OffshoreGrid: Offshore Electricity Infrastructure in Europe

OffshoreGrid

Offshore Electricity Grid Infrastructure in Europe

A Techno-Economic Assessment

3E (coordinator),

dena, EWEA, ForWind, IEO,

NTUA, Senergy, SINTEF

Final Report, October 2011

PRINCIPAL AUTHORS:

Jan De Decker, Paul Kreutzkamp (3E, coordinator)

AUTHORS:

3E (coordinator): Jan De Decker, Paul Kreutzkamp, Pieter Joseph, Achim Woyte

Senergy Econnect: Simon Cowdroy, Peter McGarley

SINTEF: Leif Warland, Harald Svendsen

dena: Jakob Völker, Carolin Funk, Hannes Peinl

ForWind: Jens Tambke, Lüder von Bremen

IEO: Katarzyna Michalowska

NTUA: George Caralis

MAIN REVIEWERS:

3E (coordinator): Jan De Decker, Paul Kreutzkamp, Natalie Picot

dena: Jakob Völker

EWEA: Sharon Wokke, Christian Kjaer, Jacopo Moccia, Frans Van Hulle, Paul Wilczek, Justin Wilkes

EDITING:

EWEA: Sarah Azau, Zoë Casey, Tom Rowe

ACKNOWLEDGEMENTS:

Wilfried Breuer (Siemens), Paul Carter (SLP Engineering), Manuela Conconi (EWEA), Frederik Deloof (Secretariat Benelux), Frédéric Dunon (Elia), Dana Dutianu (EC), Rafael E. Bonchang (Alstom Grid), Claire Grandadam (3E), Jan Hensmans (FOD Economie), Andrea Hercsuth (EC), Matthias Kirchner (Nexans), Niels Ladefoged (EC), Nico Nolte (BSH), Antje Orths (Energinet.dk), Glória Rodrigues (EWEA), Fabian Scharf (BNetzA), Christophe Schramm (EC), Alberto Schultze (Siemens), Ravi Srikandam (arepo consult), Guenter Stark (ABB), Gina Van Dijk (Tennet), Heleen Van Hoof (VREG), Jan van den Berg (Tennet), Teun Van Biert (Tennet), Karina Veum (ECN), Bo Westman (ABB)

Design: www.mardi.be;

Print: www.artoos.be;

Production coordination: Raffaella Bianchin, Cristina Rubio (EWEA);

Cover photo: Detlev Gehring/ Stiftung Offshore Windenergie

Agreement n.:	EIE/08/780/SI2.528573
Duration:	May 2009 – October 2011
Co-ordinator:	3E

COORDINATOR

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www.3e.eu

PROJECT PARTNERS:

The Deutsche Energie-Agentur GmbH (dena) - the German Energy Agency - is the centre of expertise for energy efficiency, renewable energy sources and intelligent energy systems.
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FOREWORD

The OffshoreGrid project is the first in-depth analysis of how to build a cost-efficient grid in the North and Baltic Seas.. As such, it is a compelling milestone in the development of a secure, interconnected European power system, able to integrate increasing amounts of renewable energy.

The need for cleaner and safer energy supplies to counter climate change is clear. Renewable power is key to achieving Europe's 20-20-20 targets and to cope with energy related challenges far beyond 2020. Offshore wind, in particular, has tremendous potential. It could generate more than 500 TWh per year by 2030, enough electricity to meet 15% of Europe's yearly electricity consumption.

However, reaching these goals and moving towards an efficient, integrated European electricity market will not be possible without a reliable, modernised and efficient grid, both onshore and offshore. Onshore, this means significant investments to strengthen current infrastructure, which faces strong public opposition and lengthy project lead times. Offshore, the challenge is to more efficiently connect power harvested at sea with the onshore transmission system, while at the same time building a system which can actively contribute to stability and security of supply by enabling further integration of the European power market. A coherent European long-term vision for both the onshore and offshore electricity grid is a prerequisite to make the required steps in an optimal way.

The OffshoreGrid project results are a practical blueprint for policymakers, developers and transmission grid operators, to plan and design a meshed offshore grid. They provide explicit guidance for individual projects while not losing sight of the overall grid design. The analysis of costs and benefits of different configurations addressed in this study will help policy makers and regulators anticipate developments and provide incentives that trigger the necessary investments at the right time and avoid stranded investments.

Taking the OffshoreGrid results as basis for discussion, a concrete roadmap for a grid at sea can be developed involving all stakeholders. With today's fast developments in the offshore wind industry, now is our opportunity.

Geert Palmers,
CEO, 3E

EXECUTIVE SUMMARY

- The OffshoreGrid project
- Main results in a nutshell
- Analysis of different connection concepts
- General recommendations

I. The OffshoreGrid project

OffshoreGrid is a techno-economic study funded by the EU's Intelligent Energy Europe (IEE) programme. It has developed a scientific view on an offshore grid in northern Europe along with a suitable regulatory framework that takes technical, economic, policy and regulatory aspects into account. This document is the final report of the project. It summarises the key assumptions, the methodology and the results, draws conclusions from the work and provides recommendations.

The benefits of an offshore grid

The exploitation of Europe's offshore wind potential brings new challenges and opportunities for power transmission in Europe. Offshore wind capacity in Europe is expected to reach 150 GW in 2030[1]. The majority of the sites currently being considered for offshore wind projects are situated close to the European coast, not further than 100 km from shore. This is in part due to the high cost of grid connection, limited grid availability and the absence of a proper regulatory framework for wind farms that could feed several countries at once. Looking at the North Sea alone, with its potential for several hundreds of Gigawatts of wind power, an offshore grid connecting different Member States would enable this wind power to be transported to the load centres and at the same time facilitate competition and electricity trade between countries. A draft working plan for an inter-governmental initiative known as the North Seas Countries' Offshore Grid Initiative (NSCOGI) summarises the advantages of such a grid[2]:

- **Security of supply**
  - Improve the connection between big load centres around the North Sea.
  - Reduce dependency on gas and oil from unstable regions.
  - Transmit indigenous offshore renewable electricity to where it can be used onshore.
  - Bypass onshore electricity transmission bottlenecks.
- **Competition and market**
  - Development of more interconnection between countries and power systems enhances trade and improves competition on the European energy market.
  - Increased possibilities for arbitrage and limitation of price spikes.
- **Integration of renewable energy**
  - Facilitation of large scale offshore wind power plants and other marine technologies.
  - Enabling the spatial smoothing effects of wind and other renewable power, thus reducing variability and the resulting need for flexibility.
  - Connection to large hydropower capacity in Scandinavia, introducing flexibility into the power system to compensate for variability from wind and other renewable energy sources.
  - Contribution to Europe's 2020 targets for renewables and CO_2 emission reductions.

II. Main results in a nutshell

The OffshoreGrid study confirms these advantages after having investigated both the technical and economic questions.

The first step was to study the connection of the offshore wind farms to shore, without looking into the details of an interconnected solution yet. In this regard OffshoreGrid comes to the conclusion that using hub connections for offshore wind farms – that is, connecting up wind farms that are close to one another, forming only one transmission line to shore - is often highly beneficial. OffshoreGrid assessed 321 offshore wind farm projects, and recommends that 114 of these 321 be clustered in hubs. If this were done, OffshoreGrid has calculated that €14 bn could be saved up to 2030 compared to connecting each of the 321 wind farms individually to shore – that is, investments would be €69 bn as opposed to €83 bn.

[1] EWEA, Pure Power – Wind energy targets for 2020 and 2030, 2011 update, July 2011.
[2] Draft Working Plan Proposal for Offshore Electricity Infrastructure, 3E for Belgian Ministry of Energy, Unpublished, 2010.

Based on this connection scenario (called the "hub base case scenario") in a second step two highly cost-efficient interconnected grid designs were then drawn up - the "Direct Design" and "Split Design".

In the Direct Design, interconnectors are built to promote unconstrained trade between countries and electricity markets as average price difference levels are high. Once additional direct interconnectors become non-beneficial, tee-in, hub-to-hub and meshed grid concepts are added to arrive at an overall grid design (for an explanation of these terms, see Section III of the Executive Summary).

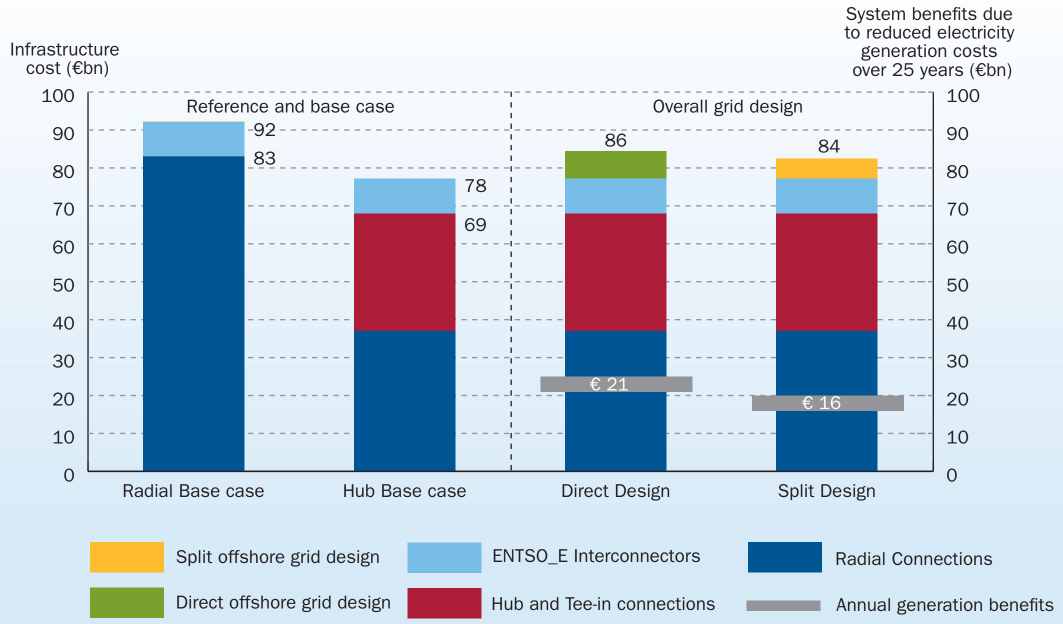
The Split Design is essentially designing an offshore grid around the planned offshore wind farms. Thus, as a starting point not only direct interconnectors are investigated but also interconnections are built by splitting the connection of some of the larger offshore wind farms between countries. These "split wind farm connections" establish a path for (constrained) trade. These offshore wind farm nodes are then - as in the Direct Design - further interconnected to establish an overall 'meshed' design where beneficial.

The overall investment costs are €86 bn for the Direct Design and €84 bn for the Split Design. This includes €69 bn of investment costs for the most efficient connection (hub-connections where beneficial as in the hub base case scenario) of the 126 GW of offshore wind farms to shore, as well as about €9 bn for interconnectors planned within the Ten Year Network Development Plan (TYNDP) of the European transmission system operator association (ENTSO-E). The rest of the investments that make up the €84 bn or €86 bn for this further interconnected grid are €7.4 bn for the Direct Design and €5.4 bn for the Split Design. These relatively small additional investments generate system benefits of €21 bn (Direct Design) and €16 bn (Split Design) over a lifetime of 25 years – benefits of about three times the investment.

Both designs are thus highly beneficial, from a socio-economic perspective. When comparing in relative terms by looking at the benefit-to-CAPEX (Capital Expenditure) ratio, the Split Design is slightly more cost-effective than Direct Design and yield a higher benefit return on investment.

The investments in offshore grid infrastructure have to be compared with the offshore wind energy produced over 25 years which amounts to 13,300 TWh. This represents a market value of €421 bn when assuming an average spot market price of €50/MWh. In this context, the infrastructure costs represent about a fifth of the value of the electricity that is generated offshore. The additional cost for creating the meshed offshore grid (even including wind farm connections

FIGURE 1.1: TOTAL INVESTMENTS FOR THE OVERALL GRID DESIGN



and TYNDP interconnectors) would amount to only about €¢ 0.1 per KWh consumed in the EU27 over the project life time [57].[3]

In addition to connecting 126 GW of offshore wind power to the grid, the offshore interconnection capacity in northern Europe is, as a result, boosted from 8 GW today to more than 30 GW.

There are many other benefits from the investments in an offshore grid, including connecting generation in Europe (in particular wind energy) to the large hydro power "storage" capacities in northern Europe, which can lower the need for balancing energy within the different European regions. Offshore hubs also mitigate the environmental and social impact of laying multiple cables through sensitive coastal areas and allow for more efficient logistics during installations. Furthermore a meshed offshore grid based on the tee-in concept and hub-to-hub interconnections makes the offshore wind farm connection more reliable and can significantly increase security of supply within Europe.

The overall circuit length needed for both offshore grid designs is about 30,000 km (10,000 km of AC cables, 20,000 km of DC cables). The hub base case scenario accounts for 27,000 km, while the additional circuit length to build the Direct or the Split Design is only about 3,000 km. As AC circuits use 1 x 3 core AC cable and DC circuits use 2 x 1 core DC cables, the total cable length is even higher.

Figure 1.1 on page 9 summarises the overall investments required of the different grid options.

III. Analysis of different connection concepts

There are different ways of building offshore grid infrastructure to interconnect power markets and offshore wind power. In this report, different innovative configurations for interconnection are assessed for feasibility, looking at factors such as technological availability, infrastructure costs, system operation costs, geographical situation, electricity production and trade patterns:

- Wind farm hubs: the joint connection of various wind farms in close proximity to each other, thus forming only one transmission line to shore.
- Tee-in connections: the connection of a wind farm or a wind farm hub to a pre-existing or planned transmission line or interconnector between countries, rather than directly to shore.
- Hub-to-hub connection: the interconnection of several wind farm hubs, creating, thus, transmission corridors between various countries (i.e. the wind farm hubs belonging to different countries are connected to shore, but then also connected to each other). This can also be interpreted as an alternative to a direct interconnector between the countries in question.

Based on all these design options as well as using conventional direct country-to-country interconnections, an overall grid design was developed (as already discussed in section II). A detailed techno-economic cost benefit analysis of the design was carried out in order to find how it could be made most cost-effective.

Which connection concept is best depends on several factors, such as the distribution of the offshore wind farms (for example, whether there is more than one farm planned in the vicinity), the wind farms' distance to shore, and in the case of interconnecting several wind farms and/or countries, the distance of the farms to each other and the electricity trade between the countries. Recommendations and general guidelines regarding the choice of the best connection concept are discussed below.

It is important to point out that policy makers and regulators will require a significant amount of advance planning and insight in order to provide the correct incentives to simulate the development of meshed grid solutions. These incentives should be targeted towards creating favourable conditions for the necessary investments required, as well as ensuring they

[3] The additional cost for creating the meshed offshore grid (excluding wind farm connections and TYNDP interconnectors) would amount to only about €¢ 0.01 per KWh.

occur in a timely manner so as to avoid stranded investments. The costs and benefits of such investments, the main parameters that influence them, and the technical and operational implications of technology choices need to be considered before investment decisions are taken.

IIIa. Wind farm hubs

Hub connections generally become economically viable for distances above 50 km from shore, when the sum of installed capacity in a small area (~20 km around the hub) is relatively large, and standard available HVDC Voltage Source Converter (VSC) systems can be used. Wind farms situated closer than 50 km to an onshore connection point are virtually always connected individually to shore. OffshoreGrid assessed more than 321 offshore wind farm projects, and recommends that 114 out of these be clustered in hubs. Apart from the costs savings, offshore hubs can also help to mitigate the environmental and social impact of laying multiple cables through sensitive coastal areas and allow for more efficient logistics during installations.

One of the primary difficulties with this kind of interconnection is long-term planning. Offshore farms are not always built at the same time or at the same speed, requiring the hub connection to be sized anticipating the capacity of all the farms once completed. Therefore it might be necessary to oversize the hub temporarily until all the planned wind farms are built. This of course also bears the risk of stranded investment should some of the wind farms never get built. However, OffshoreGrid shows that the costs of temporarily oversizing and stranded investments are limited and that hub connections can still be beneficial even if wind farms are built across a life span of more than ten years. In certain cases the hub even remains beneficial if some of the wind farms connected to the hub are not built at all.

IIIb. Tee-in connection and split wind farm connection

Whether connecting offshore wind farms to interconnectors is beneficial depends primarily on the balance between the additional costs due to trade constraints on the interconnector and cost savings due to reduced infrastructure. The trade constraints occur when an offshore wind farm is connected to the interconnector as the availability of the interconnector for international electricity exchange is reduced. The costs savings occur as the overall infrastructure costs are generally lower: the cable length to connect the wind farm to the interconnector is usually much shorter than the cable required to connect the wind farm to shore. Tee-in solutions generally become more beneficial (compared to direct interconnections) when :

- Electricity price differences between the connected countries are not too large,
- The wind farm is far from shore and close to the interconnector,
- The country where the wind farm is built has the lower electricity price of the two (the tee-in then gives the opportunity to sell to the country with the higher prices),
- The wind farm capacity is low compared to the interconnector capacity (low constraints),
- The wind farm capacity is roughly double the interconnector capacity.

An interesting case that can be considered a variant of the tee-in concept is the split connection of large wind farm hubs far from shore. By connecting the wind farm hub to two countries instead of one, the wind farm is connected to shore and at the same time an interconnector is created with a modest additional investment.

IIIc. Hub-to-hub interconnection

Hub-to-hub connections are generally beneficial when the potentially connected countries are relatively far from each other, and the wind farm hubs are far from shore but close to each other. In this manner the costs saved due to reduced infrastructure generally outweigh the negative impact that can occur due to trade constraints imposed by transmission capacity reduction. This finding is similar to the conclusions in the tee-in scenario.

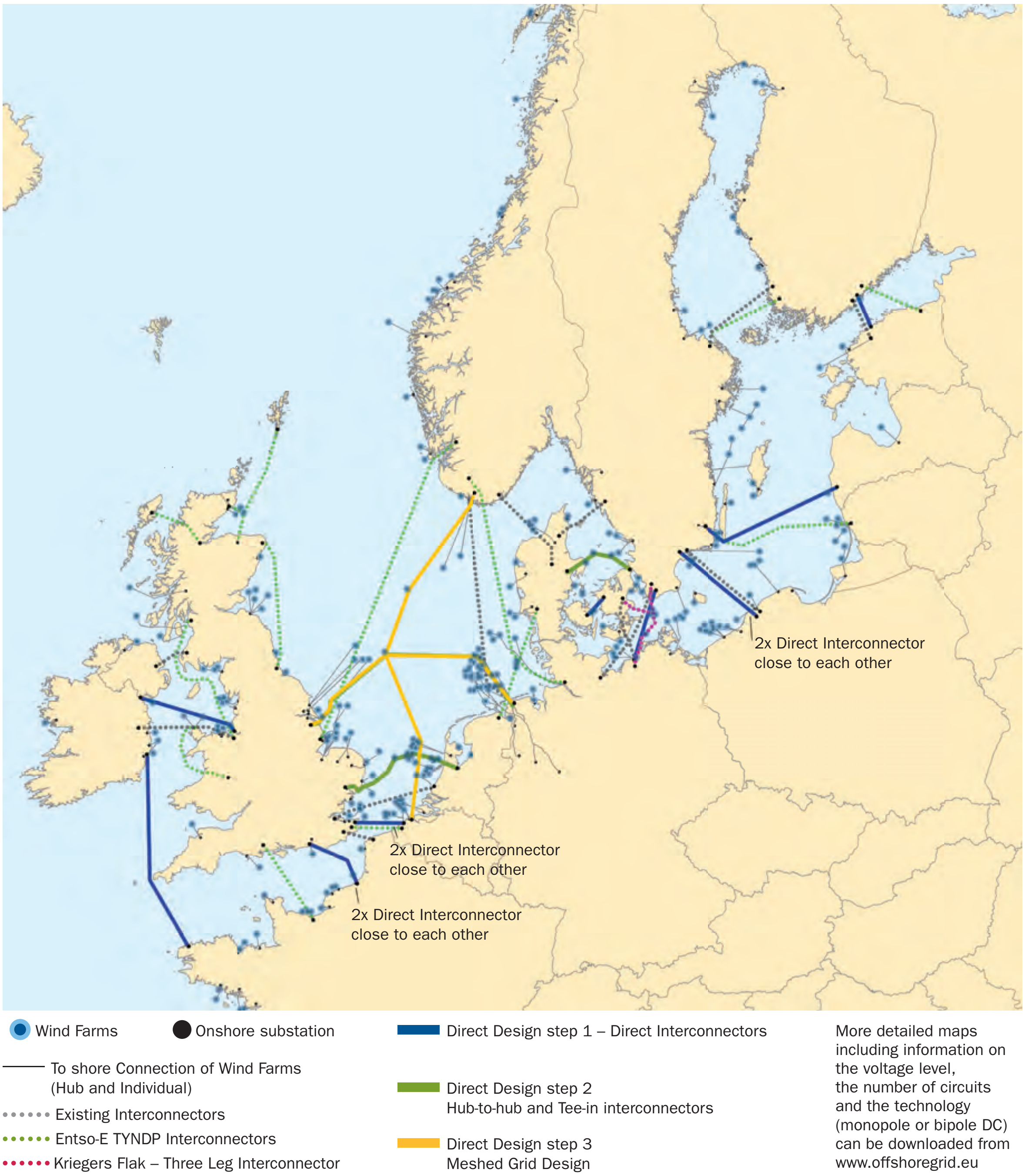
In general the hub-to-hub connection is more beneficial than direct interconnectors under the same conditions that make the tee-in connection beneficial: modest price difference between interconnected countries, the capacity of the wind farm and its connection is high compared to the interconnector capacity (lowering trade constraints), and capacity towards the country with the highest price of electricity is higher than in the other direction.

One of the keys to the successful implementation of a hub-to-hub connection is long-term planning. Often the wind farms that are to be included in the hub-to-hub connection are not all developed at the same time. Advanced planning will thus be required to take into consideration issues such as the future capacity needs of the connection to shore once the other wind farms are completed (in order to provide extra capacity for international exchange).

IIId. Overall grid design

The development of the offshore grid is going to be driven by the need to bring offshore wind energy online and by the benefits from trading electricity between countries. This involves on the one hand the connection of the wind energy to where it is most needed, and on the other hand the linking of high electricity price areas to low electricity price areas. The OffshoreGrid consortium has demonstrated the effectiveness of

FIGURE 1.2: DIRECT OFFSHORE GRID DESIGN



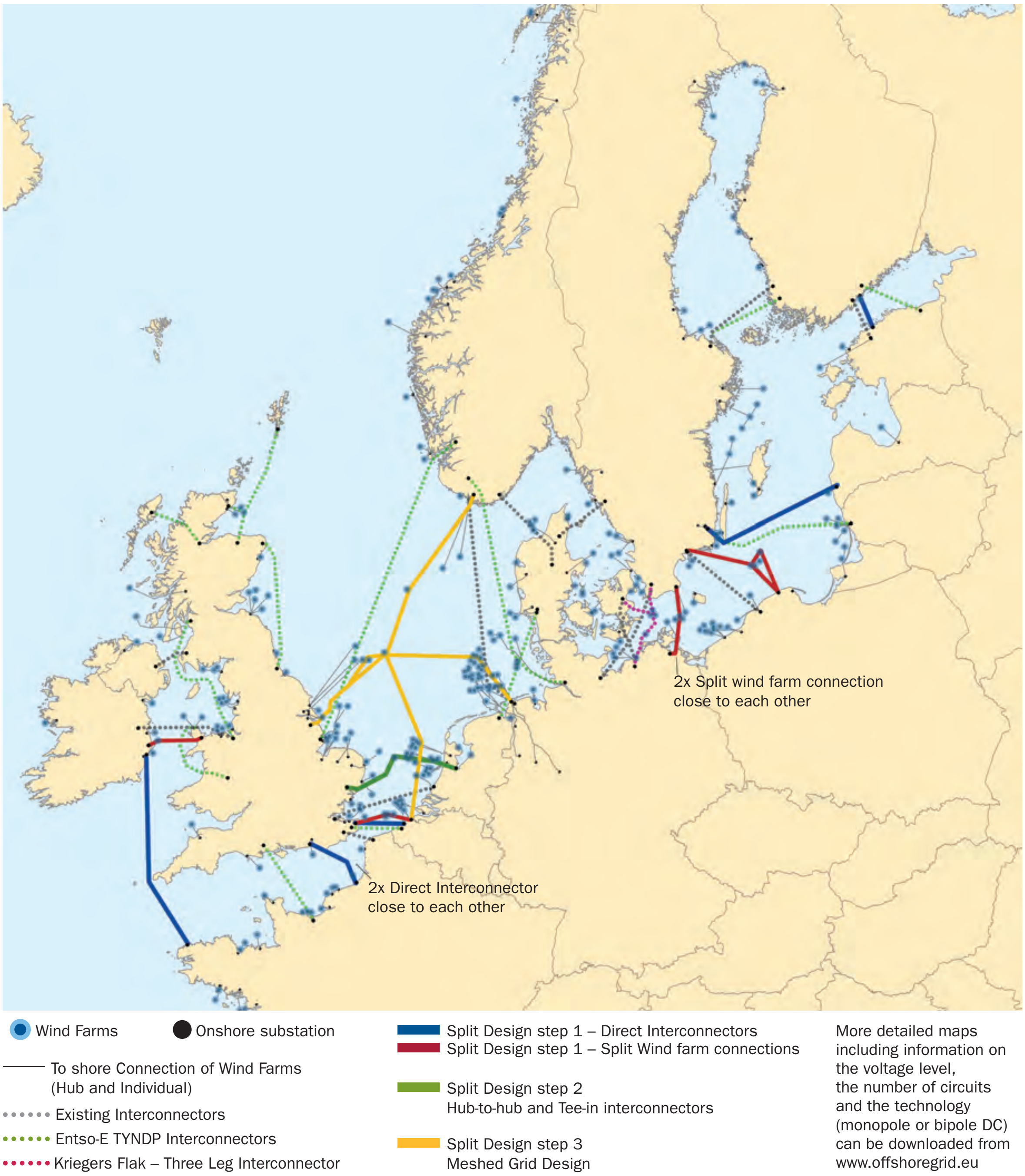
two different methodologies for the design of a cost-effective overall offshore grid:

- **The Direct Design** builds on high-capacity direct interconnections to profit from high price differences, then integrated solutions and meshed links are applied,

- **The Split Design** starts by building lower-cost interconnectors by splitting wind farm connections in order to connect them to two shores, then integrated solutions and meshed links are applied.

Both designs were developed following an iterative approach based on the modelling of infrastructure costs and system benefits. The end-result of both designs is shown in Figures 1.2 and 1.3.

FIGURE 1.3: SPLIT OFFSHORE GRID DESIGN



More detailed maps including information on the voltage level, the number of circuits and the technology (monopole or bipole DC) can be downloaded from www.offshoregrid.eu

Splitting wind farm connections to combine the offshore wind connection with trade as in the Split Design has proven to be slightly more cost-effective than building direct interconnectors only for trade. The average reduction in CAPEX from choosing a split connection over a direct interconnector is more than 65%, while the reduction in system cost is only about 40% lower on average. A comparison of the benefit per invested Euro of CAPEX revealed that in the Split Design for each Euro spent about 3 Euros are earned as benefit over the lifetime of 25 years, while for the Direct Design these are only 2.8 Euros. Thus, the Split Design is slightly more cost-effective. However both Designs are highly efficient.

In addition to its techno-economic advantages, the Split Design also has environmental benefits because it reduces the total circuit length. Moreover, it improves the redundancy of the wind farm connection, which improves system security and reduces the system operation risks, the need for reserve capacity, and the loss of income in case of faults. When doing detailed assessments for concrete cases, these merits should not be overlooked.

However, in the end both designs produce large benefits and are advantageous from the power system's perspective, but tee-in solutions, hub-to-hub solutions and split wind farm connections raise the issue of possible regulatory framework and support scheme incompatibilities between European countries. The reason is that renewable energy that is supported by one country can now flow directly into another country, so that the country paying for it cannot enjoy all the benefits. For split wind farm connections, this is even more difficult as the connection to the country in which the wind farm is located is reduced. As these complexities add risks to the development of integrated and especially split connections, they should be solved at bi-lateral, European and international level as soon as possible.

An offshore grid will be built step by step. The two designs presented (Figures 1.2 and 1.3) show two possible configurations for such an offshore grid in 2030, both of which are largely beneficial. Every new generation unit, interconnection cable, political decision or economic parameter has an impact on both the future and the existing projects and thus can have a large influence on the development of the offshore grid. The two designs, and the different conclusions drawn on the way, bring useful insights that will allow the industry to know how to react to and guide the offshore grid development process over the next few years.

III.E Additional benefits of hub connections and interconnected grid designs

The investments required for an offshore grid and the economic viability of the chosen connection and interconnection concepts are of high importance. However at the same time other aspects, such as system security and the environmental impact of different grid designs have to be taken into account.

It must be emphasised that connecting offshore wind farms in hubs not only reduces the investment costs in many cases but also reduces the number of cables, the maritime space use as well as the environmental impact due to shorter and more concentrated construction times.

Integrated design configurations such as tee-in solutions, hub-to-hub connections or even further intermeshed designs have the benefit of increased n-1 security. This does not only increase the security of supply for the consumer and facilitate system operation, it also gives additional security to the wind farm operator as losses due to single cable failures are reduced.

On the other hand, these integrated grid design configurations are also more complex in the planning and construction phase and may conflict with existing regulatory frameworks or potential incompatibilities of different national support schemes. Furthermore the safe multi-terminal operation of such an offshore grid based on HVDC VSC technology requires fast DC breakers, which are still in the development phase at the time of writing.

IV. General recommendations

To make the offshore grid more cost-effective and efficient, the innovative connection and interconnection concepts discussed above should be applied. The following selected key recommendations should be taken into account when considering the future of offshore wind development:

- Where wind farm concession areas have already been defined, regulation should be designed to ensure that wind farm integration using one of the methods proposed above is favoured over traditional individual connections, wherever this is beneficial with regards to infrastructure costs. In particular the hub connection of wind farms is technically state of the art and can be beneficial,
- In countries where there is currently no strategic siting or granting of concessions, policy makers should aim for fewer areas with a larger number of concentrated wind farms, with projects within one area to be developed all at the same time, rather than for more and smaller concession areas. In line with the expected development of technology, the optimal installed capacity in areas where a hub connection is possible should be around 1,000 MW for areas developed in the coming ten years, and 2,000 MW for areas developed after 2020,
- Integrated solutions such as tee-in and hub-to-hub solutions can be very beneficial compared to conventional solutions. For wind farms or hubs far from shore, a tee-in to a nearby interconnection (if available) or a split of the wind farm connection to two countries should be investigated. When developing international interconnection cables, the possibility of hub-to-hub solutions should be investigated, particularly when there are large wind farm hubs in each country far from shore but close to each other,
- Any new interconnector will have an economic impact on the interconnectors already in place, as it will reduce the price differences between the countries. Integrated solutions are less dependent on trade than a direct interconnector, and can therefore still be beneficial even with lower price differences. Where possible, opportunities for splitting wind farm connections should be carefully checked and pursued. The case-independent model developed in this project can serve for quick pre-feasibility studies,
- The ongoing development of direct interconnectors should not be slowed down, as this concept can already be built today independently of the development of large wind farms far from shore, which could be beneficially teed-in. However it is advisable to anticipate tee-in connections for suitable wind farms in the future,
- The policy for merchant interconnectors which receive exemption from EU regulation should be reviewed. The concept of merchant interconnectors can incentivise investments that bear high risks. However, investors in, and owners of, merchant interconnectors could have an incentive to obstruct any new interconnector, as this would reduce their return on investment. It is therefore absolutely necessary that there are no conflicts of interest, for example between private investors with a key role in grid planning, grid operation or the political decision processes concerned with these issues. Otherwise the endeavour to have a single EU market for electricity is put at risk,
- Tee-in connections, hub-to-hub connections and split wind farm connections have shown to be cost-efficient in many cases. Furthermore these grid designs can increase system security and reduce environmental impact. Policy makers and regulators should prepare measures to support such innovative solutions, which are not yet included in most current legal and political framworks. In particular, the compatibility of support schemes and the allocation of benefits should be adressed as soon as possible, bilaterally or internationally. The North Seas Countries' Offshore Grid Initiative is a good framework within which to coordinate cross-border issues surrounding the political, regulatory and market aspects,
- When considering cross-border connections, offshore grid development should be a joint or coordinated activity between the developers of the wind farms, their hub connections, and transmission system operators (TSOs). The North and Baltic Sea countries should adapt their regulatory frameworks to foster such a coordinated approach.

Photo: Dong Energy

1 INTRODUCTION

- Context and background
- Objective of OffshoreGrid
- Methodology & approach
- Stakeholders
- Further presentation and discussion of results
- Document structure

1.1 Context and background

Europe has ambitious targets for renewable energy deployment. By 2020, 20% of gross final energy consumption should be met by renewable sources [19]. Offshore wind power is expected to deliver a large contribution. An installed capacity of 40 GW of offshore wind power is expected in Europe by 2020, in 2030 this can amount to 150 GW, of which about 126 GW will be located in Northern Europe [20].

The EC 2050 Roadmap [21] fosters this development further with the long-term target to cost-efficiently reduce European Greenhouse Gas emissions by 80% to 95% by 2050. This goal is only achievable with large-scale deployment of renewable energy generation with offshore wind energy as a dominant generation source.

Consequently, the number of wind farms is expected to increase rapidly within the next decade, particularly in the North and Baltic Seas. All these wind farms will have to be connected to onshore power systems. This raises questions on how to connect the future wind power capacity and how to integrate it into the national power systems in an efficient and secure way.

The first offshore wind farms were connected individually to the onshore power system. However, these wind farms were limited in capacity and relatively close to shore. Future wind farms may be up to several thousand MW's, at distances of more than 200 km from shore. In particular for these wind farms bundling the electric connection at sea and carrying the energy over a joint connector to the onshore connection points can be more efficient than individual connections of wind farms to shore. This so-called hub connection design can reduce costs, space usage and environmental impact dramatically. Once these wind farms or hubs are in place, new connection design opportunities open: The hubs can be teed-in to interconnectors, or can be interlinked with other hubs or to other shores, creating a truly integrated offshore power system.

This thinking is particularly driven by the idea that such an offshore grid can bring a variety of benefits to the security of the power system, the European electricity market and the overall integration of renewable energy.

