energy of over 45 % for an 600 MW and 1200 MW IL, while for the Dutch WPP the decrease only occurs for HVAC scenarios, mainly because of the low energy loss in the initial case, which is a 300 MW HVAC connection to shore. For HVAC the redundancy increases with the power level, because of the parallel circuits, although the additional costs are high.

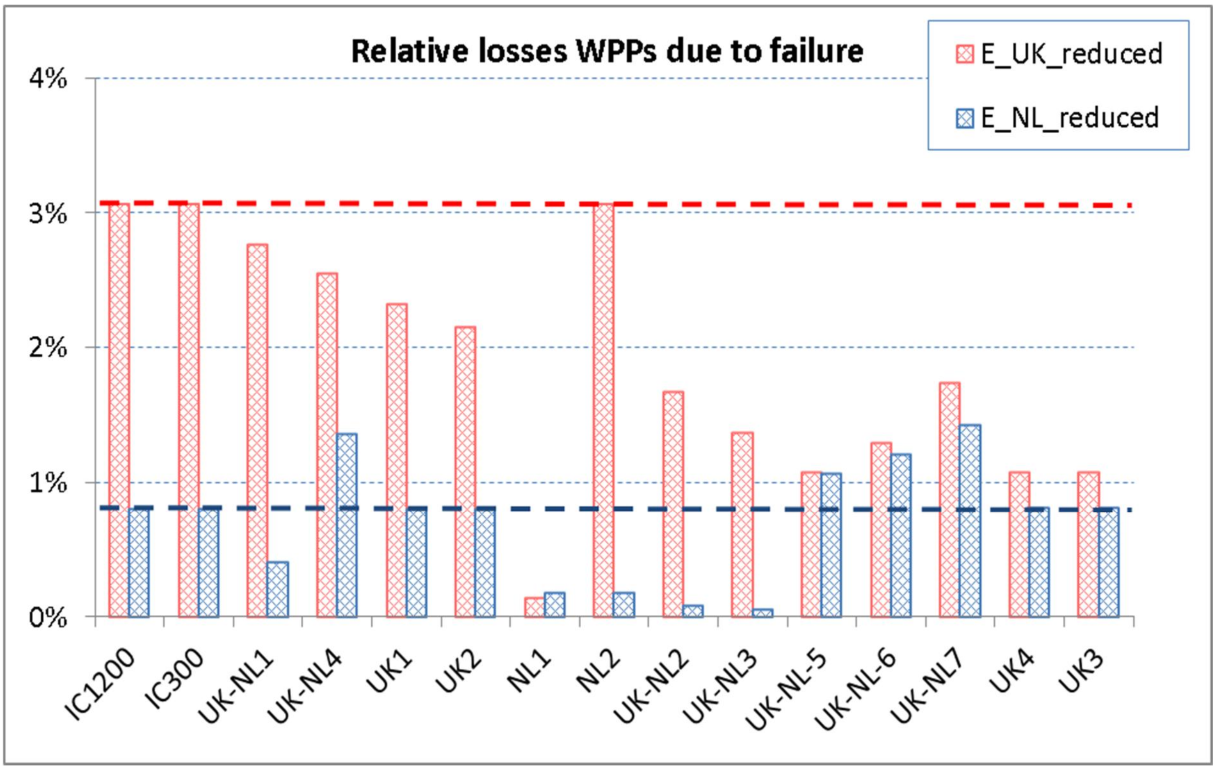

Figure 3-10: Relative losses of energy from WPPs per scenario due to component failure.

4. Regulatory analysis

4.1. Introduction[32] [33]

The construction of integrated electrical offshore infrastructure, which includes an interconnecting link between two offshore wind farms, or an offshore wind farm and the mainland of the other country, creates legal challenges. These legal challenges influence the decision making process of an investor. In this chapter we address the consequences of the findings on the regulatory framework for this decision making process.

A twofold approach will be taken. We shall address the issues which are relevant for a private investor and those which are relevant from the national perspective, with the TSO as investor. It should be noted that we shall not address issues as securities for bank loans or other financial instruments in detail.

Because some issues are relevant for both perspectives, we shall address these first before moving on to the different investor perspectives. For the sake of clarity, one should take into account that under the private investor perspective is understood the case in which an investor other than the TSO is investing in the interconnecting link.

4.2. General issues

4.2.1. Defining the interconnecting link

In this research we have assessed the legal status of the interconnecting link. It should be noted that not the entire offshore electrical infrastructure will be part of the interconnecting link. Figure 4-1 (also shown earlier in Figure 2-2) shows what is considered to be part of the interconnecting link. The red lines in the figure represent the interconnecting link.

The research shows that when a subsea cable is constructed to connect two wind farms or to connect an offshore wind farm to the onshore grid of a foreign state, this subsea cable sometimes cannot be qualified in current legal terms. The cable can within the current European legal regime not be qualified as an interconnector in case it does not connect the grids of two TSOs to each other.[34] In some connections this creates some legal uncertainty regarding the status of the cable and the obligations related to it, as multiple scenarios become possible. This is due to the fact that an unidentified cable does not fall under the scope of the Electricity Directive or Electricity Regulation. The cable is sui generis at this moment, meaning that there is no common accepted definition for this cable. This means that uncertainty exists whether the Electricity Regulation and/or Electricity Directive are fully applicable to the cable.

[32] The complete list of sources and literature which are used for the regulatory workstream of this research can be found in Appendix E.

[33] The legal research analysed the existing legislation as it was up-to-date in Augustus 2014, before the amendment of the Dutch Electricity Act '98. Updates in legislation are included in the Comprehensive Summary, Regulatory analysis (§ 4) and conclusions (§ 7) of this report.

[34] Note that this conclusion is based on the concept in which in the interconnecting link is constructed between the offshore sub-stations that are owned by two offshore wind farms. In case the connection is made between substations owned by TSO's the connection is legally an interconnector. This is the case in the Netherlands and the UK where the substations are owned by TenneT and an OFTO

If one assumes that this cable is either a transmission cable or an interconnector, then it is uncertain which legal regime is applicable to the cable. It was found that the English legislator is precise on this matter; the operator of an interconnector cannot at the same time be involved in transmission activities. Because there are specific rules on interconnectors apart from the rules concerning transmission, it would seem that these activities cannot be combined under the current legal framework. When one cable can be treated as an interconnector as well as a transmission, then two sets of rules would apply and it remains to be seen whether a cable can be operated in an effective manner if this cable is regulated to be used for transmission activities as well as interconnection activities.

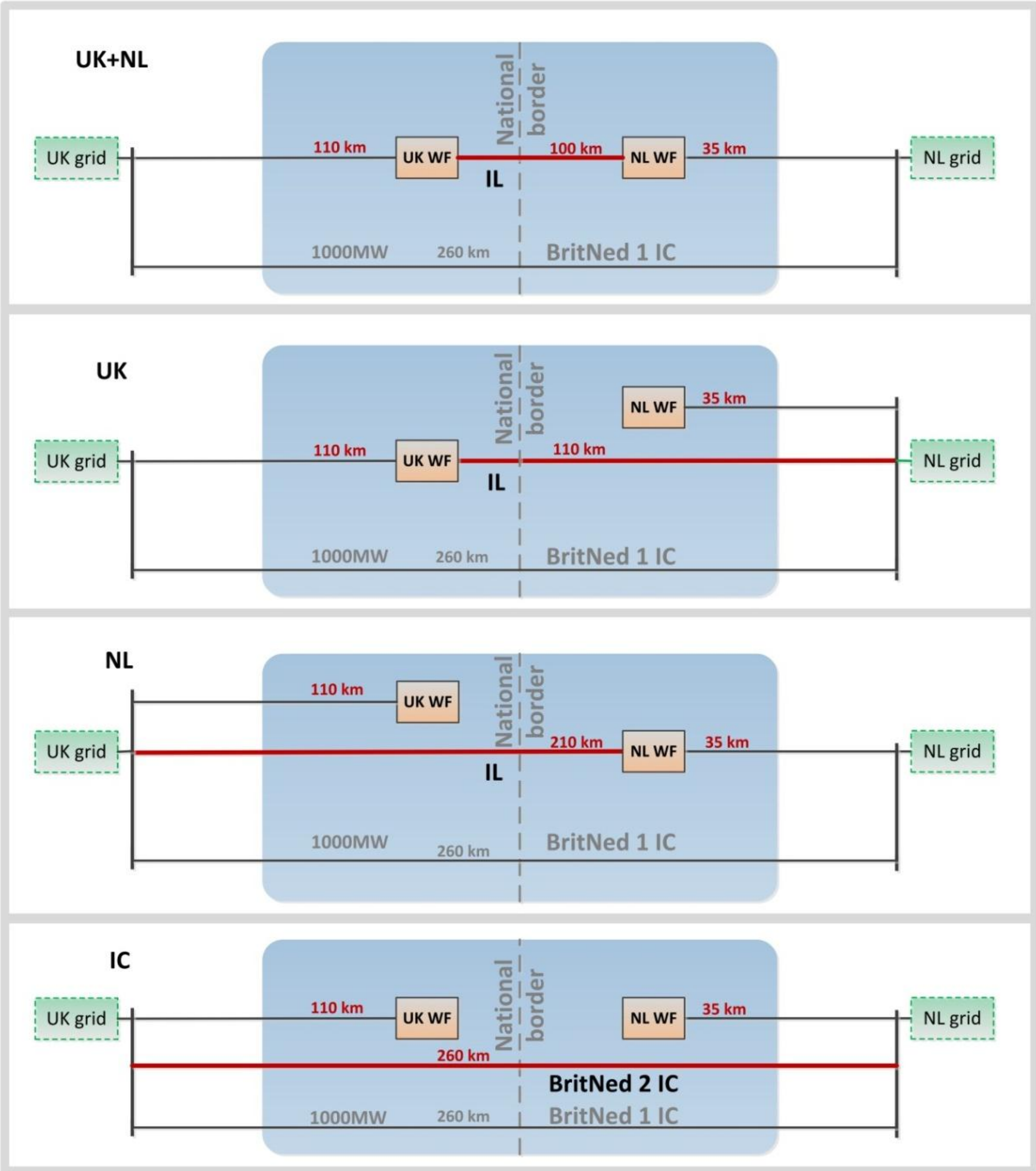

*Figure 4-1: Three basic scenario topologies (**UK-NL**, **UK** and **NL**) plus the business-as-usual scenario **IC**.*

There are two possible solutions that could solve this problem. The first solution is an extensive interpretation of the European law; this requires no additional legislative action from the European legislator. For the use of an extensive interpretation, one can focus on the aim of EU electricity legislation. The aim of the different electricity packages was and remains the creation of one internal energy market for both natural gas and electricity. To create such an internal energy market two specific matters need to be addressed.

The first is the regulation of this market. This encompasses different issues such as unbundling, regulated third party access, consumer protection and a harmonized system of market regulation by European public authorities.

The second matter is the construction of a transnational European grid on which trade can take place. One clearly sees that the creation of one European electricity market requires more than only legislative action. To this end a special regulation, Regulation (EU) 347/2013 (hereinafter: TEN-E Regulation) was created to facilitate the construction of this new European infrastructure. The EU legislator explicitly stated in 2013, one year before the planned completion of the internal energy market, that "the market remains fragmented due to insufficient interconnections between national energy networks and to the suboptimal utilization of existing energy infrastructure." It should be noted that the construction of new interconnections between the Member States does not only serve the purpose of the internal electricity market, it also aims at contributing to the realization of the 20/20/20 goals[35]. The EU legislator stated that the EU legislation should facilitate innovative transmission technologies for electricity allowing for large scale integration of renewable energy.

When one takes the TEN-E Regulation into consideration when reading the EU legislation on the internal electricity market, the use for a grammatical interpretation of the Electricity Regulation might not be as strong as it seems. All the more so when taking into account that electricity legislation is based in 1990s when no significant offshore electricity production existed. Further, legislation was based on the organization of the electricity sector at the moment of drafting, i.e. centralized onshore plants. This explains why the legislator has only recently included offshore activities into electricity legislation.

Following the increased significance of decentralized energy production and large scale offshore wind production a reinterpretation of current legislation is necessary. As part of this development, new definitions for the combination of offshore wind with Interconnectors, or with more extensive offshore grid topologies connecting different countries, could be considered.

The second solution is to develop a specific definition for this new type of infrastructure, and this definition should be laid down in new European legislation. It is assumed that the extensive interpretation would be faster to apply than the formulation of a new definition, but this also creates a degree of legal uncertainty. Drafting a new definition will be more time consuming, whereas it provides for more legal certainty on the other hand. The new definition and accompanying legal framework can be inserted in the European legislation thus making the interconnecting link a “special purpose grid”. The formulating of a new definition should be done with great caution. Critical attention should be paid to the following two matters. Firstly, the exact components of the interconnecting link should be described. The legislator has to decide whether the interconnecting link is merely the cable between the two offshore

[35] 20% less CO_2 emissions, 20% of the energy consumption from renewable sources and 20% more energy efficiency. These targets are set by the Directive 2009/28/EC.

wind farms or if the interconnecting link encompasses the entire offshore infrastructure. The choice for either option influences ownership issues and the rules that will apply for operating the interconnecting link. The choice will also influence the possible applicability of national legislation. For example, if the whole shore to shore connection is treated as a single piece of infrastructure, than the UK OFTO regime is possibly excluded. Secondly, attention should be given to the wider context. Within the EU there is the idea of creating an offshore grid in the North Sea. The new definition for the interconnecting link should not hinder the designing of a future regime for the offshore grid.

When formulating a new definition for the interconnecting link, there remains the issue on the moment of deciding on a definition. There are two options open for the legislator. Wait for the moment on which the construction of the interconnecting link is technological feasible and then regulate that type of infrastructure. Or regulate the interconnecting link at this moment by way of a temporary definition as a provisional solution. Choosing the latter option would mean that the construction of the infrastructure that is envisaged in this project will be made possible as of that moment.

4.2.2. The role of the OFTO regime

Part of the integrated electrical offshore infrastructure on the UK side will, under certain circumstances, fall under the OFTO regime. The OFTO regime is the UK regime that governs the tendering, construction and the operation of offshore transmission assets. This regime for offshore transmission infrastructure is likely to be applicable for the part of the infrastructure that connects the UK offshore wind farm to the UK shore. The preliminary question which has to be addressed is whether the OFTO licensee is a TSO. The stance of the UK regulatory authority is that this is the case. This means that all of the obligations of the European Electricity Directive and Electricity Regulation apply to the OFTO license holder.

The research has shown that the OFTO tendering regime has a number of advantages as well as disadvantages. The advantages of the OFTO tendering model can be divided in financial and operational advantages. The financial advantage is the fact the investor can expect a steady income over a longer period of time. The offshore wind farm developer benefits from the operational advantages because the OFTO regime provides some flexibility with regard to the development of the offshore wind farm. Nonetheless, the research has shown that there are also a number of disadvantages to the OFTO tendering regime. The most important disadvantage is the compensation that the offshore wind farm operator receives if the generator-build model is used. It is expected that the offshore wind farm operator in general will not receive the regulated profit of ten percent due to the fact that cost assessment is based on the construction under optimal circumstances. This makes that the wind farm operator bears the risk of any complication in the construction of the of offshore transmission assets.

Additionally, there is the question of what is exactly being tendered. It is assumed that the tendering procedure will not encompass the whole capacity on the offshore transmission infrastructure, being transmission capacity and interconnection capacity. The developer of the offshore transmission system does not have any incentive to include the optionality for interconnection into the design of the offshore substation as he will only be reimbursed for the construction of the infrastructure that is needed for connecting the offshore wind farm. He only bears additional risks should he include interconnection optionality, because he might risk constructing an offshore substation for he will not be reimbursed.

In conclusion, there are a number of advantages as well as disadvantages to the OFTO tendering regime. This is why the UK legislator should seek to improve the OFTO tendering regime and should include consideration of interconnecting links.

4.2.3. Support schemes

The operators of the offshore wind farms will need access to subsidies in order to produce electricity economically. In this report we focus on the national subsidy regimes that support the production of electricity that is generated from renewable sources. We will not address other instruments such as tax reductions. As indicated, the existing subsidies regimes are national in scope. This means that the electricity needs to be injected into the national transmission system. In order to determine whether electricity is injected into the national transmission system one needs identify the Point of Common Coupling. In the UK this Point of Common Coupling is located at the point within the offshore transmission system of the OFTO license holder that is electrically nearest to the offshore wind farm.[36] In the Netherlands the Point of Common Coupling is located at the point where the cable of the offshore wind farm is connected to the offshore substation of TenneT.[37]

In the UK, offshore wind energy generation is currently supported by a *renewables obligation* requirement under the Electricity Act until March 2017 and the Contracts for Difference (CfD) scheme. The renewables obligation is a requirement on licensed UK electricity suppliers to source a specified proportion of the electricity they provide to customers from eligible renewable sources and to produce Renewables Obligation Certificates (ROCs) in proof of this. The CfD is a subsidies scheme based on feed-in tariffs, which guarantees producers of renewable energy and electricity from low carbon sources a fixed minimal income. It should be noted that the CfD scheme is also open to nuclear energy and coal fired generating in conjunction with carbon capture and storage. The focus is not on the use of renewable energy sources, but on the generating of electricity with a low carbon footprint.

Offshore wind energy in the Netherlands may benefit from government subsidies encouraging sustainable energy production, especially renewable energy production. The current subsidy regime is the *Stimuleringsregeling Duurzame Energieproductie* (SDE+). This latest scheme is available only to businesses and organizations, and only the most cost effective techniques will be granted subsidies.

The Dutch subsidizing regime is based on the idea that in order to receive subsidies, the generated electricity needs to be fed in on the national grid. This makes it impossible for a Dutch wind farm operator to transport the electricity directly to the UK grid through its' own cable, and receive subsidies from the Dutch government. The amendment of the Electricity Act '98 created for TenneT the obligation to connect future Dutch offshore wind farms to a sub-station of TenneT. It is therefore assumed that in the future a Dutch wind farm operator will not be able to lay its' own cable to the UK. For a potential interconnection between offshore substations between the UK and NL, the risk of losing subsidies as a result of direct electricity exports through the offshore sub-station has been removed as a result of the amendment of the Electricity Act '98. The situation is different should the Dutch wind farm operator export the electricity to the UK and apply for subsidies under the CfD regime. In that

[36] See UK Grid Code, GLOSSARY AND DEFINITIONS, available at: http://www2.nationalgrid.com/UK/Industry-information/Electricity-codes/Grid-Code/.
[37] TenneT, 'Kwaliteits- en Capaciteitsdocument Net Op Zee 2016, p. 21.

case, the Dutch wind farm operator is eligible for subsidies. It should be noted that a wind farm operator in the UK cannot apply for SDE+ subsidies should he export his electricity to the Dutch grid.

To conclude, the national subsidy schemes are national in scope. Before an interconnecting link between the offshore sub-stations of the wind farm operators can be seriously considered both SDE+ and CfD needs to be modified to facilitate exchange and compensate wind energy from other countries.

4.2.4. Priority access and cooperation mechanism under the renewable energy directive

The Renewables Directive stipulates that each Member State shall ensure that the national TSOs and distribution system operators guarantee the transmission and distribution of electricity produced from renewable energy sources; provide for either priority access or guaranteed access for electricity produced from renewable energy sources; and shall ensure TSOs give priority to renewable energy installations when dispatching generating stations (Art. 16 Renewables Directive). Due to the fact that under some circumstances the interconnecting link cannot be classified as either a transmission cable or an interconnector when the line is constructed between the offshore substations of two offshore wind farms, it seems that this provision does not automatically apply to interconnecting link. However, in the case of a future interconnecting link between an UK and a Dutch wind farm the interconnector is constructed between the offshore sub-stations of the UK and Dutch TSO. The offshore wind farms will at least have priority access to the cable to shore in the future.

To assist Member States in achieving their national targets of renewable energy production, the Renewables Directive introduces the possibility of cooperation between Member States. Three specific mechanisms for cross-border cooperation are provided for by the Renewables Directive. These are statistical transfers, joint projects and joint support schemes[38]. From the private investor perspective, the instrument of the joint project is the most preferable instrument as it facilitates the realization of the envisaged infrastructure in a relative short period of time. From a regulatory perspective however, it is best that a well-designed joint support scheme should be put in place before commencing with the construction of the wind farms and the cross-border electrical infrastructure. Irrespective of the choice of either the instrument of the joint project or the joint support scheme, it is required that the authorities of the UK and the Netherland cooperate from the earliest stage as possible. It is not only important to reach consensus on financial matters, but there should also be agreement on the allocation of renewable energy production.

4.2.5. Coordinating of licensing

Additionally, for the construction of the integrated infrastructure it is required that in both countries the relevant licenses are granted. The required licenses and exemptions for both the UK and the Netherlands are listed in Table 4-1.

For the construction of the offshore wind farms and the additional electrical infrastructure, it is required that all of the licenses are obtained. This means that competent authorities in both the Netherlands and the UK should coordinate their efforts so that the licenses for an interconnecting link can be granted at the same moment. At this moment there is no

[38] See §4.2.2.1. of appendix E for a more detailed description of these instruments.

obligation for both states to coordinate their efforts. This could be different if the project was listed as a Project of Common Interest as referred to in the TEN-E Regulation.

Table 4-1: Required licenses and exemptions for the UK and the Netherlands.

UK	Netherlands
Consent to construct and operate the offshore wind farm, including all ancillary infrastructures (S. 36 Electricity Act 1989).	A license for construction of the offshore wind farm, including all ancillary infrastructures in the Dutch Exclusive Economic Zone (EEZ) or territorial sea (Art. 12 Offshore Wind Energy Act).
A License to deposit materials such as the turbine foundations and the buried cables, on the seabed (S. 5 Food and Environment Protection Act 1985).	A license for the construction for the onshore components (Art. 2.1 Environmental Licensing Act).
A consent in order to make provision for the safety of navigation in relation to the export cables (S. 34 Coast Protection Act 1949).	
A planning permission, sought as part of the section 36 application, for the onshore elements of the works required (S. 90 of the Town and Country Planning Act 1990).	
Consent for the extinguishment of public rights of navigation for the areas of seabed directly covered by the offshore structures comprising of the turbines, offshore substation and anemometry mast (S. 36A Electricity Act 1989).	
A request for the establishment safety zones of up to 500 m around all structures, which will limit the activities of certain vessels within this area. (S. 95 Energy Act 2004).	

4.2.6. The TEN-E Regulation

The EU has recognized the need for the establishment of trans-European energy infrastructure (Art. 170(1) Treaty on the Functioning of the European Union (TFEU)). In order to implement this policy the TEN-E Regulation was established. This regulation provides for procedures to coordinate and realize the timely completion of essential energy infrastructure. In addition to procedural rules, the regulation provides for financial support in specific cases (Art. 14 TEN-E Regulation). In order for a project to be subjected to the rules of the TEN-E Regulation, the project needs to have the status of a Project of Common Interest (Art. 2(4) TEN-E Regulation). There is a substantive and procedural aspect when determining whether this project can obtain the status of Project of Common Interest (PCI).

The substantive aspect focusses on the components of the project. The entire project needs to meet a number of criteria. First there are the general requirements. The first general criterion is that the project needs to be situated within a priority corridor (art. 4(1)(a) TEN-E Regulation). The North Sea is such a priority corridor which is listed on the first annex of the regulation. It should be noted that the EU legislator mentions specifically the Northern Seas offshore grid which should be used for the purpose of transporting electricity from renewable offshore energy sources. The second general criterion is that the long term benefits of the project outweighs the cost of the project (art. 4(1)(b) TEN-E Regulation). This is the case if one looks at the increased social welfare that is created with an interconnection wind farm combination. The third general requirement is that the project needs to be situated between one or more Member States or shall have distinctive benefits for more than one Member State if the project is located in one Member State. For electricity projects there are a number of additional requirements (art. 4(2)(a) TEN-E Regulation). These include among others that the project involves high voltage networks and contribute significantly to market integration and sustainability.

It is assumed that this project meets the substantive criteria to be considered a PCI (Art. 4 TEN-E Regulation). The envisaged project is situated within the North Sea priority corridor (point 1 Annex I). The project also meets the criteria of Article 4 paragraph 1 & 2. Nonetheless, there is also the procedural aspect that requires that the project is identified by the EC as a PCI. Projects similar to those assessed in this Synergies at Sea project were not included on the list of PCI that was added to the TEN-E Regulation by the delegated regulation of the EC of 16 October 2013. This means that these projects cannot benefit from the TEN-E Regulation. In 2015 the EC published a new list[39], and this means that a new project has to wait until the next round in order to be designated as a PCI in 2017.

4.3. The private investor perspective

4.3.1. Constructing the infrastructure

In order for private investors to be involved in constructing an Interconnected Link the cable has to be determined/accepted as being exempted from the Electricity Directive and Regulation. This means for example that rules on regulated TPA do not apply to this cable. However, other public law remains applicable on both the international, European and national level. From the international perspective UNCLOS is the most relevant piece of legislation. On the European level there are directives that regulate activities in the North Sea, such as the Habitats Directive, the Bird Directive and the Marine Strategy Framework Directive. These directives deal with the environmental framework and have been implemented in both the Dutch and UK legislation. Furthermore, there are the European rules on competition as laid down in the TFEU.