- Increased security of supply:
  - improve the connection between big load centres around the North Sea,
  - reduce dependency on gas and oil from unstable regions,
  - transmit indigenous offshore renewable electricity to where it can be used onshore,
  - bypass onshore electricity transmission bottlenecks.
- Further market integration and enhancement of competition:
  - more interconnection between countries and power systems enhances trade and improves competition on the European energy market,
  - increased possibilities for arbitrage and limitation of price spikes.
- Efficient integration of renewable energy:
  - facilitation of large-scale offshore wind power plants and other marine technologies,
  - valorisation of the spatial smoothing effect of wind power and other renewable power, thus reducing variability and the resulting flexibility needs,
  - connection to the large hydropower capacity in Scandinavia, thus introducing flexibility in the power system for the compensation of variability from wind power and other renewable power,
  - significant contribution to European 2020 targets.

However, there is a long list of technical and political challenges that come with an integrated (meshed) European offshore grid. Furthermore, the investment needs are high. This raises the question of how to design an optimal offshore grid that minimises costs and maximises the benefits.

1.2 Objective of OffshoreGrid

To answer these questions, the OffshoreGrid project consortium developed a scientific view on an offshore grid along with a suitable regulatory framework that considers technical, economic and policy aspects.

The study is designed to serve as background and supporting documentation for the preparation of further regulatory, legislative and policy measures. In particular, the outcomes are intended to provide input for the work on infrastructure by the European Union as outlined in the Second Strategic Energy Review, namely the Baltic Interconnector Plan, the Blueprint for a North Sea Offshore Grid and the completion of the Mediterranean ring [22][4].

The OffshoreGrid study fulfils the following strategic objectives:

- provide recommendations on methods for decisions on topology and dimensioning of an offshore grid in Northern Europe,
- provide guidelines for investment decision and project execution,
- trigger a coordinated approach for offshore wind connections with the Mediterranean ring.

Related to its specific objectives, the project provides the following:

- representative wind power time series,
- a selection of blueprints for an offshore grid,
- insight into the interaction of design drivers and techno-economic parameters,
- analysis of the stakeholder requirements.

The OffshoreGrid study is the first detailed assessment of this kind to give guidelines for the development of an efficient offshore grid design and is targeted towards European policy makers, industry, transmission system operators and regulators.

1.3 Methodology & approach

The techno-economic assessment is based on extensive market and grid modelling of the entire European power system accompanied by qualitative investigations of the political, legal and regulatory framework.

In the preparatory phase, input scenarios on power generation capacity, electricity demand, commodity prices, grid development etc. were developed. A special focus was put on offshore wind power scenarios, where time series were developed with high temporal and spatial resolution. For other marine renewables and power demand from offshore oil and gas industry installations, estimates have been made based on literature. The plausibility of the scenarios was checked by extensive assessment of the political and regulatory environment in all relevant member states.

In the modelling phase the input from the preparatory phase was used in a variety of techno-economic investigations. As a first step, different assessments for individual modules of an offshore grid – such as hub connections, tee-in solutions, hub-to-hub solutions – were carried out with a detailed cost-benefit analysis. In the second step an overall grid design was developed through an iterative process.

The approach described above was carried out for Northern Europe (the regions around the Baltic Sea and the North Sea, the English Channel and the Irish Sea). This allowed the determination of an efficient offshore grid design supplemented by generic grid design rules for the North Sea region[5].

1.4 Stakeholders

To assess, plan and build an offshore grid is clearly a multi-stakeholder process. From the very beginning the offshore grid consortium fostered an intensive exchange with the relevant stakeholders from politics, economics, industry and nature conservation.

[4] The draft final report published in 2010 has already provided input to the European Commission for the Communication on 'Energy Infrastructure Priorities for 2020 and Beyond' [23].

[5] The results have been applied to the Mediterranean region in qualitative terms. Although the potential for offshore wind energy is lower in the Mediterranean region than in Northern Europe, an in-depth analysis of the regional framework for offshore grids and electricity interconnection infrastructure is important, taking into account the need for interconnectivity and the long-term expectations for floating offshore wind turbines and solar thermal power in the region. More on this can be found in Annex E.

TABLE 1.1: STAKEHOLDERS PARTICIPATING IN THE STAKEHOLDER ADVISORY BOARD

Type of stakeholder	Stakeholders involved in the SAB
Regulatory Bodies	Ofgem, Bundesnetzagentur
Manufacturers	Acciona Energia, ABB, Siemens AG, Nexans
Project developers	Transmission Capital, Mainstream Renewable Power
Transmission System Operators	Entso-E RG NS, Tennet, Energinet.dk, 50Hertz Transmission, Statnett
European Commission	EC DG TREN D1, EC BREC, EC DG TREN TEN-E, EC DG MARE, EACI
Permitting and maritime spatial planning authorities	Bundesamt für Seeschifffahrt und Hydrographie
Utilities	RWE Innogy
Non-governmental organisations (NGOs)	Greenpeace

Fundamental scenario assumptions, the modelling approach as well as the preliminary and the final results were discussed in the Stakeholder Advisory Board (SAB), and the feedback was taken into account in the consortium's work.

All in all, three SAB meetings were organised. The participating stakeholders are shown in Table 1.1.

Next to the SAB meetings, three Stakeholder Workshops (two Northern European workshops and one Mediterranean) have been held, open to anyone. In total, these were attended by 170 people from all stakeholder groups.

Further presentation and discussion of results

In addition, many other stakeholders were involved via several presentations at high level political and technical conferences, political working groups, several meetings with and workshops organised by the European Commission, bilateral meetings with manufacturers, ENTSO-E, etc.

1.5 Document structure

This document reports on the approach, methodology, results and recommendations of the OffshoreGrid project carried out between May 2009 and October 2011. The document focuses on the results in order to increase comprehensibility and legibility. Extra and more detailed information on particular aspects such as, for instance, the applied models and the chosen scenarios can be found in Annex A to this final report on www.OffshoreGrid.eu.

The analysis of OffshoreGrid is based on well defined energy scenarios explained in Chapter 2. The project methodology, the models and the interfaces are described in Chapter 3.

Based on the chosen scenarios and models, a detailed techno-economic analysis was performed that led to the results illustrated in Chapter 4. This describes the aggregation of wind power over Europe, the cost-benefit analysis of integrated design concept, and a possible offshore grid design for Northern Europe. This techno-economic assessment is accompanied by a qualitative assessment of the socio-economic drivers and barriers, the regulatory framework and the ongoing political discussions in Chapter 5.

Chapter 6 summarises the conclusions and provides recommendations. An overall executive summary can be found at the very beginning of this document.

Photo: C-Power

2 KEY ASSUMPTIONS AND SCENARIOS

- **Offshore wind development scenarios in Northern Europe**
- **Generation capacity and commodity price scenarios**
- **Technology to connect offshore wind energy**

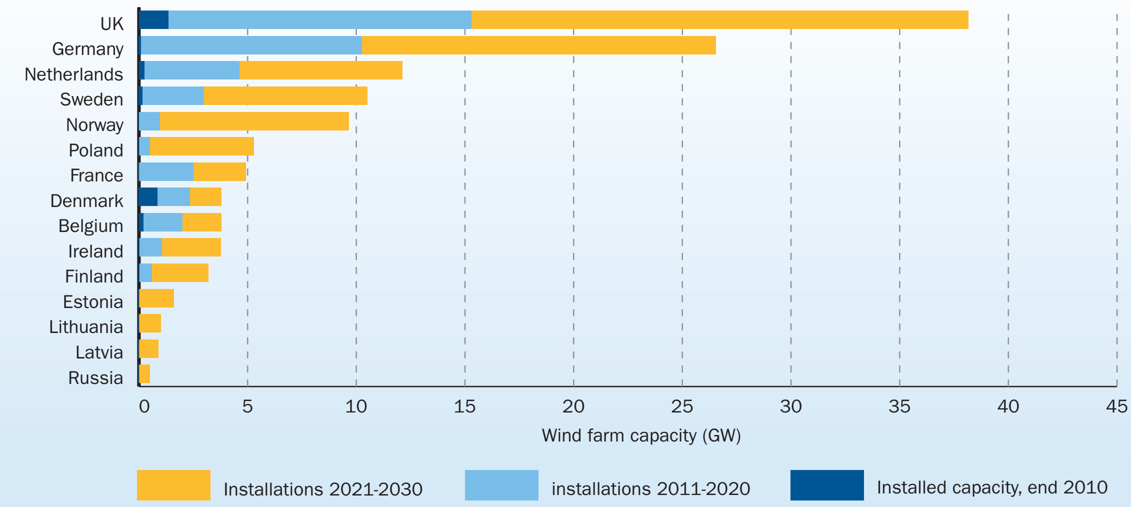
In this chapter the key assumptions and scenarios used for OffshoreGrid modelling purposes are described. This includes the assumptions on:

- installed capacities of offshore wind in Northern Europe,
- electricity generation capacities,
- electricity demand,
- fuel and CO_2 prices.

2.1 Offshore wind development scenarios in Northern Europe

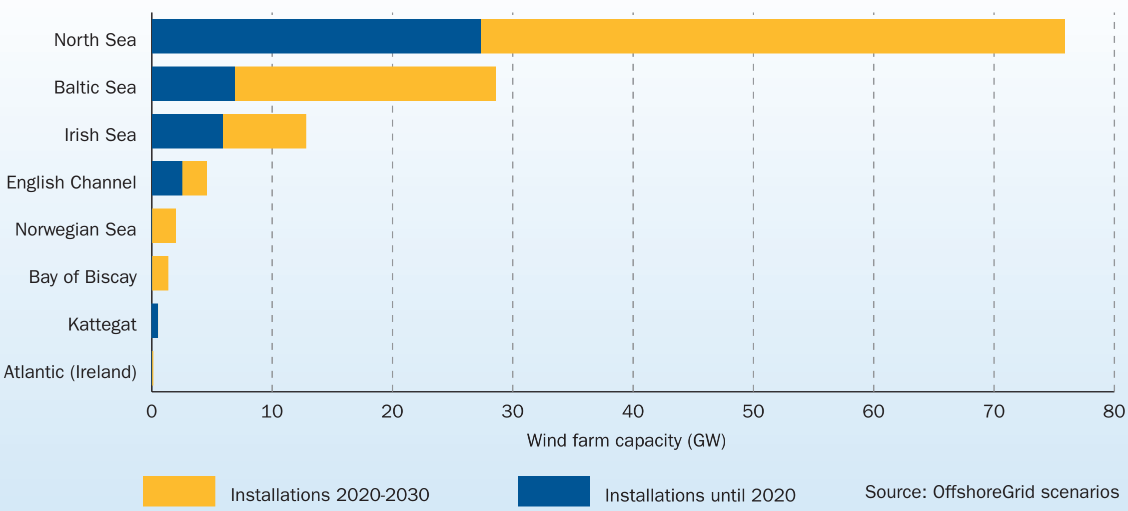
An important task in the OffshoreGrid project was the development of offshore wind power scenarios for the medium term (2020) and longer term (2030). They are mainly based on national government targets, on the latest EWEA offshore wind development scenario [20] and on the onshore wind power scenarios from TradeWind [24] updated with new available information. Figure 2.1 and Figure 2.2 provide an overview

FIGURE 2.1: INSTALLED CAPACITY OF OFFSHORE WIND FARMS IN NORTHERN EUROPE TO 2030, OFFSHOREGRID SCENARIOS



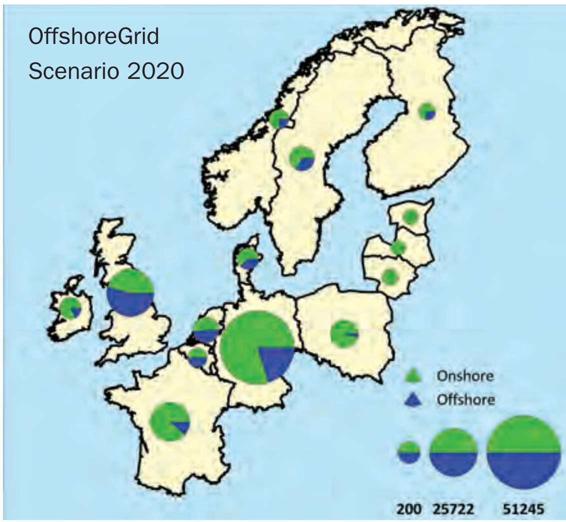
Source: OffshoreGrid scenarios

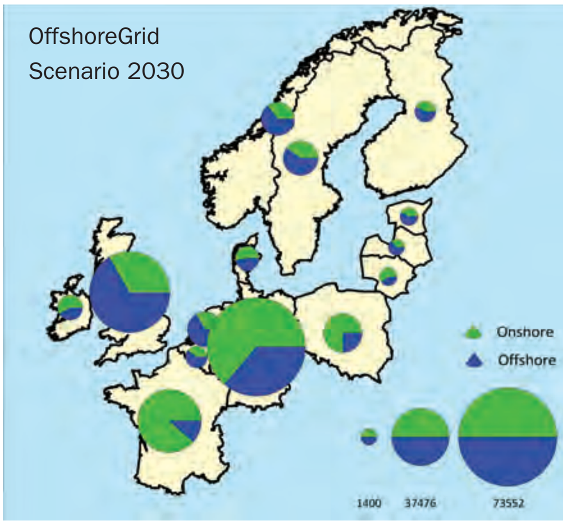
FIGURE 2.2: DISTRIBUTION OF INSTALLED CAPACITY PER SPECIFIC MARINE AREA



Source: OffshoreGrid scenarios

FIGURE 2.3: OFFSHORE AND ONSHORE WIND FARMS INSTALLATIONS IN NORTHERN EUROPE IN 2020 AND 2030, OFFSHOREGRID PROJECT SCENARIOS





per country respectively per marine area[6]. Concrete figures and more explanation on the development of these scenarios can be found in Annex A.I and in Deliverable 3.2.b, available online [25].

The most important players in the offshore wind energy market in the medium term scenario will be the UK and Germany. This leading group is followed by France, Sweden, Denmark, Belgium and the Netherlands. Total installed capacity in Northern Europe is expected to be approximately 42 GW in 2020 and 126 GW in 2030.

In the first phase, the major development of offshore wind capacity is expected to take place in the North Sea (Figure 2.2). An accelerated development of offshore wind farms in the Baltic Sea is expected to start after 2020. In 2020, the majority of wind energy installed capacity will still be onshore in most Northern European countries, except for the UK. In 2030, more than 40% of total installed wind energy capacity in Northern Europe is estimated to be offshore. In the UK, Belgium, Netherlands, Baltic States and Scandinavian countries, most of the wind energy would then operate offshore.

Offshore wind electricity generation

The 126 GW of installed capacity installed in 2030 will produce 530 TWh of electricity annually. This is more than the overall annual electricity consumption of Germany (509 TWh in 2010). Over the life time of 25 years the offshore electricity generation amounts to 13,300 TWh.

2.2 Generation capacity and commodity price scenarios

Offshore wind energy interacts strongly with the entire electric power system. Therefore, regional power markets have been analysed in order to elaborate the necessary input data for project modelling, such as:

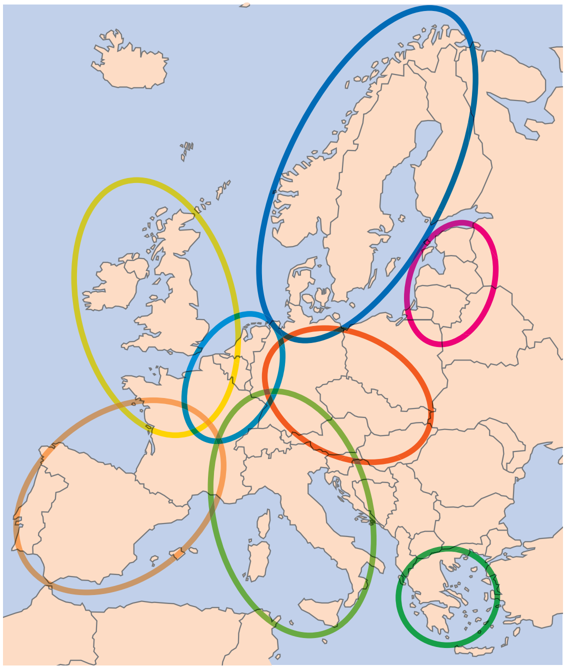
- electricity capacity scenarios for countries and regions regarded in the model,
- electricity demand,
- fuel price scenarios and CO_2 price scenarios.

Electricity generation capacity

One important input factor for the market and grid model is the installed electricity generation capacity and its future development. For this purpose, different

[6] See Annex A.II for main assumptions regarding the scenario development.

FIGURE 2.4: ERGEG MARKET REGIONS



national and transnational studies have been analysed and compared (e.g. [30][33]). The analysis of scenarios for electricity generation capacity includes information on the scenario years 2007/2008 as well as 2010, 2020, and 2030 for each of the 35 countries examined. As a result, a consistent data set for each country has been developed.

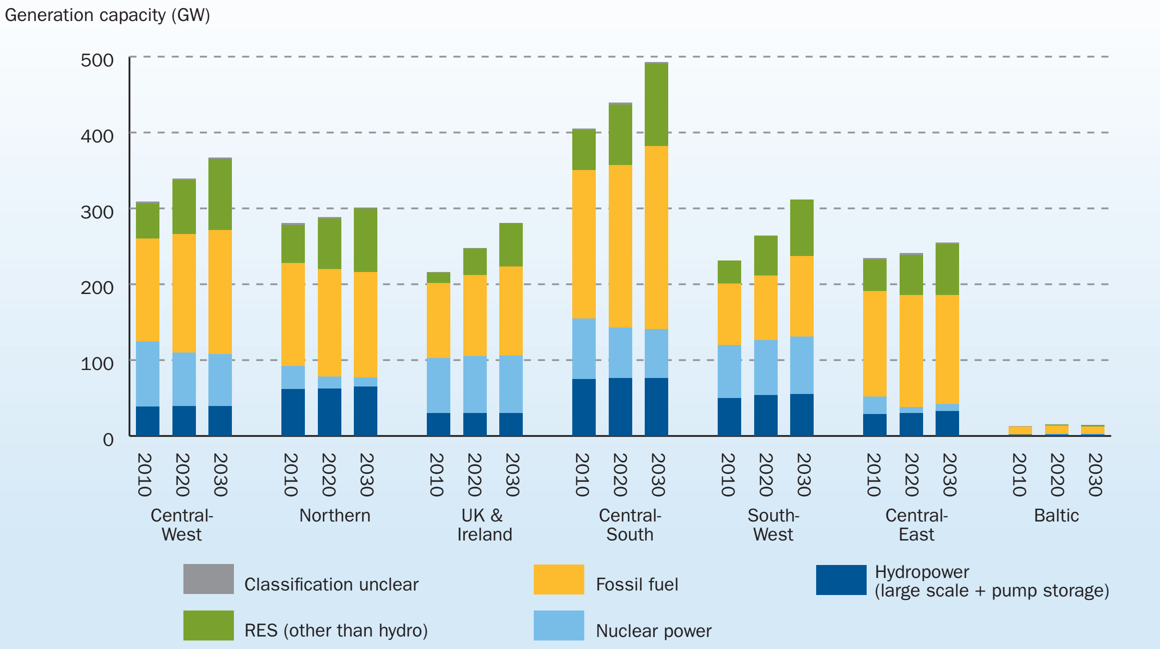
In order to give an overview of the installed generation capacity within the ERGEG market regions, the country data were transformed into regional data for the seven regional electricity markets (Figure 2.4)[7]. Figure 2.5 shows the developed electricity generation scenario.

The OffshoreGrid study is based on a nuclear phase-out for Germany and is therefore in line with current political decisions[8].

Electricity demand

For the OffshoreGrid scenario on electricity demand, the Primes 2009 Baseline scenario [33] is taken, completed with data from several national sources for the countries outside the EU. According to this source,

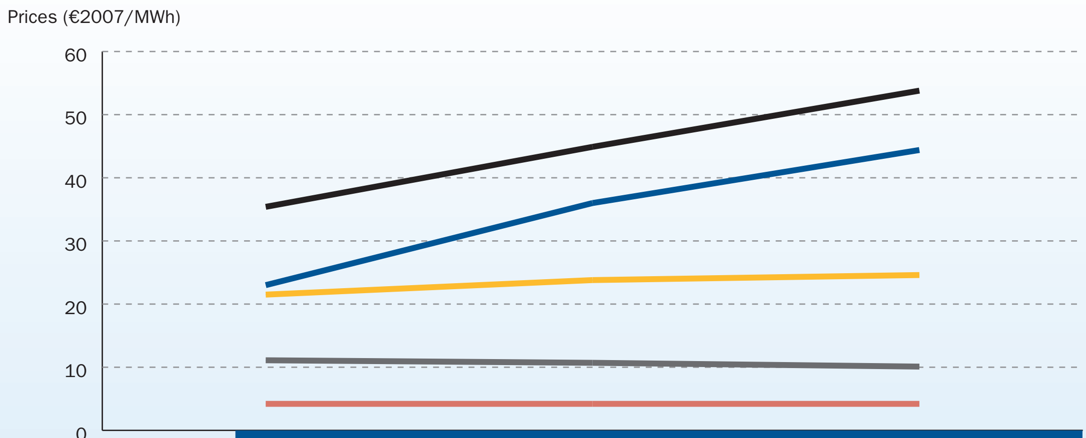
FIGURE 2.5: DEVELOPED ELECTRICITY GENERATION CAPACITY SCENARIO FOR THE ERGEG REGIONS (GW)



7 For more information about the ERGEG market regions see www.energy-regulators.eu.

8 The OffshoreGrid study is based on a nuclear phase-out for Germany according to the respective legislative act of 14 June 2000. The recent political decision requires the definite shut down of all nuclear units by 2022, somewhat earlier than previously decided. However, since OffshoreGrid only looks at the system in the years 2020 and 2030, this has no impact on the results, and it can be considered to be in line with the current political decisions.

FIGURE 2.6: COMMODITY PRICES



	2010	2020	2030
Crude oil	35,4	44,9	53,8
Hard coal	11,1	10,7	10,1
Lignite EU	4,2	4,2	4,2
Gas EU	21,5	23,8	24,6
CO_2 (€ 2007/t)	23,0	36,0	44,4

gains in energy efficiency are offset by rising electricity consumption due to robust economic growth in Eastern and Southern European countries, hence the slight increase in electricity demand in the forecast for the next two decades.

Fuel prices and CO_2 prices

Figure 2.6 gives an overview of the chosen commodity price scenarios[9]. Lignite and hard coal prices remain relatively stable until 2030. Gas prices increase slightly. The sharpest increase in prices is expected for crude oil and CO_2.

2.3 Technology to connect offshore wind energy

The OffshoreGrid consortium based its investigation on an in-depth technology analysis for onshore and offshore transmission equipment. Apart from the equipment that is available today, the OffshoreGrid study takes into account possible future technology developments. The cost specifics of the equipment were elaborated in close cooperation with the main technology suppliers, and checked within the stakeholder workshops for plausibility.

Thus the OffshoreGrid study had a complete portfolio of technologies to choose from, including detailed information on technical behaviour, as well as specific investment, maintenance and operation costs. It included different offshore and onshore transmission technologies as well as all relevant HVAC and HVDC technologies, switching equipment and substation technology. A more detailed overview is given in Annex B.I, available on www.offshoregrid.eu.

Preferred technology for offshore wind connection

The establishment of an extensive offshore grid linking countries across the North and Baltic seas, and to a lesser extent the connection of offshore wind farms to those countries, relies on High Voltage Direct

[9] Detailed explanations of the chosen prices can be found in Annex A. For gas and lignite, national prices have been considered.

Current technology. When considering the connection of the larger more distant offshore wind farms, the Voltage Source Converter (VSC) HVDC technology also becomes important.

Compared to High Voltage Alternating Current technologies and even the Current Source Converter (sometimes called Line Commutated) HVDC technology, the VSC technology is relatively immature in terms of operating experience. The first onshore application of VSC technology was the 50 MW Gotland link (Sweden) commissioned in 1999, and the first offshore application was the 84 MW Troll A link (Norway) commissioned in 2005. Hence this technology has yet to be proven over the expected lifetime of an offshore wind farm or interconnector installation.

Despite this lack of experience, the technical advantages that the VSC equipment provides for the connection and transmission of bulk power in the offshore environment means that the VSC equipment will be the transmission technology of choice for large, distant offshore wind farms. It is for this reason that the majority of the offshore grid designs analysed in this report is based on VSC technology.

However, current experience shows that the supply chain bottlenecks for the main components of HVDC technology can slow down the development of offshore wind farm connections. Therefore for singular cases it might be necessary to fall back upon AC connection concepts until the supply chain is fully able to deliver the requested equipment on time.

3 METHODOLOGY – SIMULATION INPUTS AND MODELS

- **Wind power series model**
- **Power market and power flow model**
- **Infrastructure cost model**
- **Case-independent model**

The OffshoreGrid results are based on detailed generation modelling, market and grid power flow modelling and infrastructure cost modelling. Each of the modelling tasks is already a significant challenge in its own right and there is no integrated model that could solve the envisaged optimisation goal to determine an optimal offshore grid. The consortium therefore set up a stepwise methodology in which different models are combined in an iterative approach. All in all, four major models were developed and applied: the wind series power model, the power market and power flow model, the infrastructure cost model and the case-independent model.

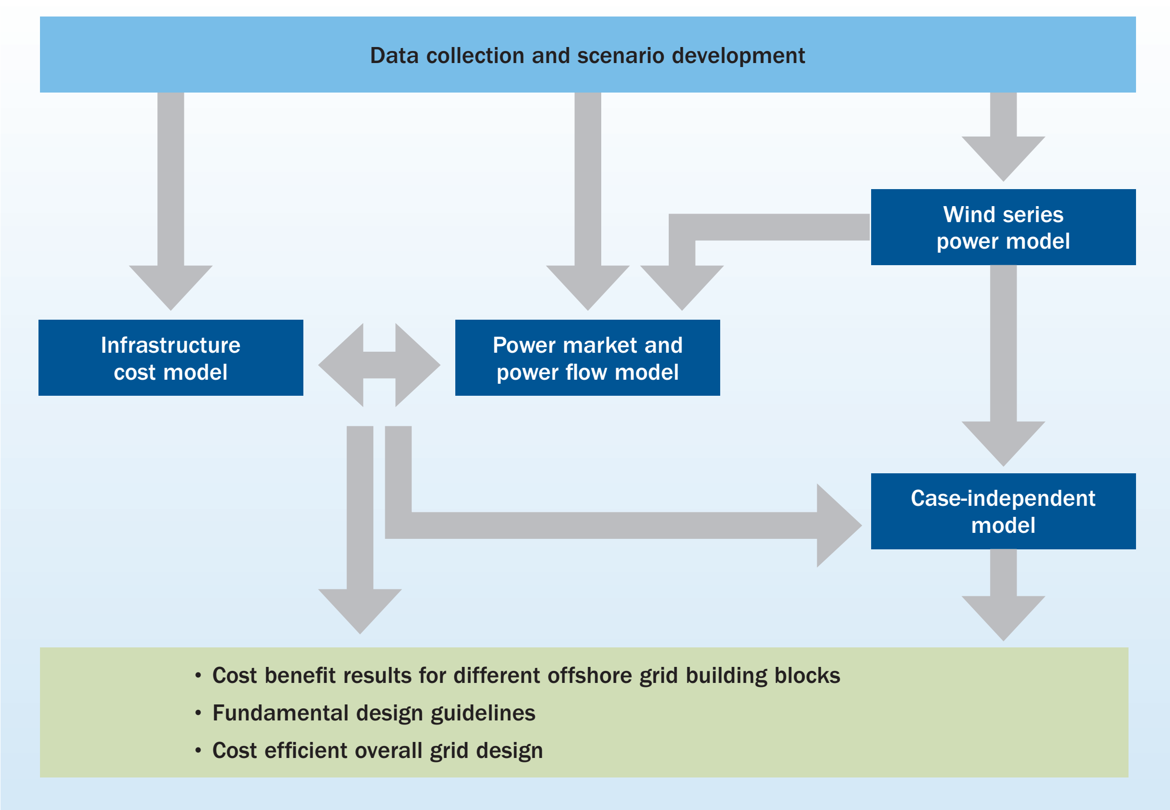
The wind series power model created wind power time series that fed into the power market and power flow model. This model was then combined with the infrastructure cost model in order to obtain results on case studies, to determine which offshore configuration was the most suitable. Output from these two models was also used in the case-independent model, which creates general overall conclusions that can be applied to most offshore scenarios. This design loop is illustrated in Figure 3.1.

The following sections briefly describe the key features of each model. Annex C explains them in more detail.

3.1 Wind power series model

On- and offshore wind power have a predominant impact on the optimal grid design of an offshore grid. It was therefore decided to apply a specialised wind power model (meso-scale numerical weather prediction model) to generate high-resolution wind power time series for every offshore wind farm and every onshore wind region identified in the developed scenarios [25]. This was performed by first modelling the wind in the desired region, which was done through

FIGURE 3.1: SCHEMATIC EXPLANATION OF THE INTERACTION BETWEEN THE MODELS IN OFFSHOREGRID



use of the applied Weather Research and Forecasting Model (WRF) [1]. WRF is a meso-scale numerical weather prediction model, able to simulate the atmospheric conditions across a wide range of horizontal resolutions from 100 km down to 1 km. Once the WRF model runs were performed and validated, the wind speed time series at more than 350 offshore sites and 16,000 onshore grid points were determined.

These wind speed time series were then converted to wind farm power generation, based on wind farm power curves. Power curves show the relationship between how much power will be produced from the wind farm under certain wind conditions. The resulting wind power time series are used as input to the power market and flow model described below.

3.2 Power market and power flow model

Power plants generate when they can sell their electricity to the market if there is enough grid capacity to transport it. The power market and power flow model [29] simulates the operation of the power system based on a detailed set of European generation data (capacity, costs, etc.) and a detailed European grid model. Both conventional power plants and renewable generation are modelled.

The tool used to perform the modelling is called the Power System Simulation Tool (PSST) [2]. PSST combines a market model with a model of the European electricity grid, and assumes a perfect market with nodal pricing. The socio-economic optimum for the overall European electricity production is found by minimising the total yearly generation cost. From the simulations both technical and economic parameters, such as generation cost, energy prices, price differences and grid utilisation (off- and onshore) for different scenarios can be extracted. The results from this model together with the infrastructure cost model (see 3.3) allow decisions to be made on whether a specific offshore wind farm configuration is the most beneficial.

3.3 Infrastructure cost model

Building offshore grid infrastructure requires large investments. The extent of these investments is a key factor to be taken into account when determining the overall costs and benefits of the considered design. The infrastructure costing model [26][27] is used to determine the capital costing of the entire OffshoreGrid infrastructure used in the modelling phases, including individual wind farm connections, hub connections, wind farm tee-in connections, direct interconnectors, meshed hub-to-hub and hub-to-shore interconnectors, and split wind farm connections. It takes into account costs of different offshore cable and equipment technology, the cable length, sea depth, bathymetric data, project timing, onshore network security criteria, etc.

The infrastructure cost model feeds directly into the net benefit model, together with the results from the power market model to assess the viability of links for arbitrage. The infrastructure cost model has two main stages, firstly incorporating a technical assessment of the required infrastructure to determine the required technology and then a costing exercise is performed to produce the capital costing for each wind farm connection.

The costs produced by the infrastructure cost model are determined mainly by what technology is required and the connection distance. Following the calculation of the route lengths a technical assessment is made to determine the topology for each link. For wind farm connections and hub connections this could be either AC or DC depending on the distance. All interconnectors for arbitrage have been assumed to be HVDC due to the distances involved in connection. The technology available is based on which technology is commercially available today and future technology established in Deliverable 5.1, available online [26].

3.4 Case-independent model

During the course of the OffshoreGrid study it became apparent that the appropriate offshore grid design is very sensitive to the specific cases under investigation: distances to shore, wind farm capacities, price profile differences between the countries, etc. The results of the specific cases are useful but general conclusions are necessary for the optimal offshore grid design and also for clear recommendations, which is one of the central goals of the OffshoreGrid study. A case-independent model was therefore developed with inputs from the infrastructure model and the power system model.

The model is built in the mathematical programming language Matlab and focuses on two design problems, namely the teeing-in of wind farms into an interconnector between two countries and the interconnection of two countries via two offshore wind farm hubs (these scenarios are described in more detail in Section 4). The model performs an extensive sensitivity analysis that looks into the impact of the price difference between countries, the direction of the price difference, the impact of cable or wind farm capacities, and the impact of cable lengths. The model then takes this information and produces general conclusions regarding the impact of changing one or more of the previously listed parameters on the viability of an offshore wind farm configuration. This allows the development of general offshore grid design rules, which are then validated using case studies.

4 RESULTS

- **Wind output statistics**
- **Wind farm hubs versus individual connections**
- **Integrated design – case studies**
- **Integrated design – case-independent model**
- **Overall grid design**

This chapter explains and summarises the results of the OffshoreGrid project. It focuses first on the statistics of the wind output (Section 4.1) when aggregated over larger regions via an offshore grid. The effect of smoothing is analysed, and concrete figures are provided on the correlation of the wind resource between countries, which is very useful for analysing the effect of interconnections.

Secondly, an evaluation of wind farm hubs is carried out in Section 4.2. This section analyses in which cases and under which circumstances wind farms should be grouped in hubs before they are connected to the shore. The impact on connection costs for the developed offshore wind scenario is investigated. Furthermore, the risk of stranded investments is assessed.

Section 4.3 analyses the possibilities for integrated designs, the basics of an offshore grid. The focus is put on two basic designs which form the building blocks of any future offshore grid design; the teeing-in of wind farms into interconnectors, and the interconnection of countries via offshore wind farm hubs. The section looks into specific cases.

With the help of a specially developed case-independent model, a thorough sensitivity analysis is done in Section 4.4. This leads to further insight into the drivers and concrete design guidelines.

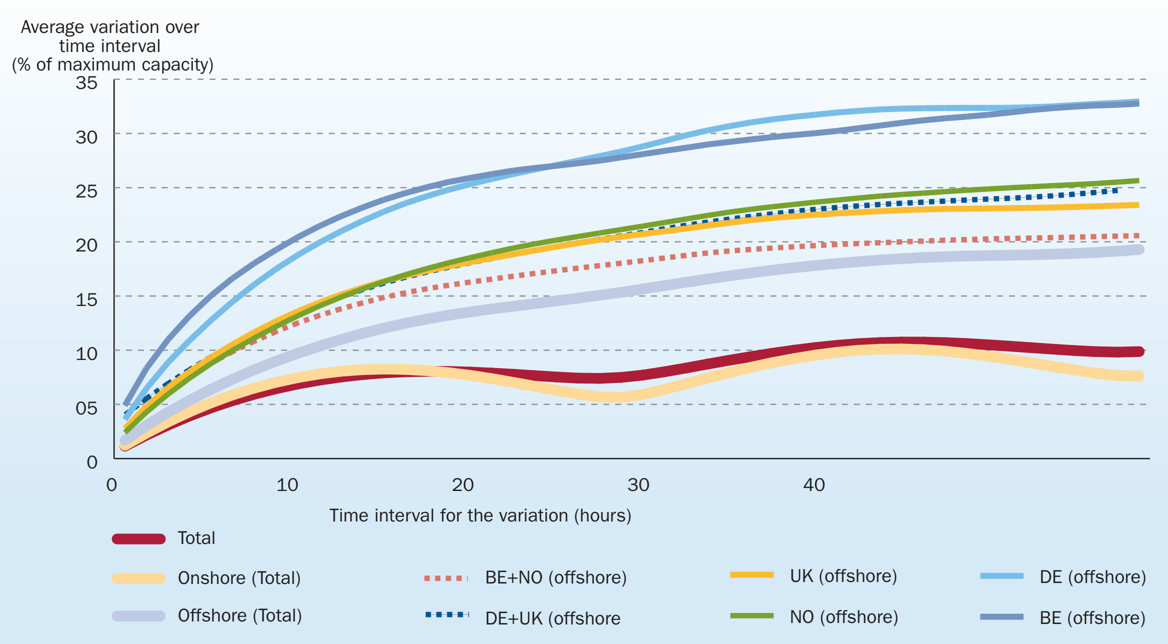
By means of a detailed iterative modelling process, taking into account the results from the previous sections, Section 4.5 shows what the offshore grid in Northern Europe could look like. Two design methodologies have been compared and lead to important conclusions on how to approach the modular building of an offshore grid.

4.1 Wind output statistics

4.1.1 Spatial smoothing of wind power

There are several techno-economic benefits directly linked to an offshore grid as outlined in the introduction. One of these benefits is the additional interconnection of wind energy generation centres across Europe which smoothes wind energy variability giving it a

FIGURE 4.1: AVERAGE VARIATION IN WIND POWER OUTPUT OVER DIFFERENT TIME INTERVALS [% OF INSTALLED CAPACITY][10]



[10] Note that a clear day-night pattern (24h interval) can be identified for the total onshore and total wind power production.

steadier generation profile. This issue was already studied by the TradeWind study [2] and was further elaborated within OffshoreGrid as more accurate wind power time series were available.

This spatial smoothing effect is illustrated in Figure 4.1, displaying the average variation (gradient) in wind power output over different time intervals. The longer the time interval, the higher the average variation is[11]. For the offshore wind farms in a small area as in the Belgian EEZ (Exclusive Economic Zone), the variation is relatively high already over one hour (4.9%), compared to a larger region like the EEZ of the United Kingdom (2.8%) or all onshore and offshore wind power in the OffshoreGrid scenario (1.1%). The differences increase with the length of the time interval. The average variation over 10 hours is only 7.2% of the total capacity for the total OffshoreGrid scenario, while for Belgian offshore wind power it is much higher (21.4%).

It is important to highlight that this large-scale wind smoothing effect is only possible if power exchange can be realised across large areas and if the power exchange is not restricted. The grid plays a crucial role in interconnecting wind power plant outputs installed at a variety of geographical locations, with different weather patterns. The larger the grid and the larger its transmission capacity, the larger the smoothing effect of wind energy will be. This effect of course also holds for aggregation of demand or other weather or resource dependent generation technologies. A reduced variability brings numerous benefits to the power system, such as more technical stability and security, more stable prices, improved predictability and thus a more efficient operation which in its turn yields reductions in costs, primary energy consumption and emissions.

The offshore grid will tremendously increase the transmission capacity over long distances and therefore largely contribute to the smoothing of wind power generation.

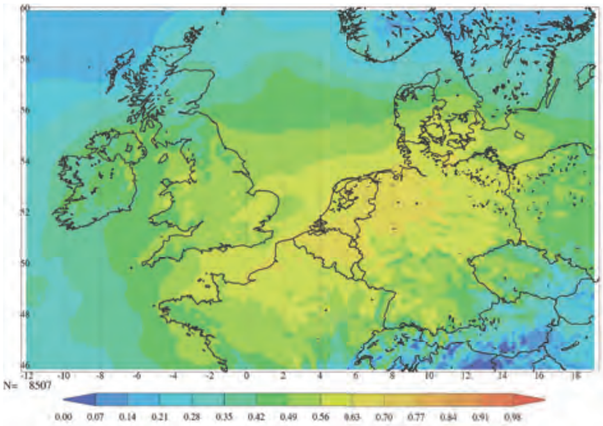
A more detailed analysis of the wind power smoothing is shown in Annex D.I.I, available on www.offshoregrid.eu.

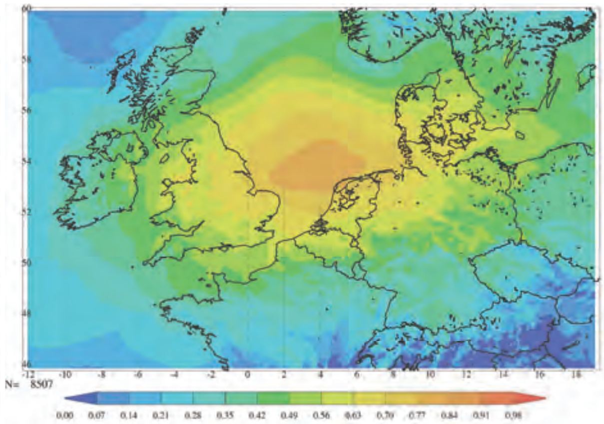
4.1.2 Spatial power correlations

Within OffshoreGrid a new way for visualisation of wind power correlations was developed in the so-called van-Bremen-maps. The idea is to calculate the correlation between time series of a certain local variable, like local wind speed at a specific point in space, and a prescribed reference time series. Then, all these correlations are plotted as a map for a high number of geographical points. In this way, the map shows the spatial characteristics of a specific correlation (for details please refer to Annex D.I.II).

Figure 4.2 shows the correlation of the local wind power time series with either the simulated offshore wind power (figure to the left) or onshore wind power

FIGURE 4.2: VON-BREMEN-MAP SHOWING SPATIAL CORRELATION BETWEEN LOCAL WIND POWER TIME SERIES AND THE SIMULATED TOTAL EU OFFSHORE WIND POWER (LEFT) OR ONSHORE WIND POWER (RIGHT)





[11] The average variation in output over one hour is obviously lower than the average change in output over a whole day.

(figure to the right) in Northern Europe, as assumed in the 2030 scenario of OffshoreGrid: areas of low correlation are illustrated in blue, high correlation in red. The figures show that most of the offshore capacities in the 2030 scenario are concentrated in the southern part of the North Sea. In contrast to this, the onshore wind power in the scenario is more or less evenly distributed over Northern Europe. In total, wind energy is clearly concentrated in the North. This concentration will pose considerable challenges for power flows in the future European electricity grid.

The correlation of the offshore wind power shows a clear west-east pattern: the figure on the left in Figure 4.2 reflects that the wind power production is more correlated from west to east than between north and south. Moreover the main wind direction is from west to east, especially the low pressure weather systems with strong wind speeds also move mainly from west to east.

The analysis shows that grid interconnections between regions of low weather correlation can significantly reduce the variability of European wind power production. Interconnectors running in a north to south direction bring the highest benefit for the reduction of wind power variability.

Spatial correlations of wind power production between countries

With the simulated wind power time series, the spatial correlations between individual countries were also investigated. The results are shown in Table 4.1, which confirms the findings above. The correlations are highest in the east-west direction, for example a correlation of 74% between the UK and the Netherlands, 67% between the UK and Germany, and still 29% between the UK and Poland. This is much less in the north-south direction, with correlations of only 44% between Norway and Denmark, 16% between Finland and Poland, and even only 5% between Norway and France. The combination Germany-UK yields higher average variations than a combination Norway-Belgium. This means that from a wind power variability point of view, a north-south interconnection between Norway and Belgium would be more beneficial than an east-west interconnection between the UK and Germany.

The figures in Table 4.1 can be used in the preliminary assessment of new interconnectors that are meant for trading wind power. Low correlation would hint at the need for new interconnecting capacity in order to fully utilise the variable wind resource.

TABLE 4.1: CORRELATION COEFFICIENTS BETWEEN COUNTRIES USING SIMULATED WIND POWER TIME SERIES FOR THE OFFSHOREGRID 2030 WIND POWER SCENARIO (ON- & OFFSHORE WIND TOGETHER) (%)

	BE	DK	ET	FI	FR	DE	UK	IR	LA	LT	NL	NO	PL	RU	SE
BE	100%	45%	12%	2%	59%	67%	66%	37%	20%	21%	79%	12%	28%	20%	22%
DK	45%	100%	32%	17%	32%	76%	49%	20%	44%	48%	77%	44%	78%	48%	73%
ET	12%	32%	100%	51%	10%	18%	16%	12%	66%	66%	22%	13%	36%	45%	69%
FI	2%	17%	51%	100%	2%	6%	7%	4%	30%	34%	10%	23%	16%	19%	49%
FR	59%	32%	10%	2%	100%	37%	49%	43%	16%	18%	46%	5%	23%	17%	20%
DE	67%	76%	18%	6%	37%	100%	67%	26%	28%	30%	87%	40%	53%	32%	43%
UK	66%	49%	16%	7%	49%	67%	100%	62%	20%	21%	74%	37%	29%	21%	27%
IR	37%	20%	12%	4%	43%	26%	62%	100%	13%	14%	33%	14%	15%	13%	13%
LA	20%	44%	66%	30%	16%	28%	20%	13%	100%	89%	32%	15%	55%	74%	69%
LT	21%	48%	66%	34%	18%	30%	21%	14%	89%	100%	34%	17%	61%	88%	72%
NL	79%	77%	22%	10%	46%	87%	74%	33%	32%	34%	100%	36%	50%	34%	49%
NO	12%	44%	13%	23%	5%	40%	37%	14%	15%	17%	36%	100%	24%	16%	30%
PL	28%	78%	36%	16%	23%	53%	29%	15%	55%	61%	50%	24%	100%	65%	73%
RU	20%	48%	45%	19%	17%	32%	21%	13%	74%	88%	34%	16%	65%	100%	59%
SE	22%	73%	69%	49%	20%	43%	27%	13%	69%	72%	49%	30%	73%	59%	100%

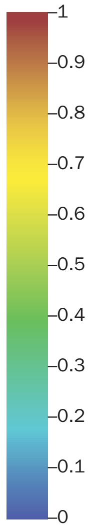
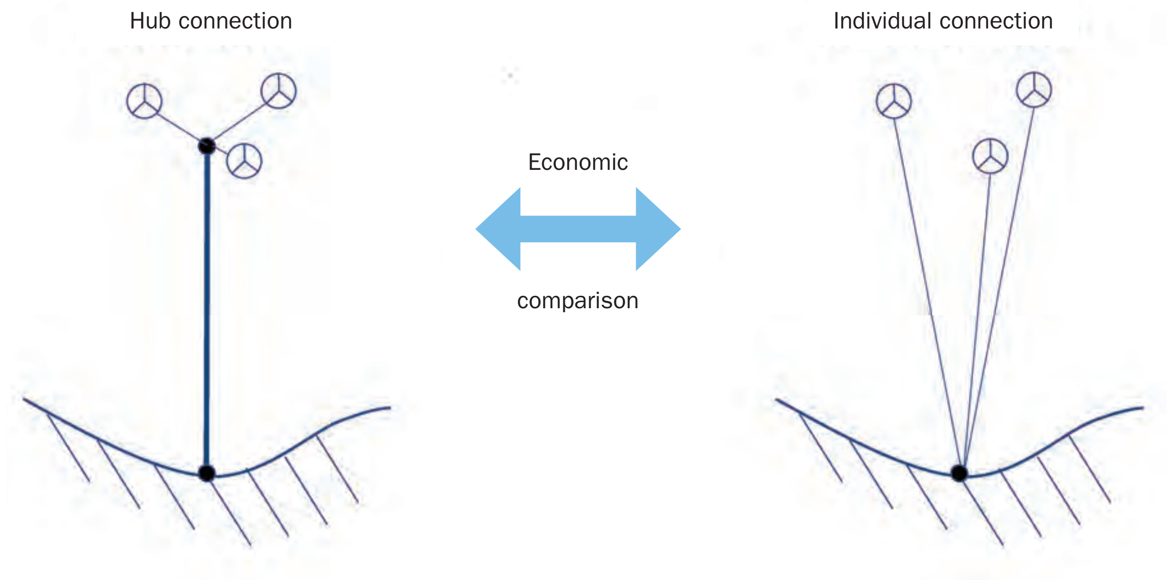


FIGURE 4.3: HUB CONNECTION VERSUS INDIVIDUAL CONNECTION



4.2 Wind farm hubs versus individual connections

Within the last decade offshore wind energy development has accelerated significantly and today numerous wind farms are planned in the North Sea. Because of space restrictions due to maritime use conflicts and following the best wind potentials, many of these wind farms are planned far from shore and in close vicinity to one another in so-called offshore wind farm clusters.

Immediately the question arose as to whether it is more efficient to bundle the electric connection of these wind farms at sea and carry the energy over a joint transmission line to the onshore connection points. This so-called hub connection (Figure 4.3) design can reduce costs, space use and environmental impact dramatically.

The question of whether to build a hub to connect a number of wind farms with a shared line or whether to connect wind farms individually is the first question to be tackled when discussing a future offshore grid. Indeed, large wind farm hubs can form the basis for further interconnection to other countries and other wind farm hubs. The economic situation however depends on a variety of parameters, such as wind farm distance to shore and wind farm sizes (rated capacity).

An economic comparison of hub connection versus individual connections was carried out, with the results presented in the following sections. All offshore wind farms planned up to 2030 were considered. Based on economic considerations, it was decided whether every single wind farm will be integrated in a hub connection, or whether it is more economic to connect it individually. Please note that this assessment does not yet take into account additional country-to-country, hub-to-hub or tee-in interconnections.

Wind farms are clustered and connected to offshore hubs, then connected to shore via shared transmission assets from these hubs. Detailed analysis shows that the advantages of hub connections strongly depend on offshore wind power siting in the different countries, that is to say the distance of each project from shore and from each other.

4.2.1 Hubs and individual connections in the sea basins in Northern Europe

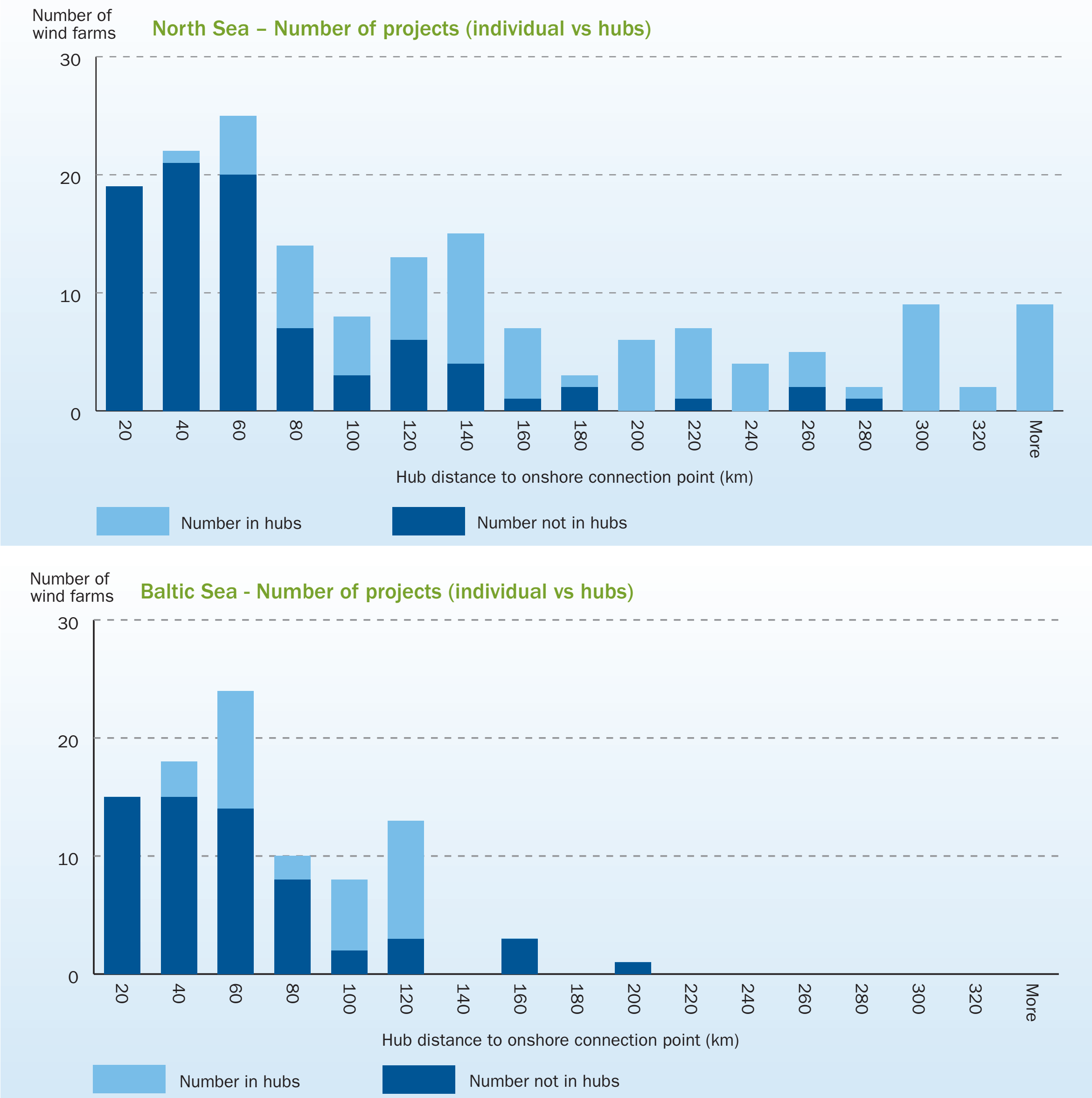
The costs of a joint hub connection versus separate individual connections for the wind farm projects in the OffshoreGrid scenario have been assessed by using the hub assessment tool [26][12]. The tool compares the costs of an individual connection with the costs of connecting the wind farm to a cluster nearby.

Figure 4.4 shows the number of projects connected with individual connections to shore and those with a hub connection as a function of the distance of the wind farm to the onshore connection point of choice for an individual connection. The results have been detailed for the North Sea, Baltic Sea, Irish Sea and English Channel as well as by country.

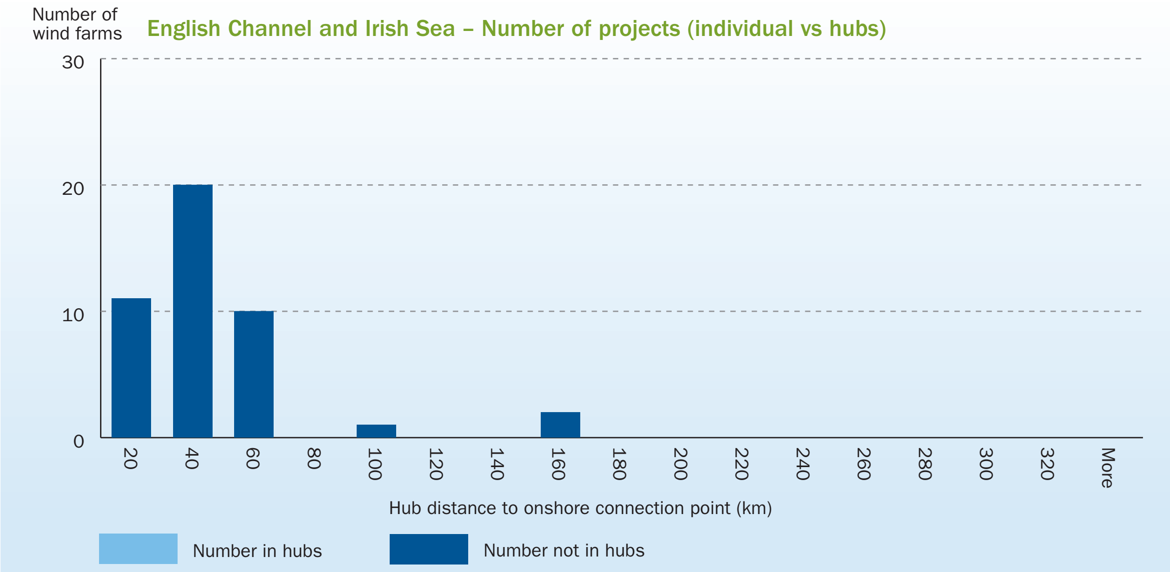
Sea basins

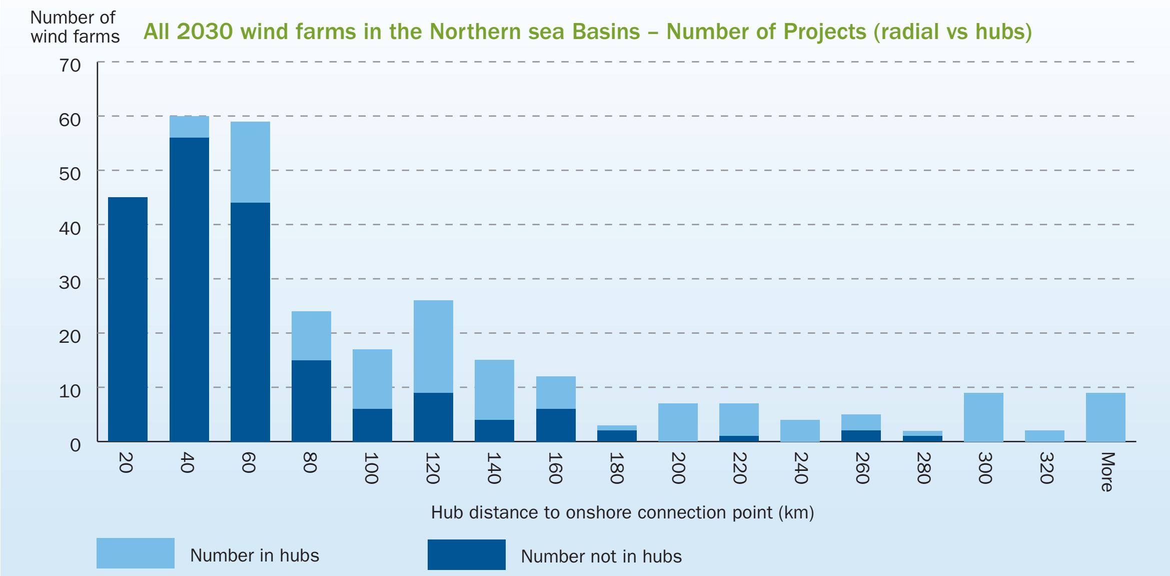
The wind farms in the English Channel and Irish Sea are close to shore and rather widely scattered. Therefore the hub connection is not beneficial for any of them. All wind farms should be connected individually.

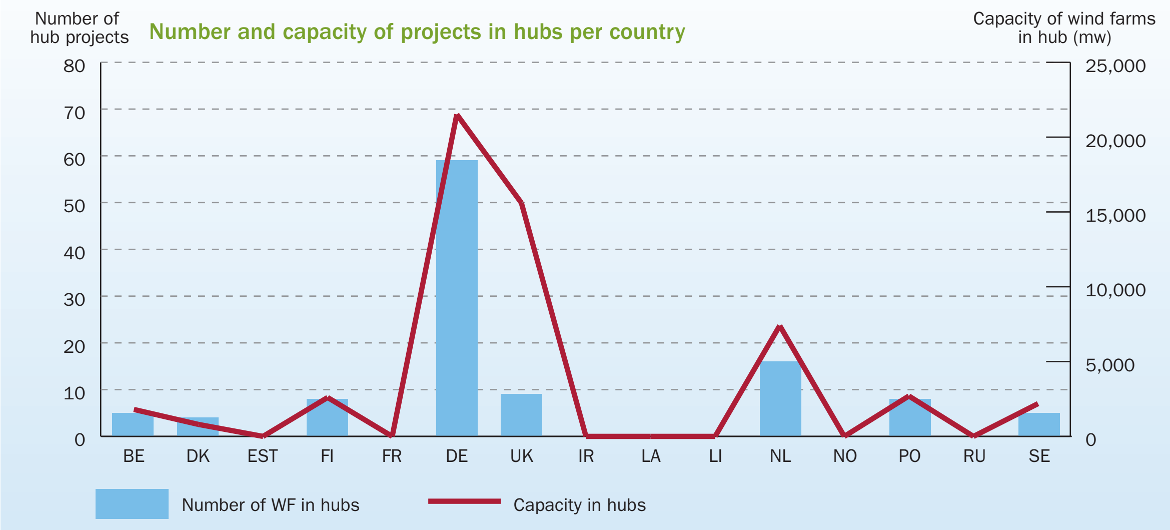
FIGURE 4.4: FREQUENCY DISTRIBUTION OF PROJECTS WITH INDIVIDUAL CONNECTIONS TO SHORE AND PROJECTS CONNECTED VIA OFFSHORE HUBS. OUT OF A TOTAL OF 321 PROJECTS, 114 ARE CONNECTED VIA HUBS AND 207 INDIVIDUALLY (2030)



[12] For an economic analysis that takes into account time delays, please refer to section 4.2.3.


Number of wind farms
English Channel and Irish Sea – Number of projects (individual vs hubs)
30
20
10
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
More
Hub distance to onshore connection point (km)
Number in hubs
Number not in hubs


Number of wind farms
All 2030 wind farms in the Northern sea Basins – Number of Projects (radial vs hubs)
70
60
50
40
30
20
10
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
More
Hub distance to onshore connection point (km)
Number in hubs
Number not in hubs


Number of hub projects
Number and capacity of projects in hubs per country
Capacity of wind farms in hub (mw)
80
70
60
50
40
30
20
10
0
25,000
20,000
15,000
10,000
5,000
0
BE
DK
EST
FI
FR
DE
UK
IR
LA
LI
NL
NO
PO
RU
SE
Number of WF in hubs
Capacity in hubs

The Baltic Sea is still a rather small sea basin and wind farms are mostly close to shore. Despite this, for 31 of the 92 wind farms in the Baltic Sea, a hub solution is beneficial.

For the North Sea, the results reveal that hubs are particularly beneficial. With 83 hub connected wind farms, almost 50% of the 170 wind farms in the scenario are integrated in hubs.

Hub wind farms per country

The situation is very different across the European countries. While for Germany 19 hubs have been defined to which 59 of the total 70 German wind energy projects should be connected, hub connections are not beneficial in Ireland or Norway. This of course largely depends on the number of wind farms planned within the countries, the vicinity of these to each other and their relative distance and the distance to shore.

In the United Kingdom and in the Netherlands, wind farms are often far from shore and concentrated in a few specific areas. Round 3 in the UK is a good example of this. These wind farms (e.g. Dogger Bank) have been assumed to be 1,000-2,000 MW each. They are indeed of the same size as the installed capacity of several wind farms in other European countries. This is a consequence of good siting and strategic planning.

As a result of the hub assessment, 114 out of 321 offshore wind projects have been clustered at hubs. Wind farms situated closer than 50 km to an onshore connection point are virtually always connected individually to shore. For wind farms situated between 50 and 150 km from shore each option may be beneficial, depending on the total capacity in the surrounding area. For wind farms located further than 150 km away from an offshore connection point, the hub connection is almost always beneficial. The few individual connections found in this range are due to the solitary location of these wind farms.

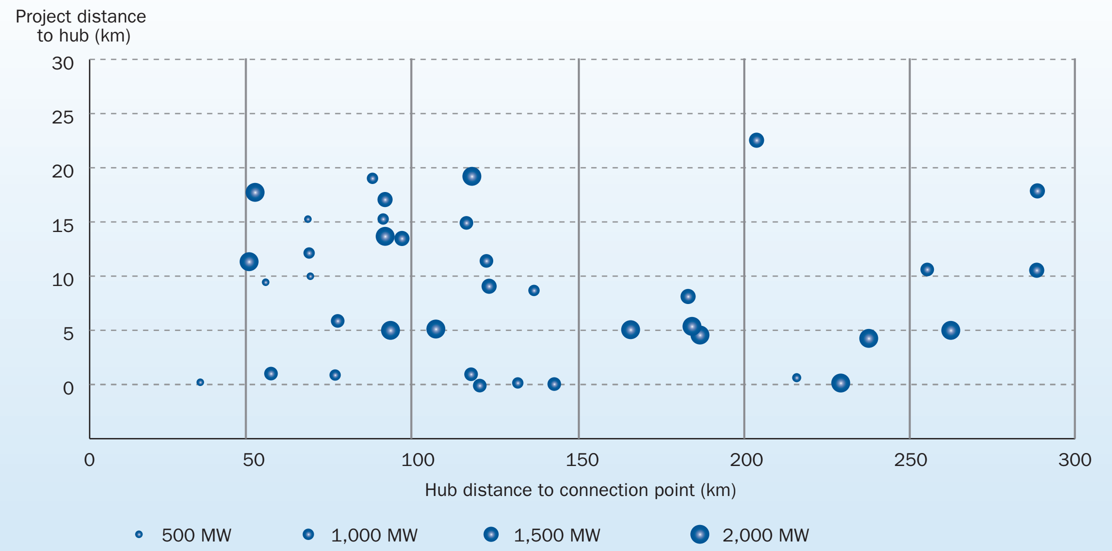
Hub size and distance to the hub

The decision whether to connect wind farms via a hub not only depends on the wind farm's distance to shore, but also on the total capacity of offshore wind within a reasonable distance of the hub location.

The technological advancement of HVDC VSC assumed in this project based on several discussions with the manufacturers, indicates that a maximum hub capacity of 2,000 MW is a reasonable limit for 2030 (see Annex B for further details).

Due to economies of scale, small hubs are not viable far from shore. Figure 4.5 maps the distance of the wind farm projects to their hub versus the hub

FIGURE 4.5: LARGEST DISTANCE FROM WIND FARM PROJECTS TO THEIR HUB FOR EACH HUB VERSUS HUB DISTANCE TO ONSHORE CONNECTION POINT. THE BUBBLE AREA REPRESENTS THE HUB SIZE (MW). (HUB BASE CASE SCENARIO 2030)



distance to the onshore connection point. As can be seen from this figure, small hubs (< 500 MW) are not present for distances beyond 75 km.

The largest distance from individual wind farms within the cluster to their hub is generally less than 20 km. Beyond a certain distance from the hub, AC technology is no longer economically viable for the connection of the wind farms to the hub. Therefore the use of AC/DC converters and an internal DC connected wind farm cluster is required. The fixed cost of these converters and associated platforms make such a hub arrangement less economic, and it has therefore not been assessed further.

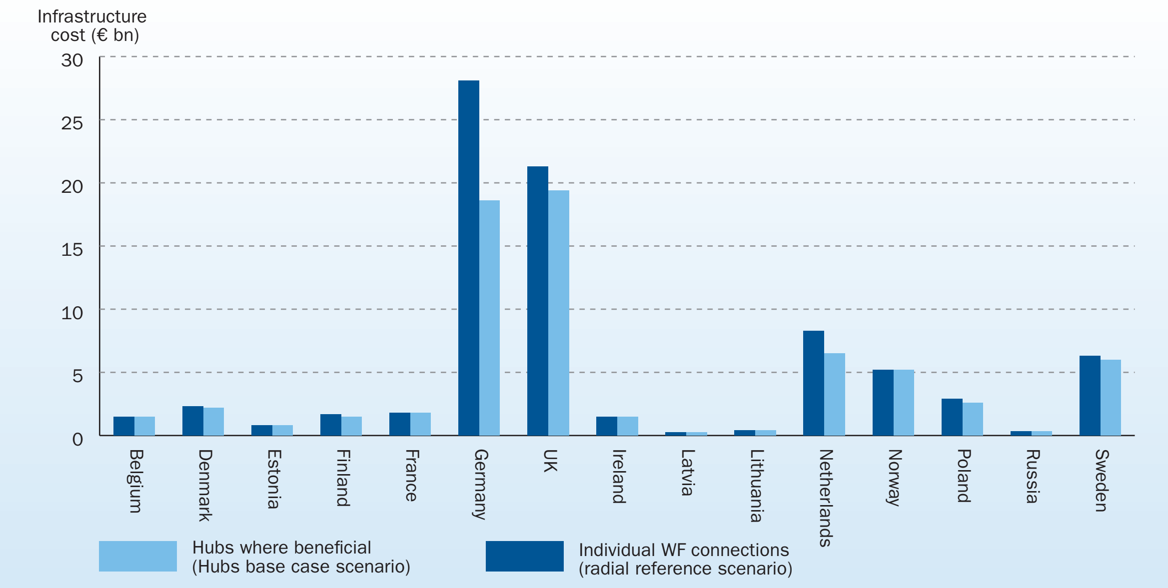
4.2.2 Overall cost reductions expected from shared connections via hubs

Our analysis concludes that the connection costs for offshore wind farms up to 2030 can be reduced by €14 bn by sharing connections via hubs compared to a business-as-usual individual wind farm connection. Figure 4.6 shows a breakdown of the total grid connection costs for offshore wind power by country. The figure compares the scenario in which all wind farms are connected with individual connections (radial connection scenario) to a scenario in which hub connections are allowed when beneficial (hubs base case scenario).

Clustering of wind farms for hub connection is particularly beneficial in Germany, the United Kingdom and the Netherlands, where wind farms are often far from shore and concentrated in a few specific areas as discussed in Section 4.2.1. The largest achievable savings are €9.4 bn (34%) for Germany, €1.9 bn (8.7%) for the United Kingdom[13], and €1.8 bn (22%) for the Netherlands. Also Finland and Poland can achieve considerable savings in relative terms, namely €270 m (15.8%) and €320 m (10.8%) respectively. In contrast, for other large countries such as France where offshore wind projects are dispersed along the northern coast line, there is no case for offshore hubs. Closer examination shows that offshore hubs are particularly beneficial when groups of wind farms are far from shore and close to each other.