4.3.2. Access to the interconnecting link

The interconnecting link, if it is considered to be a sui generis cable, could still be classified as an essential facility. There is no exact definition for essential facilities as basically any type of infrastructure can be an essential facility. This may vary from harbors to electricity infrastructure as is the case in this research. The basic idea is that it is something owned or controlled by a dominant undertaking to which other undertakings need access in order to provide products or services to customers. When the interconnecting link is treated as an essential facility, comparable to upstream pipelines in the hydrocarbon-sector, it means that market participant should have non-discriminatory access to the cable. This rule of non-discriminatory access is based on the general principle of equality and which is codified in article 102 TFEU on the prohibition of abuse of market powers. Denying a market party access to an essential facility is considered to be an abuse of a dominant market position.

It should be noted that the essential facility doctrine is used when no other legislation applies. Furthermore, it is a form of ex post regulation. Only after a party is denied access to an essential facility can he turn to the courts for protection.

[39] https://ec.europa.eu/energy/en/topics/infrastructure/projects-common-interest

4.3.3. Exemption

In the case that the interconnecting link could be classified to be an interconnector, it is required that the private investor acquire an exemption from the EC. This is necessary because a producer of electricity who operates the offshore wind farm(s) cannot own or operate the transmission infrastructure. According to Article 17(1) of the Electricity Regulation, there is the possibility to exempt, upon request to the national regulatory authorities, an interconnector from the rules in the Electricity Regulation and Electricity Directive[40]. An exemption does not necessarily have to cover all obligations but may be limited to a particular rule or rules. Furthermore, the exemption may be limited to a certain share of the overall capacity of the interconnector.

Under the current legal regime, four requests for exemptions where brought before the EC. These exemptions concerned the following interconnectors: BritNed, Estlink between Estonia and Finland, East-West Cables between Ireland and the UK, and Tarvisio-Arnoldstein between Italy and Austria. The EC assesses the criteria for granting an exemption strictly. In the case of the first three interconnectors, which are all submarine cables, exemptions were granted subject to conditions, while in the case of the Tarvisio-Arnoldstein the EC refused to grant an exemption.

The fact the EC assesses the criteria strictly, indicates that acquiring an exemption is expected to be more difficult in future. However, each request will be decided upon its individual merits. This makes it extremely difficult to predict whether an exemption will be granted or refused.

4.4. TSO investor perspective

4.4.1. TenneT as the offshore TSO

When we started this study the role of TenneT in the EEZ under the new Electricity Act was unclear. Due to the high degree of ambiguity at that time, we decided to focus on two approaches. In the first approach, the Electricity Act ’98 would be made applicable to the Dutch EEZ in full through an offshore paragraph. In the second approach, the German example would be followed by creating a regime which centered around liability for establishing the offshore grid connection for the wind farms.

Before an offshore paragraph can be inserted in the Electricity Act, it is required that the legislator formulates the relevant definition of an offshore grid. In this research the focus has been on the definitions of grids (Art. 1(1)(i) Electricity Act ’98) and interconnections (Art. 1(1)(as) Electricity Act ’98). It was found that the existing Dutch definition of a ‘grid’ is insufficient to apply to the offshore area.

The envisaged offshore paragraph should strike a balance between the ability of TenneT to operate as an offshore TSO and the needs of offshore wind farm developers. The offshore paragraph should among others provide for strategic offshore grid planning. This strategic planning is to be laid down in an offshore grid plan. This offshore grid plan must be developed by TenneT in close cooperation with the industry and the government. This is because of the three different actors which are involved in the planning of developing of offshore wind farms. Furthermore, the offshore paragraph should provide for a legal basis for delegated legislation, such as technical codes.

[40] See §3.2.6.2. of Appendix C for a more detailed description of the criteria for obtaining an exemption.

However, the situation will be completely different should the legislator opt for the implementation of the system that is used in Germany. The German regime for offshore wind farm connections is based on a liability regime. Before discussing the liability regime, it is important to mention that the German TSOs are also under the obligation to draft an offshore grid development plan (S. 17b *Energiewirtschaftsgesetz* (EWG)). This offshore grid development plan enables wind farm developers and the TSO to perform a strategic planning for the development of offshore wind farms and the connections to the transmission.

Under the *Energiewirtschaftsgesetz* (EWG), the TSO is responsible to connect producers of electricity to the grid (S. 17(1) EWG). When the TSO is unable to provide the wind farm developer with a working connection to the grid, the TSO is obliged to pay damages to the wind farm developer (S. 17e EWG).

Apart from the question which form is chosen for regulating the offshore grid, there is the issue of defining the offshore grid. If the offshore grid is to defined as a transmission grid, it could be possible that the interconnecting link can be deemed to be an interconnector. The interconnector than connects the UK offshore transmission grid, operated by the OFTO license holder, to the Dutch offshore transmission grid which is operated by TenneT.

Finally, during 2015 the government presented the bill for the new Electricity Act, but this bill was voted away in the First Chamber of the Dutch parliament. The veto of the First Chamber is viewed as a delay instead of a final rejection. In April 2016 an act was passed through parliament to 'repair' the Electricity Act '98 in order to start the tender procedures for new offshore wind farms in time.[41]

The amendment of the Electricity Act '98 was only a limited modification of the existing Electricity Act and not the complete overhaul that was proposed under STROOM.[42] The benefit of the 'reparation' of the existing Electricity Act '98 is that the construction of new offshore wind farms may commence according to the timetable of the Dutch government. Nonetheless, the disadvantage of the 'reparation' is that the uniformity of the original proposal of the government is lost. Firstly, the introduction of the more uniform terminology based on European definitions instead of national definitions was discarded. Secondly, not all of the proposed provisions under STROOM were included in the reparation amendment and may give rise to debate whether the proposals made under STROOM have been changed during the legislative procedure for the amendment of the Electricity Act '98.

For the purpose of this research it is important to mention the following changes in the Dutch Electricity Act '98. The legislator introduced a legal definition for the offshore transmission system (Art. 15a Electricity Act '98) and made TenneT responsible for establishing a connection between the offshore transmission system and the onshore transmission system (Art. 16(2)(n) Electricity Act '98). In order to steer the development of the offshore transmission system the government will draw a framework for TenneT (Art. 16e Electricity Act '98). TenneT will include the necessary investments in the capacity and quality document (Art. 21(2)(h) Electricity Act '98). This documents needs approval from the ACM and the ACM will include the cost for connecting the offshore wind farms in the tariffs of TenneT (Art. 20d(3) Electricity Act '98).

[41] Stb. 2016, 116.
[42] For more information on STROOM see: https://www.rijksoverheid.nl/doe-mee/afgeronde-projecten/toekomst-elektriciteitswet-en-gaswet

The new Dutch regime includes an arrangement for compensating wind farm developers in case the connection is not established by TenneT in due time (Art. 16f Electricity Act ’98). This arrangement is based on the experiences in Germany under the German *Energiewirtschaftsgesetz*. The regime that the Dutch legislator implement is however not precise on what sort of damages are eligible for compensation. The Electricity Act ’98 states that the wind farm developer may claim delayed income, but there is no explanation on what is considered to be delayed income.

Finally, TenneT shall receive subsidies for the construction and maintenance of the offshore transmission system (Art. 77g Electricity Act ’98). The details of this arrangement are to be laid down in a royal decree (Art. 77g(3) Electricity Act ’98), but it is already clear that the funds for the subsidy will come from the SDE+ reserves.[43]

4.4.2. The role of the ACM

When the Dutch Electricity Act will be made fully applicable to the EEZ, the ACM, as the regulatory authority, is competent to regulate TenneT. The ACM must do this with due regards for multiple and sometimes conflicting interests. These interests include those of the grid operators, the producers of electricity, the consumers and the society as a whole. It is assumed that the position of TenneT as an offshore TSO will be different than the position of TenneT as the onshore TSO. This is because of the specific circumstances in the offshore setting.

The system of regulated tariffs enables TenneT to do investments. In the parliamentary history of the amendment of the Electricity Act ’98 it is stressed that the method for tariff regulation for the offshore grid is based on the system of Directive 2009/72/EC and Regulation (EC) 714/2009.[44] The only difference is that TenneT in the role of offshore TSO will not reimburse the investment through tariffs paid by the system users but through a government subsidy.

4.4.3. The auction of capacity

In the future situation when the interconnecting link can be qualified as an interconnector as it is a connection between two offshore sub-stations of two TSOs, there is the aspect of granting access to this cable for the wind farm operators. One should recall that the European legislation prescribes the unbundling of TSOs and trading entities. This means that the party who owns the wind farms cannot have an interest in the interconnector. This means that the wind farm should get access to the cable on the ground of priority access in the case of lack of capacity. However, access to the interconnecting function of the cable in time of scarcity is only available through a competitive auction.

In order to connect the wind farm to an interconnector it is required to put a special regime in place. The wind farm in theory could acquire access on the interconnector by bidding on the day ahead spot market if there is insufficient capacity. However this is not without complications due the intermitted character of wind energy production. The exact output of a wind turbine can only be predicted with a small error for a couple of hours ahead. This makes it difficult for the wind farm operator to secure sufficient capacity when he only has access to the day ahead spot market.

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[43] *Kamerstukken II* 2015-16, 34 401, nr. 3, p. 7.

[44] *Kamerstukken II* 2015-16, 34 401, nr. 3, p. 7-8.

This means that the wind farm operator needs to apply for an exemption, so that part of the interconnector may be reserved for the offshore wind farm (Art. 17 Electricity Regulation).

4.5. Recommendations

To summarize, the following recommendations can be made.

- The responsible national ministries should advise and facilitate the European legislator should create a legal framework for the interconnecting link. This framework should deal with matters such as unbundling, third party access and investment reimbursement.
- The national regulators should aim to streamline and coordinate their licensing procedures. In order to create a legal obligation for both the Netherlands and the UK to coordinate the licensing procedures, the project should get the status of a PCI under the TEN-E regulation.
- For the UK side of the project it is important to assess how the OFTO tendering system could be made more suitable to facilitate offshore grid development.
- It is advised that the national public authorities ensure that cross-border flows of electricity can take place without impediment. Electricity that is exported directly over the interconnector should not be treated differently with regard to subsidies.
- The modernization of the Dutch Electricity Act is an important step forwards for the increase in offshore wind energy in the Dutch EEZ. Nevertheless, for an integrated synergy at sea solution to be feasible it is important that the legislation is suitable for such a solution. The legislation must not only allow for the construction of the connection between the wind farm and the shore by the TSO, but should also include the possibility of interconnection. If the government exclusively wants to focus on near shore wind farms in the foreseeable future, then the synergy solution is also unlikely.

5. Economic analysis from private investor’s perspective

Based on the worked-out technical scenarios, this chapter covers the private investor view regarding the investment in an interconnecting link. The valuation model established for this purpose aims at quantifying the intrinsic value of an interconnecting link. Therefore, results are independent from whether capacity on such infrastructure needs to be auctioned or whether it is exempted from auctioning.

The business case inputs and assumptions are covered in section 5.1, a high level model description in section 5.2, results and discussion in section 5.3, wind farm LCoE impact is covered in section 5.4 and conclusions in section 5.5.

5.1. Business case inputs and assumptions

The inputs for the valuation model can be divided in two categories: exogenous inputs and assumptions and technological parameters.

5.1.1. Exogenous inputs and assumptions

This section considers all exogenous assumption, relating to (macro-)economics. These are controlled by external (non-project related) factors. All inputs and assumptions can be found in Table 5-1.

At this stage of the study the project is assumed to be financed with 100 % equity, coming from one investor. Within the Synergies at Sea project, the subproject *New Financial Structures and Products* is dedicated to elaborate on different financing possibilities.

The *Weighted Average Cost of Capital (WACC)* is defined by the following formula:

$$WACC = f_e \cdot r_e + f_d \cdot r_d \cdot (1 - t_c)$$

$$f_e = part\ equity$$

$$r_e = cost\ of equity \qquad (5\text{-}1)$$

$$f_d = part\ debt$$

$$r_d = cost\ of\ debt$$

$$t_c = corporate\ tax\ rate$$

This definition can be interpreted in two ways. First is the project finance view. The cost of equity shows the expected equity return required by the investor and the cost of debt is the interest rate offered by banks for that specific project, constructed by that specific investor. An alternative view is the corporate finance view, where the WACC is the cost of capital for a specific investor. Since the business case is built on a 100 % equity investment, the WACC is assumed to be at the level of a Dutch TSO. Taking the same WACC as used for the social benefit analysis (chapter 6) allows better comparison between the results of the two models.

Corporate tax and inflation rate are taken from different external sources. Whereas the corporate tax rate is the actual current rate, the inflation is taken to be the target rate as set by both the Dutch Central Bank (DNB) and the European Central Bank (ECB).

The project lifetime is assumed to be equal to the certified lifetime of currently installed offshore wind turbines. It should however be noted that the new generation offshore wind turbines will have a longer certified lifetime and electrical infrastructure in general is expected to have a longer technological lifetime. Linked to this is the fiscal tax depreciation, which is assumed to have a 15 years tenor and is done following the *straight line* method. The latter means an equal share of the total asset value is depreciated per year. The tax method is *tax credit*. This means negative net earnings in a given year result in tax reduction against the profit of the rest of the investor's asset base.

The NPV or discount date is the date that (offshore) construction starts. At that point in time up to 100 % of all capital expenditures (CAPEX) are committed and a significant amount is already spent.

The change in working capital is assumed to be zero. Proprietary assumptions are used for Contractors All Risk (CAR) insurance, project management costs (both project development and construction management costs) and contingency.

Table 5-1: Exogenous business case inputs and assumptions.

Item	Unit	Value/Assumption	Source
Equity	[%]	100	Project specific
WACC	[%]	5.5	NL Ministry of Finance[a]
Corporate tax rate	[%]	25	KPMG[b] - Netherlands
Inflation rate	[%]	2	DNB[c]; ECB[d]
Project lifetime	[yrs]	20	Project specific
Depreciation tenor	[yrs]	20	IFRS
Depreciation method	[-]	Straight line	IFRS
Tax method	[-]	Tax credit	Project specific
NPV date (start of construction)	[yr]	2018	Project specific
∆Working capital	[%]	0	Project specific
CAR insurance costs	[Me]	Proprietary	Project specific
Project management costs	[Me]	Proprietary	Project specific
Contingency	[Me]	Proprietary	Project specific

[a] An interest rate of 5,5% is assumed in order to calculate the NPV. This interest rate is proposed by the Dutch Ministry of Finance for Social Cost-Benefit Analyses (Ministerie van Financiën, 2011).
[b] http://www.kpmg.com/global/en/services/tax/tax-tools-and-resources/pages/corporate-tax-rates-table.aspx
[c] http://www.dnb.nl/rente-en-inflatie/algemeen/index.jsp
[d] https://www.ecb.europa.eu/mopo/strategy/pricestab/html/index.en.html

5.1.2. Technological parameters

The technological scenarios (Figure A-2, Figure A-3 and Figure A-4 in Appendix A) form the input for the valuation of the different scenarios. Three different inputs are generated based on the technological scenarios.

First, the investment costs of the different scenarios are fed into the business case. For the purpose of determining the profitability of the interconnecting link, only the excess investment and excess returns are being regarded. This means that the costs of the wind farms including costs for a radial connection to shore are being deducted from the total costs per scenario (wind farms + interconnecting link). In similar fashion, only the revenues from trading activities on the interconnecting link are taken into account. Revenues from the wind farms are completely disregarded.

Second, the OPEX costs are assumed to be a fixed sum per year. The amount is based on previous on- and offshore electrical infrastructure projects. OPEX costs have been assumed as 1 % of the investment costs of onshore equipment and 1.5 % of offshore equipment.

Third, the electrical losses (section 3.5 and section 3.6.2) are used to model the revenues per scenario. The loss factors are used in a similar fashion as the investment costs. Only the losses of the interconnecting link are taken into account. At every time interval it is determined whether the spread between market prices in the UK and Netherlands is large enough to overcome these losses.

5.2. Model description

The modelling work consists of two separate models, a *revenue model* and a *business case model*. The first is used to simulate the expected trade volume and revenues, coming from the interconnecting link. Together with all other assumption this is fed into the business case, in order to calculate profitability per scenario. The logical flow of information through both models is covered in sections 5.2.1 and 5.2.2.

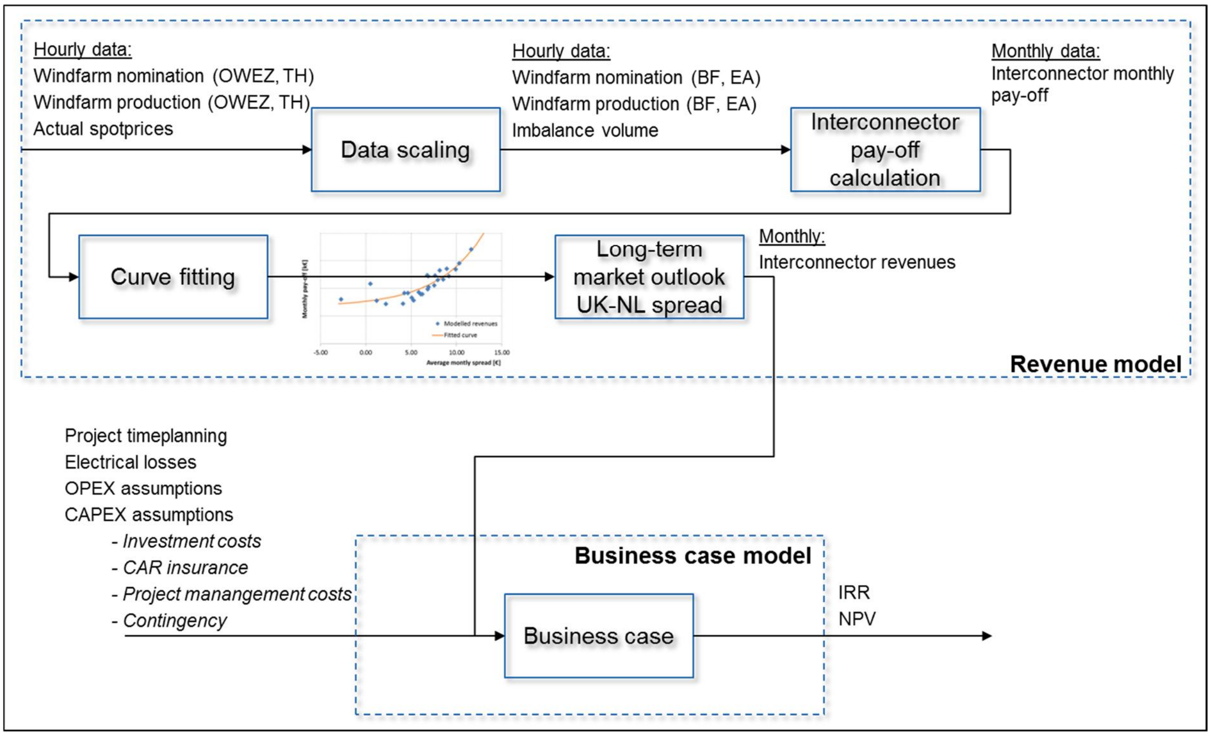

Figure 5-1: Modeling flow-chart.

5.2.1. Revenue model

In order to model the expected revenues for each scenario, actual hourly data for *Offshore Wind Egmond aan Zee* (OWEZ) and *Thanet Offshore Wind* (TH) is used. This includes both day-ahead nominated figures and actual production, together with the actual spot prices. Using the difference between nominated and actual production, the implied imbalance volume can be calculated.

The wind farm data is subsequently scaled to the size of *Beaufort Offshore Wind* (BF) and *East Anglia Offshore Wind* (EA) wind farms and for each hour the free capacity for trading on the interconnecting link is calculated. Four different scenarios can be distinguished: First is the scenario with a standard interconnector that is not connected to the wind farms. The second and third scenarios are a Dutch and British wind farm connected to the UK and the Netherlands, respectively. The fourth scenario consists of an interconnecting link with both a Dutch and British wind farm connected. For each scenario a piece of visual basic code was written in order to determine what piece of cable was limiting to trading opportunities at any given hour.

Based on the above assessment, the past pay-off for that scenario was calculated on a monthly basis. As a general principle, priority is always given to power produced by the wind farms. The residual capacity on the interconnecting link is deemed free for trading purposes. The data have been plotted in a graph that shows the monthly pay-off against the average monthly price spread between the UK and the Netherlands. The pay-off curve can be interpreted as the option pay-off curve of the hourly option to trade power over the interconnecting link. This pay-off curve is a composite of the two embedded options presented by owning an interconnecting link. The first is the pay-off of the option to trade power from the Netherlands to the UK, the second from the UK to the Netherlands. This is graphically shown in Figure 5-2, where a positive spread is defined by Dutch power prices being lower than UK power prices causing a flow from the Netherlands to the UK. It should be noted that the schematic drawings in Figure 5-2 do not include the threshold spread that needs to be overcome, caused by electrical losses and direct operational expenditures (direct OPEX). Furthermore, it doesn't show the convexity of the pay-off curve.

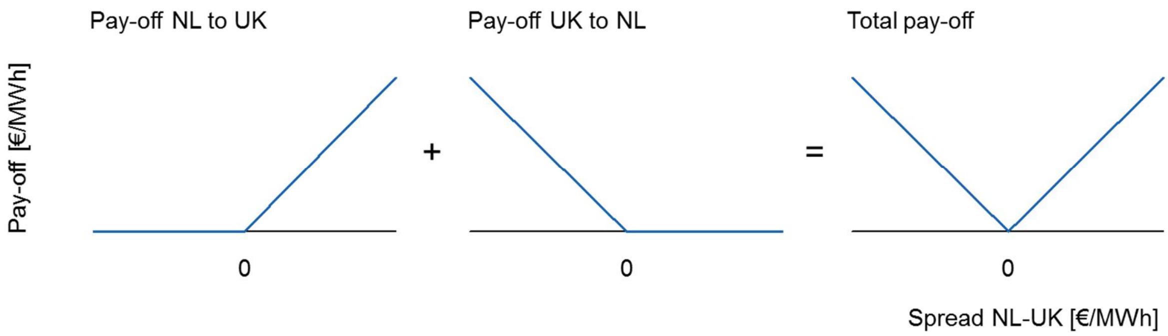

Figure 5-2: Two embedded options presented by owning capacity on an interconnecting link.

With all data points plotted, a three parameter curve was fitted for all scenarios. The curve has the following shape:

$$P(S) = a \cdot e^{bS} + c$$

$$P(S) = payoff\ as\ a\ function\ of\ spread\ (UK, NL) \qquad (5\text{-}2)$$

$$a, b, c = 1st, 2nd, 3rd\ fitting\ parameters$$

The parameters are determined by using a solver to minimize the mean squared error (MSE) of the dataset. An example of this is shown in Figure 5-3. The figure shows that the above mentioned formula only gives the pay-off curve for flows from the Netherlands to the

UK. This was chosen as the most efficient way of modelling, as it requires more complicated solvers to find the best solution for the combined pay-off curves. This choice was enabled by the fact that the average spread was negative in only one of the 26 months (18938 hours) of available data. Using a single curve leads to conservative results, as the pay-off would have been minimal at zero spread. It shows in Figure 5-3 that the pay-off for a negative average monthly spread is actually below the pay-off level at zero spread.

It should be reminded that this pay-off curve includes all factors that affected production in the past and implicitly assumes these will stay the same in the future; i.e. it is assumed that imbalance stays at the same level and there is no climate change.

After obtaining the pay-off curve, hourly forward looking price data are used to calculate the pay-off per scenario. The forward prices are based on a model making use of the expected future merit order, transmission capacity and fuel prices. The model is exogenous and price levels are therefore not affected by this specific interconnecting link, despite the fact that a certain development in transmission capacity is planned to take place.

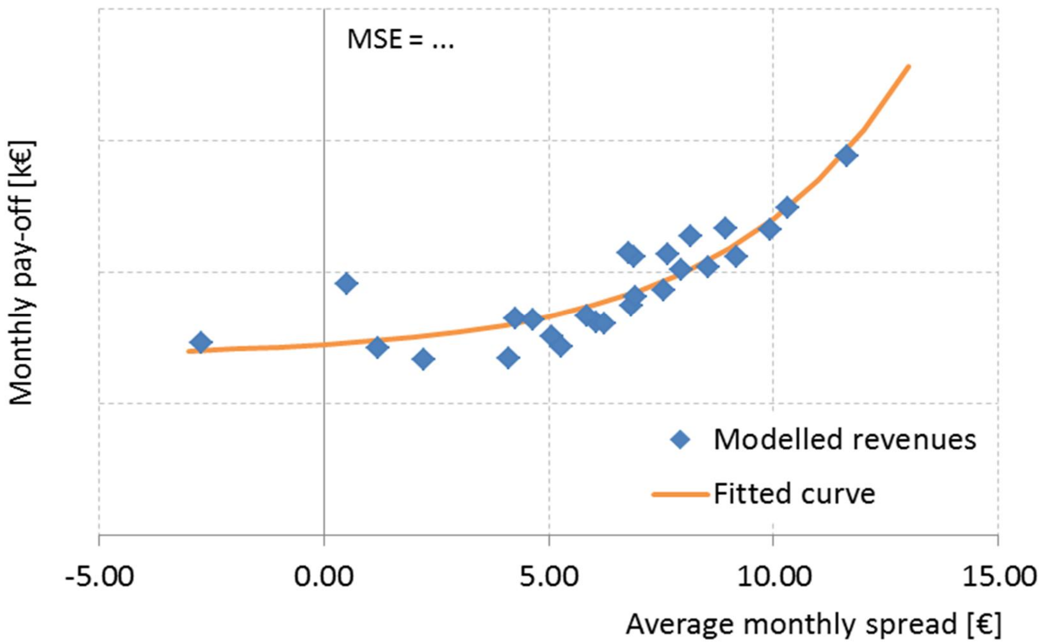

Figure 5-3: Pay-off curve.