Taking into account all offshore wind farms to be built up to 2030 implies average connection costs of €660,000 per MW when using only individual connections and €550,000 per MW when using hub

FIGURE 4.6: CAPITAL COSTS FOR THE GRID CONNECTION OF OFFSHORE WIND FARMS IN THE RADIAL REFERENCE SCENARIO (INDIVIDUAL WIND FARM CONNECTIONS, CASE 1) VERSUS A SCENARIO WITH HUBS WHERE BENEFICIAL (CASE 4); BREAKDOWN PER COUNTRY (2030)



[13] As mentioned before, this is a consequence of the strategic planning and siting of offshore wind farms in the UK. The concessions are awarded in big lots, which leads to efficient individual connections.

connections to shore where this is beneficial. In Germany the average connection cost when using an individual connection is €1.06m per MW, while the connection cost is only €700,000 per MW when hub connections are considered. The reason for this is that connection points far inland have been selected in line with the dena Grid Study I [31]. Furthermore, German offshore wind farms are located relatively far from shore. In the German case, onshore cables represent 28% of the total connection costs for the radial reference scenario and 18% in the hub base case scenario.

4.2.3 Scheduled wind farm connection – risk of stranded hub investments

The hub connection of wind farms can thus be largely beneficial compared to the individual connection. However, the approach requires the coordination of the connection of two or more wind farm projects that are often owned and operated by different private entities. The primary challenge is that the hub has to be sized for the total capacity of all wind farms to be connected, even when only one farm is operational. The hub is therefore oversized until the missing wind farms are built, and this unused oversized capacity lowers the benefits of the project. For this reason the scheduling of the construction phase of the wind farms and the adherence to the schedule are crucial for the economics of the connection.

In this context it is interesting to evaluate at what point such time delays render the project unviable. In particular it is crucial to assess what the costs of stranded investments are, which in this case includes the scenario where some of the wind farms that were planned to be connected to the hub are not built at all.

These questions were studied for a theoretical case involving the connection of 3 wind farms of 350 MW each. These are located either 60 km (Case A) or 150km (Case B) from shore, and both individual and hub connections were considered. The distances between hub and wind farms are assumed to be 10 km. For the two cases A and B, four subcases are developed (Figure 4.7).

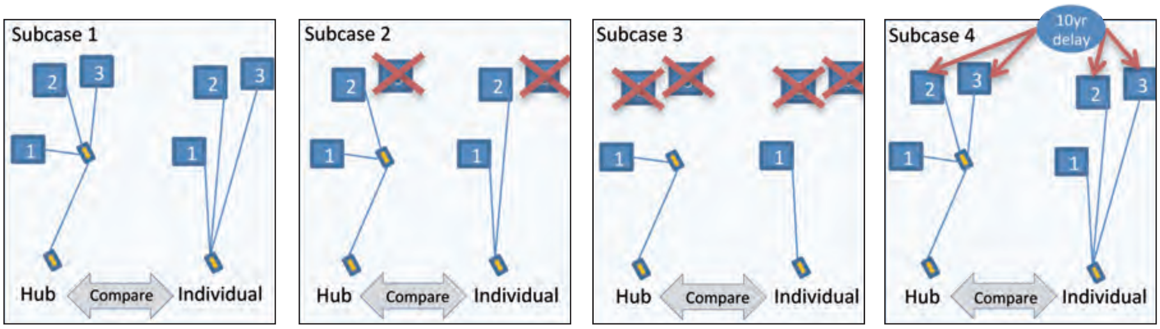
- Subcase 1
  Base case – Either all three wind farms are connected to the hub or they are connected to shore individually. All wind farms are built at the same time.
- Subcase 2
  One of the three wind farms is not built. This means the hub is designed to connect three wind farms and is therefore oversized. In the case of individual connection, only the connections for the first two wind farms are built.
- Subcase 3
  Similar to subcase 2. Here only one wind farm is built.
- Subcase 4
  Wind farms two and three are built with a delay of 10 years. The hub is sized to connect all wind farms from the very beginning. In the case of individual connection the connections for the delayed wind farms are only built upon start of construction.

For each of these cases and subcases, the costs were assessed by calculating the net present value of the investments. This was done by assuming a weighted capital interest rate of 6.6% and a depreciation period of 20 years, the typical design lifetime of a wind turbine.

The result of these calculations is displayed in Figure 4.8. The following conclusions can be drawn:

- Stranded investments – Wind farms not built:
  - even if one of the three wind farms is never built (subcase 2), a hub connection design is still beneficial compared to individual connection of two wind farms,
  - only if two of the planned wind farms are never built (subcase 3), the individual connection is economically preferable to the hub connection.
- Delay in construction – temporary stranded investment (subcase 4):
  - even if the construction of the second and third wind farms is delayed by 10 years, the hub is still beneficial. The calculations have shown that the break-even point is reached at 12 years of delay.

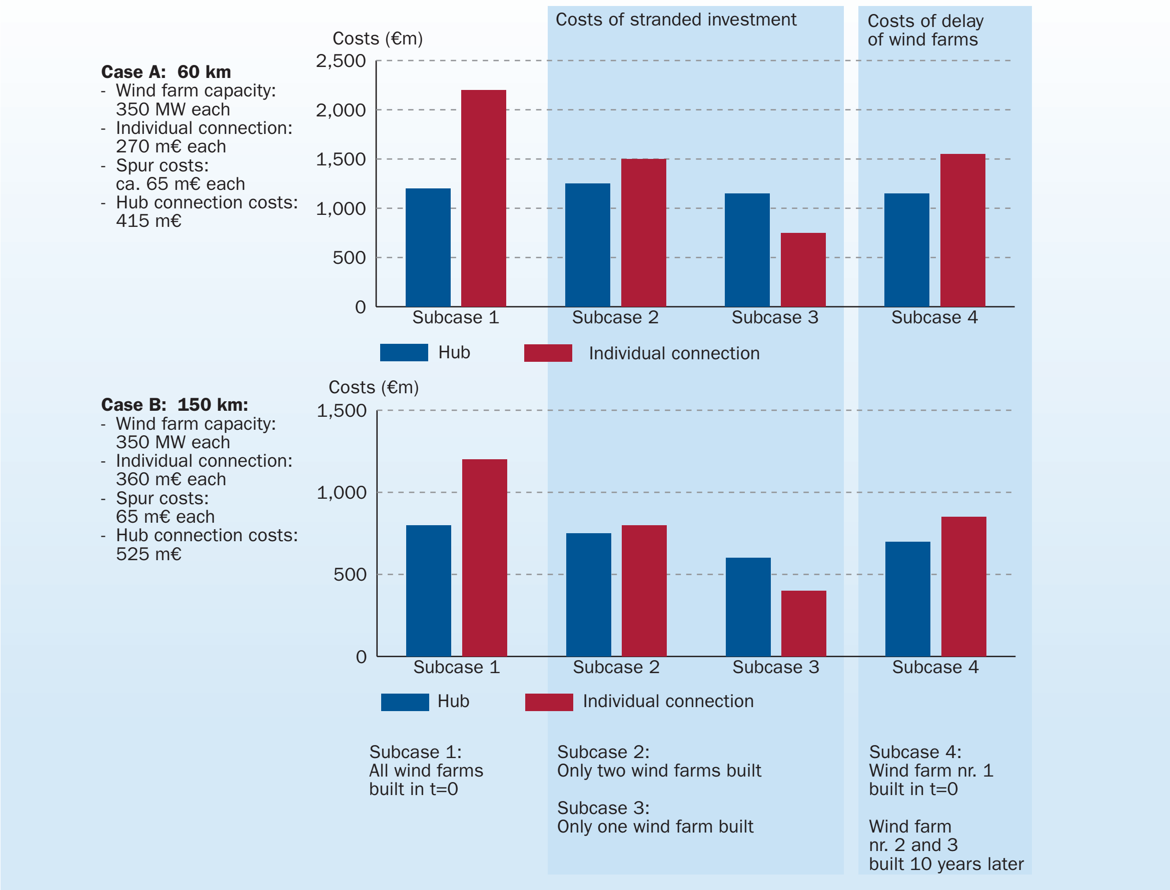
FIGURE 4.7: HUB CASES FOR ASSESSING COSTS OF WIND FARM CONSTRUCTION DELAY AND STRANDED INVESTMENTS



The results are a strong argument for hub connection and confirm the results of sections 4.2.1 and 4.2.2 where hub solutions were found to be beneficial for a large number of offshore wind farms in the 2030 offshore grid scenario. The case study further proves that the impact of stranded investments or temporary over-sizing is limited.

The economic result is of course case dependent, with wind farm size and wind farm to hub connection distance playing a role in the outcome. However the cases here were chosen to cover a wide span of possible configurations. The results properly illustrate the fundamentals of the subject and allow the drawing of general conclusions.

FIGURE 4.8: CASE STUDIES ON TIME DELAYS AND STRANDED INVESTMENTS FOR HUB CONNECTIONS



4.2.4 Conclusion and discussion on hubs versus individual connections

Clustering of wind power projects is advantageous in many cases, depending on the distance from shore and the concentration of installed capacity in the same area. A shared hub connection is most advantageous when the sum of installed wind power capacity in a small area is relatively large and equal to standard available HVDC voltage source converter (VSC) systems.

For distances from the onshore connection point of up to about 50 km, usually 50 Hertz HVAC technology is used and hubs do not generally provide much added value due to limited savings in cable length. For larger distances, the best solution depends primarily on the total available wind farm capacity in the area that could be grouped into the hub. For long distances to shore a hub connection is mostly beneficial; the benefit increases with distance.

Integrating a wind farm into a nearby hub is economically advantageous for wind farm to hub connection distances of less than 20 km. For greater wind farm to hub connection distances the benefit will be rapidly reduced. However, if the hub's size is large and if it is located far from shore, this again improves the economics. For wind farm to hub connection distances beyond 40 km, no beneficial hub cases were identified.

In view of the large potential benefits of connecting wind farm clusters via hubs, political and regulatory strategies to foster their development are of primary importance.

Additional considerations

The above assessment is solely based on economic considerations. In cases where the hub is less beneficial, decision makers may still opt for hub solutions in order to mitigate the environmental and social impact of cable laying through environmentally sensitive or highly frequented coastal areas. A hub solution may also allow more efficient logistics during construction.

Time delay costs and stranded investments

It has to be highlighted that a hub project is in general more complex. Construction schedules of wind farms in a certain area seldom coincide. The economic assessment is based on their connection schedules. If projects that are supposed to be connected are abandoned, the overall hub costs increase significantly due to stranded investments or longer transition times with oversized cables that are only partly loaded.

However, the case study analysis for a hub connection of three wind farms with a capacity of 350 MW each has shown that the costs of such delays or stranded investments should not be overestimated. In the case study the hub solution remains economically viable up to a 10 year time delay for two of the wind farms to be connected. Even if the one of the wind farms is not built at all, the hub connection is the preferred solution.

Where hub connections are clearly shown to be beneficial, a dedicated regulatory and policy framework to mitigate this risk will be required. The risk of stranded investment can be mitigated, e.g., by strategic siting and concessions with the specific aim of having groups of projects with a capacity of 1,000 to 2,000 MW per group concentrated in an area and developed approximately at the same time.

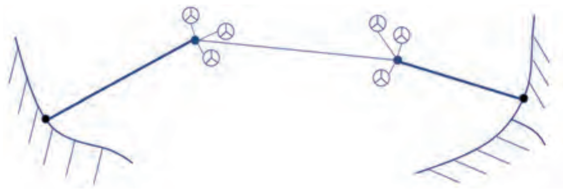
4.3 Integrated design – case studies

This section elaborates on the integration of wind farm hubs and interconnectors, the main idea behind the offshore grid in the North Sea. The OffshoreGrid project focuses on two major design concepts. Any offshore grid design can be broken down into these two fundamental building blocks:

- Teeing-in of wind farms into interconnectors (jointly developed with the wind farms or already existing) as shown in Figure 4.9.
- Interconnection of countries via wind farm hubs on either side as shown in Figure 4.10.

FIGURE 4.9: SCHEMATIC REPRESENTATION OF A WIND FARM TEED INTO INTERCONNECTOR

FIGURE 4.10: SCHEMATIC PRESENTATION OF BUILDING A COUNTRY-TO-COUNTRY INTERCONNECTION BY CONNECTING TWO WIND FARM HUBS



OffshoreGrid comes up with an understanding of the key design drivers. Based on a detailed cost-benefit analysis from the point of view of the European system, the viability and validity of various concepts has been investigated, aiming at an optimal balance between infrastructure size (and costs) and trade. By developing integrated solutions, the infrastructure costs are reduced, but at the same time constraints for electricity trade via the interconnectors are growing.

4.3.1 Tee-in solutions – case study evaluation

In trade-driven offshore grid development where power exchange between countries is the main driver for developing offshore transmission lines, connecting offshore wind farms to interconnectors can be a very interesting solution. In such a development, it can be considered to tee-in a nearby offshore wind farm already in the planning phase, or to make a provision for a later connection, if economically beneficial.

Technically, the wind farm could be connected in two ways, either teed-in via an HVDC converter to the interconnector circuits, or via an HVDC switching station at the connection point (without convertor). The cases investigated here assume the straight tee-in solution, as these are less costly and are not reliant on new technology. However, the general conclusions and insights described in this section are also valid for the solution with HVDC convertors. More information on these technical issues can be found in Deliverable 5.1 [26].

Investigated cases

The costs and benefits of a tee-in connection were investigated for three cases:

- Connection of the German Bight wind farms, Sandbank 24 and Dan Tysk (800 MW) to the planned 1,400 MW Nordlink interconnector (NO-DE),
- Connection of the wind farm Dogger Bank A (1,000 MW) to the planned 1,400 MW BritNor interconnector (NO-UK),
- Connection of German wind farms (Butendiek (400 MW) / Nordsee Ost Group (1,300 MW)) into the planned 700 MW Cobra Cable (NL-DK).

This section summarises the most interesting findings and results of the analysis for the Nordlink, BritNor and Cobra cables[14].

Reduction in infrastructure costs

In all three cases, teeing-in the wind farm into the interconnector leads to a reduction in (combined) infrastructure cost. This is mainly because the cable to shore is longer than the cable to the tee-joint.

The reduction that can be achieved depends largely on the wind farm capacity and the reduced wind farm connection cable length (= distance to the interconnector – distance to shore). For the connection of Dogger Bank A wind farm into the BritNor cable, €290 m in infrastructure costs can be saved compared to an individual connection. Teeing-in the Dan Tysk group into the NordLink cable can save about €160 m in infrastructure costs, while the teeing-in of Butendiek

[14] The Cobra cable case will be explained in further detail in paragraph 4.4.3. More background information and further details can be found in [27],[26], and [28].

and NordSee Ost Group into the Cobra cable can save roughly €207 m and €280 m respectively (see Table 4.2).

Reduction in system benefits

However, while the infrastructure costs are reduced, teeing-in reduces the available capacity for electricity trade between two countries as the cables are now also loaded with wind energy. In each hour, the produced wind power from the teed-in wind farm will be sent to the country with the highest electricity price. The interconnector capacity for trading electricity from the country with the lowest price towards the country with the highest price is thus reduced, leading to a lower system benefit than in the case of a direct shore-to-shore interconnector. As can be seen from Figure 4.11, trade is only constrained more than in the Business As Usual (BAU=No Tee-in, wind farm connected to country A, direct interconnector built) case when electricity flows from country B to country A[15].

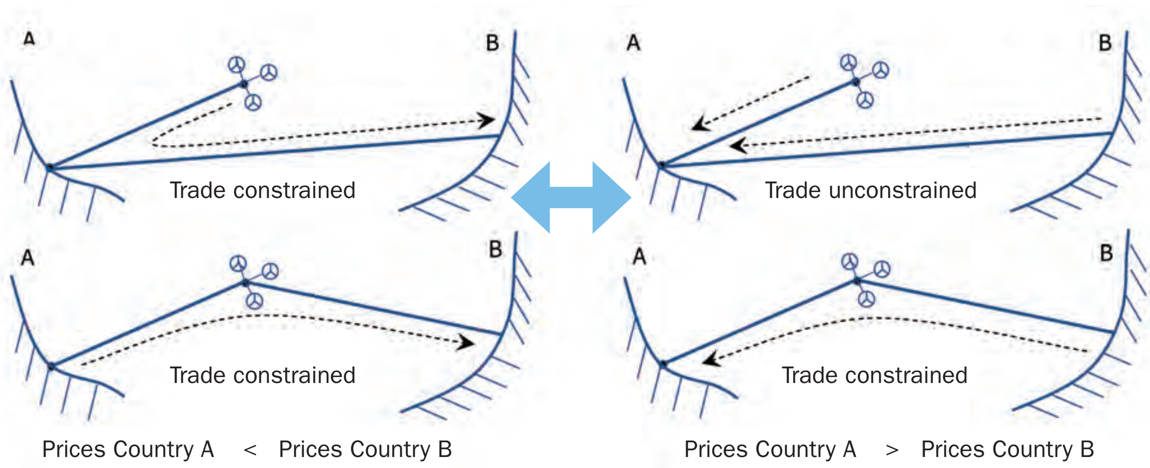
The reduction in system benefit happens in most cases, as is shown by the results for the BritNor and Nordlink cables. Teeing-in the Dogger Bank A wind farm into the BritNor cable increases the system costs over the lifetime by €400 m[16], while the tee-in solution for the Dan Tysk group into the NordLink cable increases system costs by €63 m (Table 4.2). In some other cases, particularly when the wind farm is located in a third country with lower electricity prices, different results are obtained. This is shown in the Cobra cable cases, which will be further explained in Section 4.4.3.

The eventual reduction in system benefits depends strongly on various parameters, such as the capacity of the interconnector cable, the capacity of the teed-in wind farm, the price difference between the countries, and the correlation between price difference and wind farm production over all hours. Additionally the overall trade, demand and generation situation in the European power system cannot be neglected[17].

Comparison and discussion

Three of the four investigated cases have a net benefit for the European power system (Table 4.2). While the tee-in solutions on Nordlink and Cobra are beneficial, this does not hold for the BritNor Cable where over the lifetime there is no net benefit and additional costs of €110 m arise. In the latter case, the lower trade benefits are not outweighed by reduced infrastructure costs. The other three cases clearly have a lower significance for trade, and teeing-in the wind farms only leads to a relatively low reduction in system benefits.

FIGURE 4.11: SCHEMATIC EXPLANATION OF THE REDUCTION OF SYSTEM BENEFITS BY TEEING-IN WIND FARMS INTO INTERCONNECTORS, FOR TRADE FROM COUNTRY A TO B (LEFT) AND FROM COUNTRY B TO A (RIGHT).



[15] In the scheme on the top left of this figure, trade is in fact unconstrained and the wind flows into country A. However, from a system point of view this gives the same result as the scheme on the bottom left.

[16] Present value of a cash flow of yearly system benefits over a lifetime of 25 years and with a discount factor of 6%.

[17] In practice, as for direct interconnectors, the benefits are of course also dependent on future development of other interconnectors in the region. These improve market efficiency further and reduce the possible benefits of trading electricity due to a lower price difference.

TABLE 4.2: SUMMARY OF THE RESULTS OF THE TEE-IN CASES

	Infrastructure costs changes	Additional system costs (over the lifetime)	Net Benefit (over the lifetime)
Dogger bank A into BritNor	- €290 m	+ €400 m	- €110 m
Dan Tysk group into NordLink	- €160 m	+ €63 m	+ €100 m
Butendiek into Cobra	- €207 m	- €43 m	+ €250 m
NordSee Ost group into Cobra	- €280 m	- €61 m	+ €341 m

The principal conclusions from a sensitivity analysis of the effect of changing parameters on the net benefit are:

- **Asymmetrical cable dimensions can increase the system benefits.**
  Increasing the capacity of one part of the interconnector (from the tee-joint position), can lead to better results. Capacity should then be increased at the side of the country with the highest prices (as trade flows towards the lower price level). A higher capacity would allow trade and parallel wind energy transport. The BritNor and NordLink cases demonstrate that asymmetrical cable dimensioning can increase trade possibilities to such an extent that the costs for larger infrastructure are more than compensated.
- **Tee-in benefits are largely dependent on wind farm sizes.**
  To add a different solution the following case for the 1,000 MW Dogger Bank wind farm was investigated: 500 MW were teed into the interconnector and 500 MW were connected directly to shore. It was shown that net benefits for this case are smaller in spite lower trade constraints on the interconnector. The reason is that in this case 500 MW remain to be connected individually to shore, which is relatively more expensive than connecting a 1,000 MW wind farm (lower economies of scale).
- Additional parallel trade interconnections can render a tee-joint more attractive than a direct interconnector, as price differences will be lower and trade less important.
- The effect of an additional UK-NO interconnector on the cost-benefit of the tee-in solution for Dogger Bank A is investigated. This makes the combined UK-NO market more efficient and thus reduces the value of trade between both countries. The reduction in system benefits (economic trade constraints) is therefore lower, going from €400 m to €307 m. As this is still higher than the achieved reduction in infrastructure costs, the tee-in solution for Dogger Bank A is still not beneficial.

This analysis demonstrates that the techno-economic relations are complex and that real cases do not allow generalised conclusions. Further in-depth analysis leading to such generalised conclusions is described in section 4.4.

Practical discussion

In terms of power system security, an interconnector cable with a wind farm connected in a tee-in configuration must be considered as one single asset. In case of a single fault anywhere on this asset, the interconnector plus wind farm would need to be isolated from the power system on both sides. Consequently, the power systems on both sides will experience a sudden change in power infeed, and contingency for this scenario must be considered according to the appropriate regulation. This may lead to an increased requirement for frequency reserves on either side of the tee-in, which should be considered before this option is recommended. It should be noted that discussion with representatives from some of the TSOs concerned during formal and informal stakeholder interaction[18] have indicated that TSOs would prefer a solution with fast circuit breakers on a platform to a simple tee-joint, for reasons of operational security and fault handling.

TSOs today have many years of experience with interconnectors based on Current Source Convertor (CSC) technology. The largest CSC Interconnector in Europe is rated at 2,000 MW and has been in operation since

[18] OffshoreGrid -- Stakeholder Advisory Board meeting, 21/01/2010, Brussels.
OffshoreGrid -- 2nd Northern European Stakeholder Workshop, 10/06/2010, Brussels.

1986 (the Cross Channel link connecting France and Great Britain). In contrast, the experience with HVDC VSC technology is much shorter. The largest operational VSC interconnector is Estlink (350 MW, 2006). While equipment manufacturers expect VSC systems of up to 1,000 MW to be available in the coming years, it is likely that the VSC power capacity will remain lower than that available for CSC for the next ten years.

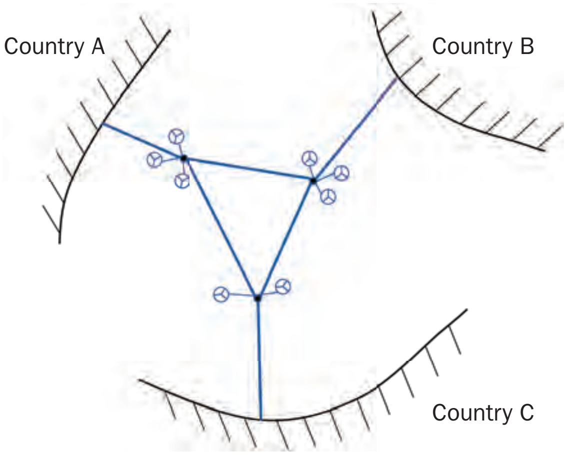
The advantages of VSC over CSC technology are the ability to independently form a voltage reference which is very useful at an offshore hub for the connection of a wind farm, its compact size (and weight) compared to CSC, and its higher operational flexibility with regards to the direction of power flows. At present the converters do incur larger power losses than their CSC equivalents. In conclusion, the advantages of VSC technology in an offshore environment mean that it will be the HVDC technology of choice for the connection of offshore wind farms. However, for those interconnectors requiring a large capacity but not the specific features of VSC technology, the interconnector project developers will probably opt for the less experimental, higher commercially available capacity of CSC technology, particularly if no wind farm connections are anticipated in the short term.

4.3.2 Hub-to-hub solutions – case study evaluation

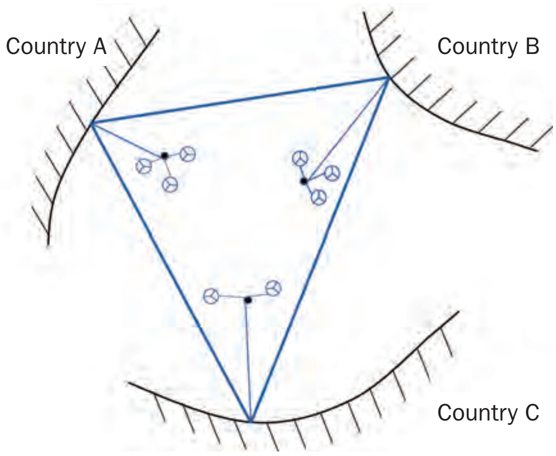
The development of interconnectors between wind farm hubs would be the beginning of a truly meshed offshore grid. Instead of connecting wind farms individually to shore and interconnecting the countries with a direct interconnection, the interconnection can be built between the wind farm hubs. The hub-to-hub solution implies that the offshore wind farms, along with their hub connection to shore, would be built first or in parallel with the hub-to-hub interconnector. This development may be considered wind driven as wind farm hub connections are the driver to install large HVDC VSC converters offshore with trade as a potentially beneficial add-on. This is similar to the option of dividing the wind farm connection in order to connect to two countries as discussed in Section 4.3.1, but is in contrast to the option of connecting wind farms to planned interconnectors where international power exchange is mostly the key driver.

Technically, to operate efficiently a complex multi-terminal meshed configuration is likely to require the use of HVDC VSC technology and the availability of fast HVDC circuit breakers in order to limit the propagation of faults throughout the whole network. Equipment manufacturers have confirmed to the OffshoreGrid

FIGURE 4.12: PROTOTYPE GRIDS WITH DIFFERENT CONFIGURATION ILLUSTRATING THE APPROACH FOR COMPARISON OF REAL SITUATIONS IN THE CASE STUDY [3]



(a) hubs with integrated interconnectors



(b) hubs and point-to-point interconnectors consortium that they will be bringing such components on the market within the next few years[19]. Manufacturers have already offered these assets to commercial projects but no contracts have been awarded yet. The integrated solutions proposed here do not rely on the use of fast HVDC breakers, although these can be added to increase security of supply.

Investigated cases

The cost-benefit analysis of hub-to-hub connections has been done with reference to the Hub Base Case 2030, in which wind farms are connected to hubs where beneficial (compare Section 4.2). Infrastructure costs and system benefits have been calculated in three case studies for a situation with interconnectors between offshore hubs (thus becoming integrated offshore grid nodes). The results were then compared to a situation where the onshore connection points of the respective offshore hubs are connected by an interconnector of the same capacity. The principle is illustrated in Figure 4.12.

Integrated hubs have been compared to point-to-point connections for the following cases:

- Great Britain to Continental Europe (Germany) by interconnecting the Dogger Bank E hub with the Gaia hub,
- Great Britain to Norway by interconnecting the Dogger Bank A hub with Idunn,
- Triangular interconnection: Norway – Great Britain – Germany between the hubs Idunn (NO) – Dogger Bank A (UK), Dogger Bank E (UK) – Gaia Group (DE) and Horizont Group (DE) – Aegir (NO).

Reduction in infrastructure costs

In all three cases interconnecting countries via the wind farm hubs leads to a reduction in infrastructure cost compared to individual connections and a direct interconnector.

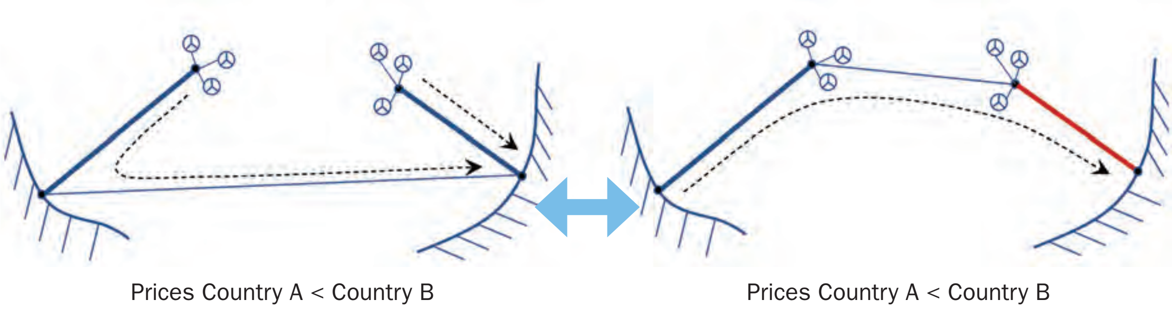
Infrastructure costs for the integrated solution are in all cases 70 to 80% lower than for the respective solution with direct lines. The ratio reflects mainly the savings in numbers of converters and cable costs, due to the use of the wind farm hubs and the shorter distances to cover with the integrated solution, respectively. For the UK-Germany interconnection, the cost reduction is about €693 m. For the UK-Norway interconnection it is €600 m, while for the triangular interconnection the total infrastructure cost reduction compared to direct interconnections amounts to €1.9 bn.

Reduction in system benefits

The system benefit for the integrated solution is always lower than for the direct line solution, due to the constraint on international power exchange. As can be seen from Figure 4.13, the interconnector between the hubs can be regarded as equally constrained as a direct interconnector would be. The trade is only constrained more than in the BAU case because of the wind farm connection in the country with the highest prices (red line in Figure 4.13). If the cable capacities are the same for both countries, this is of course identical when the price in Country A is higher than in Country B.

In relative values comparing to the system benefits in the direct line solution, the system benefits of a

FIGURE 4.13: SCHEMATIC EXPLANATION OF THE REDUCTION OF SYSTEM BENEFITS WITH HUB-TO-HUB INTERCONNECTORS, FOR TRADE FROM COUNTRY A TO B. THE RED LINE SHOWS WHERE THE SYSTEM CONSTRAINTS ARE INCREASED



[19] OffshoreGrid – 1st Northern European Stakeholder Workshop, 14/09/2009, Stockholm.
OffshoreGrid -- Stakeholder Advisory Board meeting, 21/01/2010, Brussels.
OffshoreGrid -- 2nd Northern European Stakeholder Workshop, 10/06/2010, Brussels.

UK-Germany connection are reduced by €585 m. For the UK-Germany interconnection, the system benefits are reduced by €416 m, while for the triangular interconnection the system benefits are reduced by €1.06 bn compared to a direct line solution.

Comparison and discussion

As shown in Figure 4.14, the net benefit is positive for all three cases, although differing in absolute numbers. Especially for the UK-Germany connection and the triangular solution, significant benefits can be obtained by developing the integrated solution. In the UK-Norway case, the reductions in both trade and in investment costs are equal, hence the net benefit is low. So, in this case the hub-to-hub solution will not be built, unless, for instance, one of the interconnector legs get a higher capacity to reduce trade constraints.

The case for hub-to-hub connections depends strongly on the demand for international power exchange between the market areas on each side. A first order sensitivity analysis leads to the following observations:

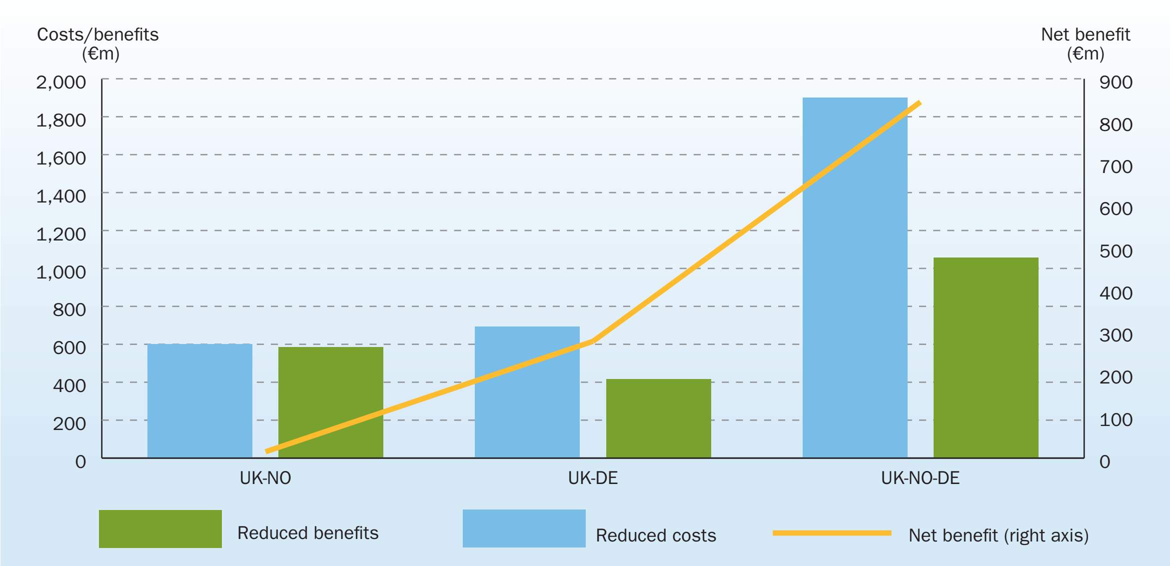
- With higher price differences between the countries, the benefits of an extra interconnector increase, both with a direct interconnector as with an interconnector between hubs,
- With lower price differences (e.g. due to an additional direct interconnector), the benefits of a hub-to-hub interconnector may still exist, but are reduced.

When there is demand for international power exchange capacity, an integrated hub-to-hub solution can be more beneficial than an additional point-to-point interconnector, particularly if the hub-to-hub interconnection yields significant savings in cable length. The investigated cases clearly show that there are opportunities which can significantly increase the net benefit from a European point of view. This was the case for the UK-Germany interconnector as well as for the triangular meshed solution.

However, since developing a hub-to-hub interconnector between hubs implies trade constraints, the net benefit of direct interconnectors increases faster than the net benefit of hub-to-hub interconnectors. Indeed, the infrastructure costs remain the same but the economic impact of trade constraints increases if the price difference is larger.

In the UK-Norway case price differences are larger, so that interconnectors are more beneficial between these countries. Because of this, the trade constraints in a hub-to-hub solution become more important, and the net benefit over a direct solution is much smaller.

FIGURE 4.14: SUMMARY OF RESULTS OF HUB-TO-HUB SOLUTION CASE STUDIES



The higher the price difference between countries, the more important the trade constraints become.

Trade constraints can be reduced by optimal dimensioning of each of the different elements. This is different in each case, and depends on the distances from shore, the distances between the hubs, the price difference profiles between the countries, and the capacity of the wind farm hubs.

4.4 Integrated design – case-independent model

As was shown in the previous section (4.3), numerous parameters influence the results. They are very case-specific, which makes it difficult to draw general conclusions. On the other hand, general conclusions are indispensible for offshore grid planning, the supporting policy making process and also for the project developers themselves. Such conclusions for case-independent concepts have been derived with help of a dedicated "offshore grid design assessment model". With this model, the tee-in solutions and the integrated hub-to-hub solutions are further assessed and concrete guidelines are developed in the following paragraphs.

Finally, a practical case study has been elaborated to check the results against a well advanced real case. The Cobra cable – a direct interconnector cable planned between Denmark and the Netherlands – has been chosen because the consortium considers this a very important and relevant project in the process towards an offshore grid (paragraph 4.4.3).

General analysis

The results of the cases presented in section 4.3 are very context-specific and thus not generally applicable. The present section aims at developing more general conclusions and understanding about the key design drivers based on a thorough sensitivity analysis with a dedicated offshore grid analysis model, that investigates under which circumstances an integrated solution is beneficial over a BAU solution. The approach focuses on two principal design optimisation problems considered to be the modular building blocks for any international offshore grid design:

- Break-even distance wind farm (WF) to shore beyond which a tee-in solution is beneficial:
  - the larger the distance from the wind farm to shore, the more cable length can be saved by going for a tee-in solution,
  - the closer to shore, the more the constraints that it introduces will be important,
  - depending on various parameters, there is a minimum distance (break-even distance) from the wind farm to shore beyond which a tee-in solution becomes preferable over a conventional individual connection and direct interconnector.
- Break-even distance between hubs below which a hub-to-hub solution is beneficial:
  - the shorter the distance between hubs, the more infrastructure costs can be saved by going for a hub to hub solution instead of a separate direct interconnector solution,
  - the larger the wind farms (respectively the hubs), the more the trade constraints that it introduces will be important,
  - depending on various parameters there is a maximum distance (break-even distance) between the hubs up to which it is preferable to choose a hub-to-hub solution over a conventional individual connection and direct interconnector.

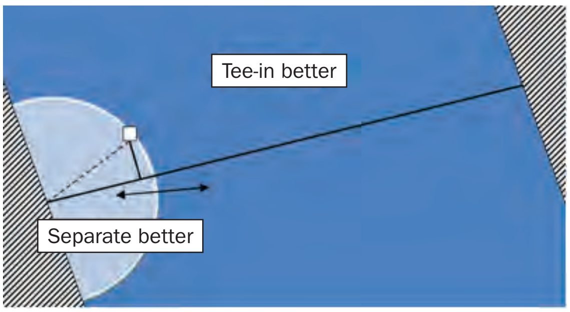
Concrete results that can be used by project developers, consultants, political decision makers, regulators, etc. are available on www.offshoregrid.eu.

4.4.1 Minimum distance for tee-in solution

Introduction

Figure 4.15 and Box 1 explain the optimisation problem. The objective is to calculate the break-even distance from the wind farm to shore beyond which a

FIGURE 4.15: EXPLANATION OF OBJECTIVE: MINIMUM DISTANCE WIND FARM TO SHORE FOR TEE-IN SOLUTION



tee-in solution becomes preferable over a conventional connection of the wind farm to shore. For wind-farm-to-shore distances lower than this minimum distance, a conventional solution is preferable. For larger distances, a tee-in solution is better.

An example (parameters are given in figure caption) of the general results of the calculations is shown in Figure 4.15 and is explained below:

- For low wind farm capacities (Area A) smaller than the interconnector capacity the break-even distances for tee-in are low, but increase with wind farm capacity.
  The trade constraints induced by the wind farm are low in this capacity range. The reduction in wind farm connection cost is thus dominant and makes tee-in solutions beneficial even with relatively modest distances.
- For larger wind farm capacities (between 1x and 2x the interconnector capacity) (Area B) the break-even distance is relatively low and decreases with wind farm size. The savings in infrastructure cost increase faster than the losses of the trade constraints.

Box 1: Explanation of the optimisation problem for tee-in solutions

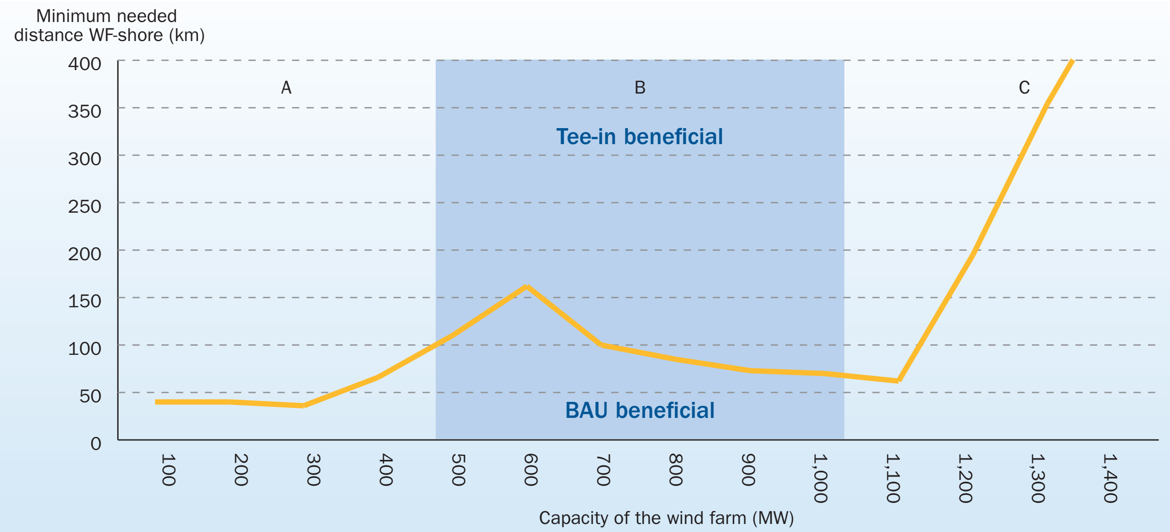
Tee-in solutions – Break even distance

- If the wind farm to be teed-in is far from shore, then the individual connection of the wind farm would be long compared with the relatively short length of the tee-in cable.
  → Tee-in here produces large infrastructure costs savings.
- If the wind farm to be teed-in is large, the interconnector cable will be constrained.
  → These trade constraints result in loss of system benefits.

To evaluate the break-even distance, which is the minimum distance of the wind farm to shore beyond which it is beneficial to tee-in:

- Low minimum distance means: Tee-in solutions are very beneficial, even for small distances.
- High minimum distance means: Tee-in solutions are only interesting for wind farms far from shore.

FIGURE 4.16: ECONOMIC BREAK EVEN WIND FARM TO SHORE DISTANCE FOR A TEE-IN SOLUTION (KM) FOR DIFFERENT WIND FARM SIZES. (INTERCONNECTOR CAPACITY OF 500 MW, AVERAGE ABSOLUTE PRICE DIFFERENCE OF €7.5, DISTANCE WIND FARM TO INTERCONNECTOR OF 40KM, UNBALANCED FLOW WITH 30% OF PRICE DIFFERENCE FLOWING TOWARDS ONE COUNTRY)[20]



[20] The curve shows some gradients which were initially not expected. It is not smooth because of the nature of the infrastructure cost tables (cheaper for standard sizes) and the nature of the duration curve of the wind power production (nonlinear curve showing that a wind farm operates more often with medium power output than with maximum or zero output).

TABLE 4.3: SUMMARY OF FINDINGS AND INSIGHTS FROM SENSITIVITY ANALYSIS ON THE MINIMUM DISTANCE WF-SHORE FOR TEE-IN SOLUTIONS

Sensitivity analysis factor	Impact on the minimum distance wind-farm-to-shore for tee-in solutions to be beneficial over the business as usual case.
Interconnector capacity	• Larger interconnector capacities reduce the benefit of tee-in solutions over the BAU case. • For wind farm capacities lower than the interconnector capacity, there is no impact. • For interconnector capacities larger than twice the wind farm capacity, energy is lost (cannot be transmitted) and this reduces the benefit of tee-in solutions.
Distance WF-interconnector	• The further a wind farm is located from an interconnector, the less beneficial it is to tee-in to it.
Absolute price difference	• The higher the absolute difference of price levels in the connected countries, the more important electricity trade becomes and the less beneficial tee-in solutions are.
Electricity price profiles	• If the price difference is not balanced, the impact of wind power production becomes larger. Depending on the usual direction of the price difference, tee-in solutions are less beneficial (when the price is most of the time higher in the original wind farm country) or more beneficial (when the price is most of the time higher in the other country).
Wind power correlation	• If the price difference is lower when there is a lot of wind, the impact of constraining the cable will be less important and tee-in solutions become more beneficial.

- For wind farm capacities higher than double the interconnector size (C), the break-even distance increases rapidly with wind farm capacity.
  Any power production which exceeds the interconnector capacity will be dissipated and lost. These energy losses have a high cost and result in a steep rise of the curve.

Two points on the graph are of specific interest:

- Wind farm capacity = interconnector capacity
  There is a peak in the curve at the capacity of the interconnector cable (500 MW in Figure 4.16). The reduction of infrastructure cost is rather low while the trade constraints are already rather high. It is the least efficient wind farm capacity to be teed-in (Area C excluded).
- Wind farm capacity = 2x interconnector capacity
  When the wind farm is double the capacity of the interconnector cable, the interconnector cable acts as a connection of the wind farm to two countries. Please note that the connection cables that form the interconnector via the wind farm taken together still have the full capacity of the wind farm. At high wind generation the full wind energy can thus be transported to shore and no wind energy has to be curtailed. The additional infrastructure costs are in this case low compared to a normal individual connection. It is an extreme case where the possibility to trade electricity is almost for free as the wind power would have to be connected anyway.

In the following chapters, this connection concept in which one wind farm is connected to two shores (split connection) is called a **split wind farm connection**.

Sensitivity analysis

An extensive sensitivity analysis is performed on these results, which is summarised in Table 4.3. More details from the sensitivity analysis with detailed graphs can be found in Annex D.II.I which is available on www.offshoregrid.eu.

Conclusions

In the following situations, it is recommended to investigate the economic case for tee-in solutions:

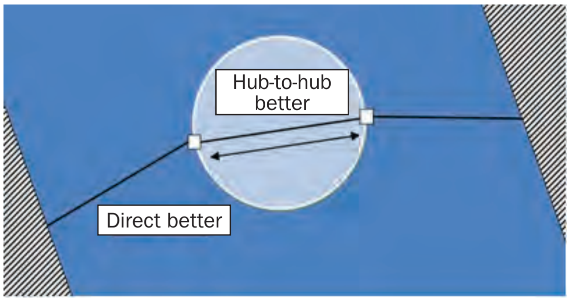
- Small wind farms (<50% of the interconnector capacity) far from shore[21].
  Small wind farms that are teed-in to an interconnector do not significantly constrain trade. Therefore, these are good cases for tee-in solutions and the break-even distance wind farm-shore is low.

[21] This can for example be an offshore wind farm near oil plaforms or on small sandbanks close to an interconnector.

- Large wind farms (capacity approximately 2x interconnector capacity).
  Teeing-in large wind farms may constrain trade, but the reduction in infrastructure costs is more important. The break-even distance to shore is therefore low (Figure 4.16).

The second conclusion can be interpreted further. Instead of connecting big wind farms to the country where they are located, they could be connected with smaller connection capacities to two countries. With more or less the same investment costs (if the wind farm is located roughly in the middle), an interconnector is created at the same time[22]. This interconnection can be used when the wind power produced is less than 50% of the capacity (about 55-60% of the time). The additional infrastructure costs consist mainly of extra connection cable length to the second country plus the equipment to couple both cables to the offshore wind farm. This needs to be compared to the additional system benefits, which are the result of the possibility to send wind power to the highest price area and to use the spare capacity for extra trade. In conclusion, this is a very interesting option for large wind farms far from shore (e.g. UK round 3). However, it introduces political and regulatory problems (not all wind will flow into the country that pays support) which need to be solved.

FIGURE 4.17: EXPLANATION OF OBJECTIVE: MAXIMUM DISTANCE BETWEEN HUBS FOR HUB-HUB SOLUTION



Box 2: Explanation of the optimisation problem for hub-to-hub solutions

Hub-to-hub solutions – Break even distance

- If the wind farm hubs are close to each other, the hub-to-hub cable that creates a hub-to-hub interconnector is short compared to the length of a separate shore-to-shore interconnector.
  → The hub-to-hub solution results in large infrastructure cost savings.
- If the wind farm hubs are large the wind energy will constrain the trade.
  → These trade constraints result in loss of system benefits.

To evaluate the break-even distance, which is the maximum distance between hubs below which it is beneficial to interconnect via the hubs instead of building a direct interconnector:

- Low maximum distance means that hub-to-hub-solutions are not interesting, or only interesting for hubs very close to each other.
- High maximum distance means that hub-to-hubs solutions are very interesting, even for hubs further from each other.

4.4.2 Maximum distance between hubs for integrated hub solution

Introduction

Figure 4.17 and Box 2 explain the optimisation problem. The objective is to calculate the break-even distance between the hubs up to which a hub-to-hub solution is preferable over the conventional connection of the hub to shore. For hub-to-hub distances lower than this maximum distance, the saved costs outweigh the trade constraints and a hub-to-hub solution is preferable. For larger distances between the hubs, the infrastucture cost reduction is not large enough to balance the trade constraints and a direct hub-shore connection plus separate interconnector is better.

As an initial hypothesis it is assumed that[23]:

- the wind farm hubs at either side have the same capacity;
- the rated capacity of the connection cable from hub to shore is equal to the rated wind farm capacity.

[22] In these cases, trade is a pleasant by-product of the connection of the wind farm.
[23] A sensitivity analysis on this is performed and described further.

FIGURE 4.18: MAXIMUM DISTANCE BETWEEN HUBS TO MAKE HUB-TO-HUB SOLUTION MORE BENEFICIAL THAN DIRECT INTERCONNECTOR FOR DIFFERENT WF CAPACITIES [KM] (INTERCONNECTOR CAPACITY OF 500 MW, AVERAGE ABSOLUTE PRICE DIFFERENCE OF €5, DIRECT INTERCONNECTOR DISTANCE 500 KM, UNBALANCED FLOW WITH 30% OF PRICE DIFFERENCE FLOWING TOWARDS ONE COUNTRY)

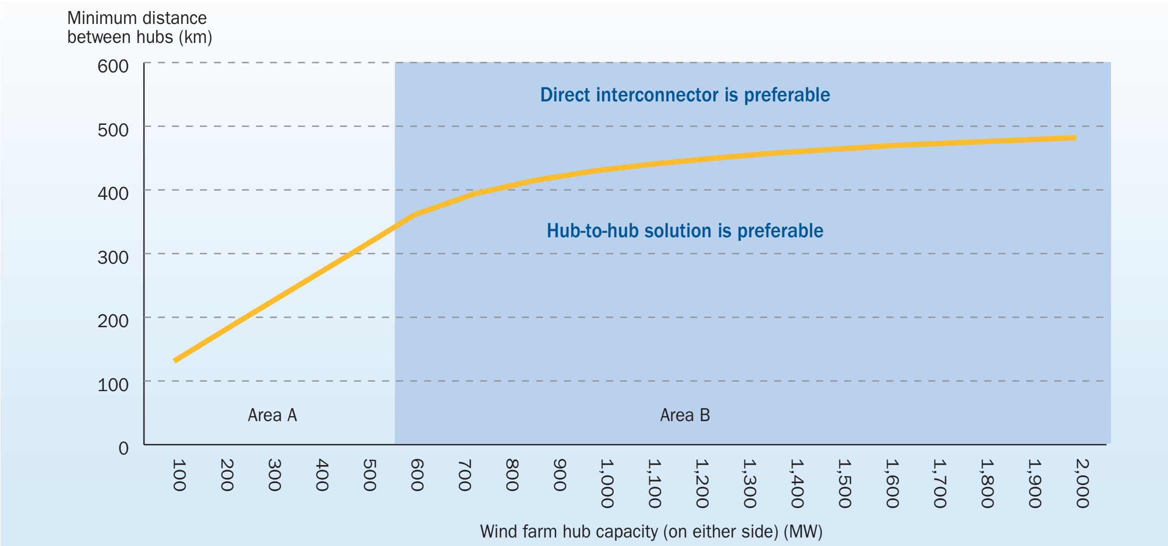


Figure 4.18 provides relevant insight and understanding into the drivers of this concept:

- Area A: the wind farms and their connections to shore are smaller than the interconnector capacity (in this case 500 MW). The hub-to-hub interconnector is therefore oversized, and the hubs need to be close together to make it beneficial over a conventional solution.
- Area B: The larger the wind farm hub capacity (and thus its connection to shore) compared to the interconnector capacity, the less constrained the system is. The inter-hub distance can be larger to still benefit from hub-to-hub connection instead of the combination of individual wind farm connections and a direct interconnector.

TABLE 4.4: SUMMARY OF FINDINGS AND INSIGHTS FROM SENSITIVITY ANALYSIS ON THE MAXIMUM DISTANCE BETWEEN HUBS FOR HUB-TO-HUB-SOLUTIONS

Sensitivity analysis factor	Impact on the maximum distance between hubs for hub-to-hub solutions to be beneficial over a direct interconnector.
Interconnector capacity	• Larger interconnector capacities reduce the benefit of hub-to-hub solutions over the BAU case. • For wind farm capacities which are smaller than the interconnector capacity, the wind farm connections are the constraining factor for trade. • Increasing the interconnector capacity further only leads to additional infrastructure costs and thus lowers the maximum beneficial distance.
Distance direct interconnector	• The larger the distance between two countries (= direct interconnector length to which it is compared), the more infrastructure costs will be saved by interconnecting hubs, and thus the more beneficial hub-to-hub solutions are.
Absolute price difference	• The higher the absolute difference of price levels in the connected countries, the more important electricity trade becomes and the less beneficial hub-to-hub solutions are.
Electricity price profiles	• Unbalanced price profiles have no impact. This is due to the fact that the constraints on the cables are independent of the direction of the price difference when cable capacities are identical (as explained in section 4.3.2 (paragraph on system benefits).
Wind power correlation	• If the price difference is lower when there is a lot of wind, the impact of constraining the cable will be less important and hub-to-hub solutions become more beneficial.
Asymmetrical WF capacities	• Imagine that the wind farm in country A is 50% smaller than the wind farm in country B. When prices are more often higher in country B, trade is less constrained which makes hub-to-hub solutions more beneficial.

- Very large wind farm hubs may even be close to the shore and still have a positive net benefit for interconnecting between them instead of installing a direct interconnector. This is for two reasons:
  - the interconnector cable (established via the hub-to-hub connection) is less constrained by the wind farm connection cables as these have larger capacity, and
  - although there is need for extra equipment offshore, no onshore substation and onshore equipment are needed.

Sensitivity analysis

An extensive sensitivity analysis is performed on these results. A summary is given in Table 4.4. More details from the sensitivity analysis with clear graphs can be found in Annex D.II.II on www.offshoregrid.eu.

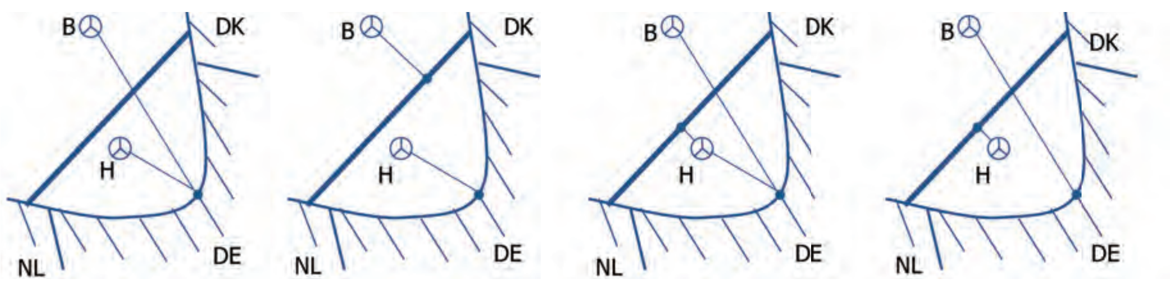
Conclusions

The case-independent model confirms that hub-to-hub solutions can be beneficial, and provides concrete guidelines. In general, the following conclusions are important:

- If the capacity of the hub-to-hub interconnector is small, it will help to send the electricity from both wind farms to the highest price area. Larger interconnector capacities are interesting when the price difference between the countries is high, but they should not exceed the connection capacity of the wind farms to the onshore point of connection.
- If the price difference between both countries is not balanced, it is worth over-sizing the shore-connection of the wind farms to the country which usually has the highest price during the lifetime of the interconnector, and under-sizing the hub-to-shore connection to the other country. This way the electricity can flow to the area with higher prices. It is the most optimal solution for overall European welfare.
- For meshed grid nodes with more than two lines coming together, similar conclusions can be drawn. The links to the country with the highest prices (over the lifetime of the interconnector) should be largest, and the other ones can be dimensioned smaller. The most efficient solution would occur if the sum of all country connection cable capacities equals the sum of the connected wind farms. This way the additional investment in integrated platforms and joints brings interconnection between three countries. If larger interconnection capacity is needed, some of the cables can be over-sized.

The case-independent model can be used to provide quick support to find a tailor-made solution out of the many possible configurations. The analysis in this section demonstrates the possibilities of choosing the optimal solution by taking into account various factors such as the distances between the shores, the distances between the wind farms, the distances between the wind farms and other connection hubs, the capacities of all cables, the market conditions in every country, the price differences and price difference profiles between the countries, as well as the other interconnectors and integrated solutions, either existing or planned. The model provides clear guidelines for such parameter considerations and thus for the design to be chosen.

FIGURE 4.19: IDENTIFIED SEVEN CASES



Case 1 | Case 2 | Case 3,4,5,6 | Case 7

4.4.3 The Cobra cable case study

To validate the results, the Cobra cable interconnection between the Netherlands and Denmark has been analysed as an additional case study. This is a very interesting case due to the following aspects:

- Tennet and Energinet.dk have received funds from the European Commission under the European Economic Recovery Programme to allow the teeing-in of future wind farms along the route.
- The investment decision will be taken shortly (in 2012).
- Due to its timing and location close to three different countries, it is generally seen as one of the first cornerstones of a future European Offshore Supergrid.

The Cobra cable was originally planned as a 700 MW direct interconnector between the Netherlands and Denmark to be built and operated by the Dutch and Danish Transmission System Operators (TSOs), Tennet and Energinet.dk respectively. Currently investigations are ongoing whether it makes sense to connect German wind farms along the route as well. The Cobra cable route passes close to several large German offshore wind farms, located far from shore and thus facing high connection costs. The Dutch and Danish wind farms located close to the Cobra cable route are closer to the shore and hence may not be as cost effective for linking to the cable against a direct connection design.

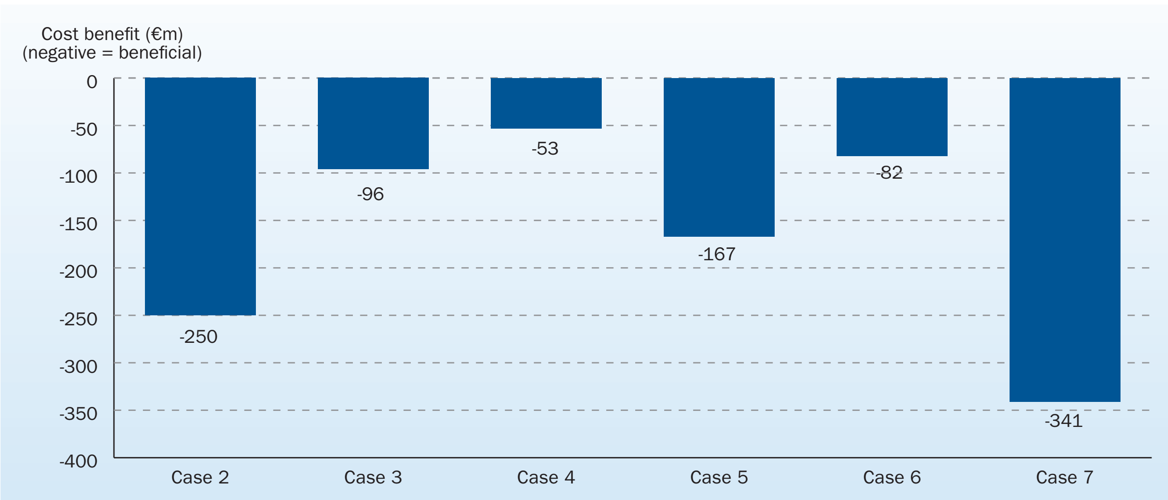
There are a variety of possible configurations for integration of the German wind farm (respectively wind farm hubs). A distinction can be made between:

- A tee-in solution in which the German wind farm (hub) is not connected individually to Germany, and

TABLE 4.5: CALCULATED CASES FOR THE EXTRA CASE STUDY: COBRA CABLE

Case	Wind Farm (hub) in focus	Wind Farm connection to Cobra Cable	Wind Farm connection to Germany
1	None – Hub Base Case 2030	Not applicable	Not applicable
2	Butendiek (400 MW)	Full WF capacity (B)	0 MW
3	HDE002 Cluster	1,000 MW	Full WF capacity (H)
4	(1,300 MW) Nordsee Ost phase 1,	500 MW	Full WF capacity (H)
5	Hochsee Testfeld Helgoland,	500 MW	Full WF capacity (H) – 500 MW
6	Meerwind phase 1,	250 MW	Full WF capacity (H) – 250 MW
7	Amrumbank West	Full WF capacity (H)	0 MW

FIGURE 4.20: COMPARISON COST-BENEFIT OBTAINED BY INTERCONNECTING A GERMAN WIND FARM INTO THE COBRA CABLE (PARTLY OR COMPLETELY) (NEGATIVE = BENEFICIAL)



- A three-leg interconnector where the teed-in wind farm (hub) is also connected to Germany. This design thus links the Netherlands, Denmark and Germany allowing multilateral electricity trade.

Investigated cases

Seven different cases are investigated (Table 4.5 and Figure 4.19). The objective is to evaluate:

- Whether the inclusion of a wind farm on the cable is beneficial. For this assessment the teeing-in of two different wind farm/hubs is analysed separately: Butendiek (400 MW) and HDE002 Cluster (1,300 MW). (Case 2 and Case 7),
- Whether developing a link between the Cobra cable and a large shore-connected German wind farm cluster (HDE002) is beneficial – the so called three-leg configuration (Case 3 and Case 4),
- Whether the connection capacity of the German wind farm cluster HDE002 to shore can be reduced in capacity (different sizes investigated) by introducing a link to the Cobra cable (Case 5 and Case 6).

Costs and benefits are compared against the Hub Base Case 2030 (Case 1).

Costs and benefits

Figure 4.20 shows the results of the cost-benefit analysis for the Cobra cable case study. It is possible to conclude that the inclusion of a wind farm on the Cobra cable is beneficial for all cases (see next section).

- Three-leg interconnector is beneficial.
  The results show that for higher connection capacities from the wind farm to the Cobra cable (i.e. the more German wind that can be sent to either the Netherlands or Denmark), the benefits are higher.
- Connecting the wind farms only to the Cobra cable and not to Germany creates the most beneficial cases - even if the capacity of the wind farm is higher than the capacity of the Cobra cable.
- Teeing-in the large wind farm cluster (almost double the capacity of the Cobra Cable) yields the biggest net benefit. This proves the conclusion on splitting the wind farm to-shore connection and connecting it to two separate countries, as discussed in Section 4.4.1.

Discussion

It may seem surprising at first sight that the tee-in design is beneficial for all cases. However, considering the overall power system configuration, the explanation is rather simple. At times of high wind generation in Northern Europe, German electricity prices are lower than Danish and Dutch electricity prices. This is due to the simple market logic that wind energy is generated at almost zero marginal costs and therefore lowers spot market prices in Germany significantly[24].

Due to these price gradients it is beneficial to export electricity from Northern Germany. This of course also holds for offshore wind energy that can be transmitted to neighbouring countries instead of being fed into the mainland grid where low electricity prices give low returns. This is in particular the case for northern Germany: with massive onshore and offshore wind power capacity, there will often be excess wind power generation during periods of high wind which lowers the spot market prices. The wind power is therefore transmitted to the Netherlands or to Denmark where higher prices promise higher returns. According to the model, this is more beneficial than an interconnection between the latter countries[25].

This conclusion is supported by the case-independent model where it was shown that increasing the connection capacity to the country which usually has the highest prices is the most beneficial option (section 4.4.1). Following this reasoning and taking into account the results from the case-independent model, the most promising grid design solution is to connect some of the German wind farms to two or three neighbouring countries. With a relatively modest extra cost

[24] The model of course allows trade exchange across national borders similar to today's coupled electricity market. However interconnection capacity is limited and therefore high wind power generation in Germany first of all lowers the electricity prices within the German boundaries.

[25] In Germany there is a strong need for onshore reinforcement between Northern Germany and the Southern part. In the model, planned onshore reinforcement is already taken into account and the offshore wind farms are connected deep inland. However, the massive wind energy deployment in the North still leads to excess energy and low prices. In case the onshore bottlenecks are solved, this might have an impact on the benefits of the tee-in solution.

compared to the individual connection to Germany only, a two- or three-leg interconnector is created which can be used, amongst other things, to relieve the stress on the German market.

Apart from techno-economic considerations, an integrated solution is heavily dependent on the political and regulatory decisions. For example, it is of course not possible without a solution for the incompatibility of support systems (see further in Chapter 6).

4.4.4 Conclusion on integrated design

Sections 4.3 and 4.4 have elaborated the results of the cost-benefit analysis on integrated design options. They have been evaluated by an extensive case study analysis with the previously described combination of an infrastructure model, a power market and flow model. The results were strongly case-sensitive and it was therefore impossible to draw general conclusions or develop universal guidelines. Therefore a case-independent model was developed in order to carry out various sensitivity analyses to develop the essential concrete grid design guidelines.

The analysis focused on two major design problems that form the basis of offshore grid concepts: the teeing-in of wind farms into interconnectors, and the interconnection of two wind farm hubs. The results, insights and conclusions are also valid for more complex design problems with nodes connecting more than two lines.

For wind farms far from shore, teeing them into an interconnector can be an interesting option. This is especially true in two cases:

- The integration of small wind farms rather far from shore but close to an interconnector (e.g. offshore wind at oil & gas platforms) that put only small electricity trade constraints on the interconnector,
- The connection of big wind farms or wind farm hubs to two countries. When connecting them to both countries with the same total connection cable capacity as in a conventional solution, the additional infrastructure costs are limited and a large interconnector is created at the same time.

Hub-to-hub interconnections have shown to be interesting under certain circumstances. In general the projects should be far from shore but close to each other. If the hub-to-hub interconnector is small, it will help to send the electricity from both wind farms to the highest price area. Bigger interconnectors are interesting when the price difference between the countries is high.

In both tee-in solutions and hub-to-hub solutions, oversizing one leg of the system and undersizing the other may benefit the design if the price difference profile is not balanced. Depending on the local parameters and the long term price expectations, an optimal solution can be calculated.

The case-independent model, based on which these overall conclusions were developed, provides concrete numbers for pre-feasibility checks on the design for specific cases. This allows quick design assessments and avoids lengthy iterative processes. The case-independent model results are directly fed into the overall grid design where these guidelines help to guide the direct grid development. The suggestions for the overall grid design were verified by concrete model calculations.

For completeness, it should be mentioned that economics are not the only basis for a decision to develop an integrated solution. Other important factors are e.g. the timing of each part of the project, the fact that an integrated solution can increase the redundancy, the ownership structure of the projects, etc.

The results have been complemented and validated with an extra case study, the Cobra cable. This analysis has confirmed the conclusion on the connection of big wind farms to two countries, as discussed in section 4.4.3. Due to high wind expectations, future German spot market prices are expected to be low. This enforces the effect of the two-country-connection.

The detailed results of the case-independent model are shown in Annex D.II on www.offshoregrid.eu. The results can be used as general guidelines for project developers, policy makers, regulators and TSOs to assess whether the discussed design solutions (hub-to-hub, tee-in, split wind farm connection) could be beneficial for the projects planned.

4.5 Overall grid design

4.5.1 Approach

The development of the offshore grid is going to be driven by the need to bring offshore wind energy online and by the benefits from trading electricity between countries. This involves on the one hand the connection of the wind energy to where it is most needed, and on the other hand the linking of high generation cost areas to low generation cost areas. There are numerous methodologies that could be applied to achieving these objectives. In this section, the OffshoreGrid consortium demonstrates the effectiveness of two different methodologies to design a beneficial cost-effective overall offshore grid.

Both methodologies use as a starting point the OffshoreGrid Hub Base Case scenario 2030. This includes the direct or hub connections to each of offshore wind farm in the North and Baltic Seas (as defined in section 4.2), and the offshore reinforcements identified in the ENTSO-E Ten Year Network Development Plan (TYNDP) [56]. Based on this, the following design development strategies are applied:

- The **Direct Design Methodology** mimics the current evolution as it is envisaged today: First, direct interconnectors are built to promote unconstrained trade as average price difference levels are high. Once additional direct interconnectors become non-beneficial, tee-in, hub-to-hub and meshed grid concepts are added to arrive at an overall grid design.
- The **Split Design Methodology** considers an approach that starts with a conclusion from the case-independent model (see section 4.4.4). The idea is that interconnections are built by splitting the connection of some of the larger offshore wind farms between countries. Thereby a path for constrained trade is established. These offshore wind farm nodes are then further interconnected to establish an overall 'meshed' design where beneficial.

A large number of iterations and sensitivity analyses were carried out for each of the two methodologies[26] in order to prove that each added infrastructure module was beneficial. Each of the methodologies is explained in detail in the following two chapters. The results are compared in section 4.5.4 to see which kind of development is most efficient in terms of reducing European total system generation costs.