5.2.2. Business case model

The business case model is a discounted cash-flow model, which is the most common type used for asset valuation. The model combines all inputs as shown in Figure 5-1. The mechanics of the model are proprietary and will therefore not be elaborated on in this report.

The business case outputs for this study are the Internal Rate of Return (IRR) and Net Present Value (NPV) of the project. The Internal Rate of Return (IRR) is the compound periodical return rate achieved by a project. Also it is the discount rate at which the NPV is zero. The higher the IRR, the better. Typically, the IRR of a specific investment needs to exceed a certain hurdle rate in order to be deemed an attractive investment. The hurdle rate is a function of all risks connected to that investment. A recent KPMG45 study stated a 10.9 % hurdle rate for offshore wind projects. The general expectation is that financiers will similarly appreciate risks of offshore electrical infrastructure including offshore platforms.

The NPV is used to calculate value of a project. Just as the IRR it takes all cash flows into account, but additionally calculates the time value of money. Given the fact that all scenarios in this study are mutually exclusive (if one is built, none of the others will), the IRR is the first decision criteria for selecting the best project.

5.3. Results and discussion

This section covers the results of the business case analysis. The relative difference between the scenarios and their validity are discussed.

There are **two** standard interconnector scenarios included (no connected wind farms), **IC1200** and IC300. They are 1200 MW and 300 MW capacity interconnectors, respectively. These scenarios don't include offshore platforms as all transformers and switchgear is located onshore and only the cable itself is located offshore. For that reason the risk profile of these scenarios is different and therefore shouldn't be benchmarked against the KPMG study. Whereas the 7 % IRR for the 1200 MW interconnector may propose an interesting investment opportunity to an entity with limited risk appetite (e.g. TSOs), the 300 MW interconnect is economically unfeasible at −1 % IRR. This implies that both interconnectors and interconnecting links need a certain scale in order to be profitable.

For that reason it is no surprise that all scenarios with a 300 MW interconnecting link (**UK-NL1**, **UK-NL4**, **UK1**, **UK2**, **NL1** and **NL2**) are all unfeasible, with IRRs ranging between −9 % to 2 % IRR.

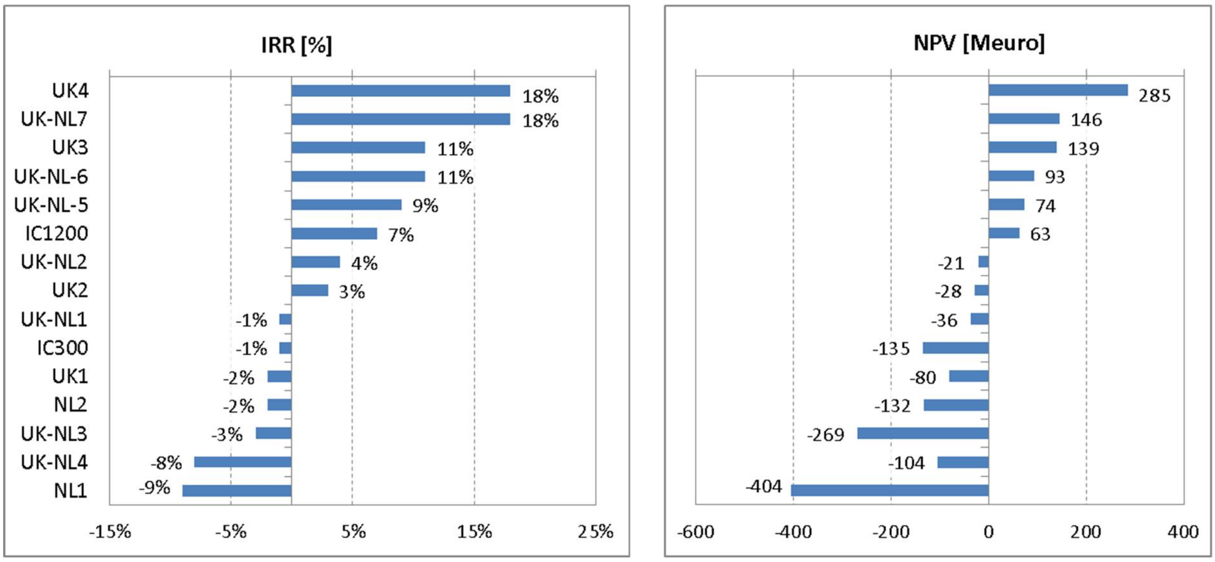

Figure 5-4: Internal Rate of Return (IRR) and Net Present Value (NPV) for the business case analysis.

UK-NL2 is the single scenario with a 600 MW interconnecting link. It is outperforming the 300 MW scenarios, but underperforming compared to the 1200 MW scenarios. This is due to

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[45] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/225619/July_2013_DECC_EMR_ETR_Report_for_Publication_-_FINAL.pdf

the fact that compared to the 1200 MW scenarios the investment costs are marginally lower, whereas revenues are significantly lower.

There is one scenario with a 1200 MW interconnecting link that comes out particularly poor, **UK-NL3**. This is due to the large investment costs, which are almost twice the average of all other 1200 MW scenarios. On the revenue side, this scenario is performing average and therefore it's underperforming in total.

The **UK-NL5** scenario performs similar to the **IC1200** scenario, but below the hurdle rate. This scenario is relatively generating large cash flows due to power trading activities on the surplus capacity. This upside is however more than compensated for by the additional investments that have to be made in order to upgrade the electrical infrastructure to a 1200 MW interconnecting link.

There are four scenarios with an IRR exceeding the hurdle rate of 10.9 %. These are **UK4**, **UK-NL7**, **UK3** and UK-NL6. These scenarios make most advantage of the cost synergies presented by combining offshore wind farms with an interconnecting link. Furthermore, these are making use the technological and economic advantages presented by HVDC technology.

In general, it can be stated that the ratio of wind farm to interconnecting link capacity is crucial. In the **UK3** and **UK4** scenarios, the UK wind farm is connected to the Dutch grid and the Dutch wind farm has a radial (separate) connection. Here, the profitability increases when the capacity of the UK wind farm decreases. This means the interconnecting link capacity that is not used to transmit wind power, generates more value than is required in terms of additional investments. Varying the capacity of the Dutch wind farm does obviously not affect the profitability, as it is connected separately. In the **UK-NL5**, **UK-NL6** and **UK-NL7** scenarios both UK and Dutch wind farms are connected to the interconnecting link. Here the inverse is true, meaning an increased capacity of the wind farms increases profitability. This adds more value than is lost by means of less cable capacity being available for trading purposes. All in all, the **UK4**, **UK-NL7** scenarios are both potentially attractive. The first generates almost twice the NPV, meaning much larger cash flows. This comes together with a much larger investment though.

The fact that the two best performing scenarios make use of multi-hub HVDC connections makes it difficult to plan decision making and investments. Initial design of the grid connection for the two stand-alone wind farms will be oversized. Next to that, the innovative character of the technology will increase the risk profile of the project. These two scenarios both assume complete efficiency in the process of designing two wind farms and an interconnecting link, i.e. they are being designed as one system. In practice, this will not necessarily be the case as an interconnecting link may be added to the existing infrastructure of wind farms. For these reasons, a more detailed analysis needs to be made for decision making and the sequencing of investments. This is part of the scope of subproject 2 of the Synergies at Sea project, named "New financial structures and Products".

When comparing these results with the results from the social benefit analysis (chapter 6), it should be taken into account that the business case considers the costs and revenues directly attributable to this project. In the social benefit analysis, also the effect this investment has on other generation- and transmission capacity is taken into account. It therefore evaluates the sum of all project cash flows, plus the change in cash flows caused to every other asset.

Conclusion

Two scenarios show the highest and equal level of Internal Rate of Return of 18%. These are **UK4**, and **UK-NL7**. This level is higher than the hurdle rate of 10.9%, implying that both would be financial attractive projects for a private investor.

5.4. Wind farm LCoE impact

A further assessment was made of the impact the interconnecting link has on the Levelized Cost of Energy (LCoE) of offshore wind energy in the Netherlands. LCoE is defined as the present value of all costs (CAPEX and OPEX) divided by the present value of the production volume.

Therefore, the output is in €/MWh. The formula for calculating LCoE is:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{C_t + O_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{P_t}{(1+r)^t}}$$

$C_t = CAPEX\ in\ time\ interval\ t$ *(5-3)*

$O_t = OPEX\ in\ time\ interval\ t$

$r = Discount\ rate$

$n = Project\ lifetime$

For the purpose of assessing the impact of the interconnecting link on the LCoE of offshore wind, two factors are taken into account. First is redundancy of the electrical grid, leading to higher (energy) availability of the system. This is a direct impact as it means a higher overall availability of the wind farm. The second effect is caused by the surplus return generated by the interconnecting link. Return surplus is defined as the excess NPV that causes the project return to be above the 10.9 % IRR threshold defined by the study mentioned in section 5.2.2. One may reason that an investor is willing to acquire the project rights at exactly that price. The mechanism through which this happens is assumed to be of no influence to the value, i.e. there's no distinction assumed whether that value is transferred to the wind farm owner or to society directly via a competitive tender. The impact of both is calculated for the two best performing scenarios, **UK4**, **UK-NL7**.

The redundancy figures are the result of calculations on the scenarios in figures A.1 and A.2 in appendix A. These show the difference in wind farm availability between a radial connection and an interconnecting link. It should be noted that for the Dutch wind farm, a DC interconnecting link connection will reduce availability compared to a radial AC connection. In order to calculate the NPV surplus, the project NPV is reduced until the IRR reaches 10.9 % hurdle rate. The NPV surplus assumed to be divided pro-rata to capacity between the UK and Dutch wind farms. Both the redundancy and NPV surplus input figures for the two best performing scenarios are shown in Table 5-2.

Table 5-2: LCoE reduction input.

	UK4	UK-NL7
Δ availability NL [%]	0.00%	-0.66%
Δ availability UK [%]	2%	1.34%
NPV surplus [M€]	116.9	63.15

In order to translate these results into a percentage of cost reduction, the publically available OT-model of ECN was used to calculate a benchmark LCoE for offshore wind in the Netherlands. This model was adapted in order to accommodate a 20 year project lifetime and 5.5 % discount rate, as shown in table 5.1. Furthermore, the production level was adapted to what turbines currently available on the market are able to achieve in the Dutch and British North Sea. The results of the LCoE analysis can be found in Table 5-3.

Table 5-3: LCoE reduction output.

[€/MWh]	UK4	UK-NL7
Δ LCoE availability NL	+0.00	+0.54
Δ LCoE availability UK	-1.58	-1.07
Δ LCoE NPV surplus NL	-1.60	-0.58
Δ LCoE NPV surplus UK	-1.60	-0.58
Δ LCoE Wind farm average	-2.39	-0.84
Δ LCoE Wind farm average [%]	3,0 %	1,0 %

The results for both scenarios are in the same order of magnitude and should be regarded as a current best estimate of the potential cost reduction presented by an interconnecting link. It should be noted that the two analyzed effects are not exhaustive. Factors that are not considered include, but are not limited to: economies of scale in project development, synergies in maintenance & operations and lower financing costs due to risk diversification.

5.5. Conclusions

15 scenarios were analyzed from a private investor perspective. Two of these were standard interconnectors, 13 were interconnecting links with one or two wind farms connected.

Only the 1200 MW standard interconnector presents a potentially interesting investment opportunity to a low risk-return appetite party, like a TSO. This is mainly driven by the fact that the transformer stations are located onshore, compared to offshore for the other scenarios. The 300 MW interconnector is unfeasible from an economic point of view. The same holds for all 300 MW interconnecting link scenarios.

There are two scenarios that well exceed the IRR hurdle rate, being **UK4**, **UK-NL7**. The UK scenario only involves a UK wind farm, whereas the UK-NL scenario involves both a UK and Dutch wind farm. It can be stated that from an economic point of view there's no preference for having one or two wind farms connected to an interconnecting link. Both are potentially profitable, when used in the right technological setup. Because the UK scenario involves less wind power capacity (900 MW), it requires larger additional investments to construct the 1200 MW interconnecting link. On the other hand, associated cash flows, and therefore NPV, are higher accordingly. The UK-NL scenario has twice capacity of wind power (1800 MW) and therefore requires lower additional investments. Similarly, due to less capacity remaining available for trading this setup generates lower cash flows and NPV.

These two scenarios maximize the benefits presented by new technology, in this case a (multi-hub) HVDC connection. However, there are associated risks coming with this technology, as it would require the wind farms to be initially developed with an oversized grid connection. This increases the project risk and reduces profitability. For that reason this pre-investment will likely only be done if it's the same party planning to construct both the wind farms and interconnecting link. The sequencing of decision making and investment, in order to retain an attractive project, will be elaborated on in the Synergies at Sea subproject New Financial Structures and Products.

By studying the impact of redundancy and return surplus of the scenarios on LCoE, it was found that the impact ranges between a 1.0 % to 3.0 % reduction for the best performing scenarios.

6. Economic analysis from society perspective

6.1. Background

A socio-economic feasibility study of integrating offshore wind infrastructure scenarios connecting two wind farms was performed: one near the shore of the Netherlands (Beaufort), and the other near the shore of UK (East Anglia). In this study fifteen infrastructure scenarios are constructed and compared to a scenario where the offshore wind farms Beaufort and East Anglia are only connected to the nearest shore via radial lines with a capacity equal to their nominal wind farm capacity. This scenario is referred to as the zero-alternative. Except for the two business-as-usual scenarios called **IC1200** and **IC300** that includes a second BritNed interconnection, all other scenarios, the so-called project alternatives, assume a combined use of the offshore infrastructure; i.e. besides transporting the generated wind, the transmission capacity is also available for cross-border trade of electricity. This unique combination of utilization, i.e. synergy at sea, was found to boost the business case for (commercial) investments in an offshore grid since the scarce cross-border transmission capacity can also be sold.

The TSOs, that by definition have a social welfare perspective[46], are generally the designated investors in new (cross-border) transmission capacity. In this study, the envisioned investor in an offshore grid is however a private (commercial) investor. This adds another dimension or perspective to choosing a preferred infrastructure scenario. Although the preferred project alternative should be at least desirable from an investor's perspective, investment decisions like (cross-border) transmission capacity expansion need to be approved by the government(s). Since governments hold by definition a social welfare perspective, it is important to complement the business case analysis as presented in chapter 5 with a social welfare analysis.

It is not only the private investor that might gain or lose benefits under certain project alternatives. Impacts on all stakeholders need to be included in the society perspective. Stakeholders such as the consumers of electricity, producers of electricity and the Transmission System Operators (TSOs) are affected as well:

The consumer

Benefits to the consumer are captured by the consumers' surplus. The consumers' surplus is defined as the difference in total consumers' payments (demand times wholesale electricity prices) in the project alternative compared to the zero-alternative. Consumers gain in case electricity prices are decreasing.

The producer

The producers of electricity get a revenue from selling the electricity that is produced. The benefits to the producer are defined by subtracting the costs of production from the revenues of selling electricity. The benefits to the producer are also referred to as the producers' surplus.

The Transmission System Operator (TSO)

The TSO receives money when transmission capacity is scarce and the TSO has to provide

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[46] In a social welfare perspective, the effects on all stakeholders in the economy are included, notably all electricity producers and consumers.

a service by reallocating production resulting in a price difference between country A and B, respectively. The benefits to the TSO are defined as the product of the difference in electricity prices and the flow on a cross-border interconnection. This is also referred to as the (theoretical) congestion rent.

In the analysis from the viewpoint of society, it is common practice to focus on the impacts on all major stakeholder groups in society, in contrast with the private investor's perspective, in which only the costs and benefits of the private investor are included. The sum of the benefits to the TSOs, producers and consumers minus the corresponding investment costs of the offshore infrastructure give an indication of the impact to society as a whole, i.e. level of social welfare. The impact on social welfare is generally calculated on a country basis. In addition, due to the complexity of determining indirect effects (e.g., externalities[47]) and non-monetary effects such as the effects on CO_2 emission, these have been excluded from the analysis. Only the direct effects of investments in transmission lines for integration of the offshore wind farms Beaufort and East Anglia are considered.

Different desirable project alternatives could result from the business case analysis (i.e. private investor's perspective) and from the social welfare analysis presented in this chapter. Hence, the intention is not necessarily to come up with a single preferred scenario, but mainly to rank and analyze the relative merits and address the difficulties for choosing a single preferred scenario under different perspectives.

6.2. **Methodology**

In order to quantify the impact of various offshore infrastructure scenarios (project alternatives) with respect to a scenario without additional infrastructure (zero alternative), ECN's European electricity market model COMPETES is utilized.

Since the investments and the benefits accrue at different points in time, future values need to be discounted to a base year in order to compare costs and benefits. A common method to calculate social welfare effects and compare project alternatives is by calculating the NPV. A project alternative is beneficial from a social welfare perspective when the NPV is equal to, or larger than zero. The NPV is defined as:

$$NPV = \Sigma_0^T \frac{Net\ cash\ flow_t}{(1+i)^t}, \qquad (6\text{-}1)$$

t = year
T = lifetime
i = (assumed) interest rate[48]

The investment alternatives are assumed to have a construction time of two years, starting in the year 2018, which is also assumed as the base year. The total infrastructure investment costs are divided fifty-fifty over the construction years. For analyzing the impact on social welfare per country, investments costs of the infrastructure are assumed to be paid by the

[47] Indirect effects are effects on third-party stakeholders, e.g. an investment in a transmission line might impact the dispatch of units in Europe in such a way that total gas demand in the gas sector is also affected. An externality, positive or negative, is a special type of an indirect effect and is said to occur when the production or consumption decisions of one agent have an impact on the utility or profit of another agent in an *unintended* way and when no compensation is made by the generator of the affected party (Perman et al., 2003).

[48] An interest rate of 5.5% is assumed in order to calculate the NPV. This interest rate is proposed by the Dutch Ministry of Finance for Social Cost-Benefit Analyses (Ministerie van Financiën, 2011)

UK and the Netherlands on a fifty-fifty basis. The investment costs of East Anglia and Beaufort fully accrue to the UK and the Netherlands, respectively. Furthermore, benefits of the investment can be gathered over the lifetime of the investment which is assumed 20 years, as in 5.1.1.

6.3. **Analysis**

The analysis assesses the desirability of the project alternatives from a social welfare perspective on the EU level and for the UK and NL. Based on the results from the business case analysis and the social welfare analysis, two project alternatives are selected as most promising. The topologies of the scenarios are described in Appendix A.1.

When considering all project alternatives, **UK4** is the first-best option from a private investor's perspective. From a social welfare perspective in Europe **UK4** is the third best option for Europe, with a NPV of 102 M€ (Figure 6-1). Since the Netherlands and the UK bear all the costs, the combined economic benefits for the Netherlands and the UK combined are negative. In case the governments of the UK and the Netherlands were aware of the loss in social welfare if the private investor chooses **UK4** this scenario will in that case not be preferable from the society perspective.

In general, the increased interconnection capacity between the Netherlands and UK stimulates flows of relative cheap supply from the European mainland to the UK. Thus, in the UK, the increased imports lead to a decrease in electricity prices and production (mainly thermal units) resulting in lower producers surplus and higher consumers surplus. On the other hand, a general price increase can be seen in the rest of Europe. Opposite to what is seen in the UK, producer's surplus in the rest of Europe is increasing while the consumer's surplus is decreasing due to (slightly) higher prices. Since production is only increasing in a few countries (e.g. Germany) while average electricity prices are to some extent increasing in all European countries (except for UK and Ireland) the decrease in consumers surplus is in general more significant than the increase in producers surplus in the relative low wind scenarios. Only with higher wind infeed the increase in electricity prices is suppressed thereby mitigating the negative impact on consumers to some extent. The alternatives with a relative high wind capacity are most beneficial to social welfare in Europe since consumers of electricity face slightly lower electricity prices while producers of electricity are not affected too much. Hence it is not surprising that the first-best option from a social welfare perspective in Europe and the UK and the Netherlands combined is the alternative with the highest wind capacity, i.e. **UK-NL7** in Figure 6-1. This alternative is actually the second-best option from a private investor's perspective.

The scenario with the lowest wind production is the least beneficial to society; i.e. **NL1**. The scenario with the most significant impact on production, electricity prices and flows in Europe is **IC1200**. However, IC1200 cannot be compared directly with the other scenarios. The total connection capacity to both UK and NL combined in this scenario is 3900 MW, which is 1200 MW higher than in the two other scenarios with the highest total connection capacity (UK3 and UK4, with a total of 2700 MW). The highest connection capacity in case of the IC1200 scenario likely requires also the largest additional effort in strengthening the onshore grids. But information was lacking to quantify the impacts on the onshore grids, which has therefore not been taken into account.

The reason why the impact on production, electricity prices and flow is highest in the IC1200 scenario is intuitive; since by assuming a separate use of IL's transporting generation of offshore wind to the nearest shore and ILs used for cross-border trade, the simultaneous demand for utilization of the (scarce) transmission capacity of the 1200 MW IL will not occur and hence (trade) flows are less constrained. Even though this scenario results in the most cost-efficient allocation of production, social welfare on a European level is decreasing due to high investment costs and a more significant decrease of consumers surplus in comparison to the increase in producers' surplus (except for UK and Ireland).

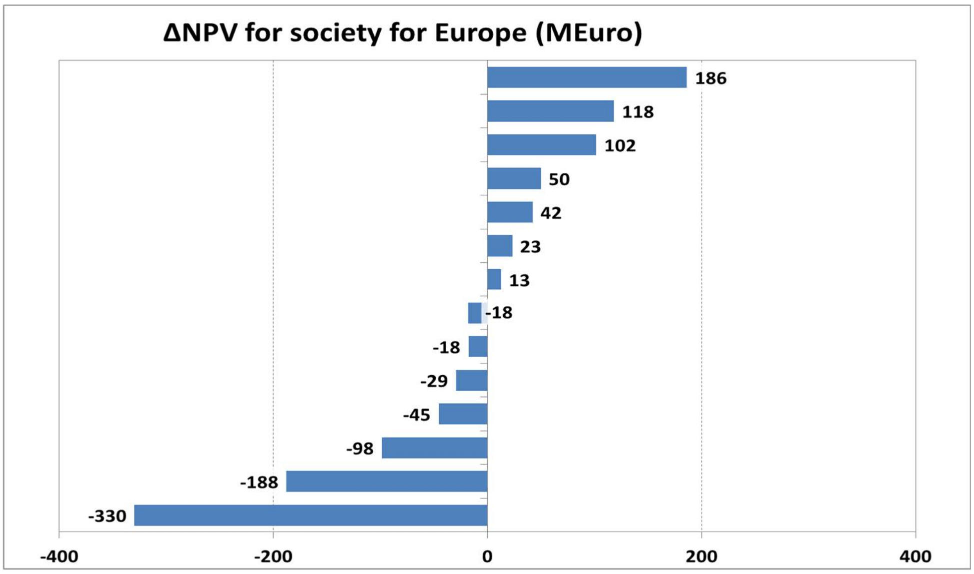

Figure 6-1: Social welfare perspective represented by the NPV per project alternative for Europe.

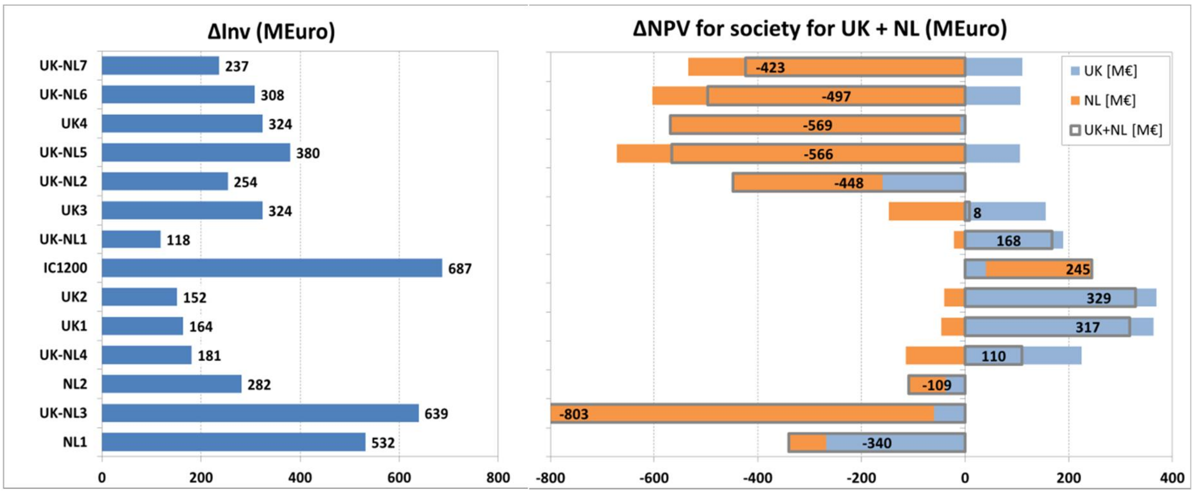

Figure 6-2: Additional investments (left) and social welfare perspective represented by the NPV per project alternative for the Netherlands and the UK and combined (right).

Even though the second-best option to the private investor, i.e. **UK-NL7**, is expected to be beneficial from a social welfare perspective in Europe and of the Netherlands and UK combined. Figure 6-2 (right) shows that this does not necessarily imply that the Netherlands and UK will benefit equally. A simple way to distribute costs and benefits more evenly is by assuming that the country that benefits the most also has to pay a larger share of the investment costs. In case the Netherlands would bear 322 M€ less of the investment costs of the infrastructure in **UK-NL7**, while the UK would bear the same amount more, the net costs to society would be divided equally, leading to a negative result in both countries of 212 M€.

6.4. Concluding remarks

This analysis focusses on the impact under certain offshore infrastructure scenarios on social welfare in case the investor has a private investor's perspective. From this analysis it becomes clear that within a highly integrated European electricity market, the choice to invest in a certain offshore grid topology and capacity (either including or excluding a combined use of ILs), is of high importance to social welfare in Europe and on a country level as shown by the significant differences in the level of the NPV. In addition to the fact that there will always be winners and losers from a transmission capacity investment, not only between countries, but also within a country, the situation is becoming more complex in case a private investor has the intention to invest, as the profitability for society and the private investor does not always align.

6.5. Integrating the private investors perspective with the social welfare perspective

It is already a complex question to choose a single preferred scenario from a social welfare perspective taking into account a single country and/or multiple countries. In cases where a private investor needs to invest this complexity is increased because financial profitability does not always align between both business models. If the first-best option from a private investor's perspective was chosen (**UK4**), social welfare is not expected to be also at its highest. When both perspectives are considered, it is likely that the preferred scenario is not the first-best option, but a second best or Nth-best option from one or both perspectives. Thus negotiations on choosing a preferred alternative among a set of project alternatives seem unavoidable. Even though it implies lower returns compared to the first-best options, if the private investor decides to invest in the second-best option, **UK-NL7** social welfare in Europe and in the Netherlands and UK combined is also expected to increase. If a preferred scenario needs to be chosen from a private investor's perspective under the condition that social welfare on European level, in the Netherlands, and in UK separately is not allowed to be negatively affected, none of the project alternatives is desirable. Under the condition that it is sufficient when the winners can compensate the losers with respect to social welfare, the preferred scenario is **UK-NL7**.

All in all, in order to make a careful considered decision on a single preferred project alternative from both a private investor's perspective and a social welfare perspective, this analysis shows that in order to identify the possible winners and losers it is desirable and recommended to analyze a wide range of alternatives. In addition, only a single generation and demand scenario has been assumed while the future remains uncertain. Further research is necessary in order to retrieve more robust results by not only modifying offshore wind farm capacities and offshore IL capacities, but also important factors such as generation mix, fuel- and CO_2 prices, and cross-border transmission capacities.

7. Conclusions

From the feasibility study of a combined infrastructure for wind power grid connection and cross-border trade, the following conclusions and recommendations are stated on the methodology and results of this study, from an economic, regulatory and technical perspective. These conclusions are based on the specific case of an interconnection between the UK and the Netherlands and can therefore not be generalized to other cases without further study.

7.1. Methodology

The feasibility assessment has been conducted addressing regulatory, economical and technical aspects. For the economic assessment the two perspectives from a private investor and from the socio-economic perspective have been treated separately. For ownership of interconnectors, three alternatives exist:

1. regulated cable owned by TSOs and considered from a combined national perspective,
2. merchant cable owned by a Joint Venture between the TSOs involved,
3. merchant cable owned by commercial companies[49].

A common set of scenarios has been defined, based on the topologies shown cf. Figure 2-2 by including specific nominal capacities and technologies to each wind farm and connection.

The choice for these link capacities and technologies is based on a technology review, which is explained in section •. Each scenario is compared to a representative zero-case (internally labeled as the 0 scenario), in which the same offshore wind farm capacities are installed, but connected with the ’default’ radial connections to shore.

7.2. Regulatory issues[50]

7.2.1. General observations

In order to combine an interconnector with offshore wind farms a number of legal arrangements need to be made upfront. It was found that such a development is hindered by the current national and European legislation (see below). This contributes to a lack of demand to invest in these complex integrated solutions and the required technological developments are hindered as a consequence. This study shows that from a financial and economical point of view, when a favorable technical set-up is chosen, the combined or *synergy* solution is preferred over individual connections of wind farms and a conventional interconnector, provided the legal barriers have been cleared (See Conclusion for combined business and society perspectives).

[49] In the first case the costs and benefits are treated from societal perspective, while for the latter two cases it is treated from private investor perspective.

[50] The legal research analysed the existing legislation as it was up-to-date in Augustus 2014. Updates in legislation are included in the Comprehensive Summary, Regulatory analysis (§ 4) and conclusions (§ 7) of this report.

7.2.2. Conclusions on regulatory issues

In the regulatory part of this research we identified a number of obstacles and formulated possible solutions to overcome these obstacles. A key issue that needs to be addressed is the need for a support scheme which takes into account that wind generation is fed into both countries. This is formulated under item 1 in the list below. On top of that four additional legislative issues are identified that need to be settled:

1. **National support schemes should facilitate direct cross-border trade (See section 4.2. of Appendix C)**

Both the current SDE+ as well as the UK offshore wind support schemes do not allow electricity to be fed into a foreign grid. Dependent on where the national grid starts this can pose a problem as for a successful link free flow of electricity is needed without any (financial) impediments.

A. It does not pose a problem in case:

The connection is made between two national grids, e.g. when a connection is made between an OFTO (TSO) and TenneT (owner and operator of the substation in NL). Prerequisite is that both connection points are officially part of the national grid. In the UK this so-called Point of Common Coupling is on the OFTO platform, according the UK grid code “Glossary and Definitions”.[51]

B. It does pose a problem in case

One of the two connection points is not a national grid at the time of connection. Then the power of the wind farm delivered to the foreign country is not eligible to receive subsidies, hindering the free flow of electricity. This would make the existing subsidizing regimes unsuitable for an integrated wind farm interconnection concept.

To remove this potential barrier, a recommendation is to delete this requirement from national support systems. Additionally, a statistical transfer of green credits between the member states might be required when the electricity is exported directly through the interconnector link. This seeks to prevent member states from running into problems with meeting their renewable energy targets in 2020 under Directive 2009/28/EC.

2. **Integrated wind-interconnector infrastructure is legally not well defined, creating legal uncertainties for some connections (See section 5.2.1. of Appendix C)**

This study shows that when a direct subsea cable is constructed to connect the sub-stations of two offshore wind farms or to connect an offshore wind farm to the onshore grid of a foreign state, the subsea cable sometimes cannot be qualified in current legal terms. National and EU legislation do not contain a fitting definition for the envisaged infrastructure. As a result, legal uncertainty exists with regards to the rights and obligations that are connected to the construction and use of this type of infrastructure.

Before discussing the consequences of this legal uncertainty it is important to point out that the risk of having to deal with this type of legal uncertainty has diminished for connections between offshore substations between the UK and NL. In early 2016, the Dutch legislator amended the Electricity Act ’98. As a result of this amendment the Dutch offshore wind farms will no longer have to construct their own cable to the shore. The Dutch TSO TenneT will, in

[51] http://www2.nationalgrid.com/UK/Industry-information/Electricity-codes/Grid-code/The-Grid-code/

the future, connect the offshore wind farms to an offshore sub-station of TenneT which is part of the national transmission system of TenneT. In the future there will be no legal uncertainty if an interconnector is constructed between the sub-stations of TenneT and a British OFTO.

In the case that an interconnecting link is constructed between the sub-stations of two offshore wind farms the legal uncertainty regarding the status of the cable remains. This legal uncertainty has significant consequences for an important aspect concerning the use of interconnectors. This is a matter of capacity allocation on an interconnector. It should be reminded that two fundamental principles of the European energy legislation are unbundling and non-discriminatory grid access for system users. This means that system users should under normal circumstances have equal access to the interconnector. With the integration of offshore wind farms on an interconnector, new questions arise. For example, does the transportation of electricity from offshore wind farms have priority over cross-border trade flows? A special element in this case is the different value of electricity that is traded through the cross-border connection and the electricity that is produced offshore. It is assumed that the existing legislation does not provide clear cut answers for this question.

There are two possible solutions that could solve this problem; the first is an extensive interpretation of the existing rules for interconnectors and the second is the formulation of a new definition for this innovative type of infrastructure. It is advised that the European legislator should include a legal framework for the interconnecting link within the existing Regulation (EC) 714/2009 on cross-border electricity trade. This framework should deal with matters such as unbundling, third party access and investment reimbursement.

3. Regulations in the UK need adjustment (See section 3.3.1. of Appendix C)

The current OFTO regime hinders the development of combined infrastructure. Under the existing regime, it is not possible to combine offshore transmission and interconnection activities, due to the statutory ban on the combination of these activities. This means that the OFTO regime should be made suitable for more than only connecting offshore wind farms to the UK shore by using radial transmission connections. The UK legislator should also review its policy and legislation on interconnectors. Therefore, it was found that UK legislation at this moment hinders the construction of electrical infrastructure that is used for transmission and interconnecting activities. It is advised that possible solutions are taken into account in the Integrated Transmission Planning and Regulation (ITPR) project that is being performed by Ofgem. The aim of ITPR is to make network planning more economically efficient and better coordinated. In addition to this, the ITPR project aims to protect UK consumers against undue costs and risks. One of the issues that will be addressed is the regulation of new types of transmission assets, such as multi-purpose projects and the connections of non-GB generators to the UK grid. The results of the ITPR project were made public in March 2015.**Coordination of licensing procedures (See section 5.2.4. of Appendix C)**

The national public authorities should aim to assist wind farm developers as much as possible when they wish to apply for all the necessary licenses. It was found that there are numerous licenses which have to be applied for in both countries. Because these licenses and consents are constitutive, it is required to obtain all of the permissions before one can start the construction of wind farms and the interconnecting link. It is important for national public authorities to coordinate their procedures. An important stimulus could be to use the European regulation for promotion of trans-European energy networks. This can be achieved by declaring the combined wind farm interconnector initiative to be a project of common interest under the TEN-E Regulation.

4. **Regulations in the Netherlands need (further) adjustment (See section 3.3.2. of Appendix C)**

The former Dutch legislation concerning offshore wind energy was found to be a major obstacle in this study for developing a wind farm interconnector combination. During 2015 and in early 2016, the Dutch legislation was amended. In this paragraph, we shall provide an update on how the Dutch legislation has changed and what consequences this will have for the synergy solution.

Under the old legislation, the wind farm developer had to construct the offshore wind farm and the connection to shore. The cable that linked the wind farm to the onshore transmission system was considered to be part of the offshore wind farm project. This situation has changed with the introduction of new legislation on the tendering of sites for offshore wind farms (Wet *windenergie op zee)* and the revision of the Dutch electricity legislation (STROOM). The plan of the legislator was to have the new tendering regime and the Electricity Act enacted by the end of 2015. However, due to a veto of the First Chamber of the Dutch parliament the new Electricity Act became stranded and the government had to implement the parts dealing with offshore wind energy in a separate repair act.[52]

The existing Dutch legislation on offshore wind energy differs substantially from the previous regime and this will have consequences for the planning of future wind farm interconnection projects. Under the new regime the government will select sites on the North Sea which are suitable for the development of offshore wind farms and will organize a tender. Wind farm developers can participate in these tenders and the party that is able to construct and operate the wind farms in the most efficient manner will win the tender. The party who wins the tender is granted the license to construct and operate the offshore wind farm, as well as SDE+ subsidy for the lifetime of the offshore wind farm. Also new in the system is that the wind farm developer no longer is required to establish a connection with the onshore transmission grid with his own cable to the shore. The cable from the offshore wind farm to the onshore transmission system is no longer part of the offshore wind farm project. With the amendment of the *Elektriciteitswet 1998* TenneT is under the obligation to establish a connection with the offshore wind farm through an offshore transmission grid that is to be constructed and owned by TenneT.

It is assumed that this new legal framework in the Netherlands will have substantial benefits for the planning and construction of offshore wind farms in the future.[53] Nonetheless, under the new regime the focus is on the timely construction of wind farms and the connection with the onshore transmission system. It is not clear whether the Dutch legislation allows for the construction of an offshore transmission system for an offshore wind farm that has the possibility of interconnection included. The *Elektriciteitswet 1998* only speaks of connecting the offshore wind farm and is silent on the optionality of interconnection.

7.2.3. Recommendations on regulatory issues

- The development of offshore wind farms will require public funding. Both the UK and the Netherlands have support schemes in place that facilitate for the development of offshore wind farms, but these schemes are national in scope. This means that in order to receive subsidies, the electricity needs to be fed in into the

[52] Wet tijdig realiseren doelstellingen Energieakkoord (Stb. 2016,116).

[53] J.C.W. Gazendam, H.K. Müller, & M.M. Roggenkamp, 'Elektriciteitsnetwerken op zee onder STROOM', NTE 2015/0304, p. 136-148.

national grid. This requires that the offshore wind farm needs to be connected to an offshore sub-station of the TSO as the electricity needs pass through national transmission before it can be exported. The requirement that electricity needs to be injected into the national grid before it can be exported is also mandatory under Directive 2009/28/EC as only domestically produced electricity counts towards the national renewable energy targets. The integration of offshore wind farms through the use of interconnecting links creates new challenges. Under the existing European legislation, an offshore wind farm will not be entitled to subsidies if the electricity is directly exported through the interconnecting link. Therefore it is important that the interconnector is always a connection between the offshore sub-stations of the two TSO involved. This is deemed to be a hurdle for some scenarios in which wind farms are directly connected to the transmission of another state without an interconnector.[54] It is therefore advised that in the future national support schemes should be opened for foreign generators in combination with a statistical transfer of green credits.

- The European legislator should create a legal framework for the interconnecting link. This framework should deal with matters such as unbundling, third party access and investment reimbursement. Special attention should be devoted to the matter of capacity allocation for the offshore wind farms. It was found that from an economic perspective the wind farms should have guaranteed access due to the higher value of the produced offshore electricity. However, this means that a deviation from the principle of non-discriminatory network access will be required.
- Due to the fact that the development of offshore wind farms takes place on the member state level, it is required that the national governments take the initiative. For the development of synergy solutions the optionality of interconnection should be included in the planning of offshore wind energy projects. Close cooperation of the TSOs involved is therefore required. Additionally, cooperation with European institutions such as ENTSO-E, ACER and the EC could be beneficial. However, it must be stressed that the member states remain in the drivers' seat.
- For the UK side of the project, it is important to assess how the OFTO tendering system could be made more suitable to facilitate offshore grid development. In 2015, the results of the ITPR project of Ofgem were made public. It is expected that the future British regimes will be better suited to facilitate an integrated solution.
- It should be assessed whether the existing Dutch legislation[55] is compatible to facilitate an integrated wind farm interconnector solution. An essential cornerstone in the new Dutch legislation is the offshore role of TenneT in combination with the central planning of offshore wind farm development through the new tender procedures. At present, it is not clear whether the existing regime allows for the government to instruct TenneT to include the option of interconnection in order to connect the tendered offshore wind farms. This matter should be resolved in the near future before the next tenders for offshore wind farm locations are opened.

[54] UK wind farm directly connected to the Dutch onshore transmission system and NL wind farm directly connected to the UK onshore transmission system.
[55] As it stands after the amendment of April 2016.

- In order to create a legal obligation for both the Netherlands and the UK to coordinate the licensing procedures, a future integrated infrastructure project could apply for the status of a Project of Common Interest (PCI) under the TEN-E regulation. This application can be made at the EC by the member states. This will not only enhance the legal status of the project and help to accelerate licensing procedures, but it will also contribute to the political commitment by the national governments and TSOs.

7.3. **Technical implementation**

7.3.1. Conclusions on transmission system technologies

- Interconnecting Dutch and UK wind power plants is possible with current technology based on a combination of HVAC and point-to-point HVDC links. HVAC links are generally less expensive but are limited to about 140 km. HVDC links are not limited in distance and, currently, converter platforms of up to 900 MW are on the market.
- For applying point-to-point HVDC links up to 1200 MW new offshore platform designs are needed, which are expected to be available on the market before 2020, provided there is sufficient market development. Without sufficient demand from TSOs or other parties these components are unlikely to be developed. The same holds for power ratings beyond 1200 MW, but for this it is also required to develop higher HVDC cable voltage ratings.
- Extending this power level combined with higher voltages is expected to have a significant positive impact on the Cost of Energy (CoE). Furthermore, cost reductions are expected before 2020 by increased competition, standardized voltage levels, reduced converter losses and increased reliability.
- For extending the connection distance of HVAC, mid-point compensation is already envisaged in HVAC offshore platform designs and will be available on the market before 2018. Control and protection of long HVAC (meshed) offshore grids needs attention; however, no fundamental problems are expected.
- Although the largest market for interconnectors is based on Line-Commutated Converter (LCC) technology, its application is not suitable for implementation on offshore platforms. Combining onshore LCC, or other Current Source Converter (CSC) technology, with offshore VSC technology is not considered before 2020, although LCC enables higher power ratings and improved DC-fault protection.
- DC-fault blocking and recovery, either inside the converters or by separate DC-breakers offers improved reliability and less stability issues in the connected grids. Applying these will enable (extension to) larger power levels and more complex Multi-Terminal DC (MTDC) grids. However, for the size and level of complexity as considered in this study, the connected terrestrial grids can handle the power drop by a temporary disconnection of the MTDC grid, therefore, operation without DC breakers should be possible. Therefore, it is considered possible to realize MTDC networks with limited power ratings before 2020 based on fast AC-circuit protection schemes. Yet many design issues like insulation coordination, grounding and protection schemes and power flow control need to be solved.

7.3.2. Recommendation on transmission system technologies

- Standardization of a number of main characteristics relevant for investors and suppliers, such as voltage levels, platform capacities, etc. is needed to increase market volume, reduce costs of offshore networks and facilitate future integration of systems from different manufacturers. Most of the technologies for the realization of future offshore grids appear to be in place. However, up to now, any proposed multi-terminal network is supplier specific, which results in a limited number of choices that limits the flexibility and modularity of existing and future systems.

7.3.3. Selected scenario implementations

The 15 studied scenarios are a representation of the many possible combinations for topologies, technologies and rated capacities.

As a result of the iterative selection process, it proved that the larger interconnecting capacities are most economic. A capacity of 1200 MW was chosen as this was considered to be the maximum available capacity for offshore HVDC links before 2020. It also showed that, because of the dominant power flow towards the UK, reducing the UK Wind Farm to 900 MW while keeping the export link to the UK at 1200 MW significantly increases effective transport capacity for cross-border trade. Thirdly, the sensitivity for the Dutch wind farm installed capacity has been analyzed. Finally, as during 2014 the proposed roll-out concept for the Dutch offshore grid became clear, one scenario was added (most-right in the figure) that was building further on this concept. Although this concept is technically feasible, it is less attractive from economic perspective.

Figure 2-1 provides an overview of the selection process, starting from a relatively small interconnecting capacity of 300 MW, based on the power rating of a single 220 kV HVAC circuit. The wind farm capacities were rounded as multiples of 300 MW, as closely linked to the planned wind farms Beaufort (NL) and East Anglia One (UK). These are presented in Figure 7-1 in the column "Initial scenarios". The scenario naming convention is explained in Table 3-7. Details of these scenarios are presented in the technical work section of the main report, 3.3 and in Appendix A.

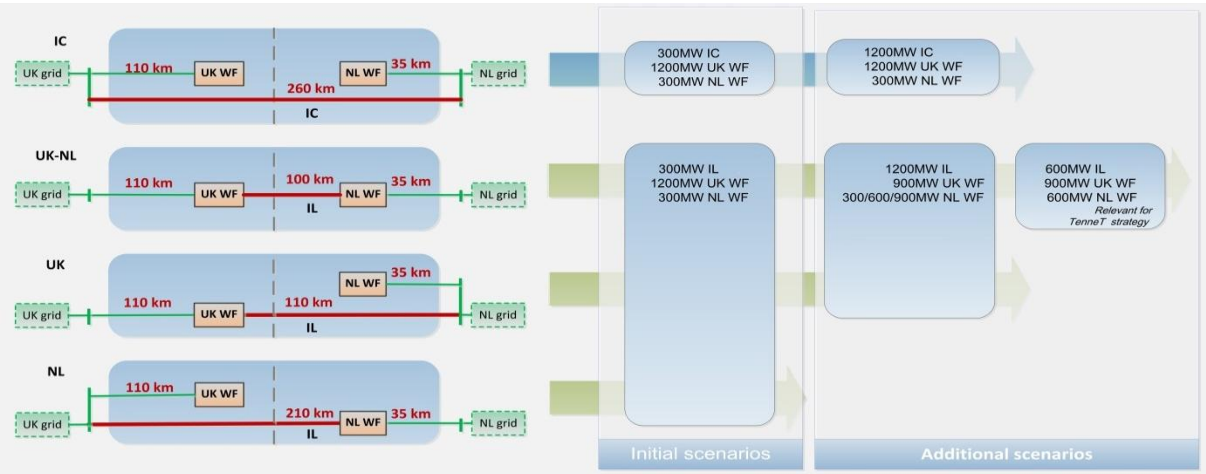

Figure 7-1: Overview of scenario topologies and capacities.

Table 7-1shows the connection capacities to shore. The differences in costs for the onshore substations have been calculated. Cost effects for the onshore grid and land use have not been included.

Table 7-1: Overview of required additional connection capacities to shore per scenario in MW.

Scenario	IC/IL [MW]	WF UK [MW]	WF NL [MW]	To UK {MW]	To NL [MW]	To UK+NL [MW]
IC300	300	1200	300	300	300	600
IC1200	1200	1200	300	1200	1200	2400
UK-NL1, UK-NL4	300	1200	300	0	900	900
UK1, UK2	300	1200	300	0	1200	1200
NL1, NL2	300	1200	300	300	0	300
UK-NL2	600	900	600	0	0	0
UK-NL5	1200	900	300	300	900	1200
UK-NL3,UK-NL6	1200	900	600	300	600	900
UK-NL7	1200	900	900	300	300	600
UK4	1200	900	300	300	1200	1500
UK3	1200	1200	300	0	1200	1200

7.4. Economic analysis in two perspectives: the private investor and society

Fifteen different implementations (scenarios) of an offshore grid have been assessed. For each scenario the additional costs and benefits have been compared to a specific zero-case in which the same nominal capacities for the two wind farms in the Netherlands and the UK were assumed. These assessed scenarios include differences in grid topology, nominal capacities of the connections and of the connected wind farms and different technologies. Costs and benefits have been analyzed for a private investor, investing in an interconnecting link and benefitting from the trade. A similar analysis has been conducted from the perspective of society, which includes the effects on all forms of electricity generation and the effects on consumers.

7.4.1. Economic findings: private investors perspective

For a private investor in offshore transmission infrastructure, benefits are determined by the trade driven by electricity price differences between the two countries connected. A private investor has two main criteria to compare *profitability* of different investment opportunities: an annual return percentage (IRR) or the net benefits over the lifetime of a project (NPV) in M€. Direct comparison or ranking of options based on NPV is only allowed in case all projects are of the same scale (notably installed wind and transmission capacity capacities). In the scenarios considered here, the installed capacity of wind farms in the Netherlands differs from 300 MW to 900 MW, implying that for the ranking of these different alternatives, only the IRR can be applied.

There are four scenarios with an IRR exceeding the hurdle rate of 10.9 %, which is the minimum level of return assumed here for a private investor[56], see Figure 7-2. These scenarios make most advantage of the cost synergies presented by combining offshore wind farms with an interconnecting link. Furthermore, they are making use of the technological and

[56] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/225619/July_2013_DECC_EMR_ETR_Report_for_Publication_-_FINAL.pdf

economic advantages presented by HVDC technology.