TABLE 4.6: ENERGY PRICE DIFFERENCES (IN €/MWH) AS DETERMINED BY POWER MARKET MODEL FOR THE HUB BASE CASE SCENARIO 2030

	BE	DE	DK	EE	FI	FR	GB	IE	LT	LV	NL	NO	PL	SE
BE		4.6	9.7	6.4	23.7	10.1	9.4	8.2	6.9	6.4	7	17.5	6	25.9
DE	4.6		7.5	5.4	22.1	9.5	8.8	8.8	5.4	5.4	5.3	15.7	4.4	24.0
DK	9.7	7.5		6.2	16.2	7.6	8.9	11.4	5.8	6.2	6.3	10.1	6.9	17.0
EE	6.4	5.4	6.2		18.8	8.5	10.0	10.4	1.2	0.0	8.1	13.4	3.7	21.1
FI	23.7	22.1	16.2	18.8		16.5	20.3	23.4	19.0	18.8	20.7	9.9	20.9	7.3
FR	10.1	9.5	7.6	8.5	16.5		8.9	11.3	8.5	8.5	8.3	10.6	9.6	17.2
GB	9.4	8.8	8.9	10.0	20.3	8.9		6.1	9.9	10.0	6.5	15.0	10.0	21.2
IE	8.2	8.8	11.4	10.4	23.4	11.3	6.1		10.6	10.4	8.6	10.1	10.2	24.8
LT	6.9	5.4	5.8	1.2	19.0	8.5	9.9	10.6		1.2	7.8	13.4	2.8	20.5
LV	6.4	5.4	6.2	0.0	18.8	8.5	10.0	10.4	1.2		8.1	13.4	3.7	21.1
NL	7.0	5.3	6.3	8.1	20.7	8.3	6.5	8.6	7.8	8.1		14.7	7.2	21.2
NO	17.5	15.7	10.1	13.4	9.9	10.6	15.0	18.1	13.4	13.4	14.7		14.8	8.8
PL	6.0	4.4	6.9	3.7	20.9	9.6	10.0	10.2	2.8	3.7	7.2	14.8		22.1
SE	25.9	24.0	17.0	21.1	7.3	17.2	21.2	24.8	20.5	21.1	21.2	8.9	22.1	

[26] Please note that the two methodologies only differ in the first step. The Direct methodology focuses first on direct interconnectors, while the Split methodology focuses first on split wind farm connections.

4.5.2 The direct design methodology

The Direct Design Methodology is built on three steps:

Step 1) The construction of direct interconnectors taking the large price difference between countries as guidance.

Step 2) Beneficial tee-in solutions or the interconnection of countries via hub-to-hub connections were identified.(Step 2 was only started when step 1 could not identify any more beneficial direct interconnectors)

Step 3) Beneficial meshed connections were identified. (Step 3 was only started when neither step 1 nor step 2 could identify beneficial connection solutions)

Each step is explained in more detail below.

Step1: Direct design methodology – direct interconnectors

To assess the economic viability of direct interconnectors within Northern Europe a justification formula was developed to test the profitability of interconnectors. This worked as follows:

- The power market model was used to initially create a reference case of energy price differences between the countries around the North and Baltic Seas,
- The price differences were used to determine the potential interconnector revenue. The capital cost of each interconnector is calculated,
- Costs and revenues are compared, and the interconnectors are ranked according to profitability,
- The ten most promising links are selected and studied in detail in the power market model[27].

The starting point for all calculations is the Hub Base Case scenario 2030. The price differences for this case are shown in Table 4.6. Based on these, the potential revenue for interconnectors between all countries which can be connected geographically was calculated using the following assumptions:

- 25 year payback period, 6% discount rate
- Minimum interconnector utilisation of 63.7%
- 1,000 MW building blocks for each interconnector[28]
- Interconnector receiving revenue derived from either 60% or 100% of the price differences multiplied by the expected utilisation (depending on the type of contracts)[29].

Some of the ten interconnectors identified were between countries that also shared a land border. Adding links between adjacent countries via an offshore grid is unlikely to be the most economically efficient solution and including such links in the model may affect the overall effectiveness of the offshore grid design. Hence, despite the remit of this project excluding reinforcements to the onshore network, it was reasonable to add onshore AC 1,000 MW capacity reinforcements into the power market model where the price differentials indicated a need case between adjacent countries in order to make the evaluation of an offshore grid design as realistic as possible.

Following the identification using the above described process, the power market model was run with each interconnector added in turn to produce the total electricity generation cost for the European system. The direct interconnectors were beneficial when the total generation cost was reduced by more than the capital cost of the assets over their lifetime. The direct inter-

[27] Ten proved to be a sufficiently large number. If it had shown that there would have been more than ten beneficial links, the number of selected links to be tested would have been increased. Furthermore please note that, as explained below, an iterative process was carried out and step 1 of the Direct Design was repeated in order not to miss any beneficial direct interconnectors.

[28] Note that this methodology did identify that multiple 1,000 MW interconnectors between the same countries could be beneficial, and hence in order to separately identify the net benefit, each interconnector has been modelled discretely at 1,000 MW. In reality where a net benefit is identified for multiple interconnectors between the same countries, a more cost effective design such as a single 2,000 MW bipole may be implemented.

[29] Either based on long term supplier/interconnector capacity contracts (60%) or on short term supplier/interconnector capacity contracts (100%). The interconnector utilisation figure was derived from the average utilisation of the England France (2,000 MW), Moyle (Scotland – Northern Ireland, 500 MW) and NorNed (700 MW) interconnectors using data downloaded from the ENTSO-E website from 2008 to 2010.

connectors that were beneficial were retained and any that were not beneficial were removed from the model.

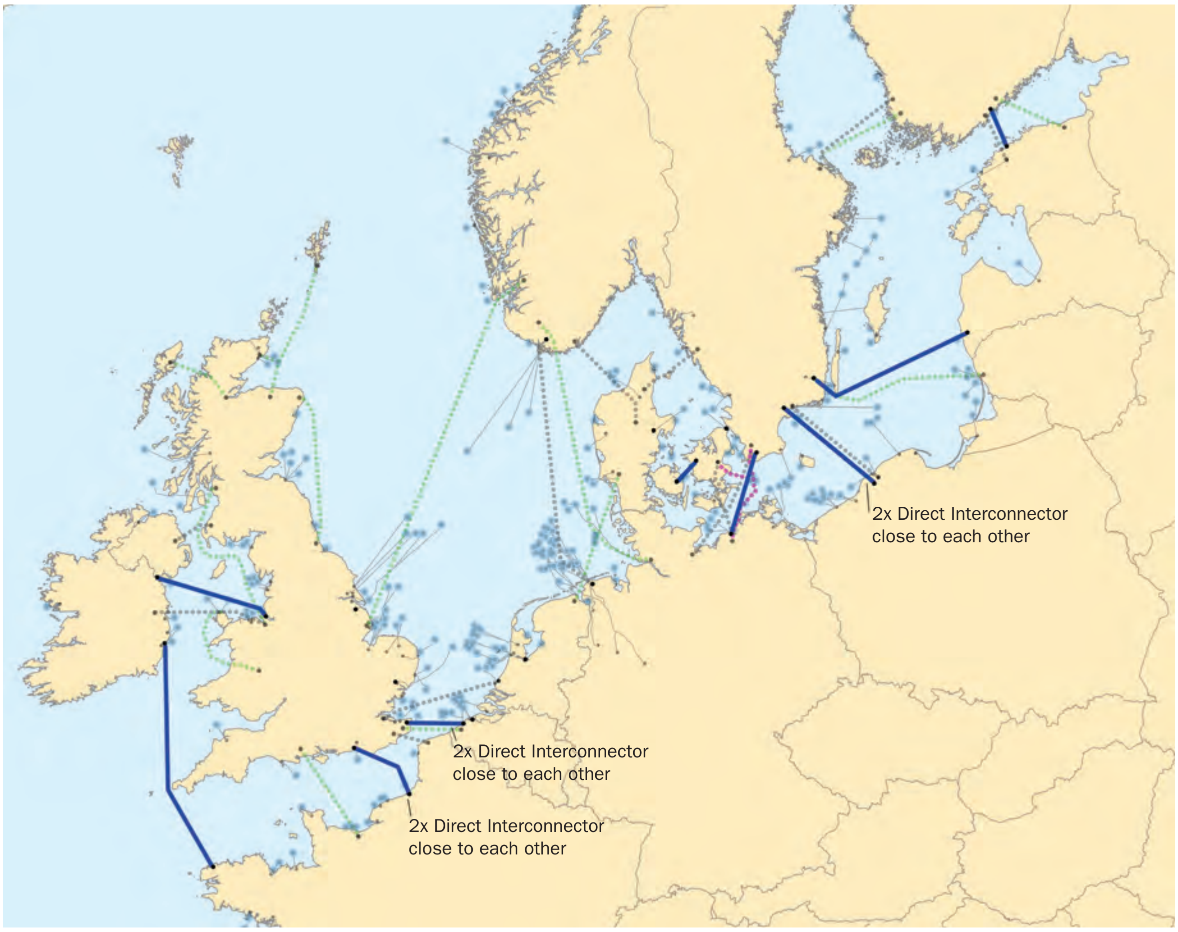
Besides reducing the total generation costs, adding interconnectors also reduces the price differences between countries. Accordingly, the building or omitting of direct interconnectors has an immediate impact on the price levels and the profitability of the remaining proposed interconnectors. To come around this, an iterative process was performed and step 1 was repeated. Within this process the updated price differences were used to identify more interconnectors to study in the power market model until the price differences were lowered sufficiently so that adding further direct interconnectors produced no net benefit. The beneficial direct interconnectors selected as a starting point for step 2 of the Direct Design Methodology are shown in the map in Figure 4.21.

The development of the price level differences that go along with the different offshore grid design steps are given in detail in Annex D.III on www.offshoregrid.eu.

Step 2: Direct design methodology – hub-to-hub and tee-in connections (integrated design)

The most promising cases assessed for either hub-to-hub connection or wind farm tee-in connection possibilities, are those direct interconnectors that

FIGURE 4.21: DIRECT DESIGN METHODOLOGY – STEP 1: MAP OF THE SELECTED DIRECT INTERCONNECTORS



Wind Farms
Onshore substation
To shore Connection of Wind Farms (Hub and Individual)
Existing Interconnectors
Entso-E TYNDP Interconnectors
Kriegers Flak – Three Leg Interconnector
Direct Design step 1 – Direct Interconnectors
Direct Design step 2 Hub-to-hub and Tee-in interconnectors
Direct Design step 3 Meshed Grid Design

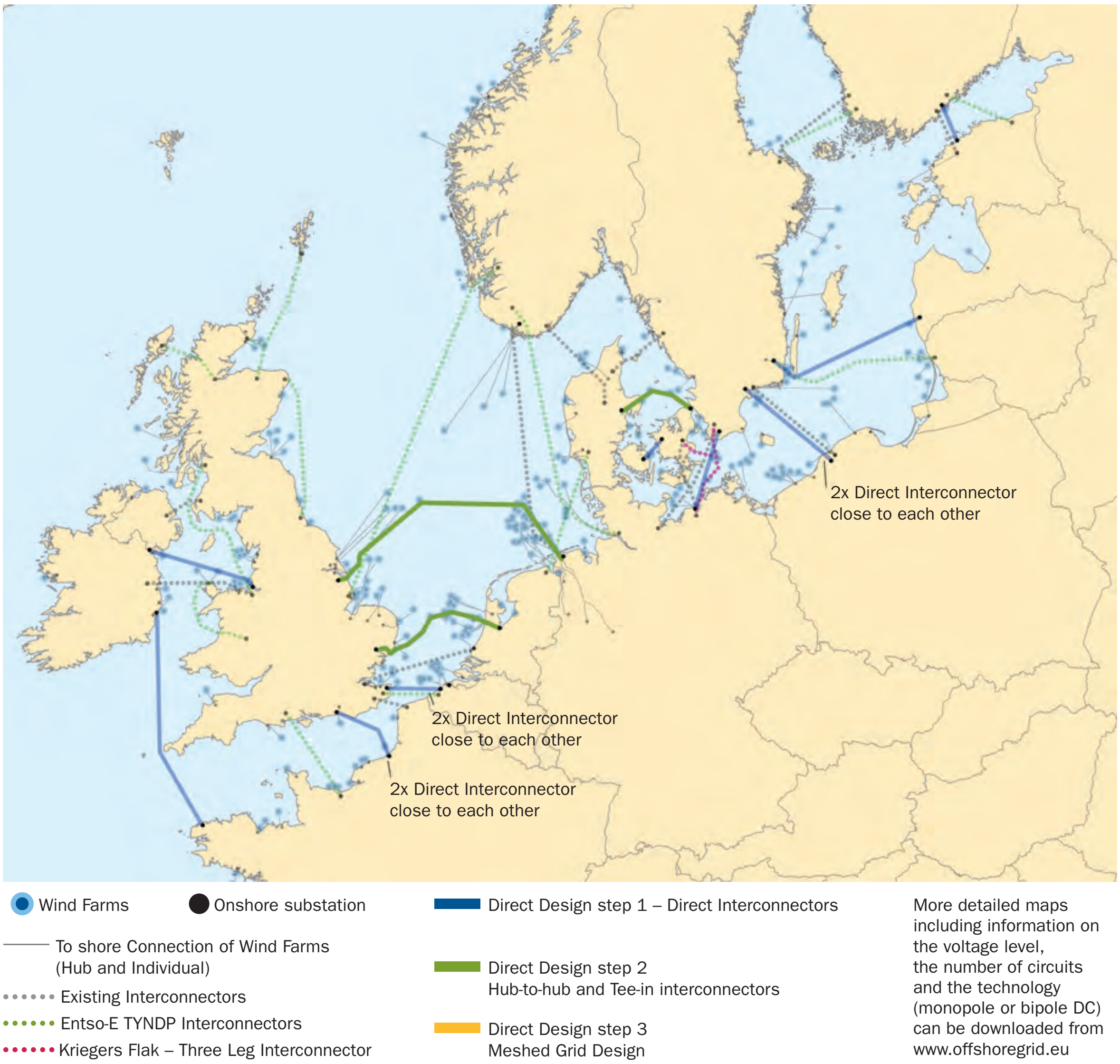
More detailed maps including information on the voltage level, the number of circuits and the technology (monopole or bipole DC) can be downloaded from www.offshoregrid.eu

were rejected as being not beneficial in the previous stage. The reasoning behind this is that the high price differential still indicates that there could be benefit in linking the two countries concerned (for details on the price differentials after step 1 refer to Annex D.III.). Integrated solutions provide trade opportunities at a lower capital cost, even though this trade is not always unconstrained as the lines are sometimes loaded with offshore wind energy. Thus, the reduced capital costs may make a tee-in or hub-to-hub connection beneficial where a direct interconnection was not.

Once the potential tee-in and hub-to-hub connections to be assessed have been chosen, the number of cases to be studied was further reduced by comparing the proposed cases with the conclusions of the case-independent model described in section 4.4. As discussed, the case-independent model is useful as a guidance to quickly evaluate whether a certain case needs further investigation or not. Cases where the case-independent model clearly showed that there is no benefit in going for an integrated solution have thus not been investigated further[30].

The promising cases were ranked according to the net benefit of the corresponding direct interconnectors (the non-beneficial ones from the previous phase), with the most beneficial being assessed first. The

FIGURE 4.22: DIRECT OFFSHORE GRID DESIGN - STEP2: MAP OF THE SELECTED HUB-TO-HUB CONNECTIONS



[30] Cases where the case-independent model indicated that the benefit is positive have thus been further analysed with the infrastructure cost model and the power market model. As the case-independent model only gives a guidance to be backed up with more detailed case-specific analysis, the cases with a marginal or only slightly negative benefit have also been investigated.

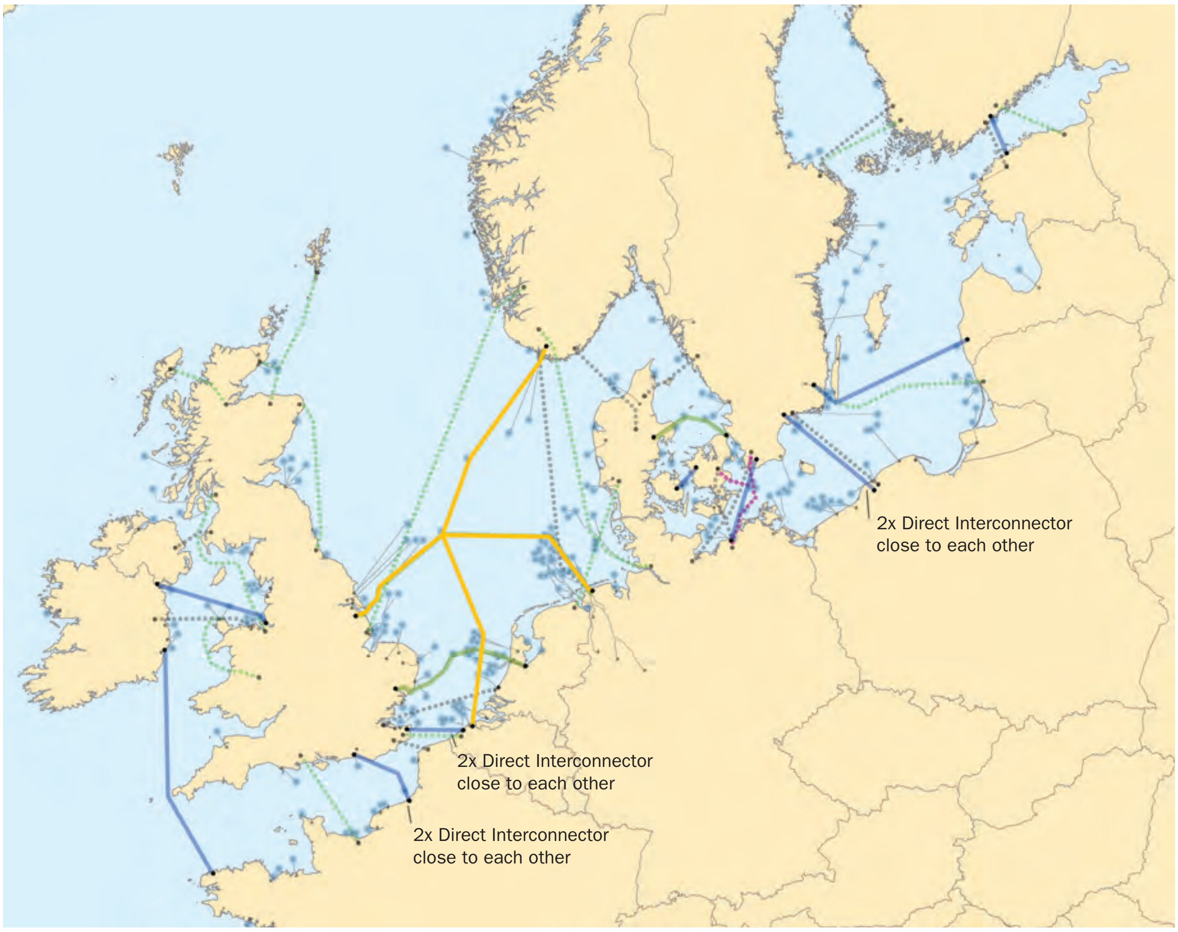
connections were tested in multiple iterations similar to the process for the direct interconnectors in step 1. The hub-to-hub connections that demonstrated a positive net benefit were retained for each of the next phases.

Step 3: direct design methodology – mesh design

The price differentials between each country that were still remaining after step 2 were analysed (cp. details on price differentials in Annex D.III.). The countries with high price differentials were earmarked as potential connection points for an offshore mesh. These potential connection points were further refined by ignoring any price differentials between countries that were impractical and uneconomic to interconnect via offshore links such as Belgium and Finland, or Norway and Latvia.

What remained were consistently high price differentials between Norway and to a lesser extent Sweden and the northern European countries of Germany, the Netherlands, Belgium, France, and Great Britain. Because additional direct interconnections and in some cases hub-to-hub connections between these various countries had not proven to be beneficial over those established in the previous step, these price differentials indicated that variations of a mesh design that linked offshore hubs in these countries could prove beneficial. Various combinations of links between some of the offshore hubs in these countries were analysed.

FIGURE 4.23: DIRECT OFFSHORE GRID DESIGN - STEP 3: MAP OF THE SELECTED MESH IN THE NORTH SEA



Wind Farms
Onshore substation
To shore Connection of Wind Farms (Hub and Individual)
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Direct Design step 3 Meshed Grid Design

More detailed maps including information on the voltage level, the number of circuits and the technology (monopole or bipole DC) can be downloaded from www.offshoregrid.eu

To that extent, a 1,000 MW 'spine' was established between the Idunn hub off Norway, the Dogger Bank hub off the UK and the IJmuiden hub off the Netherlands to Belgium[31]. Sensitivities were then performed on this initial mesh around[32]:

- the effectiveness of each of the links within the 'spine',
- adding additional 1,000 MW offshore links to Belgium and Sweden from the IJmuiden hub and Idunn hub respectively,
- adding additional 1,000 MW offshore links to Belgium and Sweden from the Dutch and Norwegian onshore networks mesh connection points respectively,
- uprating the individual mesh links to 2,000 MW,
- removal of the 'redundant' hub-to-hub link between Idunn and IJmuiden from the base model.

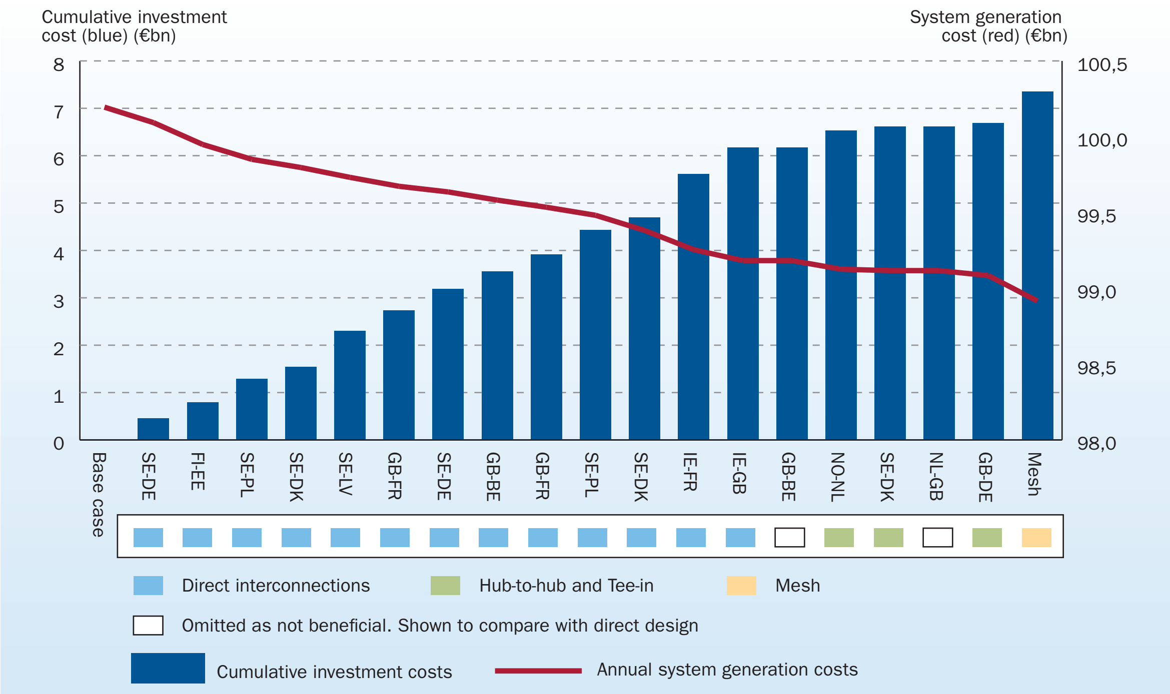
Figure 4.23 shows the overall final grid design after step 3 of the Direct Design Methodology for the North and Baltic Seas.

Results – direct design

Figure 4.24 shows the infrastructure costs (cumulatively) and the total system generation costs, and Figure 4.25 shows the net benefit of the overall Direct Design.

As can be seen from Figure 4.24, the cumulative investment cost curve (blue bars) for the Direct Design is reasonably linear for the direct interconnectors. This reflects the discrete investment required in converters and cable for every investment. The few larger steps for Sweden-Latvia and Ireland-France reflect the greater amounts of subsea cable required for longer interconnections. The investment cost curve begins to plateau for the hub-to-hub cases implemented, as these require only an investment in extra subsea cable and utilise the

FIGURE 4.24: DIRECT DESIGN - CUMULATIVE CAPEX INVESTMENT COSTS (BLUE, LEFT) AND SYSTEM GENERATION COSTS (RED, RIGHT) [€ BN]



[31] As can be seen from Figure 4.23, some parts of this 'spine' already existed in the model. As a result of the hub-to-hub analysis, the Dogger Bank hub was already connected to the Gaia hub in Germany, and the Idunn hub was already connected directly to the IJmuiden hub. Belgium, France, and Sweden were already connected to the Netherlands and Norway respectively via onshore reinforcements in the base model.

[32] Unlike for the direct interconnections and the hub to hub connections the possible variations in mesh topology were not exhaustively modelled although several sensitivities assessing the effect of changes in capacities, connection points and removal of links around the core initial mesh and alternative mesh designs were analysed to arrive at the design presented here. (Further details of these sensitivity studies are represented in Annex D.III.I to this report).
Whilst other alternative mesh designs are certainly possible and may even be more beneficial, it was felt that the proposed design demonstrated the benefit of a meshed offshore grid and was already sufficiently complex to make implementation by 2030 ambitious.

existing HVDC converters at each hub. Thus, the hub-to-hub investment costs are relatively low.

Along with these infrastructure investments the electricity generation costs (in Figure 4.24, red curve) in the European power system decrease. The annual generation cost curve shows - similar to the cumulative investment curve - linear reductions for the direct interconnections, a flattening of the curve for the hub to hub cases and a further sharp reduction when the mesh is introduced. The entire Direct Design reduces the system costs by €1.3 bn per annum (=€20.5 bn over 25 years) for a total investment cost of €7.4 bn.

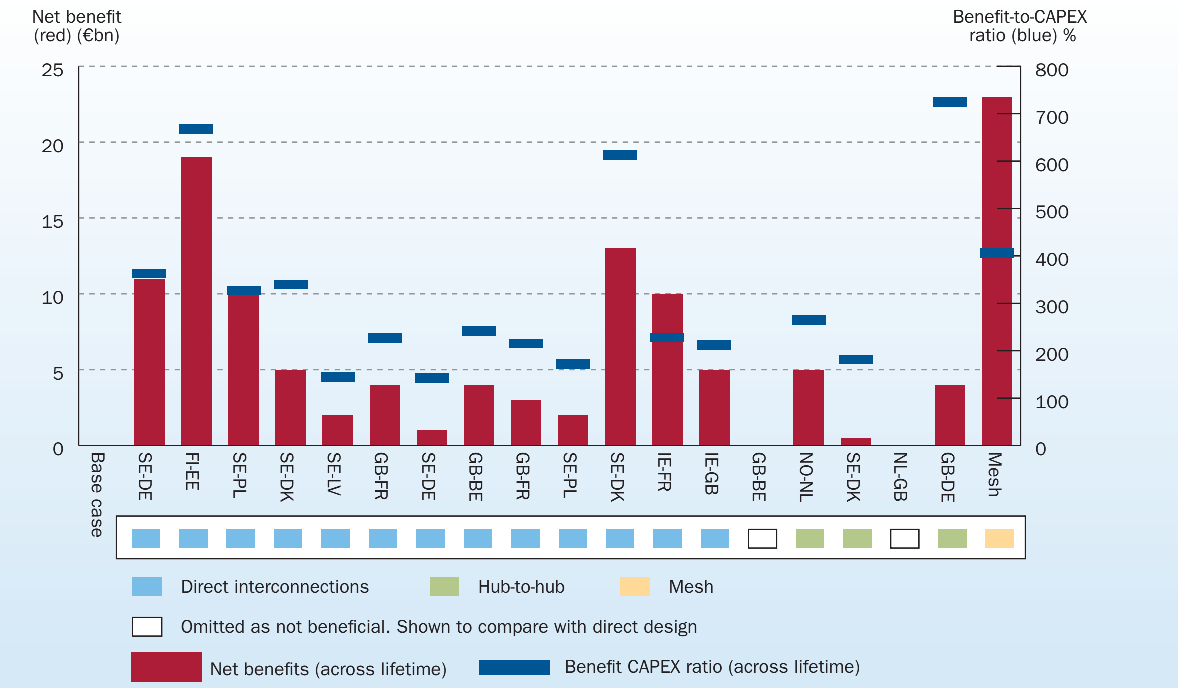
How large the benefit per investment is, is best shown in Figure 4.25. Here the net benefits (red bar) and the benefit-to-CAPEX ratio (blue marker) of each project are given for a life time of 25 years. In particular the meshed network exhibits a large benefit-to-CAPEX ratio. As all investments are beneficial and produce net benefits, the benefit-to-CAPEX ratio is always bigger than 100%. Some investments produce benefits of up to 7 times the initial investment (benefit-to-CAPEX ratio of 700%).

The final step of the meshed grid design creating a meshed network between Norway and Great Britain, Germany, the Netherlands and Belgium generates significant net benefits over 25 years (€2.3 bn) for a relatively modest investment cost (€670 m) reaching a benefit-to-CAPEX ratio of almost 400%. Again, this is because the additional investment is only in extra cabling, as the existing hub converters are utilised.

4.5.3 The split design methodology

The case independent model (section 4.4) clearly identified that splitting the connection of wind farms (or hubs) to two separate shores can be a very cost effective and beneficial solution: the wind farm is connected to shore and at the same time a relatively cheap interconnector can be built. It was further identified that the splitting solution is most beneficial for large wind farms or hubs which are far from the onshore connection point but are relatively close to another country, and when the price difference (see Annex D.III. for price level differences) between the two countries is high enough to make up for the additional infrastructure costs. As these findings presented a very promising grid design solution, the split wind farm concept was taken into account for the second methodology. Similar to the Direct Design methodology, the starting point is the Hub Base Case scenario 2030 with hub-connected wind farms and again the three-step methodology was applied. However, this time also split wind farm connections were considered in the first step. Even though the second and third steps for the Split Design

FIGURE 4.25: GRID DESIGN: NET BENEFIT (RED, LEFT) AND BENEFIT-TO-CAPEX RATIO (BLUE, RIGHT) [€BN]. (PLEASE NOTE THE DIFFERENCE BETWEEN NET BENEFIT AND BENEFIT.)



Methodology remain the same, the changes in the first step have of course an impact on the results of step 2 and step 3:

Step 1) The methodology is based on step 1 of the Direct Design. Split wind farm connections were considered where it was possible to replace direct interconnectors. Those split wind farms that are beneficial to retain were identified, along with the direct interconnectors where splitting wind farm connections was not possible. Thus as a result of step 1 beneficial direct interconnectors and split wind farm connections are obtained.

Step 2) Beneficial tee-in solutions or the interconnection of countries via hub-to-hub connections were identified. (Step 2 was only started when no further beneficial split wind farm connections could replace the direct interconnectors of step 1 in the Direct Design).

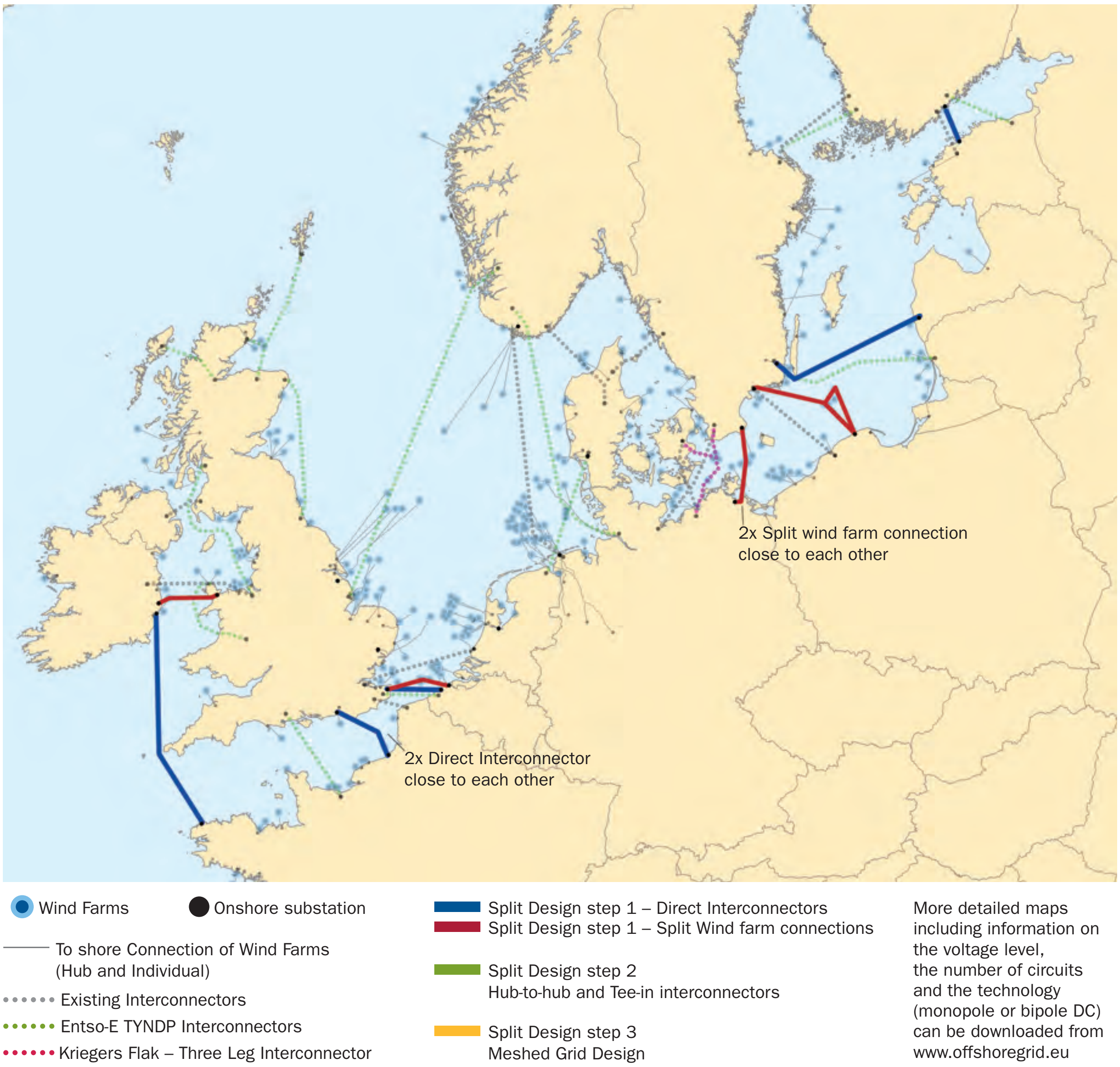
Step 3) Beneficial meshed connections were identified. (Step 3 was only started when neither step 1 nor step 2 could identify beneficial connection solutions)

Each step is explained in more detail below.