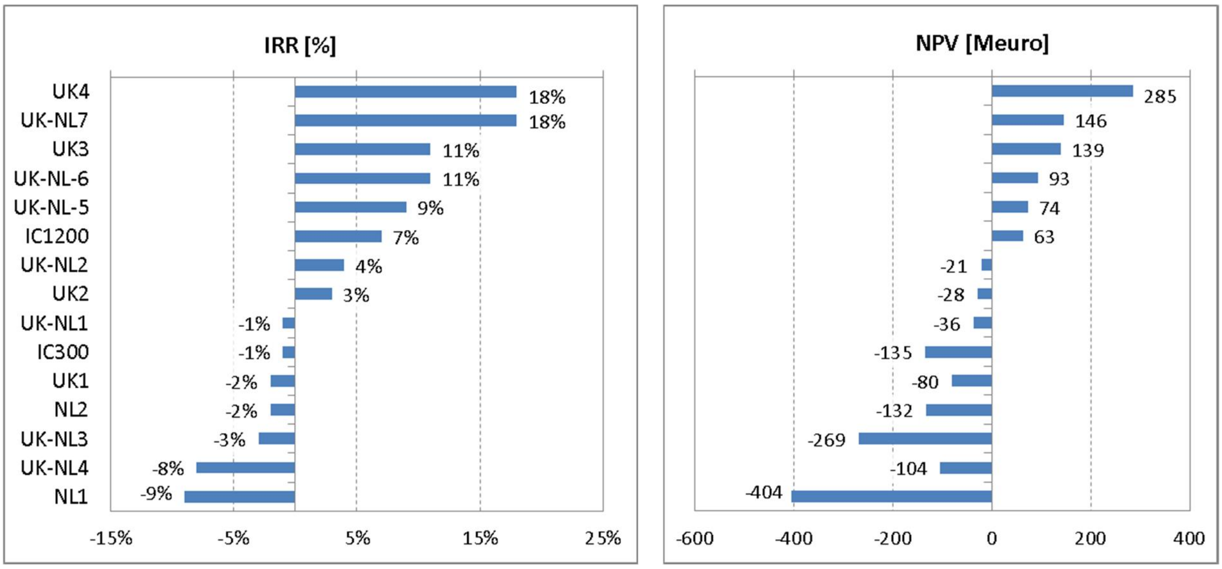

Figure 7-2: Business case results for the different technological scenarios. Respective scenario descriptions can be found in appendix A.

Of all studied scenarios, only the scenario with a separate 1200 MW interconnector **IC1200** represents a potentially interesting investment opportunity to a low risk, low return appetite party (like a TSO). The fact that the transformer stations are located onshore instead of offshore makes this scenario, technologically, less complex compared to the other scenarios. However, this scenario requires additional onshore connection capacity compared to the other alternatives. The additional costs for strengthening the onshore network have not been included in this analysis. Therefore, the **IC1200** and **IC300** scenarios cannot be directly compared to the other scenarios.

The scenario with a separate 300 MW interconnector **IC300** is unfeasible from an economic point of view. The same holds for all 300 MW interconnecting link scenarios (**UK-NL1&2**; **NL1&2**; **UK1&2**). There are two scenarios that well exceed the IRR hurdle rate, being **UK4** and **UK-NL7**. The **UK** scenario only involves a UK wind farm, whereas the **UK-NL** scenarios involve both a UK and Dutch wind farm.

It can be stated that, from an economic point of view, there is no strong preference for having one or two wind farms connected to an interconnecting link as is illustrated in Figure 7-3. Both are potentially profitable, when used in the right technological setup. Because the **UK4** scenario involves less wind power capacity (1200 MW), it requires larger additional investments to construct the 1200 MW interconnecting link. On the other hand, associated cash flows, and therefore NPV, are higher accordingly. The **UK-NL** scenario has 600 MW additional capacity of wind power (1800 MW) and, therefore, requires lower additional investments. Similarly, due to less capacity remaining available for trading, this setup generates lower cash flows and NPV.

When considering the current Dutch wind farm deployment strategy, scenario **UK4** is to be preferred. The reason is that in the Dutch strategy wind farm, development zones are located close to shore and connected through an HVAC grid, to be developed and operated by TenneT TSO. The scenario **UK4** is completely independent from this development, and also of the actual nominal capacity of the Dutch wind farm. These two scenarios meet the minimum hurdle rate of 10.9 %.

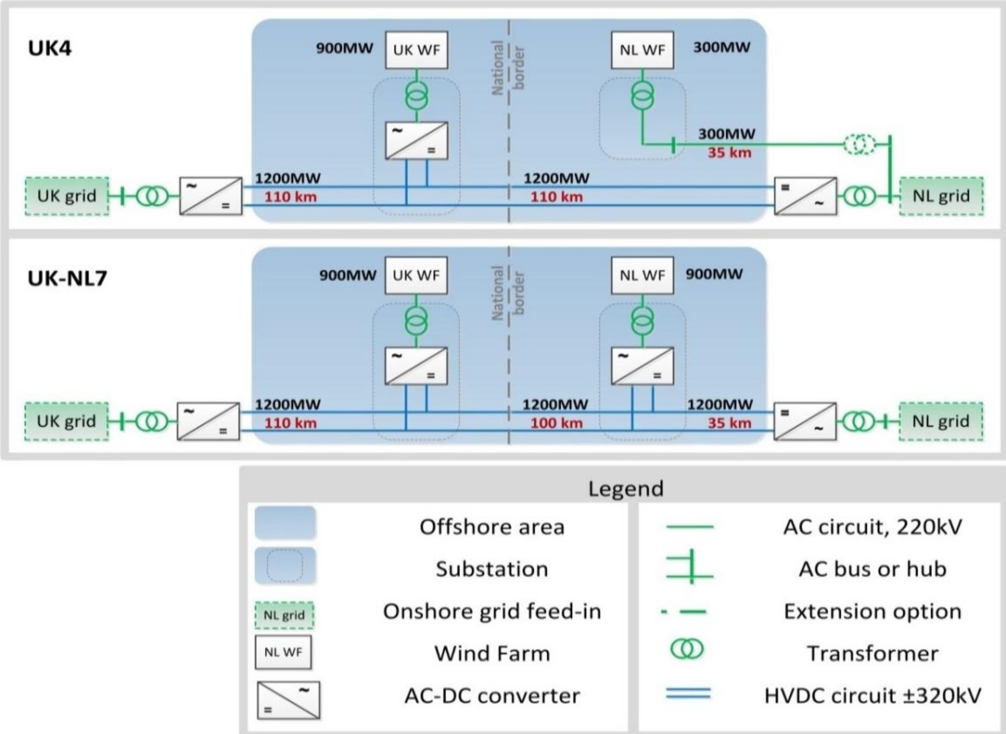

Figure 7-3: The two scenarios with the highest benefits to society. by studying the impact of redundancy on levelized cost of energy (LCOE), it was found that the impact of the increased availability ranges between a 1 % to 3 % reduction of the LCOE for the best performing scenarios. Under the current assumptions in the scenario analysis, electricity prices in the UK are, most of the time, higher than in the Netherlands. This affects the outcomes, especially the ranking of scenarios. Different assumptions regarding future price differences will possibly change this ranking.

7.4.2. Economic findings: society perspective

From the viewpoint of society, more or less the same scenarios were found to be preferred as was obtained from the business perspective (the two scenarios with the highest NPV according to the business perspective are also in the top three of the highest NPV according to the economic perspective). In the society perspective, costs and benefits for all stakeholders are included, differing from the business perspective which focuses on a single stakeholder, the owner of the transmission infrastructure. In practice, net benefits to society are determined as the sum of the benefits of the TSO, producers and consumers minus the corresponding investment costs of the offshore infrastructure. This provides an indication of the impact on society as a whole, i.e. level of social welfare. The TSOs, which are regulated in order to safeguard the social welfare interests, are generally the designated investors in new (cross-border) transmission capacity.

In general, the increased interconnection capacity between the Netherlands and UK stimulates flows of relatively cheap electricity supply from the European mainland to the UK. Thus, in the UK, the increased imports lead to a decrease in electricity prices and production (mainly thermal units), resulting in lower producers' surplus and higher consumers' surplus. On the other hand, a general price increase can be seen in the rest of Europe. Opposite to what is seen in the UK, producer's surplus in the rest of Europe is increasing while the consumers' surplus is decreasing due to (slightly) higher prices.

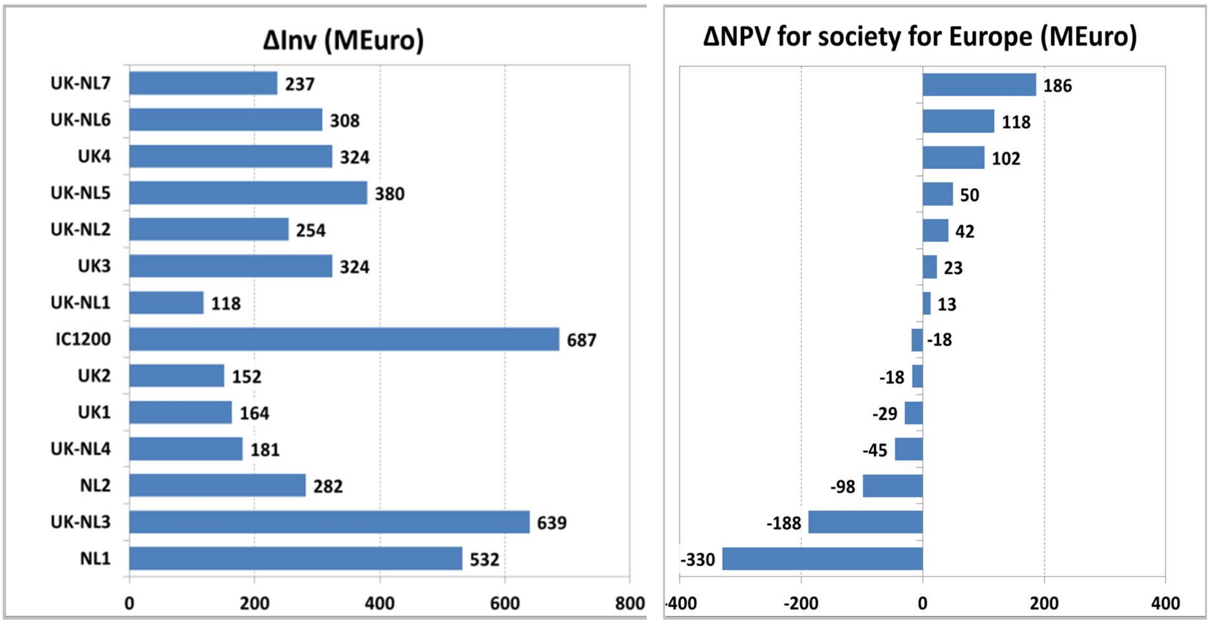

Figure 7.6.: Differences in investment costs compared to the 0-scenario without interconnector (left) and differences in NPV for the EU (right), both in M€.

7.4.3. Comparison of the two perspectives

Figure 7.6 shows differences in investments costs between the different integrated scenarios and the 0-scenario[57], in which the wind farms are only connected to the nearest shore. In the cost estimates, there is a substantial amount of uncertainty in the total investment costs related to underlying development in commodity prices (e.g. copper) and cable laying costs which depends upon the availability of appropriate cable laying vessels. These are difficult to quantify but are estimated by the project team to be in the order of 20 % of the total investment costs. This implies an uncertainty in the calculated NPV of around 60 M€. Applying this assumption on uncertainty would render the following three scenarios significantly more beneficial from a business perspective than the case of building an interconnector without any wind farms connected, i.e. **IC1200**:

1. **UK4**,
2. **UK-NL7**,
3. **UK3**.

In the society perspective, there are five scenarios which are significantly more beneficial than the case of building an interconnector without any wind farms connected. These include two of the three scenarios as found for the business perspective, with the exclusion of **UK3**. The additional net benefits of scenario **UK3** of 41 M€ compared to scenario **IC1200**, are not significant, taking into account the 60 M€ uncertainty level. Additionally, three scenarios were found to also be significantly more beneficial than the case **IC1200**[58] for the society perspective only.

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[57] Actually, four different 0-scenarios have been applied, depending on the amount of installed wind in the UK and the Netherlands. For each integrated scenario, the corresponding 0-scenario was chosen, with exactly the same amount of installed wind capacity

[58] 5(?!)Please note that the costs of strengthening onshore grids have not been included, and these are relatively higher in case of the **IC1200** and **IC300** scenario. This can result in more options to be significantly more be7neficial than the case with a separate interconnector.

These are:

1. **UK-NL7**,
2. **UK4**,
3. **UK-NL6**,
4. **UK-NL5**,
5. **UK-NL2**.

The integrated solutions are expected to be even more beneficial compared to the **IC1200** scenario, because these need no additional connection capacity onshore and less reinforcement behind this point.

7.4.4. Conclusion for combined business and society perspectives

Due to the higher risks associated with the new HVDC multi-terminal technology, a higher than usual level of uncertainty needs to be applied. Explicitly taking into account an uncertainty range of at least 60 M€, and combining this with a requirement that scenarios should be sufficiently beneficial under both business and society perspectives, results in two scenarios, which are significantly beneficial under both perspectives. These are:

1. **UK4**

consisting of an HVDC connection between a 900 MW UK wind farm to the Dutch grid.

2. **UK-NL7**

consisting of a direct HVDC connection between a 900 MW UK wind farm to a 900 MW Dutch wind farm.

7.5. Overall recommendations

It is recommended to continue considering integrated solutions for connecting offshore wind farms which could be implemented in the period after 2023. Furthermore, it is recommended that future analyses of all to be built offshore substations will include:

- Additional costs to strengthen onshore networks are included for all scenarios;
- Differences in onshore congestion between the different scenarios are quantified;
- A range of investment costs and electricity price scenarios are applied in a sensitivity analysis;
- Alternatives for the division of costs and benefits between countries and stakeholders within countries are analyzed explicitly;
- Assess all potential bilateral connections for all wind farms in development in Europe as part of offshore wind policy. These bilateral assessments do not have to wait for a common regional or European approach and can, therefore, be implemented in the nearer future;
- From a European perspective, alternatives need to be assessed at a higher level involving more than two countries. The most relevant organization for this purpose is ENTSO-E. For collaboration in between the North Sea counties the North Sea Countries Offshore Grid Initiative (NSCOGI) is the relevant organization, which is closely linked to the national governments and the ENSTO-E. For all close combinations of wind farms at both sides of the border, an assessment needs to be conducted if a connection would be feasible.

Appendix A Scenarios

A.1 Basic topologies

A summary of what is connected with what (the so-called topology) shows that the project considered three basic alternatives in which offshore wind farms are connected to another country, either directly or via an offshore wind farm of the other country. These three alternatives are:

1. UK-NL: an offshore wind farm in one country is connected to an offshore wind farm in another country;

2. UK: the UK offshore wind farm is connected to the Netherlands;

3. NL: the NL offshore wind farm is connected to the UK

A conventional interconnector connects two parts of the transmission grid in two different countries. The three alternatives listed above, connect a wind farm to another country. This differs from a conventional interconnector, which connects two sections of the transmission grid. These three alternatives have a connection between a wind farm in one country and either a wind farm or the national grid in another country. These differ from the standard interconnections between the grids of two countries. These grid sections are therefore labeled with the label: interconnecting link (IL). A logical reference situation to compare these new alternatives with is a conventional interconnector between the Netherlands and the UK, labeled as scenario **IC** (interconnector).

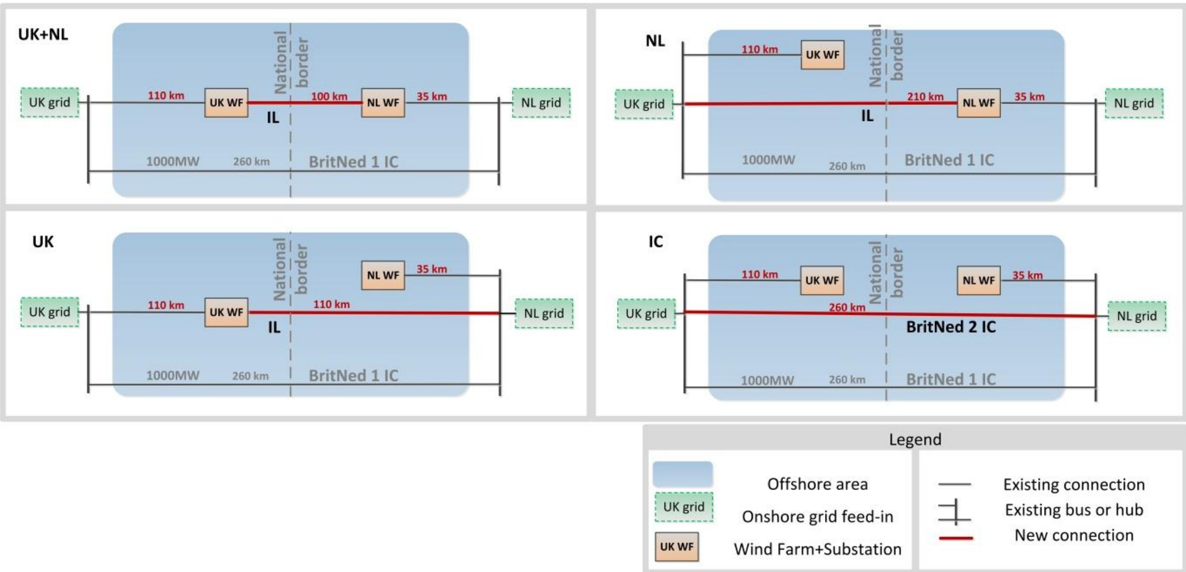


Figure A-1: Basic topologies

All scenario results are outcomes of a differential analysis using 0-scenarios

All assessed scenarios have been compared with the relevant 0-scenario in which the offshore wind farms are only connected to the country on which offshore territory they are located. Different 0-scenarios are applied for scenarios with different amounts of installed wind capacities. All scenario costs and benefits figures presented in this report are differences between the outcomes of the ‘project’ scenario minus the relevant 0-scenario. Since there are in total four different combinations of installed wind capacities in the scenarios, there are also four different 0-scenarios applied. Mainly for the practical reason of reducing the complexity of the description of analysis outcomes, the application of the 0-scenario is not mentioned explicitly in each of the tables and graphs.

The basic topologies for the scenarios are presented in figure A1. Contrary to all other graphs, in this case also the topology of the 0-scenario is shown. Figure A2 shows the scenarios where the offshore wind farms in the UK and the Netherlands are connected to each other. Figure A3 shows the scenarios with an interconnection via either an offshore wind farm in the UK or in the Netherlands. And figure A4 shows the two scenarios with an interconnector parallel to the existing BritNed interconnector.

A.2 Scenarios overview

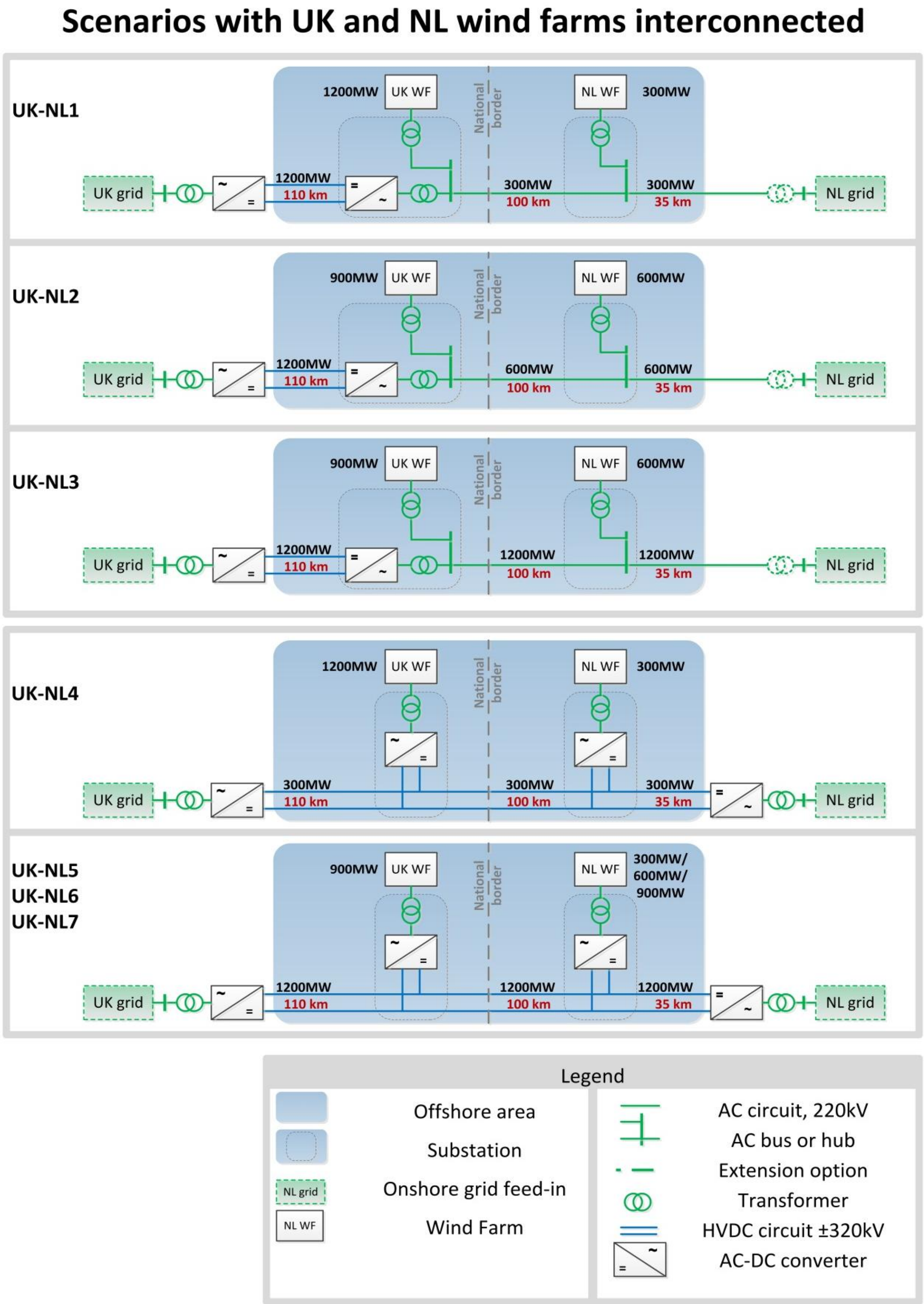


Figure A-2: Scenarios with UK and NL wind farms interconnected

Scenarios with interconnection via either UK or NL wind farm

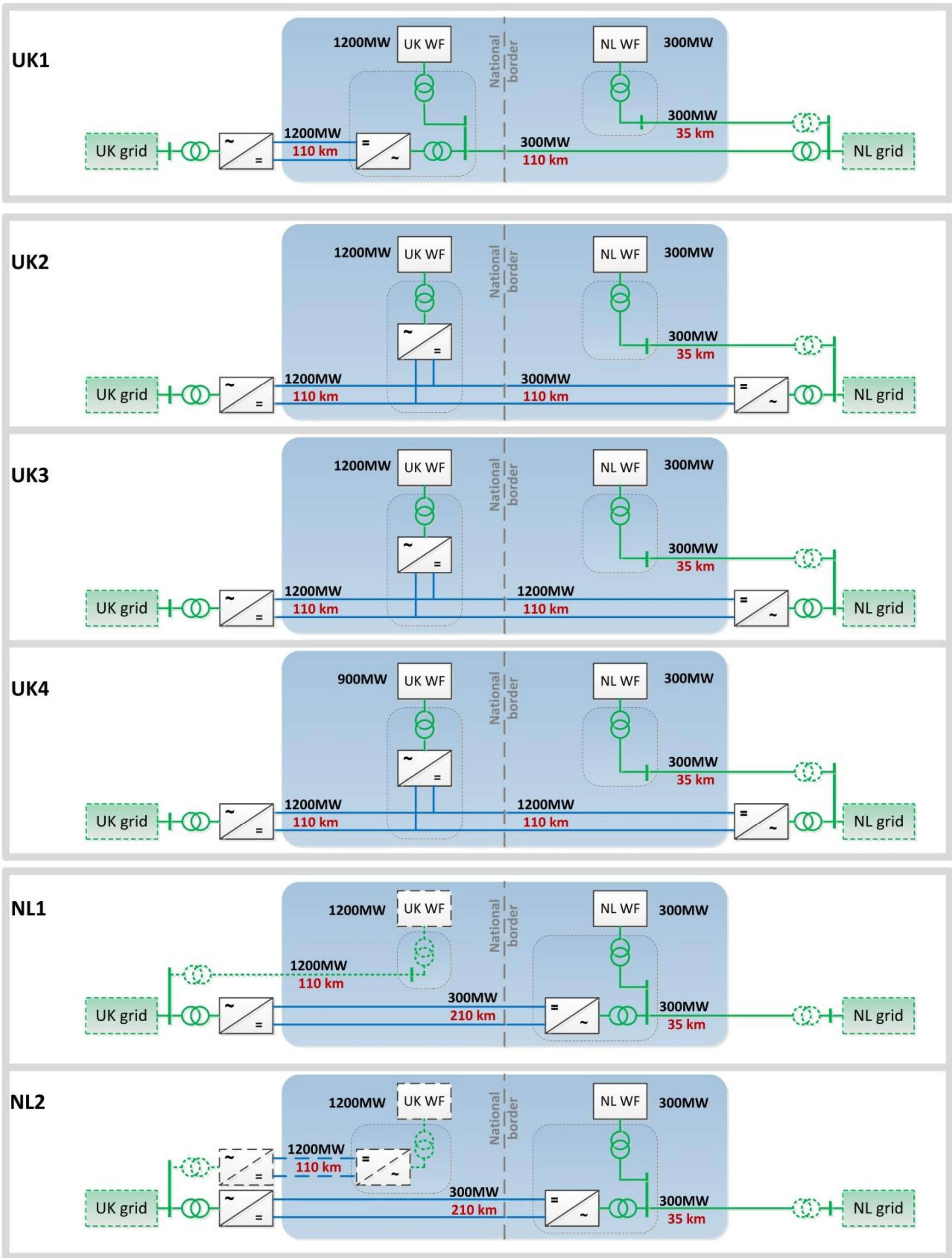


Figure A-3: Scenarios with either UK or NL wind farms interconnected

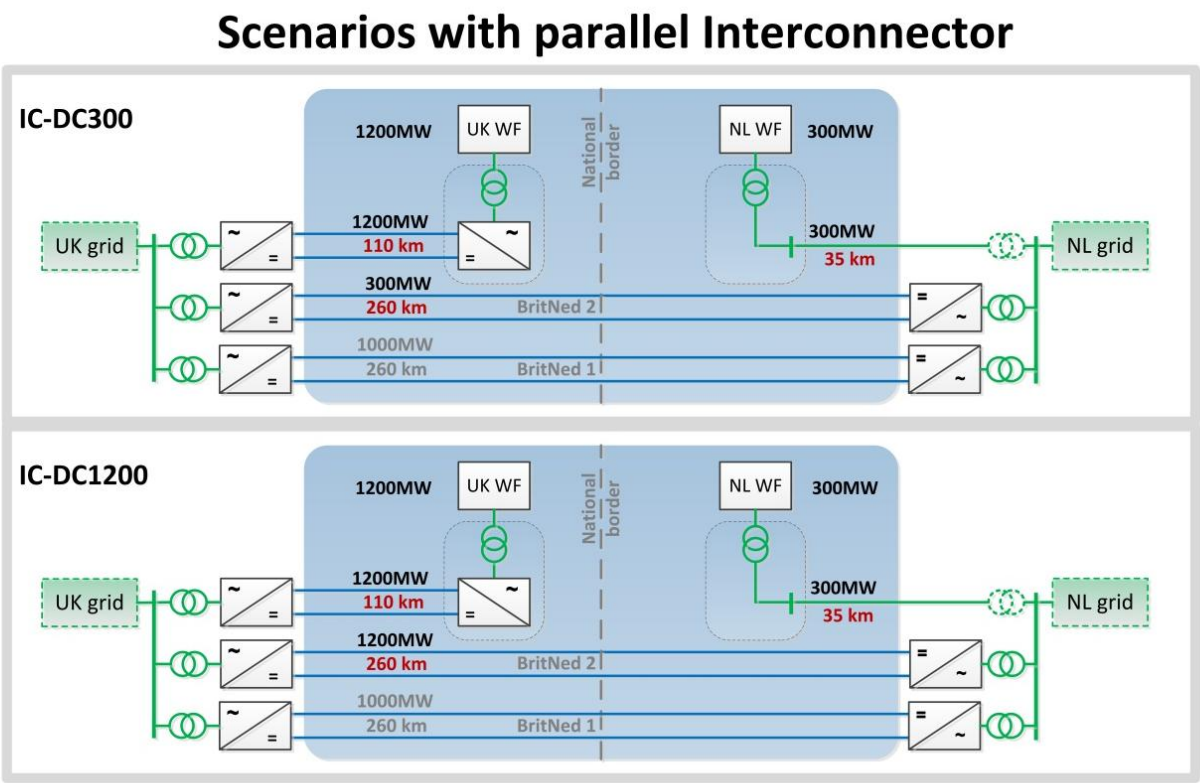


Figure A-4: Scenarios with parallel interconnector

Appendix B Technical feasibility

B.1 Technology review

For the technical feasibility first a technical review has been performed by TU Delft as a basis to select appropriate technologies for the different scenarios. The evaluation of the selected technical scenarios described here addresses research question 3 and limited to stationary performance and costs. The modeling and evaluation is done in the ECN model EeFarm-II with the use of power flows resulting from the COMPETES model from ECN Policy Studies. The process of modelling and evaluation, holds defining assumptions and inputs for costs and losses modeling. The complete technical feasibility report is available as a separate document: Appendix B1 - Technology Review.pdf.

B.2 Cost modelling

The cost modelling in EeFarm-II cost database is based on confidential data provided by suppliers and developers as well as on public data sources. These data include investment costs and installation costs of the main components. Operational costs are not included. In order to be able to share cost data the approach has been to aggregate the cost data of individual components such that the data source cannot be traced. This aggregation has been performed at the level of line segments and also per scenario. For some components that are not included in the database, for instance specific component ratings, cost functions have been made using a set of similar components as an estimate.

The economic evaluation assumes the investments to be made in 2020. Anticipating on technology and market developments 20 % cost savings are foreseen, which have been applied in the presented figures. The prices are presented in 2010 Euros. This section presents an overview of the costs modeling in EeFarm-II and the cost allocation.

B.2.1 Component costs

The following component types have been applied in the modelled scenarios:

- Cables (HVAC and HVDC);
- Transformers and inductors;
- Converter station (VSC);
- Platforms (HVAC and HVDC);
- Onshore substation.

The EeFarm database includes capital costs of these components, including installation costs. The prices of the different components originate from the period 2008 - 2012. Old prices need to be corrected for fluctuating (material) prices and inflation. For instance, the copper price has a significant effect on cable prices.

Regarding correction of cable prices the following assumptions have been made:

1. an increase of the copper price of a factor 3.5/2.14 US$/lb between 2009 and 2012;
2. a 33 % share of the copper price in the cable procurement costs.

This is an estimate for both HVAC and HVDC cables, although the contribution is relatively higher for HVAC and also differs with the current rating. The estimate is in accordance to the ENTSO-E report 59 estimated range of 30 to 40 cost share.

Other prices have been corrected by comparing these with actual prices combined with scaling rules, such as constant costs per installed MVA (e.g. for transformers), or maximum support weight (e.g. for platforms). A more detailed comparison of prices of DC-components is available[60].

HVAC export cables

The selected cable type cableAC_30, which is a 3-core XLPE cable with 1000 mm^2 copper conductor, rated 220 kV / 330 MVA. For this cable recent price information is available, so no corrections or approximations were required. Compared to the price range specified by ENTSO-E of between 575 and 863 k€/km for a 220 kV / 300 MVA 3-core cable, the price within this range.

HVDC cables

For the 300 MW HVDC connections cableDC_16 is selected, which is a 320 kV XLPE cable, with a copper conductor of 185 mm2, rated at 381 MW in bipolar configuration. For the 1200 MW HVDC connections cableDC_20 is selected, which is a 320 kV XLPE cable, with a copper conductor of 1200 mm2, rated at 1146 MW in bipolar configuration.

The price correction for this cable was made by a factor that is derived from two similar cables:

- 1x630 mm^2, 150 kV DC, 374 MW (price info 2009);
- 1x500 mm^2, 150 kV DC, 300 MW (price info 2012).

Compared to the price range specified by ENTSOE of between 345 and 518 k€/km for a 320 kV / 2000 mm^2 cable, the price of cable_20 is slightly above the maximum.

Cable laying costs

Constant cable laying costs of 350 k€/km have been assumed. It is well known that these costs have a very high uncertainty, depending on the location, soil conditions, cable types and equipment costs. The ENTSO-E report specifies a wide range between 230 and 977.5 k€/km.

Transformers and inductors

For HVAC systems two transformer models are used: trafo_8 and trafoQ_<rating>. Trafo_8 refers to an existing transformer type of which the price dates from 2012. The price range is at the high end of the price range specified by ENTSO-E.

For several other voltage and power ratings no suitable transformers were available. Therefore a linear approximation of several other transformer prices has been performed, leading to a price of 8.1 k€/MVA, which is in the lower part of the range of the ENTSO-E estimation when only considering 2 winding transformers. Besides, the electrical parameters

[59] NSCOGI. *Offshore Transmission Technology*. Tech. rep. ENTSO-E, 2012.

[60] F.D.J. Nieuwenhout and M. van Hout. *Cost, benefits, regulations and policy aspects of a North Sea Transnational Grid, chapter 4*. Tech. rep. ECN Policy Studies, 2013, http://www.nstg-project.nl/uploads/media/9_ECN-E-13-065_NSTG_WP7_Cost_benefits_regulations_policy_aspects.pdf

have been scaled with the power and voltage ratings and originate from a set of large 400 kV and 500 kV two-winding inter-bus transformer specifications[61,62]

The inductor price is based on only few data and is scaled linearly with the power rating. The price per MVA is considerably lower than specified by ENTSO-E, considering an inductor of 100 MVA / 275 kV. So it could be considered to base the prices on the ENTSOe data instead.

Converters

The converter price is based on public data of several interconnection projects, which is presented in the previously mentioned report of ECN-Policy Studies. Price for a pair of VSCs is estimated as:

$$Cost\ VSC_2 = 110 + 0.1178 \cdot P\ [M€] \quad (B\text{-}1)$$

For a ±320 kV / 1200 MW VSC it results in 125 M€, which is in range of the ENTSO-E price estimation of 121 - 150 M€ for a 1250 MW / 500 kV VSC. For a ±320 kV / 300 MW VSC it results in 72.6 M€, which is in line with the ENTSO price estimation of 75 - 92 M€ for a 500 MW / 300 kV VSC.

Platforms

In the EeFarm-II database three HVAC platforms are included and four platforms for AC/DC (VSC) converter stations are included, varying between 300 and 1100 MW.

The 300 MW HVAC platform PlatF_8 price is in agreement with the estimates of ENTSO-E. For the HVDC platforms some old prices were not accurate anymore, therefore the ENTSO-E platform prices have been used for the case of a 1000 MW VSC ±500 kV, 8000 tonnes capacity platform of 157 M€.

In some scenarios also a platform for a smaller VSC is required, which is not available in the EeFarm-II database. Also in this case the ENTSO-E cost data is used: case 400 MW / 300 kV, 3500 tonnes, with a maximum price of 73.65 M€.

Onshore substation

Only a single onshore substation is available in the database, which is from a 300MW HVAC connected wind farm. Therefore price of this substation is used for all onshore substations.

Recommended cost comparisons

The ODIS database 2011 has been used by NUON for the first cost estimate and the ODIS database has also been used in the ISLES study. A comparison with this database would help to assess or improve the accuracy of the cost figures.

Also a comparison with the Irene-40 database is an opportunity to assess or improve the accuracy of the cost figures.

---

[61] url: www.leonardo-energy.org/sites/leonardo-energy/files/documents-and-links/Cu0144_Efficiency%20and%20Loss%20Evaluation%20of%20Large%20Power%20Transformers_v1.pdf
[62] url: www.xianelectriic.com

B.2.2 Cost allocation

The additional costs for the interconnection are calculated as the total costs minus the costs of a representative zero-case. This zero-case includes a DC-connected offshore wind farm connected to the UK and an AC-connected offshore wind farm connected to NL without any interconnection. The wind farm capacities are chosen identical to the specific scenario with interconnection.

For the socio-economic benefits all additional costs are shared on a 50%/50% basis between UK and NL.

B.3 Performance (Losses) modelling

The losses assessment has been performed in the ECN tool EeFarm-II, just as the cost assessment. These losses include transmission losses as well as lost energy due to unavailability (failure) of components. The basis for the modelling is component models and the model inputs. The component models include detailed loss models, including Ohmic losses as well as reactive power characteristics, failure rates, redundancy calculation and Mean Time To Repair (MTTR). The model inputs in this case consist of hourly power production of the two offshore wind farms is based on yearly averaged wind speeds provided by Vattenfall. The production variations due to wind fluctuations were modelled based on the data from the IJmuiden offshore met mast and the met mast at ECNs test site in the Wieringermeer, which have roughly the same distance to each other as between East Anglia and Beaufort.

B.3.1 Links between EeFarm-II and COMPETES models

The energy flows in the offshore network used to determine to check the design ratings and to evaluate the losses are imported from the ECN market model COMPETES. This market model uses the same wind production data as specified above. The flow scheme in Figure B-1 visualizes the process of losses calculation and further processing.

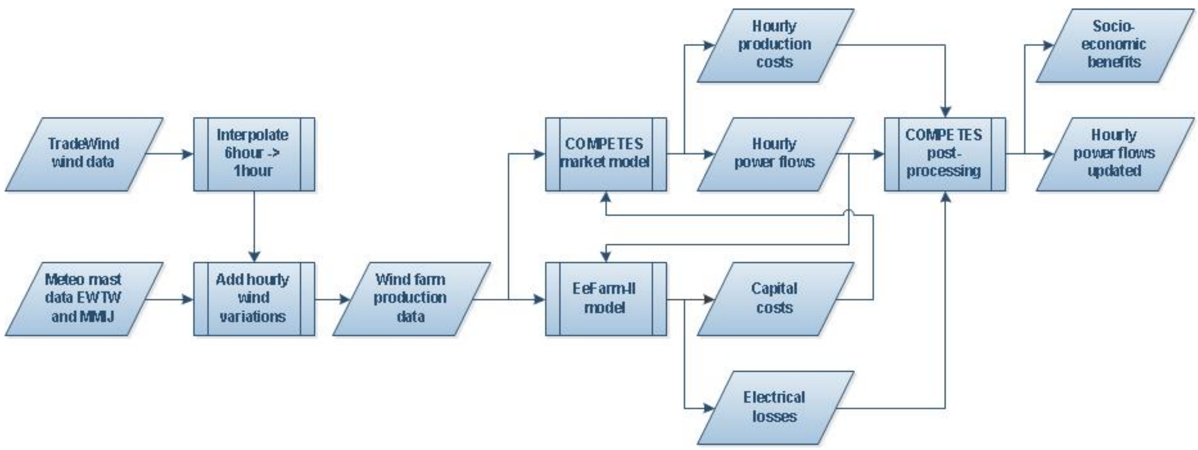


Figure B-1: Overview of the combined electrical and socio-economic scenario evaluation

B.3.2 Wind farm inputs

Wind farm production figures at the two locations: hourly time series. The same generated wind farm production figures are applied as input in the technical models as in the market simulations. The average wind speed at the locations of the two offshore wind farms are taken from the TradeWind database, which is based on *Re-analysis* data from the *European Centre for Medium-Range Weather Forecasts* (ECMWF). The spatial resolution and time resolution of six hours of these data are rather large, so that the wind speed variations and wind speed differences between the two wind farms are expected to be very small. Therefore we have selected a single location (more or less in between the two offshore wind farms) and added wind speed variations, according to the following procedure:

1. From a single TradeWind one-year time-series separate time-series have been made by scaling the data to match the annual mean wind speeds of the UK wind farm and NL wind farm of 9.7 m/s and 9.3 m/s at hub height.
2. Measured hourly wind speeds of the following two locations have been retrieved over the period 2 November 2011 until 14 July 2013 (not overlapping with TradeWind data)
    a. *Meteo mast IJmuiden*. wind speed at 92 m
    b. *ECN Wind turbine Test site Wieringermeer*. Meteo Mast 3, wind speed at 108m. These locations are also about 100 km apart in East-West direction.
3. After the data quality checks a full year is selected and both data series have been scaled to an average wind speed of 10.0 m/s.
4. The variations have been added to the two series derived in item 1 of this procedure:

$$V_{UK-WF} = V_{TW\,UK-WF} + 0.5 \cdot (V_{MMIJ} - V_{EWTW})$$
$$V_{NL-WF} = V_{TW\,NL-WF} - 0.5 \cdot (V_{MMIJ} - V_{EWTW}) \qquad (B\text{-}2)$$

5. The two resulting wind speed series have been combined with a power-wind speed characteristic (power curve), which is a 10 MW reference turbine defined by DTU (DK).
6. Finally the two power series are scaled to match the annual energy production.
7. As a check the cross-correlations of the different wind farm power series, indicating the power variability in time, have been plotted in Figure B-2. For each series the wind farm power has been normalized to 1 MW.

The peak values of the power at zero time difference are equal to averaged square of the power, so a value of 0.4 means an average power of about $P_{rated} \cdot \sqrt{0.4} \approx 0.63 \cdot P_{rated}$, which equals 0.63 × 8760 [hrs/y] = 5519 [full-load hours/y]. Figure B-2 shows that the averaged power (and therefore the annual energy production) of the resulting time series (in red) match the original values computed directly from the TradeWind dataset (in black) as intended. The peaks of the MMIJ and EWTW series are higher because of the higher average wind speed (scaled at 10 m/s). Because of the wind speed probability distributions of MMIJ and EWTW differ. The power annual output at MMIJ is a little higher than at EWTW at the same average wind speed. Furthermore, the peaks of the resulting time series (in red) are sharper than of the original time-series (in black), but less than of the measured time series (in blue). This is logical as the red curve is a combination of the two curves (black and blue). The sharper peak means that the power variation with time has increased.

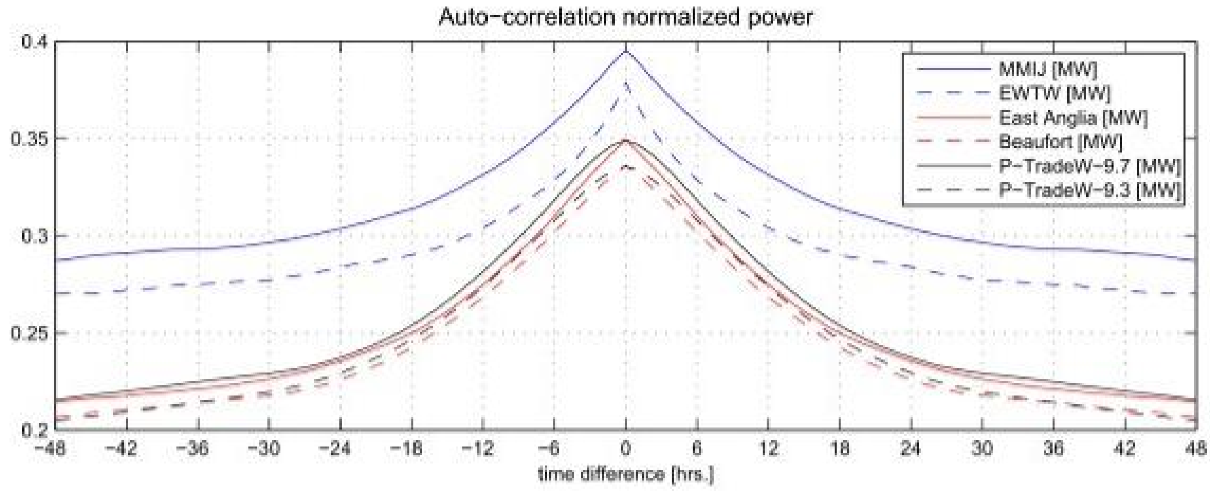


Figure B-2: Auto-correlation of normalized wind farm power time series

Figure B-3 shows how much the power time series of the two neighboring wind farms are correlated, with the blue curve for the difference between the measured time series and the red curve for the difference between the resulting offshore wind farm power time series. The cross-covariance is a cross-correlation but after subtracting the mean value of the two inputs, which emphasizes the differences. Like in the previous figure, the correlation between the resulting offshore wind farm power series is somewhat larger than of the power series derived from the measurements. The data from the measurements show a time offset of about one hour, because the main wind direction is from the West. Unfortunately, the measurement campaigns do not overlap with the TradeWind data, therefore the wind directions of both series are uncorrelated and the cross covariance becomes symmetrical around zero (I.e. the time shift disappears in the end result). In the model this might lead to less benefits of the interconnector than what would be the case in practice.

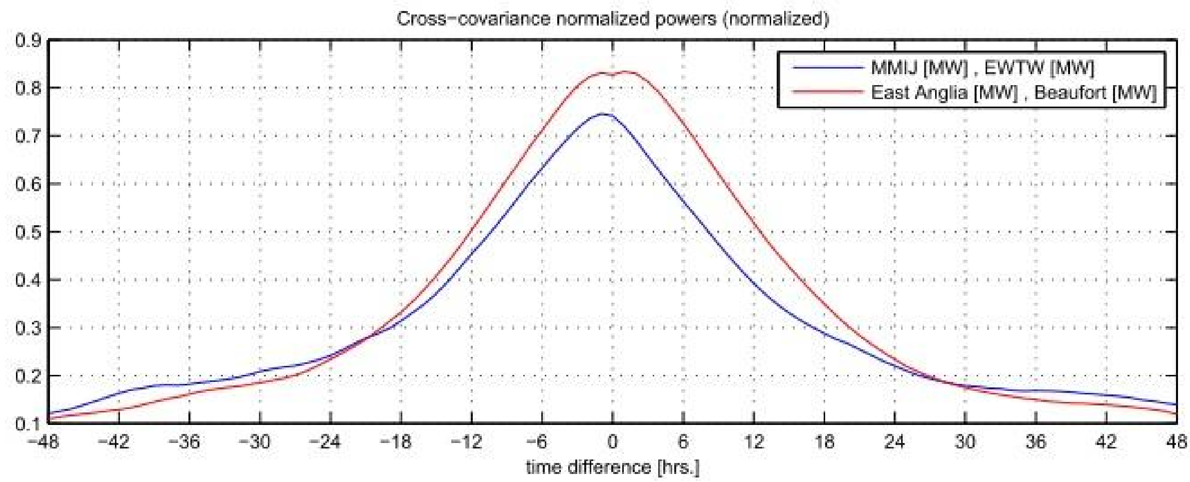


Figure B-3: Normalized cross-covariance of wind farm power differences

B.3.3 Component models

The components were selected from a component library *EeFarm2_Library_version7*[63], dated 2013-09-01, and linked to a EeFarm-II component database named *database_selected_comp_SaS_20131106*. The used components have been listed in appendix B.4.

Summarizing the component models include:

- reactive power characteristics;
- failure rates, MTTR;
- loss models, including Ohmic losses, no-load losses and non-availability (single failure);
- investment costs and installation costs.

The components are coupled through standardized buses to store and transmit both the electrical, availability and cost results per component and accumulated.

B.3.4 Building the models

The modelling includes:

1. Linking the hourly energy flows to the models;
2. Linking the wind farm model outputs;
3. Specify components and parameters.

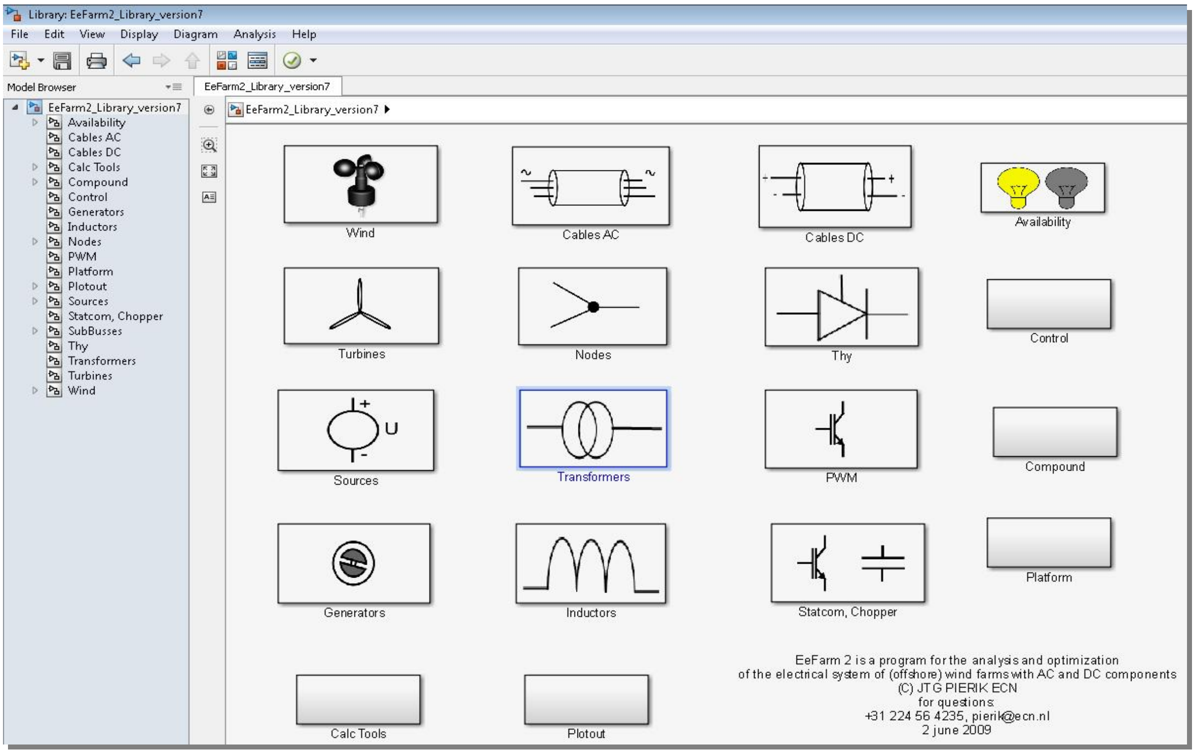


Figure B-4: Overview of EeFarm component library

[63]J.T.G. Pierik (ECN Wind Energy), U. Axelsson, E. Eriksson, and D. Salomonsson (Vattenfall). *EeFarm II, Description, testing and application*. Tech. rep. ECN-E–09-051

Link hourly energy flows to market model output

The power flows in the electrical models are determined by setting the power inputs at the two wind farms and at the NL grid side. Consequently the UK grid terminal is considered as output (slack node). For the three inputs terminals the generator sign convention is chosen and for the UK grid terminal the motor sign convention. The power setting at the NL grid side (hourly data) is derived from the corresponding market scenario simulation result. In addition to the scenario **IC1200** with a 1200 MW interconnector the scenario **IC300** with a 300 MW interconnection has been modeled, in order to compare costs and losses with the project scenarios. For the **IC300** scenario the power flows from the scenario IC1200 are used and then limited to ±300 MW.