Step 1: Split design methodology – split wind farm connections

To select the wind farms that can be split, a methodology based on the aforementioned characteristics was developed. In order to compare the results with the Direct Design, the beneficial interconnectors (both

FIGURE 4.26: SPLIT OFFSHORE GRID DESIGN - STEP 1: MAP OF THE SELECTED SPLIT WIND FARM CASES



direct and integrated) identified as being beneficial were mirrored with appropriate split wind farm connections. This means that the split wind farm connections connect the same countries as the direct interconnectors in the Direct Design approach.

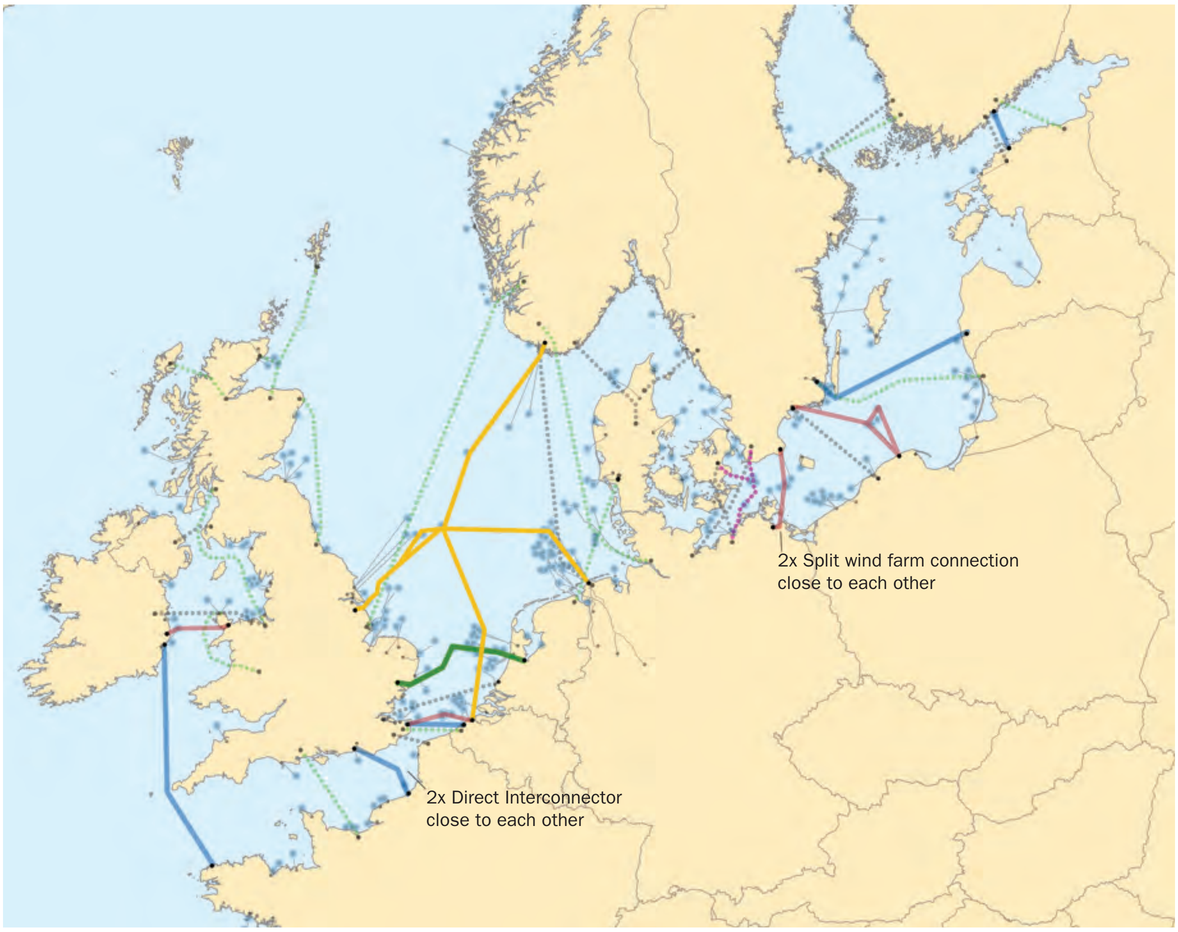
The wind farms or wind farm hubs to be split have been selected based on their capacity and on the additional cable length to the other country. The wind farm (hub) for each comparative link from the Direct Design method which came out best, was then modelled as a split connection in the power market model to assess overall benefit. For those direct interconnectors identified in the Direct Design method where no appropriate wind farm (hub) for splitting the connection could be identified, the original direct interconnector was retained in the model.

Sensitivity studies were performed initially around the capacity of the split connection links. The options studied (suggested by the case-independent model) were:

- Each connection link from the offshore wind farm carries half of the installed capacity of the wind farm (50% option).
- The connection link to the country with the lower generation price is rated half of the installed capacity of the wind farm. The connection link to the country with the higher generation price is rated to carry the full installed capacity of the wind farm (50/100% option).

The result of the sensitivity analysis showed that the 50% option was already beneficial, but the 50/100%

FIGURE 4.27: SPLIT OFFSHORE GRID DESIGN - STEPS 2 AND 3: MAP OF THE MESH DESIGN



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Kriegers Flak – Three Leg Interconnector

Split Design step 1 – Direct Interconnectors
Split Design step 1 – Split Wind farm connections

Split Design step 2
Hub-to-hub and Tee-in interconnectors

Split Design step 3
Meshed Grid Design

More detailed maps including information on the voltage level, the number of circuits and the technology (monopole or bipole DC) can be downloaded from www.offshoregrid.eu

option was better. Following these results, all the split connections in the model were designed according to the 50/100% option.

Step 2: Split design methodology – hub- to-hub and tee-in connections

Step 2 tested whether there are any beneficial hub-to-hub or tee-in connections. The connection of two hubs in different countries allows trade across the newly established interconnectors via the hubs. Trade is of course also possible via a tee-in connection. Accordingly the price differentials between the countries are used as indicators to identify potentially beneficial hub-to-hub or tee-in connections (compare Annex D.III.IV.).

Several potentially beneficial hub-to-hub interconnections as identified in the Direct Design were tested with the market model. The infrastructure measure was regarded as beneficial when the generation costs reduction of the power system was higher than the infrastructure costs.

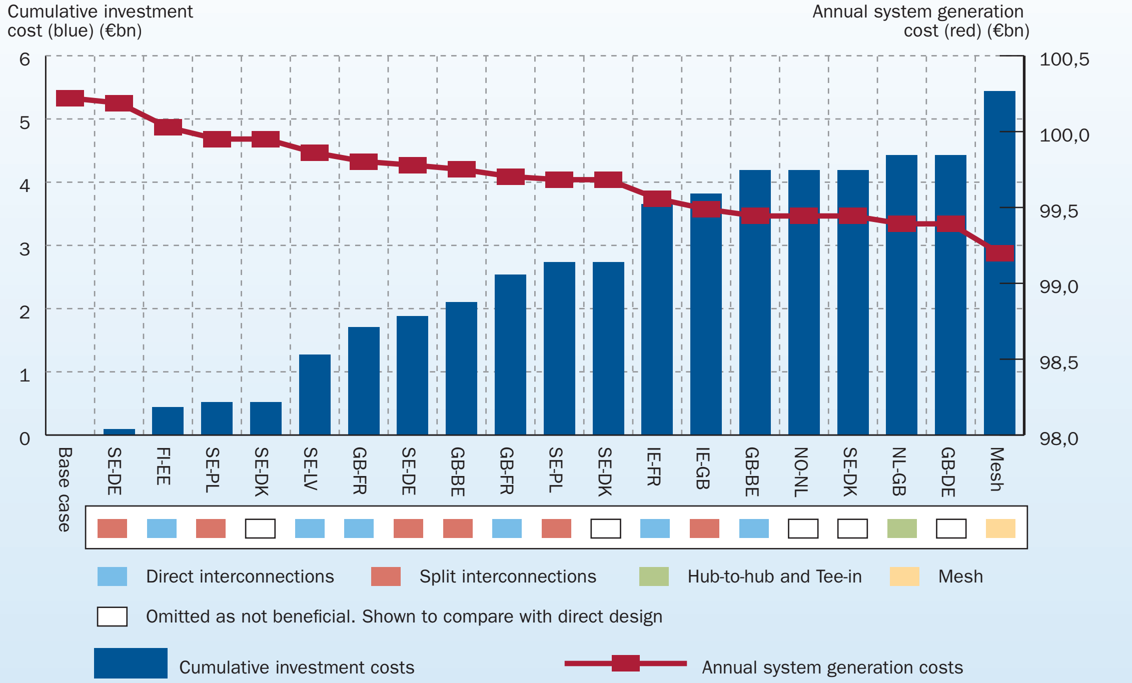
Within step 2 the hub-to-hub cable connecting NL and GB was identified to be beneficial. That only one case was identified is due to the split wind farm connection of step 1 that already boosted the cross-border capacity between the countries and further reduced the price differences.

Step 3: Split Design Methodology – Mesh Design

Again sensitivities of mesh design were run in addition to the interconnections already identified in steps 1 and 2 above. The same topology of mesh design to the direct case was found to be most beneficial, with a 'spine' running from the Idunn hub in Norway, to the UK Dogger Bank, to the IJmuiden hub off the Netherlands[33] and then to Belgium. The mesh also includes an interconnector between the Dogger Bank and the German Gaia hub.

The price differentials between the countries developed differently in the Split Design compared to the Direct Design. Therefore the cable capacities of the mesh

FIGURE 4.28: SPLIT OFFSHORE GRID DESIGN: CUMULATIVE CAPEX INVESTMENT COSTS (BLUE, LEFT) AND SYSTEM GENERATION COSTS (RED, RIGHT) (€ BN)



[33] As can be seen from Figure 4.23, some parts of this 'spine' already existed in the model. As a result of the hub-to-hub analysis, the Dogger Bank hub was already connected to the Gaia hub in Germany, and the Idunn hub was already connected directly to the IJmuiden hub. Belgium, France, and Sweden were already connected to the Netherlands and Norway respectively via onshore reinforcements in the base model.

configuration were rated differently than in the Direct Design in order to achieve the optimal design. Rating the Norway to Great Brian to Netherlands sections of the mesh at 2,000 MW was found to be most beneficial.

With the direct and split mesh design having the same topology, it allows the benefit-to-CAPEX ratio to be compared.

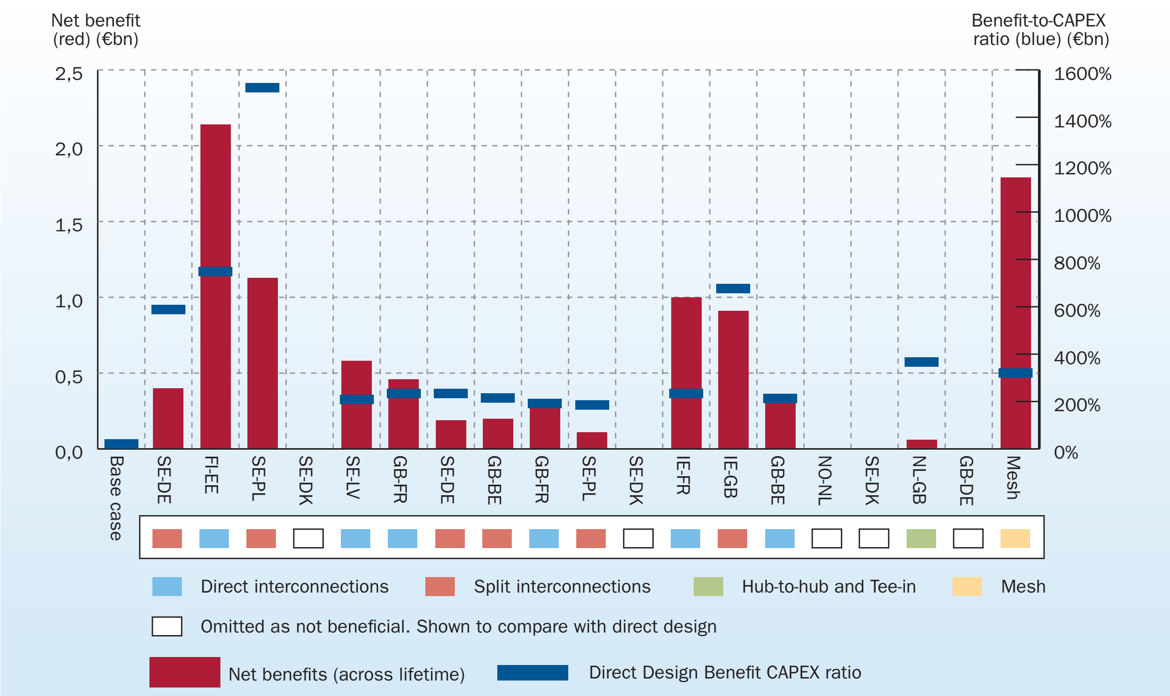
Results – Split Design

The investment costs in the split wind farm designs are lower than for their direct interconnector counterparts in the Direct Design (see Figure 4.28). This is due to the fact that the split farm connection represents two-in-one: a direct connector and a wind farm-to-shore connection. When comparing the system costs in Figure 4.28 with Figure 4.24, it is also clear that reduction in overall system costs is smaller for the Split Design due to the higher trade constraints[34].

Some of the direct interconnectors that are not beneficial in the Direct Design, such as the second Great Britain to Belgium link, are now producing positive net benefits (Figure 4.29). This proves that the offshore grid design with the split wind farms reduces the system costs (and thus the price differences) with smaller steps due to the higher trade constraints on the interconnector. The higher price differences make the remaining direct interconnectors more beneficial. However, this does not mean that the split wind farm connections are less effective. As is shown below the split wind farm connections even generate a higher relative system cost reduction when put in relation to the investment costs (benefit-to-CAPEX ratio).

The introduction of a mesh in step 3 also produces significant net benefits of €1.8 bn across 25 years for an investment of only €1 bn. Note that the mesh is less beneficial than in the Direct Design. The reason is that the mesh is now built between wind farms that are already connected to two countries with the split design concept identified in step 1. The split connection already leads to an increased utilisation of the cables, so that the actual mesh cables between the wind farm hubs are constrained more severely. This leads to a lower absolute reduction in system costs than in the Direct Design[35].

FIGURE 4.29: SPLIT OFFSHORE GRID DESIGN:NET BENEFIT (RED, LEFT) AND BENEFIT-TO-CAPEX RATIO (BLUE, RIGHT) (€ BN). (PLEASE NOTE THE DIFFERENCE BETWEEN BENEFITS AND NET BENEFITS.)



[34] Note that in the results the Finland–Estonia, Sweden–Latvia, Great Britain–France, Ireland–France, and Great Britain–Belgium links all remain as direct interconnectors.

[35] Step 3 in the Split Design methodology is strongly based on step 3 in the Direct Design methodology for reasons of comparability. The specific development of a mesh design for the Split Design will probably yield higher net benefits.

The overall Split Design reduces the system costs by €15.8 bn across 25 years for a total investment cost of €5.4 bn.

4.5.4 Comparison of methodologies

It should be highlighted that both the Direct Design and the Split Design methodology lead to significant net benefits. Immediately the question raises which of the two leads to the most cost-efficient offshore grid design. Such a comparison would be most sound on an equal basis: either with equal total cumulative costs in order to see which design brings the most reduction in system cost, or with equal total system cost reduction in order to identify which design has the lowest CAPEX. In our case where neither equal system reduction costs nor equal CAPEX are given, comparison of relative benefits by evaluating the reduction in system cost per invested euro is most useful.

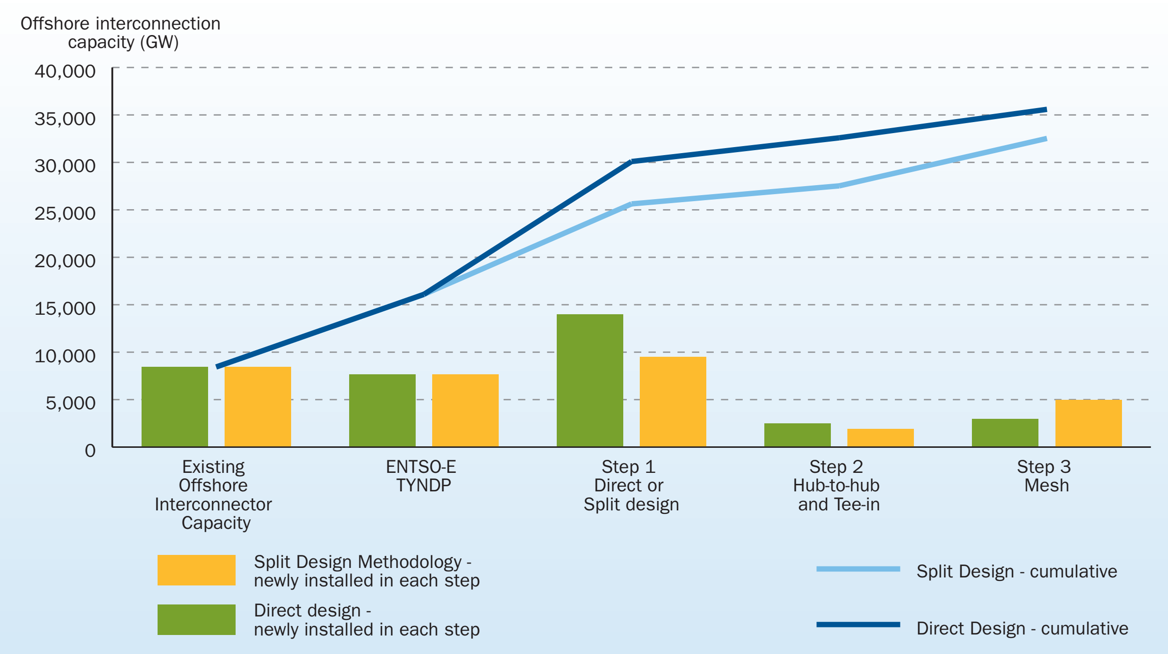
In the following paragraphs, a comparison is made based both on relative and absolute terms[36]. However, first of all it is instructive to shortly analyse the interconnector capacities that come along with the two design approaches.

Interconnection capacity – comparison for the direct and split design approach

OffshoreGrid starts to develop an overall grid design based on the Hub Base Case scenario 2030. This scenario includes all existing grid infrastructure and adds the connection of all 2030 offshore wind farms with individual connections and hub connections where beneficial. The existing infrastructure exhibits an offshore interconnection transmission capacity in Northern Europe of about 8 GW. Furthermore the planned interconnectors of the ENTSO-E TYNDP were added, which represent further offshore interconnection capacity of 8 GW.

Thus, the overall grid design development within OffshoreGrid starts with an offshore interconnection capacity of 16 GW. Based on this the overall grid design is developed with the Direct and Split Design methodologies in three steps as aforementioned.

FIGURE 4.30: COMPARISON THE CAPACITY OF ALL EUROPEAN INTERCONNECTORS TODAY, WITH THE ENTSO-E TYNDP INTERCONNECTORS, WITH THE THREE STEPS OF THE DIRECT AND SPLIT DESING METHODOLOGY



36 Please note that the overall cumulative investment costs and the reduction in system generation costs shown in Figure 4.30 to Figure 4.34 only consider the investments made for the steps described in paragraphs 4.5.2 and 4.5.3. The total costs of the overall grid design are further detailed in section 4.5.5.
A number of cases does not follow this general rule.

FIGURE 4.31: COMPARISON OF CAPEX SPEND PER INTERCONNECTION, FOR THE DIRECT AND SPLIT OFFSHORE GRID DESIGN METHODOLOGIES (€ BN)

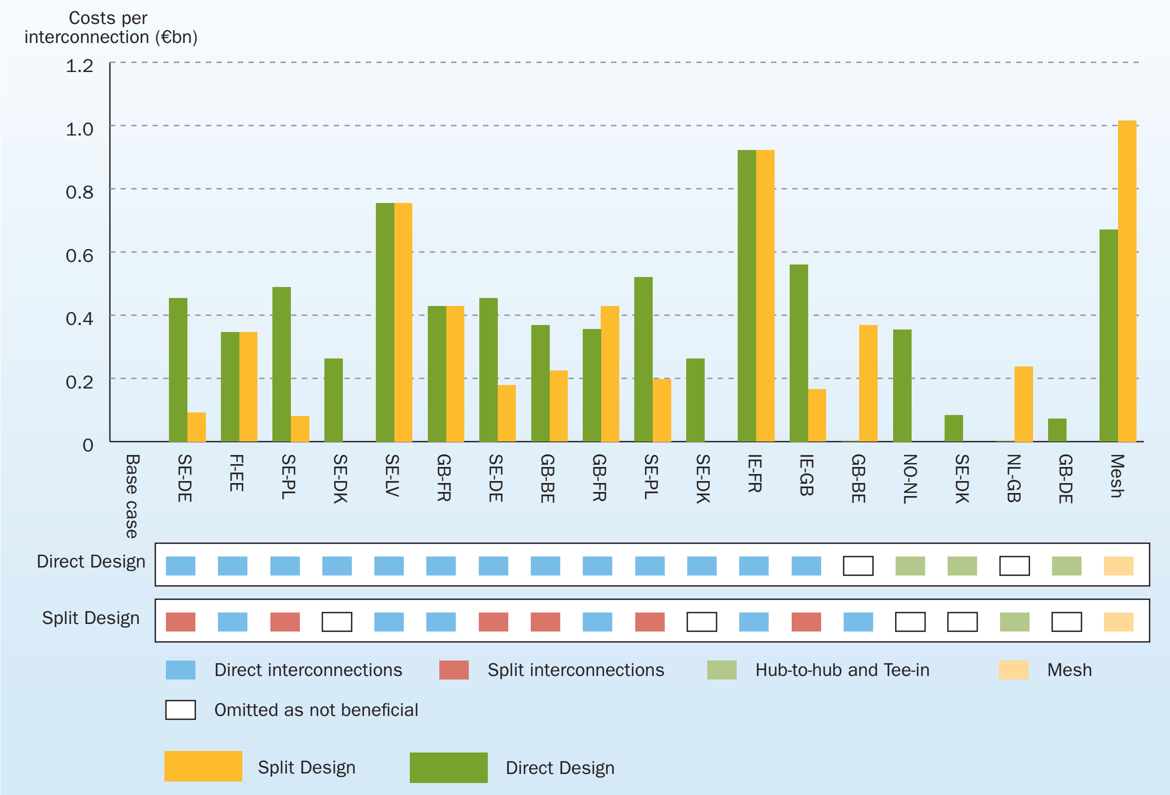


FIGURE 4.32: COMPARISON OF ANNUAL REDUCTION IN SYSTEM COSTS PER INTERCONNECTION, FOR THE DIRECT AND SPLIT OFFSHORE GRID DESIGN METHODOLOGIES (€ BN)

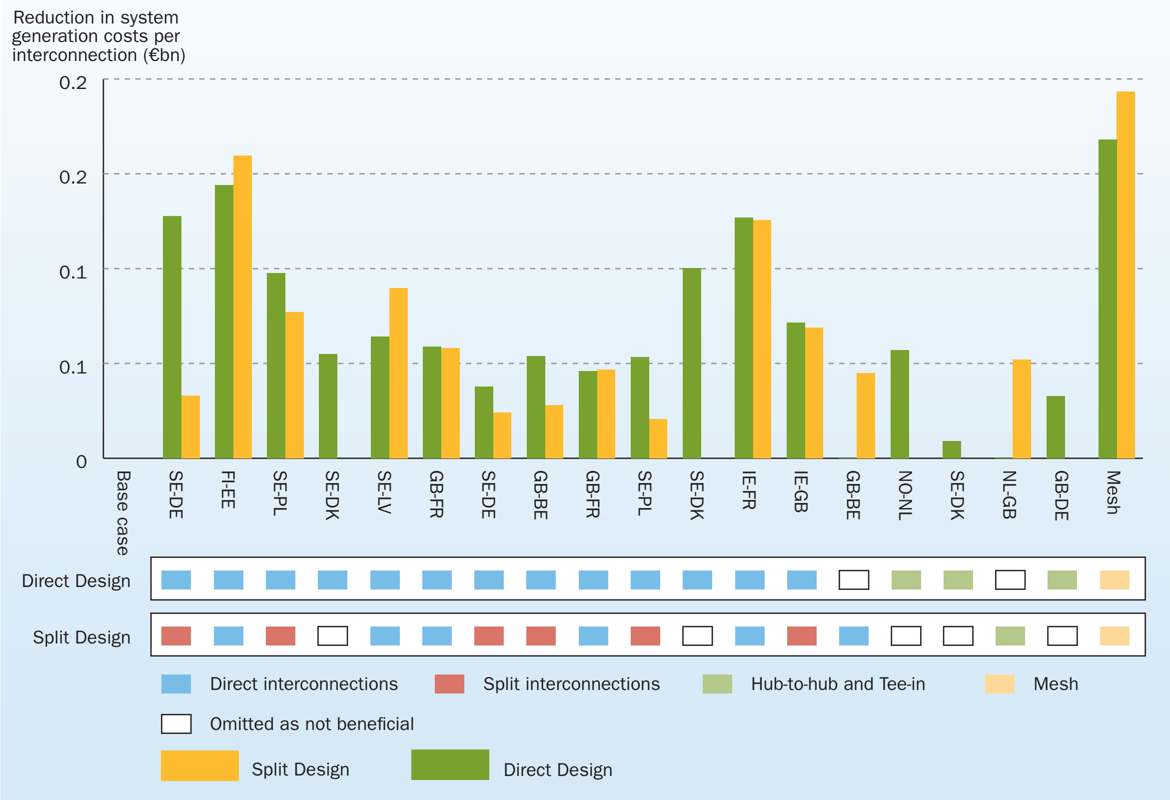
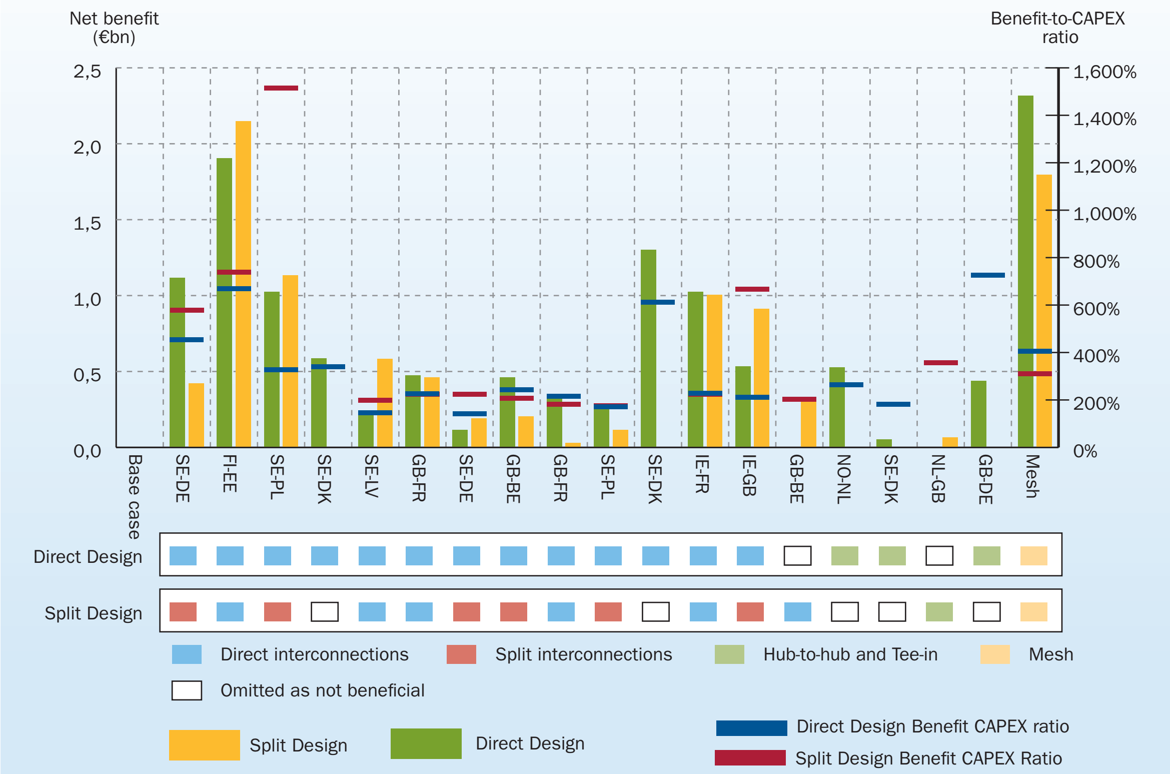


FIGURE 4.33: COMPARISON OF NET BENEFIT AND BENEFIT-TO-CAPEX RATIO PER INTERCONNECTOR CABLE FOR THE DIRECT AND SPLIT OFFSHORE GRID DESIGN METHODOLOGIES (€ BN)



The increase of the interconnector capacity with each step and for each methodology is shown in Figure 4.30. In step 1 and step 2 the additional capacity is larger for the Direct Design compared to the Split Design. This is because split wind farm connections were dimensioned with slightly lower capacity to be most beneficial. Furthermore only one beneficial hub-to-hub connection was identified in the Split Design in step 2. In step 3 the optimal mesh is dimensioned slightly larger for the Split Design and therefore the interconnector capacity increase is larger as well.

The additional grid interconnector capacity that is added to the existing European interconnector capacity to develop the OffshoreGrid overall designs is 27 GW (20 GW excluding the TYNDP interconnectors) for the Direct Design Scenario and 24 GW (16 GW when excluding the TYNDP interconnectors) for the Split Design Scenario.

Case-by-case: relative comparison

Figure 4.31 and Figure 4.32 show a case-by-case comparison between the Direct and Split offshore grid design methodologies, for the reduction in total yearly system costs respectively for the CAPEX spend. They clearly show that the infrastructure costs are generally lower for the Split methodology. Accordingly, the reduction in system costs is also lower in the Split Design as lower additional interconnections capacity is installed (also compare Figure 4.30)[37].

It is obvious from Figure 4.31 that splitting wind farm connections (marked with red boxes) is indeed cheaper than building direct interconnectors. In the Split Design, 6 direct interconnectors are replaced compared to the Direct Design[38]. The average reduction of the CAPEX by choosing a split connection over a direct interconnector is more than 65% (ranging from 40%-84%). At the same time for these split wind

[37] For the infrastructure costs in Figure 4.30, the Split Design is more expensive for three cases. This is either because the distances are too short to cover for the additional equipment (GB-FR), or because a higher capacity is used (second SE-DK, Mesh).

[38] For the reduction in yearly system costs in Figure 4.31, the Split Design reduces the system cost more than the Direct Design in four cases. This is either because no wind farm connection is split and the direct interconnector is still used with higher price differences because of the constraints in the previous cases (FI-EE, SE-LV), or because the capacity is higher ánd the price differences are higher (second SE-DK, Mesh).
Note that this is a result of the chosen method to replace the direct interconnectors from the Direct Design. If an offshore grid would be independently built on split wind connections, the number of possibilities would be higher.

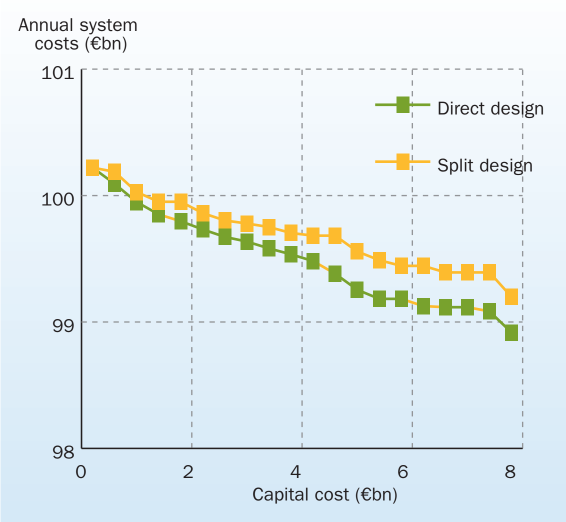
farm connections, the reduction in system cost is only about 40% (ranging from 5-74%) smaller on average, compared to the direct interconnector (Figure 4.31).

Figure 4.33 shows a comparison of the net benefit between the Direct Design and the Split Design[39], and the benefit per invested euro (benefit-to-CAPEX ratio). For the six split wind farm connections, the benefit per invested euro is 1.7 times higher than for the mirrored direct interconnectors of the Direct Design. The net benefit per invested euro CAPEX is on average even 2.6 times higher for the Split Design, which means that each euro is spent 2.6 times more effectively.

Case-by-case: comparison of absolute benefits

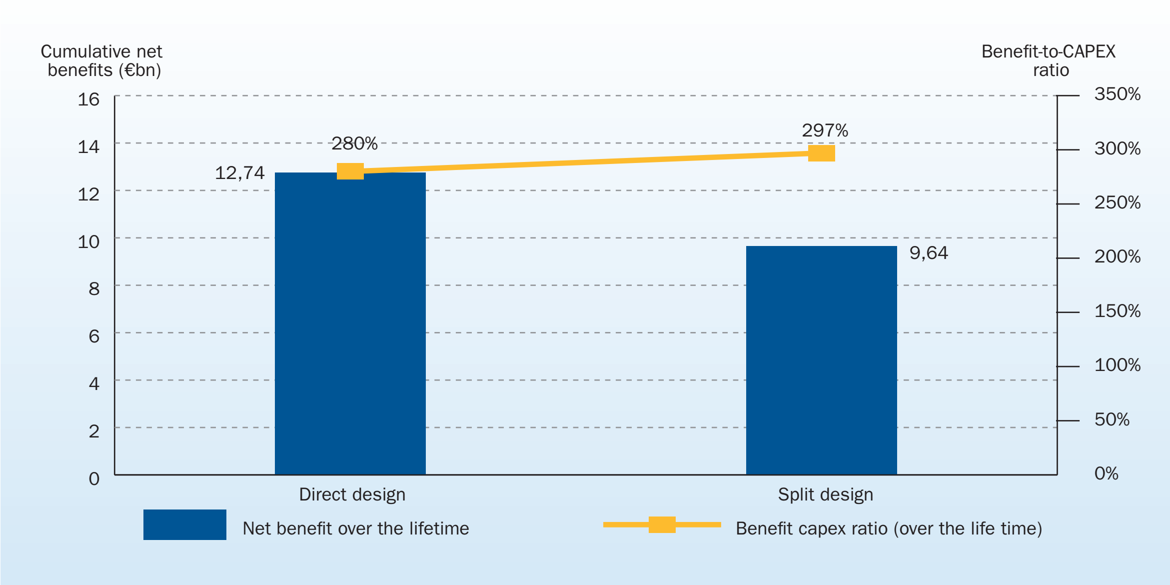
Both methodologies build on step-wise modular grid expansion. In each step new interconnection capacity is added to the system and the infrastructure integrated in each design differs in size and costs. Therefore it is difficult to make an absolute comparison of the cost-efficiency. The graph in Figure 4.34 however gives some more insight in the efficiency of both design approaches. It shows the system cost reductions mapped against the step-wise infrastructure investments.