Linking wind farm model outputs

As the wind farms are identical in all scenarios, the wind farms are represented with their electrical characteristics at the medium-voltage side of the offshore substation, as shown in Figure B-5. The internal wind farm models themselves are not included. For each value of the power production the reactive power and voltage levels are derived from previous simulations of a 300 MW offshore wind farm. For the 1200 MW wind farm in the UK waters, the 300 MW wind farm output current is scaled up with a factor 4.

Specify models and parameters

As said the modeling in this phase of the project is limited to stationary behavior and only the main components are included. Obviously, the correct power ratings and suitable voltage ranges should be selected. Further, the following guidelines have been applied:

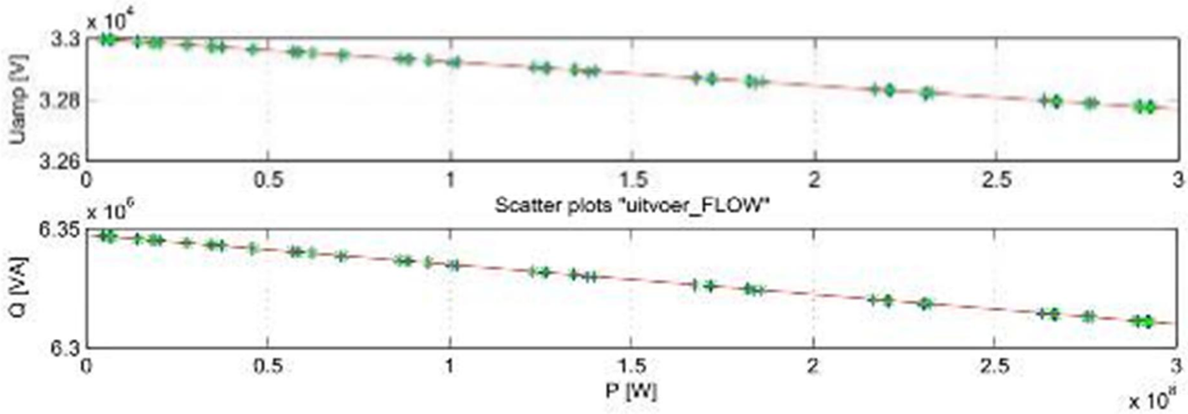


Figure B-5: Stationary electrical characteristic of 300 MW wind farm

- Maximum transformer size is 600 MVA, for larger ratings parallel units are applied;
- At offshore platforms two parallel transformers are chosen for reasons of redundancy and for other technical reasons in combination with HVDC VSCs;
- HVAC lines are limited both in power rating and transmission distance. A typical power rating that is possible for a single cable is about 300 MW when choosing a nominal voltage of 220 kV. Higher ratings are only feasible by means of parallel cabling systems;
- Long HVAC cables are modeled using a number of cascaded PI-sections in order to approximate the voltage profile along the cable;
- For compensating the reactive power produced by the HVAC cables only static

compensation is applied. The size of the reactance's is chosen such that half of the produced reactive power at nominal voltage is consumed at either side of the cable;

- Compensating the reactive power consumption by the transformers, which is current dependent, is not yet considered. It will be in case the grid code requirements are violated or significant transmission losses occur;
- For long HVAC cables no mid-point reactive power compensation is applied, except for the landfall in the UK, because of the significant onshore distance to the substation;
- The HVDC rectifier station operates at nominal DC-voltage set-point and the inverter stations at nominal AC-voltage and zero reactive power set-point, meaning minimal conduction losses. A contribution to reactive power control can be considered at a later stage. This also holds for optimizing the DC voltage and possibly other settings with respect to losses and security aspects;
- As no HVDC land cables are in the database an offshore type cable is used. Using dedicated onshore cables may lead to somewhat lower costs;
- The current selection of scenarios includes HVDC connections of 300 MW and 1200 MW. In order to be able to make interconnections ±320 kV is chosen for both power levels;
- In the **IC1200** scenario the interconnector rating is 1200 MW, while in the project scenarios it is only 300 MW. The comparison between the scenarios can still be made using Levelized Transport Costs. Although an interconnector of only 300 MW between NL and UK is assumed to be too small to be feasible, it is added as **IC300** in order to compare costs and losses with the project scenarios.

The EeFarm-II models for the selected scenarios are presented in appendix B.3.5.

As an example a screenshot of the EeFarm-II model of scenario Tech-UK-NL-2 is presented. The model is split into three parts that are simulated in a sequence and that can be re-used in other scenarios. These parts A, B and C indicated by the green, red and purple dashed boxes in Figure B-6. Shown in a more detailed way in Figure B-7, the blue boxes are either time-series input blocks or electrical components. The block name shows the (generic) component type while the block annotations show the loaded component parameters and whether the specific component is used for wind power export or trading. The white input and output blocks link the different parts A, B and C of the model. The yellow blocks show and store the simulation results at the locations these are inserted in the scheme. The block annotations show the variable name to which the result is stored.

B.3.5 Simulink models per scenario

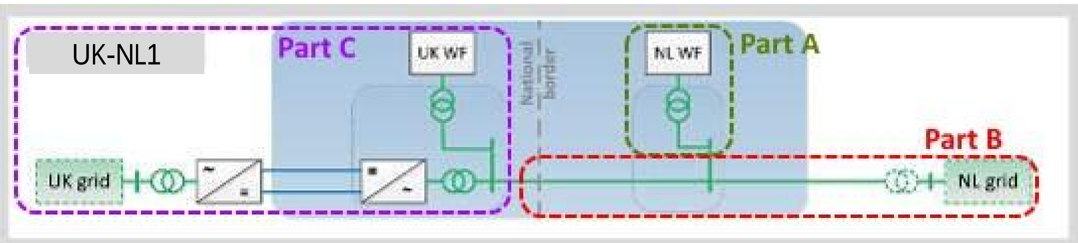
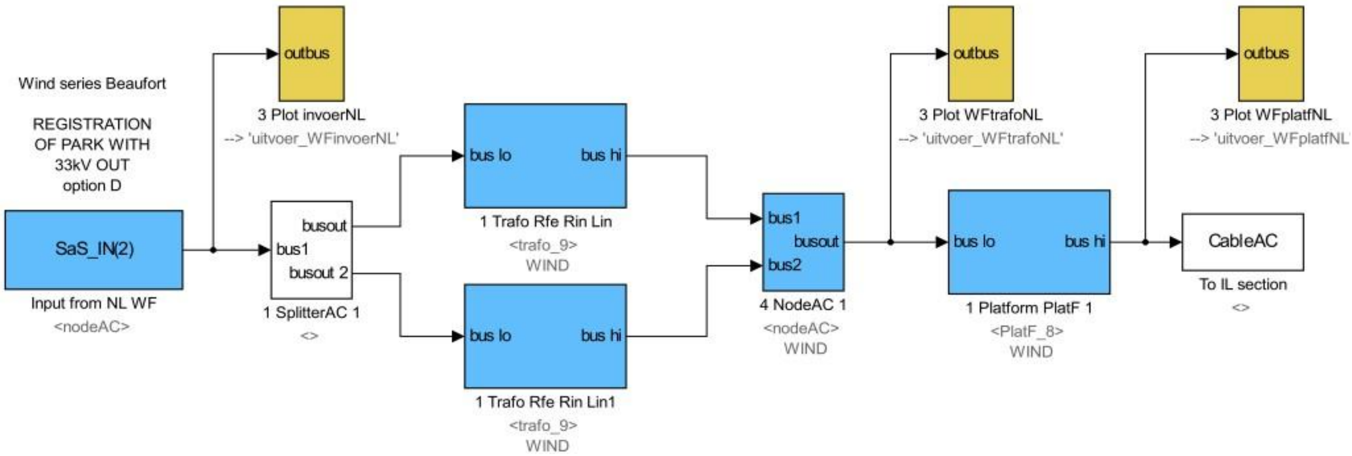
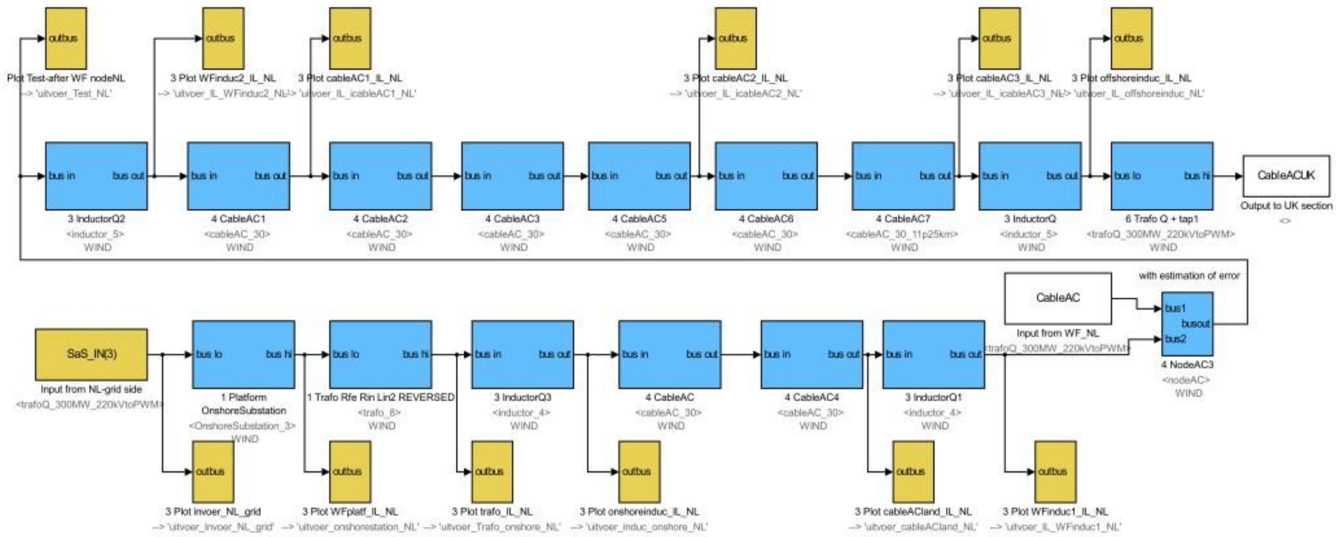


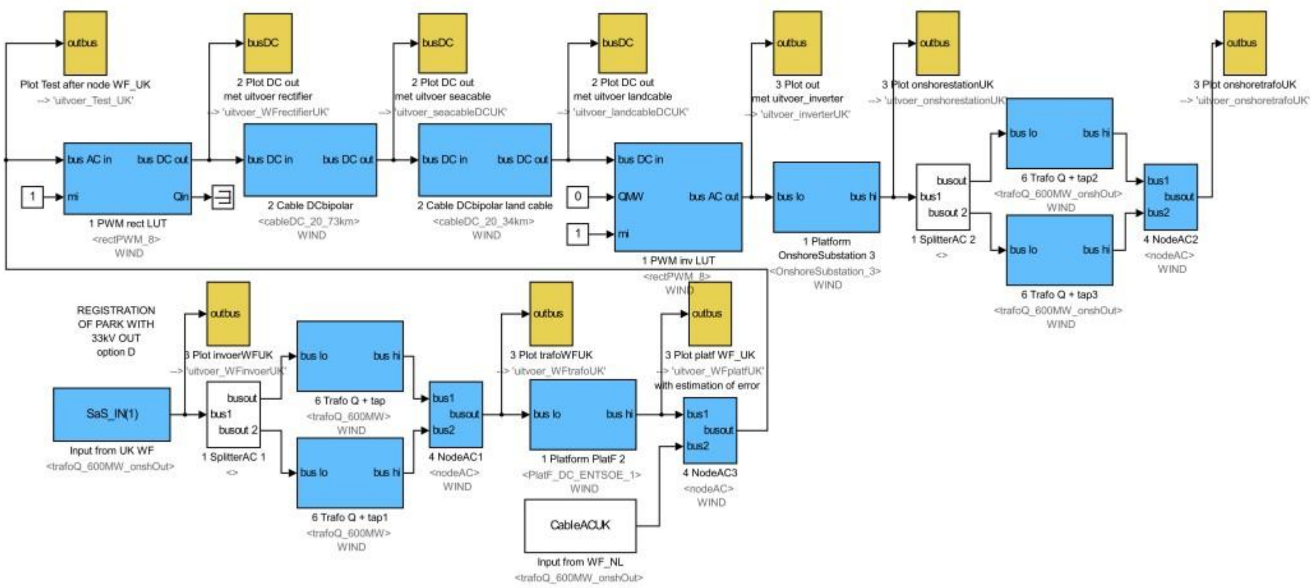
Figure B-6: UK-NL1 with three model parts indicated with colored boxes



(a)NL wind farm



(b)NL grid and interconnecting link



(c)UK Wind farm and DC connection to UK grid

*Figure B-7: Model of scenario **UK-NL1***

B.4 Parameter list

B.4.1 Parameter list summary

In Table B-1, a summary of the parameters used in the Synergies at Sea scenarios is given.

Table B-1: List of parameters used in the SaS scenarios

Variable name	Reference	Rating
cableAC_30 (17.75km) cableAC_30_19p5km cableAC_30_11p25km	Subsea XLPE HVAC export cable. ABB	220kV/330MVA. Cu-1x3x1000mm^2
inductor_4	Offshore. 50MVA/220kV	220kV. 50MVA
inductor_5	Onshore. 100MVA/220kV	220kV. 220MVA
inductor_7	Onshore. 150MVA/220kV	220kV. 150MVA
trafo_8	Onshore	220kV/380kV. 320MVA
trafo_9	Offshore	33kV/220kV. 160MVA
trafoQ_600MW		33kV/420kV. 600MVA
trafoQ_600MW_onshInp		380kV/420kV. 600MVA
trafoQ_600MW_onshOut	Onshore, upscaled Interbus trafo. ONAF	420kV/380kV. 600MVA
trafoQ_300MW_220kVtoPWM		220kV/420kV. 300MVA
trafoQ_300MW_220kVto380kV		220kV/380kV. 300MVA
trafoQ_160MW_320		33kV/420kV. 160MVA
trafoQ_160MW_220kVtoPWM		220kV/420kV. 160MVA
trafoQ_160MW_onshOut		420kV/380kV. 160MVA
trafoQ_160MW_onshInp		380kV/420kV. 160MVA
PlatF_DC_ENTSOE_1	ENTSOE. 1000MW VSC +/-500kV. 8000 tonnes	
PlatF_DC_ENTSOE_2	ENTSOE. 400MW VSC +/-300kV. 3500 tonnes	
PlatF_8	Offshore. 220kVAC/300MW, install. Included	
OnshoreSubstation_3	Onshore. 220kVAC/300MW, install. Included	
rectPWM_8 rectPWM_9	ABB HVDC Light converter, parameters from rectPWM_6 and rectPWM_7. losses updated for multi-level VSC	±320kV/1216MW ±320kV/ 300MW
cableDC_16_35km cableDC_16_73km cableDC_16_100km cableDC_16_110km	Subsea XLPE export cable for ABB HVDC light	320kV /381MW bipolar. Cu 185mm^2
cableDC_20_73km cableDC_20_34km	Subsea XLPE export cable for ABB HVDC light	320kV /1146MW bipolar. Cu 1200mm^2

B.4.2 Parameter list details

The following list contains all parameters of the components used in the scenario models, with exception of the cost price information and references to sources of proprietary data.

```
|--- cableAC_30
|       |
|       |-- type : '--XLPE. Cu -1x3x1000  '
|       |-- Ref : '  subsea export cable  '
|       |---------- typename : 'FarmCable'
|       |----------- catname : 'WIND'
|       |---------------- nr : 30
|       |----------- kVeffpp : 220
|       |-------------- SMVA : 330
|       |----------------- I : 866.025
|       |-------------- area : 1000
|       |------------- Rac20 : 0.027
|       |------------- Rac90 : 0.0344277
|       |------------- Rdc20 : 0
|       |------------- Rdc90 : 0
|       |----------------- L : 0.00039
|       |----------------- C : 1.9e-07
|       |---------------- Wd : 0
|       |---------- tandelta : 0
|       |------- notavail_km : 0.000138082
|       |---------- Tandelta : 0
|       |--------------- Rkm : 0.027
|       |--------------- Ckm : 1.9e-07
|       |--------------- Lkm : 0.00039
|       |-- fail_peryr_perkm : 0.0008
|       |------ repairtimehr : 1512
|       |---- nr_of_sections : 2
|       |------------ Length : 17.75
|       O
|
|--- cableAC_30_11p5km
|       |
|       |------------ Length : 11.5
|       |------ <other fields identical to
|       |       "cableAC_30">
|       O
|
|--- cableAC_30_19p5km
|       |
|       |------------ Length : 19.5
|       |------ <other fields identical to
|       |       "cableAC_30">
|       O
|
|--- inductor_4
|       |
|       |-- type : ' Offshore 220kV. 2 ex.'
|       |-------- Ref : ' 50MVA 220kV'
|       |--- typename : 'FarmInduc'
|       |---- catname : 'WIND'
|       |--------- nr : 4
|       |---- kVeffpp : 220
|       |------- SMVA : 50
|       |---------- I : 131.216
|       |-------- Rpu : 968
|       |-------- Rfe : 1e+06
|       |-------- Rcu : 2.904
|       |------ PcukW : 150
|       |---------- L : 3.08124
|       |----- Lcheck : 3.08124
|       |--- notavail : 0
|       O
|
V
```

```
V
|--- inductor_5
|       |
|       |--- type : ' Onshore 220kV. 2 ex.'
|       |-------- Ref : ' 100MVA 220kV'
|       |--- typename : 'FarmInduc'
|       |---- catname : 'WIND'
|       |--------- nr : 5
|       |---- kVeffpp : 220
|       |------- SMVA : 100
|       |---------- I : 262.432
|       |-------- Rpu : 484
|       |-------- Rfe : 1e+06
|       |-------- Rcu : 1.452
|       |------ PcukW : 300
|       |---------- L : 1.54062
|       |----- Lcheck : 1.54062
|       |--- notavail : 0
|       O
|
|--- inductor_7
|       |
|       |--- type : ' Onshore 220kV. 2 ex.'
|       |-------- Ref : '150MVA 220kV'
|       |--- typename : 'FarmInduc'
|       |---- catname : 'WIND'
|       |--------- nr : 7
|       |---- kVeffpp : 220
|       |------- SMVA : 150
|       |---------- I : 393.648
|       |-------- Rpu : 322.667
|       |-------- Rfe : 1e+06
|       |-------- Rcu : 0.968
|       |------ PcukW : 450
|       |---------- L : 1.02708
|       |----- Lcheck : 1.02708
|       |--- notavail : 0
|       O
|--- trafo_8
|       |
|       |---- type : '220/380 kV. 320 MVA'
|       |---- Ref : ' 220kV Onshore. 1 ex.'
|       |----------- typename : 'GridTrafo'
|       |------------ catname : 'WIND'
|       |----------------- nr : 8
|       |---------- kVeffpplo : 220
|       |---------- kVeffpphi : 380
|       |--------------- SMVA : 320
|       |---------- PlossfekW : 122
|       |---------------- Ife : 0.320167
|       |-------------- Rfelo : 396721
|       |---------------- Ilo : 839.782
|       |-------------- Rpulo : 151.25
|       |-------------- Lpulo : 0.481444
|       |---------------- Rin : 0.27225
|       |---------------- Lin : 0.0577732
|       |-------------- PcukW : 576
|       |----------- QleakMVA : 38.4
|       |----------------- Lm : 0
|       |--------------- Rout : 0
|       |--------------- Lout : 0
|       |--------- fail_peryr : 0.0248
|       |------- repairtimehr : 510
|       |----------- notavail : 0.00144384
|       |---------------- Ulo : 220
|       |---------------- Uhi : 380
|       O
V
```

```
v
|       |--- trafo_9
|       |
|       |----- type : ' 33/220 kV. 160 MVA'
|       |--- Ref : ' 220kV Offshore. 2 ex.'
|       |----------- typename : 'FarmTrafo'
|       |------------ catname : 'WIND'
|       |----------------- nr : 9
|       |---------- kVeffpplo : 33
|       |---------- kVeffpphi : 220
|       |--------------- SMVA : 160
|       |---------- PlossfekW : 56
|       |---------------- Ife : 0.979746
|       |-------------- Rfelo : 19446.4
|       |---------------- Ilo : 2799.27
|       |-------------- Rpulo : 6.80625
|       |-------------- Lpulo : 0.021665
|       |---------------- Rin : 0.0170156
|       |---------------- Lin : 0.00389969
|       |-------------- PcukW : 400
|       |----------- QleakMVA : 28.8
|       |----------------- Lm : 0
|       |--------------- Rout : 0
|       |--------------- Lout : 0
|       |--------- fail_peryr : 0.0248
|       |------- repairtimehr : 1896
|       |----------- notavail : 0.00536767
|       |---------------- Ulo : 33
|       |---------------- Uhi : 220
|       O
   |
|--- trafoQ_600MW
|       |
|       |- Name:'Upsc. Interbus trafo ONAF'
|       |---------- typename : 'FarmTrafo'
|       |----------- catname : 'WIND'
|       |---------- Ll1_orig : 0.00121324
|       |---------- Ll2_orig : 0.00121324
|       |------------ M_orig : 29930.4
|       |----------- R1_orig : 0.0049005
|       |----------- R2_orig : 0.0049005
|       |-------- Ploss_orig : 1.44e+06
|       |--- Ploss_orig_RelR : 0.0018
|       |-- Ploss_orig_Relfe : 0.0006
|       |---- Ploss_orig_Rel : 0.0024
|       |--------------- Lin : 0.000404413
|       |---------------- Lm : 127058
|       |--------------- Rin : 0.0016335
|       |-------------- Lout : 0.000404413
|       |-------------- Rout : 0.0016335
|       |------------- Rfelo : 3025
|       |--------------- Ulo : 33000
|       |--------------- Uhi : 420267
|       |------------ Srated : 6e+08
|       |------- Uin_ph_zero : 19052.6
|       |--------------- Iin : 10497.3
|       |------ Uout_ph_zero : 242641
|       |-------------- Iout : 824.263
|       |---------------- TR : 0.0785216
|       |------ PlossRinRout : 1.08e+06
|       |------------- Ifelo : 6.29837
|       |---------- PlossRfe : 360000
|       |--------- PlossRelR : 0.0018
|       |-------- PlossRelfe : 0.0006
|       |---------- PlossRel : 0.0024
|       |---------- notavail : 0.0017
|       O
v
```

```
v
|
|--- trafoQ_160MW_320
|       |
|       |- Name:'Upsc. Interbus trafo ONAF'
|       |---------- typename : 'FarmTrafo'
|       |----------- catname : 'WIND'
|       |---------- Ll1_orig : 0.00454964
|       |---------- Ll2_orig : 0.00454964
|       |------------ M_orig : 29930.4
|       |----------- R1_orig : 0.0183769
|       |----------- R2_orig : 0.0183769
|       |-------- Ploss_orig : 384000
|       |--- Ploss_orig_RelR : 0.0018
|       |-- Ploss_orig_Relfe : 0.0006
|       |---- Ploss_orig_Rel : 0.0024
|       |--------------- Lin : 0.00151655
|       |---------------- Lm : 127058
|       |--------------- Rin : 0.00612563
|       |-------------- Lout : 0.00151655
|       |-------------- Rout : 0.00612563
|       |------------- Rfelo : 11343.8
|       |--------------- Ulo : 33000
|       |--------------- Uhi : 420267
|       |------------ Srated : 1.6e+08
|       |------- Uin_ph_zero : 19052.6
|       |--------------- Iin : 2799.27
|       |------ Uout_ph_zero : 242641
|       |-------------- Iout : 219.803
|       |---------------- TR : 0.0785216
|       |------ PlossRinRout : 288000
|       |------------- Ifelo : 1.67956
|       |---------- PlossRfe : 96000
|       |--------- PlossRelR : 0.0018
|       |-------- PlossRelfe : 0.0006
|       |---------- PlossRel : 0.0024
|       |---------- notavail : 0.0017
|       O
|
|--- trafoQ_600MW_onshOut
|       |
|       |- Name:'Upsc. Interbus trafo ONAF'
|       |---------- typename : 'FarmTrafo'
|       |----------- catname : 'WIND'
|       |---------- Ll1_orig : 0.196774
|       |---------- Ll2_orig : 0.196774
|       |------------ M_orig : 2125
|       |----------- R1_orig : 0.794808
|       |----------- R2_orig : 0.794808
|       |-------- Ploss_orig : 1.44e+06
|       |--- Ploss_orig_RelR : 0.0018
|       |-- Ploss_orig_Relfe : 0.0006
|       |---- Ploss_orig_Rel : 0.0024
|       |--------------- Lin : 0.0655914
|       |---------------- Lm : 640.468
|       |--------------- Rin : 0.264936
|       |-------------- Lout : 0.0655914
|       |-------------- Rout : 0.264936
|       |------------- Rfelo : 490622
|       |--------------- Ulo : 420267
|       |--------------- Uhi : 380000
|       |------------ Srated : 6e+08
|       |------- Uin_ph_zero : 242641
|       |--------------- Iin : 824.263
|       |------ Uout_ph_zero : 219393
|       |-------------- Iout : 911.606
|       |---------------- TR : 1.10596
|       |------ PlossRinRout : 1.08e+06
|       |------------- Ifelo : 0.494558
|       |---------- PlossRfe : 360000
|       |--------- PlossRelR : 0.0018
|       |-------- PlossRelfe : 0.0006
|       |---------- PlossRel : 0.0024
|       |---------- notavail : 0.0017
|       O
v
```

```
V
|
|--- trafoQ_160MW_onshInp
|        |
|        |- Name:'Upsc. Interbus trafo ONAF'
|        |---------- typename : 'FarmTrafo'
|        |----------- catname : 'WIND'
|        |---------- Ll1_orig : 0.603277
|        |---------- Ll2_orig : 0.603277
|        |------------ M_orig : 2599.22
|        |----------- R1_orig : 2.43675
|        |----------- R2_orig : 2.43675
|        |-------- Ploss_orig : 384000
|        |--- Ploss_orig_RelR : 0.0018
|        |-- Ploss_orig_Relfe : 0.0006
|        |---- Ploss_orig_Rel : 0.0024
|        |--------------- Lin : 0.201092
|        |---------------- Lm : 958.214
|        |--------------- Rin : 0.81225
|        |-------------- Lout : 0.201092
|        |-------------- Rout : 0.81225
|        |------------- Rfelo : 1.50417e+06
|        |--------------- Ulo : 380000
|        |--------------- Uhi : 420267
|        |------------ Srated : 1.6e+08
|        |------- Uin_ph_zero : 219393
|        |--------------- Iin : 243.095
|        |------ Uout_ph_zero : 242641
|        |-------------- Iout : 219.803
|        |---------------- TR : 0.904188
|        |------ PlossRinRout : 288000
|        |------------- Ifelo : 0.145857
|        |---------- PlossRfe : 96000
|        |--------- PlossRelR : 0.0018
|        |-------- PlossRelfe : 0.0006
|        |---------- PlossRel : 0.0024
|        |---------- notavail : 0.0017
|        O
|
|--- trafoQ_160MW_onshOut
|        |
|        |- Name:'Upsc. Interbus trafo ONAF'
|        |---------- typename : 'FarmTrafo'
|        |----------- catname : 'WIND'
|        |---------- Ll1_orig : 0.737903
|        |---------- Ll2_orig : 0.737903
|        |------------ M_orig : 2125
|        |----------- R1_orig : 2.98053
|        |----------- R2_orig : 2.98053
|        |-------- Ploss_orig : 384000
|        |--- Ploss_orig_RelR : 0.0018
|        |-- Ploss_orig_Relfe : 0.0006
|        |---- Ploss_orig_Rel : 0.0024
|        |--------------- Lin : 0.245968
|        |---------------- Lm : 640.468
|        |--------------- Rin : 0.99351
|        |-------------- Lout : 0.245968
|        |-------------- Rout : 0.99351
|        |------------- Rfelo : 1.83983e+06
|        |--------------- Ulo : 420267
|        |--------------- Uhi : 380000
|        |------------ Srated : 1.6e+08
|        |------- Uin_ph_zero : 242641
|        |--------------- Iin : 219.803
|        |------ Uout_ph_zero : 219393
|        |-------------- Iout : 243.095
|        |---------------- TR : 1.10596
|        |------ PlossRinRout : 288000
|        |------------- Ifelo : 0.131882
|        |---------- PlossRfe : 96000
|        |--------- PlossRelR : 0.0018
|        |-------- PlossRelfe : 0.0006
|        |---------- PlossRel : 0.0024
|        |---------- notavail : 0.0017
|        O
V
```

```
V
|
|--- trafoQ_300MW_220kVtoPWM
|        |
|        |- Name:'Upsc. Interbus trafo ONAF'
|        |---------- typename : 'FarmTrafo'
|        |----------- catname : 'WIND'
|        |---------- Ll1_orig : 0.107843
|        |---------- Ll2_orig : 0.107843
|        |------------ M_orig : 4489.56
|        |----------- R1_orig : 0.4356
|        |----------- R2_orig : 0.4356
|        |-------- Ploss_orig : 720000
|        |--- Ploss_orig_RelR : 0.0018
|        |-- Ploss_orig_Relfe : 0.0006
|        |---- Ploss_orig_Rel : 0.0024
|        |--------------- Lin : 0.0359478
|        |---------------- Lm : 2858.8
|        |--------------- Rin : 0.1452
|        |-------------- Lout : 0.0359478
|        |-------------- Rout : 0.1452
|        |------------- Rfelo : 268889
|        |--------------- Ulo : 220000
|        |--------------- Uhi : 420267
|        |------------ Srated : 3e+08
|        |------- Uin_ph_zero : 127017
|        |--------------- Iin : 787.296
|        |------ Uout_ph_zero : 242641
|        |-------------- Iout : 412.131
|        |---------------- TR : 0.523477
|        |------ PlossRinRout : 540000
|        |------------- Ifelo : 0.472377
|        |---------- PlossRfe : 180000
|        |--------- PlossRelR : 0.0018
|        |-------- PlossRelfe : 0.0006
|        |---------- PlossRel : 0.0024
|        |---------- notavail : 0.0017
|        O
|
|--- trafoQ_160MW_220kVtoPWM
|        |
|        |- Name:'Upsc. Interbus trafo ONAF'
|        |---------- typename : 'FarmTrafo'
|        |----------- catname : 'WIND'
|        |---------- Ll1_orig : 0.202206
|        |---------- Ll2_orig : 0.202206
|        |------------ M_orig : 4489.56
|        |----------- R1_orig : 0.81675
|        |----------- R2_orig : 0.81675
|        |-------- Ploss_orig : 384000
|        |--- Ploss_orig_RelR : 0.0018
|        |-- Ploss_orig_Relfe : 0.0006
|        |---- Ploss_orig_Rel : 0.0024
|        |--------------- Lin : 0.0674021
|        |---------------- Lm : 2858.8
|        |--------------- Rin : 0.27225
|        |-------------- Lout : 0.0674021
|        |-------------- Rout : 0.27225
|        |------------- Rfelo : 504167
|        |--------------- Ulo : 220000
|        |--------------- Uhi : 420267
|        |------------ Srated : 1.6e+08
|        |------- Uin_ph_zero : 127017
|        |--------------- Iin : 419.891
|        |------ Uout_ph_zero : 242641
|        |-------------- Iout : 219.803
|        |---------------- TR : 0.523477
|        |------ PlossRinRout : 288000
|        |------------- Ifelo : 0.251935
|        |---------- PlossRfe : 96000
|        |--------- PlossRelR : 0.0018
|        |-------- PlossRelfe : 0.0006
|        |---------- PlossRel : 0.0024
|        |---------- notavail : 0.0017
|        O
V
```

```
V
|
|--- trafoQ_300MW_220kVto380kV
|        |
|        |- Name:'Upsc. Interbus trafo ONAF'
|        |---------- typename : 'FarmTrafo'
|        |----------- catname : 'WIND'
|        |---------- Ll1_orig : 0.107843
|        |---------- Ll2_orig : 0.107843
|        |------------ M_orig : 4059.4
|        |----------- R1_orig : 0.4356
|        |----------- R2_orig : 0.4356
|        |-------- Ploss_orig : 720000
|        |--- Ploss_orig_RelR : 0.0018
|        |-- Ploss_orig_Relfe : 0.0006
|        |---- Ploss_orig_Rel : 0.0024
|        |--------------- Lin : 0.0359478
|        |---------------- Lm : 2337.23
|        |--------------- Rin : 0.1452
|        |-------------- Lout : 0.0359478
|        |-------------- Rout : 0.1452
|        |------------- Rfelo : 268889
|        |--------------- Ulo : 220000
|        |--------------- Uhi : 380000
|        |------------ Srated : 3e+08
|        |------- Uin_ph_zero : 127017
|        |--------------- Iin : 787.296
|        |------ Uout_ph_zero : 219393
|        |-------------- Iout : 455.803
|        |---------------- TR : 0.578947
|        |------ PlossRinRout : 540000
|        |------------- Ifelo : 0.472377
|        |---------- PlossRfe : 180000
|        |--------- PlossRelR : 0.0018
|        |-------- PlossRelfe : 0.0006
|        |---------- PlossRel : 0.0024
|        |---------- notavail : 0.0017
|        O
|
|--- PlatF_DC_ENTSOE_1
|        |
|        |Ref'ENTSOE.1000MW VSC500kV.8000 t'
|        |--- typename : 'Platform'
|        |---- catname : 'WIND'
|        |--------- nr : 1
|        |--------- MW : 1000
|        O
|
|--- PlatF_DC_ENTSOE_2
|        |
|        |-Ref:'ENTSOE.400MW VSC300kV.3500t'
|        |--- typename : 'Platform'
|        |---- catname : 'WIND'
|        |--------- nr : 1
|        |--------- MW : 400
|        O
|
|--- PlatF_8
|        |
|        |-Ref:'220kVAC 300MW install incl.'
|        |----------- typename : 'Platform'
|        |------------ catname : 'WIND'
|        |----------------- nr : 8
|        |--------------- SMVA : 300
|        |---------- typetrafo : 1
|        |------------ typeVSC : 0
|        O
|
|--- OnshoreSubstation_3
|        |
|        |-Ref:'220kVAC 300MW install incl.'
|        |----------- typename : 'Platform'
|        |------------ catname : 'WIND'
|        |----------------- nr : 3
|        |--------------- SMVA : 300
|        |---------- typetrafo : 1
|        |------------ typeVSC : 0
|
V
```

```
V
|--- rectPWM_8
|        |
|        |type:'HVDC Light.+/-320kV 1216 MW'
|        | Ref:'SaS. param from rectPWM_6&7'
|        |------------- typename : 'FarmPWM'
|        |-------------- catname : 'WIND'
|        |------------------- nr : 8
|        |------------ kVaceffpp : 420.267
|        |----------------- kVdc : 320
|        |----------------- SMVA : 1216
|        |------------------ Ron : 0.45
|        |------------------- Fs : 1150
|        |------------------ Ton : 5e-06
|        |----------------- Toff : 5e-06
|        |----------- noloadloss : 0
|        |----------- fail_peryr : 0.12
|        |--------- repairtimehr : 288
|        |------------- notavail : 0.01
|        |---------------- f_inv : 50
|        |------------------- mi : 1.07233
|        |------------------- rT : 0.15
|        |------------------- rD : 0.025
|        |------------- Idcrated : 1900
|        |------------ Psw_rated : 2.09876e7
|        |----------------- ETon : 3820.18
|        |---------------- EToff : 3820.18
|        |---------------- EDrec : 1910.09
|        |-------------- IacDiff : 0.1
|        |------------------ fsw : 1150
|        |------------ Ieffrated : 1670.51
|        |------------ Itoprated : 2362.45
|        |----------------- Inom : 2362.45
|        |----------------- Vnom : 640000
|        |------------------ R0T : 0.15
|        |------------------ R0D : 0.025
|        |------------------ Csw : 10.9188
|        |-loss_table_Pin_pu:  [1x15 Array]
|        | loss_table_Ploss_pu:[1x15 Array]
|        O
|
|--- rectPWM_9
|        |
|        |- type:'HVDC Light.+/-320kV 300MW'
|        | Ref:'SaS. param from rectPWM_6&7'
|        |------------- typename : 'FarmPWM'
|        |-------------- catname : 'WIND'
|        |------------------- nr : 9
|        |------------ kVaceffpp : 420.267
|        |----------------- kVdc : 320
|        |----------------- SMVA : 300
|        |------------------ Ron : 0.45
|        |------------------- Fs : 1150
|        |------------------ Ton : 5e-06
|        |----------------- Toff : 5e-06
|        |----------- noloadloss : 0
|        |----------- fail_peryr : 0.12
|        |--------- repairtimehr : 288
|        |------------- notavail : 0.01
|        |---------------- f_inv : 50
|        |------------------- mi : 1.07233
|        |------------------- rT : 0.15
|        |------------------- rD : 0.025
|        |------------- Idcrated : 468.75
|        |------------ Psw_rated : 5.175e+06
|        |----------------- ETon : 942.478
|        |---------------- EToff : 942.478
|        |---------------- EDrec : 471.239
|        |-------------- IacDiff : 0.1
|        |------------------ fsw : 1150
|        |------------ Ieffrated : 412.131
|        |------------ Itoprated : 582.842
|        |----------------- Inom : 582.842
|        |----------------- Vnom : 640000
|        |------------------ R0T : 0.15
|        |------------------ R0D : 0.025
|        |------------------ Csw : 10.9188
|        |-loss_table_Pin_pu:  [1x15 Array]
|        | loss_table_Ploss_pu:[1x15 Array]
|        O
|
```

```
V
|--- cableDC_16_73km
|        |
|        |--- name : ' . 1x185mm2. 320kVdc '
|        |-- type : '381 MW (bipol. copper)'
|        |--------------- Ref : '  '
|        |---------- typename : 'FarmCable'
|        |----------- catname : 'WIND'
|        |-- fail_peryr_perkm : [ ]
|        |------ repairtimehr : [ ]
|        |---------------- nr : 16
|        |-------------- kVdc : 320
|        |--------------- PMW : 381
|        |-------------- area : 185
|        |------------- Rdc20 : 0.0991
|        |------------- Rdc90 : 0.126
|        |------------ Irated : 595.313
|        |------- notavail_km : 1e-05
|        |------------- R20km : 0.0991
|        |------------- R90km : 0.126
|        |--------- Tconstant : 40
|        |------------ Npolar : 2
|        |------------ Length : 73
|        O
|
|--- cableDC_16_34km
|        |------ <other fields identical to
|        |       "cableDC_16_73km">
|        |
|        |------------ Length : 34
|        O
|
|
|--- cableDC_16_100km
|        |
|        |------ <other fields identical to
|        |       "cableDC_16_73km">
|        |------------ Length : 100
|        O
|
V
```

```
V
|--- cableDC_16_110km
|        |
|        |------ <other fields identical to
|        |       "cableDC_16_73km">
|        |------------ Length : 110
|        O
|
|--- cableDC_20_34km
|        |
|        |-- name : ' . 1x1200mm2. 320kVdc '
|        |--- type: '1146MW (bipol. copper)'
|        |--------------- Ref : '  '
|        |---------- typename : 'FarmCable'
|        |----------- catname : 'WIND'
|        |---------------- nr : 20
|        |-------------- kVdc : 320
|        |--------------- PMW : 1146
|        |-------------- area : 1200
|        |------------- Rdc20 : 0.0151
|        |------------- Rdc90 : 0.019
|        |------------ Irated : 1790.63
|        |------- notavail_km : 1e-05
|        |------------- R20km : 0.0151
|        |------------- R90km : 0.019
|        |--------- Tconstant : 40
|        |------------ Npolar : 2
|        |------------ Length : 34
|--- cableDC_20_73km
|        |
|        |------ <other fields identical to
|        |       "cableDC_20_34km">
|        |------------ Length : 73
|        O
O
```

B.4.3 Cost parameters

The investment costs in Table B-1 (in Euros-2012) are the basis for the economic calculations as presented in sections 5 and 6. As part of the component cost data is based on confidential sources, the costs have been aggregated to main subsystems.

Section B.2.1 explains about the sources and modelling of these costs.

Table B-1: Investment costs of subsystems

Subsystem Prated / Investments	HVAC station			HVDC station					HVAC cable system*	HVDC cable system**		
Prated	300	600	1200	300	600	900	1200	MW	300	300	1200	MW
Offshore Investments	59	118	225	N/A	212	273	292	M€	1.192	0.421	1.471	M€/km
Onshore Investments	41	81	164	105	N/A	N/A	162	M€	N/A	N/A	1.185	M€/km

N/A: Not Applicable

*: Includes fixed reactive power compensation

**: Costs of a cable pair (bipolar or symmetric monopole)

B.5 The Detailed results from technical evaluation

B.5.1 Costs

Table B-1: Investment costs for offshore transmission system per scenario

Scenario ID Prated / Investments	UK-NL1	UK-NL2	UK-NL3	UK-NL4	UK-NL5	UK-NL6	UK-NL7
UK WF (MW)	DC-1200	DC-900	DC-900	DC-1200	DC-900	DC-900	DC-900
NL WF (MW)	AC-300	AC-600	AC-600	DC-300	DC-300	DC-600	DC-900
IL (MW)	AC-300	AC-600	AC-1200	DC-300	DC-1200	DC-1200	DC-1200
IL (km)	100	100	100	100	100	100	100
UK WF (M€) HVOS	292	290	290	292	273	273	273
Cable	148	148	148	148	148	148	148
HVS	162	162	162	162	162	162	162
Subtotal	602	600	600	602	583	583	583
NL WF (M€) HVOS	59	118	118	152	151	212	273
Cable	33	66	132	15	52	52	52
HVS	41	81	164	105	162	162	162
Subtotal	133	265	414	272	365	426	487
IL (M€)	118	237	473	42	147	147	147
Total (M€)	853	1102	1488	916	1096	1157	1218
Reference scenario	Ref-A	Ref-C	Ref-C	Ref-A	Ref-B	Ref-C	Ref-D
Reference costs	734	848	848	734	716	848	981
Δ Investments (M€)	118	254	639	181	380	308	237

Scenario ID Prated / Investments	UK1	UK2	UK3	UK4	NL1	NL2	IC300	IC1200
UK WF (MW)	DC-1200	DC-1200	DC-1200	DC-900	AC-1200	DC-1200	DC-1200	DC-1200
NL WF (MW)	AC-300	AC-300	AC-300	AC-300	DC-300	DC-300	AC-300	AC-300
IL (MW)	AC-300	DC-300	DC-1200	DC-1200	DC-1200	DC-1200	DC-300	DC-1200
IL (km)	110	110	110	110	210	210	260	260
UK WF (M€) HVOS	292	292	292	273	225	292	292	292
Cable	148	148	148	148	502	148	148	148
HVS	162	162	162	162	123	162	162	162
Subtotal	602	602	602	583	850	602	602	602
NL WF (M€) HVOS	59	59	59	59	80	80	59	59
Cable	33	33	33	33	33	33	33	33
HVS	41	41	41	41	41	41	41	41
Subtotal	133	133	133	133	154	154	133	133
IL (M€)	164	152	324	324	262	261	308	687
Total (M€)	899	886	1059	1040	1266	1016	1042	1422
Reference scenario	Ref-A	Ref-A	Ref-A	Ref-B	Ref-A	Ref-A	Ref-A	Ref-A
Reference costs	734	734	734	716	734	734	734	734
Δ Investments (M€)	165	152	324	306	532	282	308	687

Ref-scenario ID Prated / investments	Ref-A	Ref-B	Ref-C	Ref-D
UK WF (MW)	DC-1200	DC-900	DC-900	DC-900
NL WF (MW)	AC-300	AC-300	AC-600	AC-900
UK WF (M€) HVOS	292	273	273	273
Cable	148	148	148	148
HVS	162	162	162	162
Subtotal	602	583	583	583
NL WF (M€) HVOS	59	59	118	177
Cable	33	33	66	99
HVS	41	41	81	122
Subtotal	133	133	265	398
Total (M€)	734	716	848	981

Note: For the 900MW UK wind farm a conservative estimate for the transmission system was made for the offshore platform, i.e. equal price with 1200MW offshore platform.

B.5.2 Losses

The calculated losses per line segment and in total are reported in Table B-2 and Table B-3. Based on the absolute losses and net energy transport per line the relative losses have been calculated. The split into different line segments is needed because of the different utilization. The relative losses (transmission + due to failure) are calculated as a fraction of the gross transported energy. The relative transmission losses are calculated after subtraction of the energy lost due to failure.

Table B-2*: Detailed losses per scenario*

Scenario ID	UK-NL1	UK-NL2	UK-NL3	UK-NL4	UK-NL5	UK-NL6	UK-NL7
Net Energy Transported [GWh/y]							
UK Wind farm trafo	4702	3527	3527	4702	3527	3527	3527
NL Wind farm trafo	1143	2289	2289	1144	1144	2289	3433
UK connection	6113	5357	10270	6131	9370	10294	10295
NL connection	1737	3269	5967	1718	5851	5851	5546
Interconnecting Link	1925	4430	7835	1915	6769	7736	7663
Overall (≠ sum)	6600	7810	10561	6616	9595	10570	10970
Transmission Losses [GWh/y]							
UK Wind farm trafo	13	10	10	13	45	45	45
NL Wind farm trafo	3	6	6	3	3	6	10
UK connection	216	246	366	200	270	299	298
NL connection	15	31	56	46	117	132	142
Interconnecting Link	46	97	165	24	47	56	55
Overall (≠ sum)	294	390	603	286	483	538	551
Transmission Losses [%]							
UK Wind farm trafo	0.3%	0.3%	0.3%	0.3%	1.3%	1.3%	1.3%
NL Wind farm trafo	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
UK connection	3.4%	4.4%	3.4%	3.2%	2.8%	2.8%	2.8%
NL connection	0.9%	1.0%	0.9%	2.6%	2.0%	2.2%	2.5%
Interconnecting Link	2.3%	2.1%	2.1%	1.3%	0.7%	0.7%	0.7%
Weighted average [%]	4.3%	4.8%	5.4%	4.1%	4.8%	4.8%	4.8%
Energy Lost due to Failure [GWh/y]							
UK Wind farm trafo	3	2	2	3	2	2	2
NL Wind farm trafo	2	1	1	1	1	1	2
UK connection	197	226	392	179	278	318	318
NL connection	11	8	4	33	97	108	114
Interconnecting Link	32	31	14	14	67	78	77
Total	245	268	413	230	444	508	513
Energy Lost due to Failure [%]							
UK Wind farm trafo	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
NL Wind farm trafo	0.2%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%
UK connection	3.0%	4.0%	3.7%	2.7%	2.9%	3.0%	3.0%
NL connection	0.6%	0.2%	0.1%	1.8%	1.6%	1.8%	2.0%
Interconnecting Link	1.6%	0.7%	0.2%	0.7%	1.0%	1.0%	1.0%
Weighted average [%]	3.4%	3.2%	3.6%	3.2%	4.2%	4.4%	4.3%
Total Losses							
Total [GWh/y]	539	658	1016	516	926	1046	1064
Weighted average [%]	7.5%	7.8%	8.8%	7.2%	8.8%	9.0%	8.8%

Table B-3: *Detailed losses per scenario (continued)*

Scenario ID	UK1	UK2	UK3	UK4	NL1	NL2	IC300	IC1200
Net Energy Transported [GWh/y]								
UK Wind farm trafo	3527	4702	4702	3527	4708	4702	4702	4702
NL Wind farm trafo	1143	1143	1143	1143	1143	1143	1143	1143
UK connection	8443	6082	9388	8443	4591	4403	4403	4403
NL connection	1125	1125	1125	1125	1531	1531	1125	1125
Interconnecting Link	5742	1995	5742	5742	2293	2293	2355	9204
Overall (≠ sum)	9736	7321	10744	9736	6958	6770	7883	14732
Transmission Losses [GWh/y]								
UK Wind farm trafo	10	13	13	10	10	13	13	13
NL Wind farm trafo	3	3	3	3	3	3	3	3
UK connection	237	198	286	237	132	165	165	165
NL connection	11	11	11	11	15	15	11	11
Interconnecting Link	134	57	134	134	139	140	161	490
Overall (≠ sum)	395	282	447	395	298	336	354	683
Transmission Losses [%]								
UK Wind farm trafo	0.3%	0.3%	0.3%	0.3%	0.2%	0.3%	0.3%	0.3%
NL Wind farm trafo	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
UK connection	2.7%	3.2%	3.0%	2.7%	2.8%	3.6%	3.6%	3.6%
NL connection	1.0%	1.0%	1.0%	1.0%	0.9%	0.9%	1.0%	1.0%
Interconnecting Link	2.3%	2.8%	2.3%	2.3%	5.7%	5.7%	6.4%	5.1%
Weighted average [%]	3.9%	3.7%	4.0%	3.9%	4.1%	4.7%	4.3%	4.4%
Energy Lost due to Failure [GWh/y]								
UK Wind farm trafo	2	3	3	2	1	3	3	3
NL Wind farm trafo	2	2	2	2	2	2	2	2
UK connection	236	177	291	236	6	142	142	142
NL connection	7	7	7	7	10	10	7	7
Interconnecting Link	133	39	133	133	98	98	111	542
Total	381	228	436	381	116	255	265	696
Energy Lost due to Failure [%]								
UK Wind farm trafo	0.1%	0.1%	0.1%	0.1%	0.0%	0.1%	0.1%	0.1%
NL Wind farm trafo	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
UK connection	2.7%	2.7%	3.0%	2.7%	0.1%	3.0%	3.0%	3.0%
NL connection	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%
Interconnecting Link	2.3%	1.9%	2.3%	2.3%	3.9%	3.9%	4.2%	5.3%
Weighted average [%]	3.6%	2.9%	3.7%	3.6%	1.6%	3.5%	3.1%	4.3%
Total Losses								
Total [GWh/y]	776	510	883	776	414	590	618	1378
Weighted average [%]	7.4%	6.5%	7.6%	7.4%	5.6%	8.0%	7.3%	8.6%

Appendix C Legal analysis and consequences for investment decisions

The complete legal analysis report is available as a separate document:

Appendix C - Legal Analysis.pdf