FIGURE 4.34: ABSOLUTE COMPARISON OF DIRECT AND SPLIT OFFSHORE GRID DESIGNS



Often for a similar investment cost, the system cost reduction in the Split Design is higher than in the Direct Design. As an example, for a CAPEX of €4 bn, the Split methodology leads to an extra 9% of system cost reduction (=€944 m across 25 years) compared to the Direct methodology. Basically only for the cumulative investment of about €1.5 bn the Direct Design is more effective.

FIGURE 4.35: CUMULATIVE NET BENEFIT COMPARISON [€ BN)



[39] When comparing case-by-case, please note that the price difference development is changing differently for the Direct and Split Design as the infrastructures measures are not always the same. Thus, also the benefits of following projects are influenced.

FIGURE 4.36: DC CABLE CIRCUIT AND AC CABLE CIRCUIT LENGTH IN THE DIFFERENT SCENARIOS

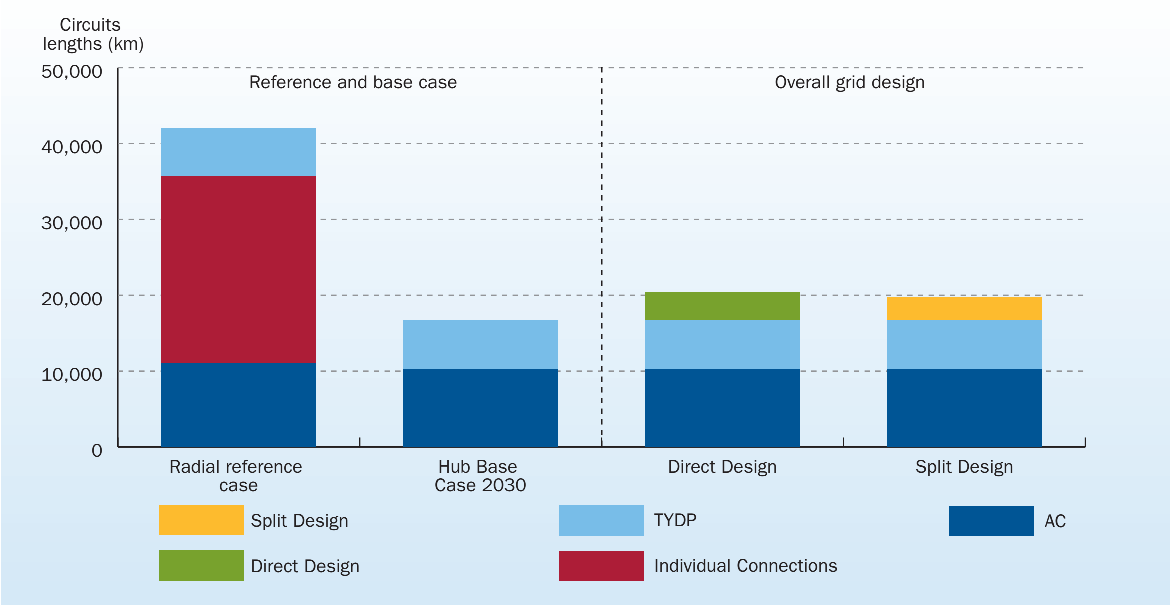
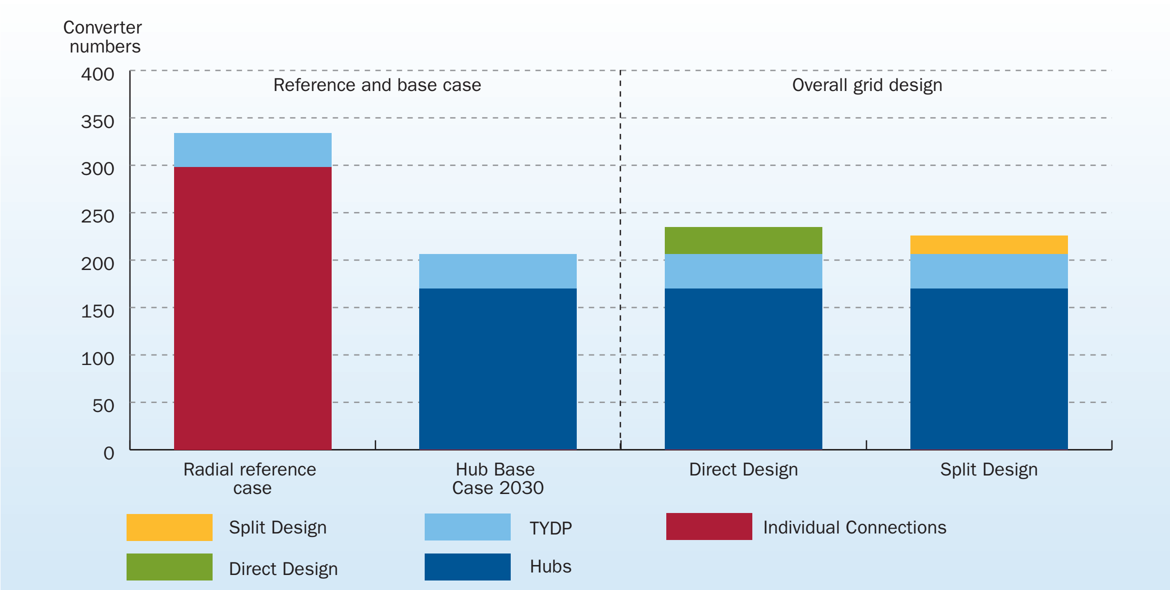


FIGURE 4.37: NUMBER OF INSTALLED DC CONVERTERS IN THE DIFFERENT SCENARIOS



Overall design comparison

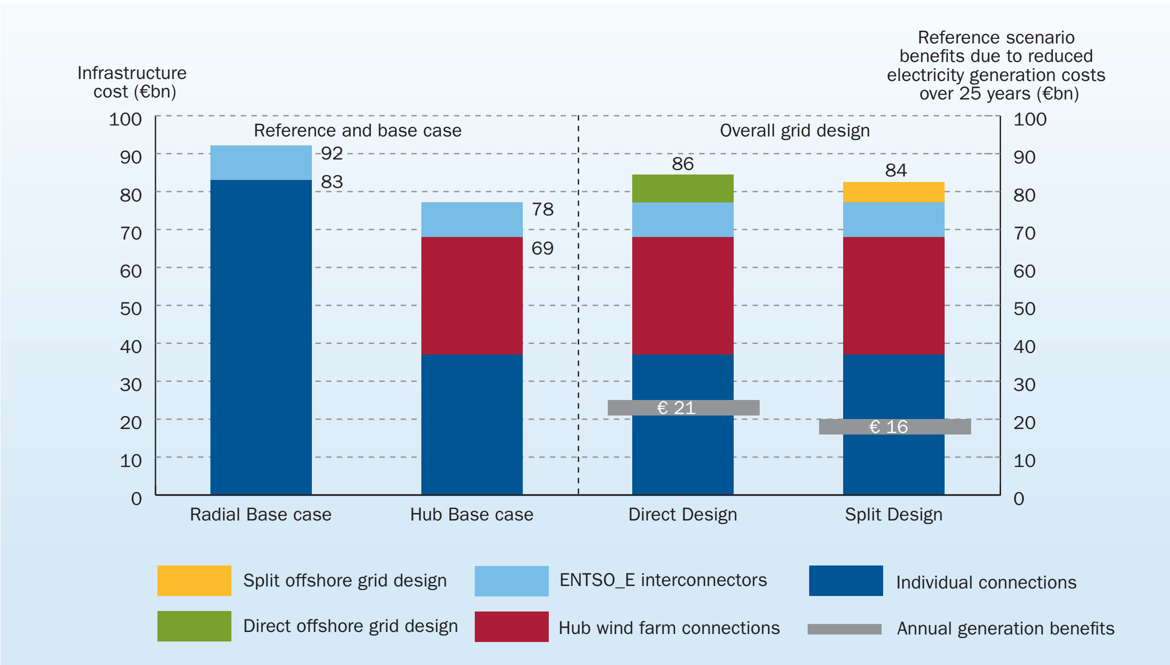
Figure 4.35 compares the cumulative net benefit for the Direct and Split offshore grid designs on an absolute and relative basis (benefit-to-CAPEX ratio). Although the net-benefit of the Direct Design is larger and outweighs the one of the Split Design by €3.1 bn, this does not mean that the Direct Design is more efficient. In fact, this only proves that the Direct methodology has gone further in the development: more is invested in the trade of energy in order to reduce the system cost more. The relative comparison is more interesting here. Even though both designs are highly beneficial and the difference between them is small, the Split Design returns 297% of the initial investment as benefits over 25 years, while the Direct design only returns only 280% of system benefit per invested euro. When evaluating this figure, it should be kept in mind that the Split Design is build based on mirroring the interconnectors in the Direct Design. A complete optimisation starting with split wind farm connections might yield higher benefits when the same overall investment is done.

4.5.5 Infrastructure investment – circuit length and total costs

The previous paragraphs have analysed the additional costs for adding the Direct Design or Split Design to the Hub Base Case scenario. To complete the analysis, this paragraph gives an overview of the total costs of an offshore grid in Northern Europe. Furthermore it is instructive to have a look at the overall circuit length and the number of DC inverters that are implemented in each design. The following scenarios will be compared:

- Radial reference scenario, where all 2030 offshore wind farms are connected with individual connections. The ENTSO-E TYNDP direct interconnectors are included. In this scenario no hub connections are realised.
- Hub Base Case scenario, where the 2030 offshore wind farms are connected via hubs where beneficial. The ENTSO-E TYNDP direct interconnectors are also included. As mentioned before, this is the base case used for most comparisons in the whole document.
- Direct Design scenario: An overall grid design built on the Hub Base Case scenario as described in chapter 4.5.2.

FIGURE 4.38: TOTAL COSTS FOR THE OVERALL GRID DESIGN



- Split Design scenario: An overall grid design built on the hub case scenario as described in chapter 4.5.3.

Cable circuit length and number of installed DC converters

The installed AC and DC cable circuit length for each scenario is displayed in Figure 4.36. The "worst case" Radial reference scenario, in which all offshore wind farms are connected individually, exhibits with 42,000 km the largest overall circuit length to be installed. The circuit length is dramatically reduced to 28,000 km for the Hub Base Case scenario 2030 in which the offshore wind farms are connected to hubs.

The Hub Base Case scenario served as the starting point for the overall grid design development. The additional circuit length to develop these was 3,000 km for the Split Design and 3,800 km for the Direct Design.

The overall circuit length for the overall grid design is 31,000 km for the Split Design and 32,000 km for the Direct Design, 10,000 km of which are AC cables in each of the cases. Note that these figures show the circuit length. As AC circuits use 1 x 3 core AC cable and DC circuits use 2 x 1 core DC cables, the total cable length is higher.

The DC converter numbers for each scenario exhibit the same characteristics for the different scenarios. In the Radial reference scenario almost 300 DC inverters are installed, but the the number is largely reduced to 206 for the Hub Base Case.

In the final Direct Design the overall installed converter number is 235. In the Split Design 226 converters are used.

Overall costs of the different scenarios

Finally, Figure 4.38 summarises the overall costs and lists the overall electricity generation costs. It is important to highlight that the costs should always be compared taking into account the system benefits of reduced electricity generation costs due to larger trade capacities via the additional infrastructure. Please note that the infrastructure costs have only been assessed up to the onshore connection point.[40] Costs for onshore grid reinforcement needs are not included.

- **Costs and benefits of the Radial reference scenario**
  It is clearly most expensive to connect all offshore wind farms individually without considering hubs connections. Including the ENTSO-E TYDNP interconnectors, the investment costs until 2030 would amount to €92 bn.

TABLE 4.7: UTILISATION OF WIND FARM CABLES

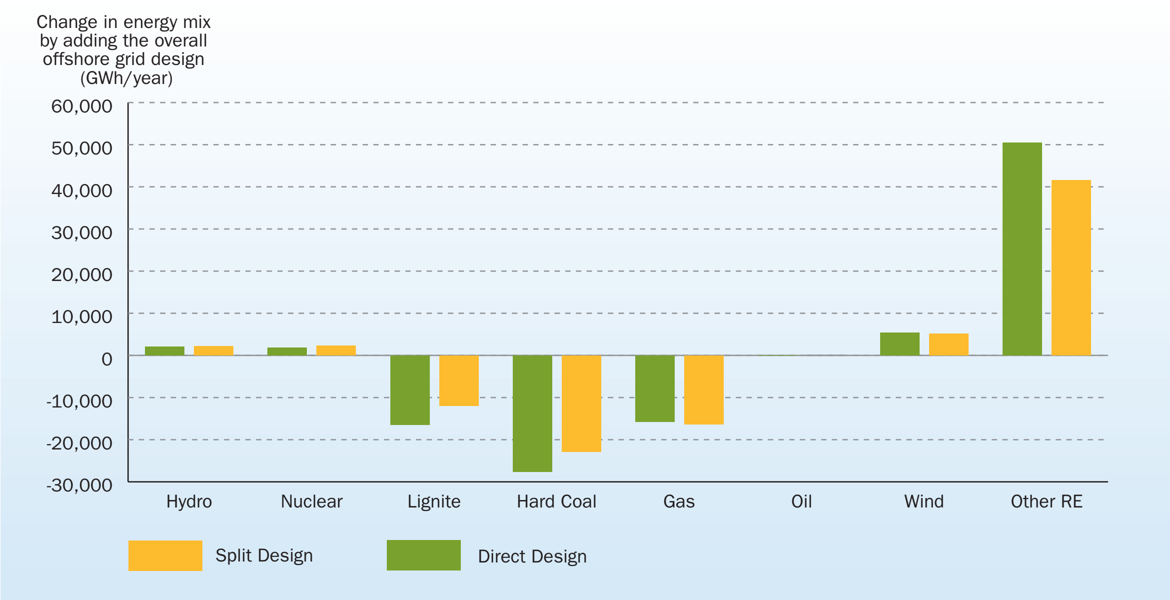
Connection		DogC-GB	DogE-GB	NorfB-GB	Ljm_5-NL	Ljm_2-NL	Idunn-NO	Ægir-NO	Gaia-DE
Hub Base Case (Step 0)	Cap MW	1,800	1,800	1,800	1,800	1,350	990	900	1,710
	Util %	53.8	53.6	53.0	53.4	53.3	56.5	57.1	55.0
Direct Design (Step 2, before mesh)	Cap MW	1,800	1,800	1,800	1,800	1,350	990	900	1,710
	Util %	53.8	71.3	68.4	67.7	68.4	59.0	57.1	65.2
Direct Design (Step 3)	Cap MW	1,800	1,800	1,800	2,800	1,350	990	900	1,710
	Util %	53.8	81.8	59.7	77.1	53.3	74.8	57.1	62.8
Split Design (Step 2, before mesh)	Cap MW	1,800	1,800	1,800	1,800	1,350	500	500	1,710
	Util %	53.8	53.6	59.3	53.4	53.3	85.1	85.2	55.0
Split Design (Step 3)	Cap MW	1,800	1,800	1,800	2,800	1,350	2,010	500	1,710
	Util %	78.3	79.1	55.8	73.0	53.3	79.7	81.5	62.8

[40] For Germany onshore connection points have been chosen far inland. This approach is based on the detailed national study dena-Netzstudie I (dena grid study I). The connection points far inland increase the overall connection costs to certain extend.

- **Costs and benefits of the Hub Base Case scenario 2030**
  The costs for the offshore wind farm connections are significantly reduced in the Hub Base Case scenario. As a large number of wind farms is connected with cost efficient hub design concepts, the overall infrastructure costs are decreased by €14 bn to €78 bn (incl. TYNDP interconnectors). However the hub design connections do not build new transmission corridors between countries, therefore the annual power system generation costs remain at the high level and no generation costs benefits are produced.
- **Costs and Benefits of the Direct Design scenario and the Split Design scenario**
  The direct and Split Designs are built on the Hub Base Case scenario 2030. Additional grid infrastructure is added: direct interconnections, hub-to-hub interconnections, tee-in interconnections and meshed grid designs. As additional infrastructure is added in both cases the costs are increased compared to the Hub Base Case scenario. The overall costs of the Direct Design offshore grid amount to €86 bn. The Split Design offshore grid is €2 bn less expensive and costs €84 bn in total. At the same time the annual system generation costs are largely decreased as both designs add new electricity trading capacity to the system. The annual benefits of €1.02 bn (Split Design) and €1.3 bn (Direct Design) amount to a net present value benefit of €16 bn (Split Design) and €21 bn (Direct Design) across a lifetime of 25 years.
- The additional infrastructure costs to develop the Direct or Split Design on top of the Hub Base Case scenario 2030 are relatively low. They represent only 7% (Split Design) to 9% (Direct Design) of the Hub Base Case wind farm connections and the ENTSO-E TYNDP interconnectors. At the same time they generate large benefits of about three times the investments.

The enormous investments into offshore grid infrastructure have to be put into relation to the offshore wind energy produced. The offshore wind farms considered in OffshoreGrid produce about 530 TWh annually which is about the annual consumption of Germany. Across 25 years this amounts to 13,300 TWh. Based on average spot market prices of €50/MWh, the value

FIGURE 4.39: CHANGE OF PRODUCTION PER TECHNOLOGY IN ENERGY MIX BY ADDING THE OVERALL OFFSHORE GRID DESIGN (FOR THE DIRECT DESIGN AND THE SPLIT DESIGN) [CHANGE IN GWH/YEAR]



of this electricity would be €421 bn. In this regard the infrastructure costs only represent about a fifth of the electricity value that is generated.

Please note that in the calculation of the net investment for the overall grid design, only the additional benefits of the OffshoreGrid overall design were taken into account. As the ENTSO-E TYNDP interconnector plans were included in the base cases (Radial reference scenario and Hub Base Case scenario 2030), their system benefits were not explicitly calculated.

4.5.6 Power system impact of the offshore grid

The power market model provides a large number of interesting results. In the following paragraphs, the impact of the offshore grid and the chosen design on the power system and the infrastructure is investigated, in particular for the following issues:

- Utilisation of wind farm grid connection cables: The offshore grid combines the transmission of wind energy and the trade of electricity, and thus leads to an increase in wind farm connection cable utilisation (full load hours of the cable use).
- Influence on energy mix: As the offshore grid enables more trade of electricity over large distances, power can be generated where it is cheapest.
- Flexibility provision: The offshore grid leads to the spatial smoothing of short term renewable energy variations, as discussed in section 4.1. As such, this reduces the balancing needs in the system.

The utilisation of wind farm grid connection cables and the influence of the offshore grid on the energy mix are explained below. A more detailed analysis on the balancing of wind power can be found in Annex D.III.V.

Utilisation of cables for wind farm grid connection

As discussed above, some wind farm hubs are nodes within the offshore grid and thus not only transport wind energy but are also used for trade. Accordingly, the utilisation of the cables connecting these hubs changes with the development of the offshore grid as also the power flows change.

Table 4.7 illustrates the increase in utilisation of some representative wind farm hub connection cables that connect the hub to shore. Of course only those hubs were selected that connect to more than one country as otherwise the utilisation of the cables would be independent of the offshore grid development and remain constant. The analysis compares the utilisation of the cables in the hub base case scenario with the utilisation after step 2 and step 3 within the Direct and Split Design (compare sections 4.5.2 and 4.5.3).

For the values marked in the table, the wind farm connection is just an individual connection to one onshore connection point within the associated design step[41]. No electricity is traded via these lines and therefore these do not exhibit changes in utilisation as long as no wind power is curtailed due to onshore grid constraints.

Typically the utilisation of the wind farm cables to shore will increase when the hub is connected to an offshore grid or to another shore. This is because the connections are then also used for electricity trade. On average, for the connections that are coupled to another point in the Direct Design (before the mesh), the utilisation rate is improved with 22%. For the Split Design the increase is even larger (29.7%). Adding the mesh in step 3 to the design improves the utilisation rate with about 3-4% in both cases.

As can be seen from the table, there are some exceptions which see rather a decrease of the utilisation rate when adding the mesh (e.g. the connection of Norfolk B to Great Britain, or the connection of Aegir to Norway). There are always two possible reasons for these:

- The mesh connection is mostly used to send the wind energy to a higher priced area so that the original individual cable connection is used less,

[41] For individual wind farm connections, the capacity of the wind farm connection cable is 90% of the wind farm capacity, as described in Deliverable 5.1, available online [26].

- There are other connections that already take up the price difference and provide the arbitrage needed so that no trade is necessary any more.

Where such impacts can be expected, a detailed assessment should be done to optimise the rating of the different lines. For example, in the exceptions described above, a lower cable capacity from the wind farm to shore can be a better option.

Offshore grid influence on energy mix

Improved grid infrastructure enables more power flow, and therefore more flexibility in the power production. This in turn gives reduced system costs, since it allows a better use of the generation units with lower marginal costs. Figure 4.39 shows how large the change in production is for each technology in the energy mix.

As expected, it is clear that the offshore grid facilitates a shift from more expensive gas and hard coal to cheaper generation, in particular "Other RE". The category "Other renewables" stands in this case for all renewable technologies that are neither wind energy nor hydro, such as bio energy, solar, tidal and wave. This shift in generation mix can be best understood when considering the marginal costs for the generation technologies, which are:

- Other renewables ~ €50.6/MWh
- Lignite coal ~ €58.3/MWh
- Hard coal ~ €62.0/MWh
- Gas ~ €70/MWh

The small increase in wind power is due to reduced grid constraints because of the offshore grid[42]. The increase is indeed small compared to the total annual production of 530 TWh. The change in hydro power output is due to pumping facilities.

The change of the energy mix is bigger for the Direct Design since it involves a higher interconnection capacity, as described above.

4.5.7 Conclusion and discussion

Summary of the techno-economic conclusions

Two methodologies have been assessed for the development of an offshore grid in northern Europe. The first approach, the Direct Design, was based on the consideration that currently various direct country-to-country interconnections are being developed. In order to develop a most realistic approach the most beneficial direct interconnectors were identified in a first step. After that, hub-to-hub and tee-in solutions as well as a mesh were assessed. The second approach, the Split Design, is based on results of the case-independent model (see section 4.4). The case-independent model showed that it is promising to create interconnections by splitting the connection of large wind farms far from shore to two countries. This way, the wind farm is connected to shore and at the same time an interconnector is established at relatively low costs.

A high number of interconnection cases and design variations have been assessed with the model. They have been narrowed down from the vast number of possible designs by considering the results of the case-independent model. Furthermore the electricity price levels within the different countries were analysed to identify the most promising trading corridors.

The results confirmed that it can indeed be beneficial from a European welfare point of view to tee-in wind farms, to interconnect countries via wind farm hubs, and to split the connection of large wind farms in order to connect it to two shores.

As shown in section 4.5.4, the conclusion of the case-independent model on the split wind farm connections is confirmed, by the relative comparison of the six split wind farm connections in the Split Design versus the corresponding direct interconnectors in the Direct Design. The average reduction in CAPEX from choosing a split connection over a direct interconnector is more than 65%, while the reduction in system cost

[42] There are fewer constraints so that more wind power can be transmitted. Due to the interconnections, some of the wind generation that would otherwise be curtailed because of the 90% assumption can now also be transported.

is only about 40% lower on average. A comparison of the benefit per invested Euro of CAPEX revealed that in the Split Design for each Euro spent about 3 Euros are earned as benefit over the lifetime of 25 years, while for the Direct Design these are only 2.8 Euros. Thus, the Split Design is slightly more cost-effective.

In conclusion, both developed overall grid designs prove to be highly cost-effective and largely reduce the system generation costs. Both designs return the investment made within short time and lead to large net benefits.

Total costs

The overall costs for the Direct Design are about €86 bn and €84 bn for the Split Design respectively. This includes investment costs for the Hub Base Case scenario as a starting point which represents connection of 126 GW of offshore wind as well as the ENTSO-E TYNDP interconnectors.

The costs for a further interconnected grid built on top of this Hub Base Case are only €7.4 bn for the Direct Design and €5.4 bn for the Split Design. These relatively small additional investments generate system benefits of €16 bn (Split Design) and €21 bn (Direct Design) across a lifetime of 25 years – benefits of about three times the investment.

The total circuit length of the Split and Direct Design is about 30,000 km (10,000 km AC, 20,000 km DC). The hub base case scenario however already accounts for 27,000 km, while the additional circuit length to build the Direct or Split Design is only about 3,000 km. The overall offshore interconnection capacity is boosted from the existing 8 GW to more than 30 GW in the Direct and Split Design.

The investments into offshore grid infrastructure have to be put into relation to the offshore wind energy produced. The offshore wind farms considered in OffshoreGrid produce about 530 TWh annually which is almost the annual consumption of Germany. Across 25 years this amounts to 13,300 TWh. Assuming today's average spot market price of €50/MW the value of this electricity is €421 bn. In this relation the infrastructure costs only represent about a fifth of the electricity value that is generated offshore.

Discussion of the results in a broader context

- **Strong business case of split wind farm connections**
  As clearly shown by the OffshoreGrid results, any interconnector has in general a negative impact on the already existing interconnectors. This is a serious investment risk for the developer. The business case of any new interconnector should therefore be very strong to withstand the negative impact of future infrastructure measures. The split wind farm connections are ideal candidates for such strong business cases since both the wind farm connection and the economical trade add to the benefits of the project. It is less dependent on trade than a direct interconnector, and can therefore still be beneficial even with lower price differences.

- **Merchant interconnector concept to be reviewed**
  Following the same reasoning on the negative impact of new interconnectors on the existing ones, the policy for merchant interconnectors which receive exemption from EU-regulation should be reviewed. Investors in and owners of merchant interconnectors are encouraged to obstruct to any new interconnector, as this will reduce the price difference and thus their return on investment. This can put the strive to have a single EU market for electricity seriously at risk.

- **Beyond the economics – technical advantages of an interconnected grid**
  Apart from the techno-economic reasons as described above, the Split Design provides further advantages. It reduces the total cable length and thus provides environmental benefits. Moreover, it improves the redundancy for the wind farm connection as two connections to shore are established. This improves system security and reduces the system operation risks, the need for reserve capacity, and the loss of income in case of faults.

These merits also hold for tee-in connections and hub-to-hub connections. It should be highlighted that they need to be taken into account when assessing single concrete cases.

- **Interconnected grids require an appropriate regulatory framework**
  On the other side, tee-in solutions, hub-to-hub solutions and split wind farm connections are confronted with the unsolved problem of regulatory framework and support scheme incompatibilities between European countries (also see section 5.1.2). The reason is that renewable energy that is supported by one country can now flow directly into another country. The country paying for the generated energy cannot "enjoy" all benefits that go along with it.
  For split wind farm connections, this is even more difficult. The reason is that the ideal split connection links the wind farm to two different countries, and the connection capacity to the country in which the wind farm is located is reduced. The question is then e.g. which support scheme is applied and to which national RES account the produced wind energy is added to. These complexities can significantly slow down the development of integrated and especially split connections. Therefore solutions at international or bilateral levels have to be developed as soon as possible.

An offshore grid will be built in modular steps. Every new generation unit, interconnection cable, political decision or economical parameter has a serious impact on both the future and the existing projects, and thus influences the design of a future offshore grid. However, the two designs presented bring useful understanding and conclusions that allow bringing the actual developments forward with modular steps in the best possible way.

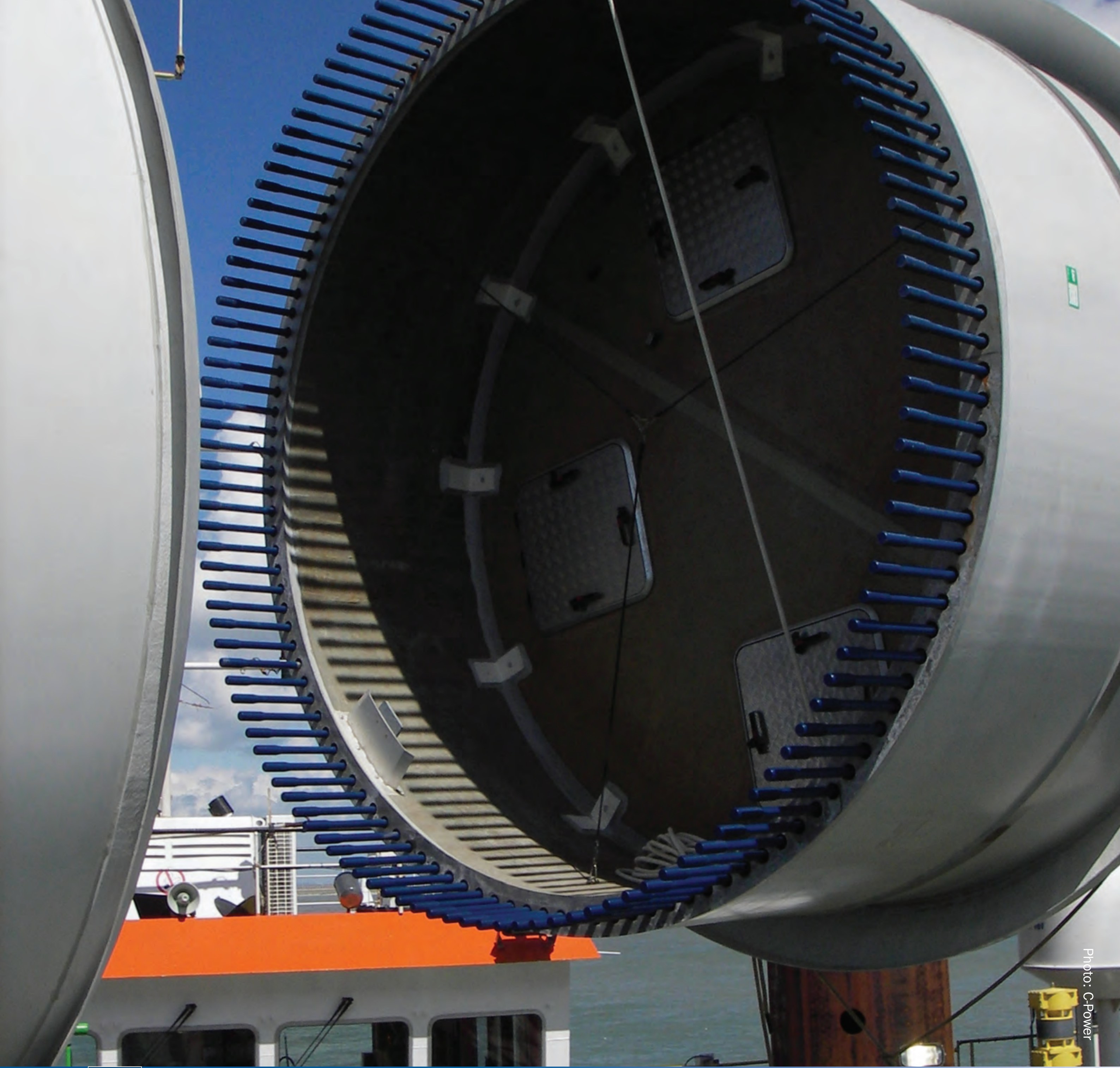


Photo: C-Power

5 TOWARDS AN OFFSHORE GRID – FURTHER CONSIDERATIONS

- Challenges and barriers
- Ongoing initiatives – policy – industry

5.1 Challenges and barriers

OffshoreGrid focuses on the techno-economic assessment of the offshore grid. Policy trends, regulatory issues and industry developments are taken into account directly or indirectly, for instance during the scenario development (nuclear phase outs, support schemes and their development), or while identifying concrete cable paths when the maritime spatial planning was analysed. This ensures technical and political feasibility of the project, but at the same time asks for adaptations or discussion on some regulatory, industry or policy issues. The OffshoreGrid consortium identified a optimal offshore grid design. Its realisation within a reasonable time frame raises further challenges, as discussed in the table below. These challenges and issues are sorted according to the following categories:

- Operation and maintenance of an offshore grid and further technical challenges
- Regulatory framework and policy
- Market challenges and financing
- Offshore industry supply chain

The relative magnitude of these challenges are outlined in Table 5.1, as split into the four categories listed above.

TABLE 5.1: CHALLENGES ON THE WAY TOWARDS THE OFFSHOREGRID DESIGN

• = Small challenge
•• = Medium challenge
••• = Large challenge

The categorisation of the challenges from small to large challenges is based on a qualitative assessment of the OffshoreGrid consortium. It is understood as guidance for the reader in order to identify the key issues that need concerted attention.

Operation and Maintenance of an offshore grid and further technical challenges	
•	Offshore Grid Maintenance
•••	Timing of technology development
••	Commodity Prices
•	Standardisation
•••	Onshore bottlenecks
Regulatory Framework and Policy	
•••	Support Scheme
••	Permitting
••	Operational responsibilities and offshore grid codes
Market Challenges and Financing	
•••	Financing the large investments
•••	Capital attraction
Supply chain	
••	Supply bottlenecks

5.1.1 Operation and maintenance of an offshore grid and further technical challenges

For the installation of an international offshore grid, various challenges regarding operation and maintenance as well as technical barriers have to be overcome.

Offshore grid maintenance

Offshore grid faults in times of high wind penetration have to be counteracted with quick and large primary control reserves. Whether these primary control reserves are already present at all sites is questionable. If not, their construction or market integration is a necessary condition for maintenance of an offshore grid.

The time needed to repair offshore grid outages can be significantly longer than would be the case for onshore grid maintenance, due to difficulties in accessing the equipment offshore (cables and converters). However, as the fault can be isolated, the downtime only affects an isolated section while the remaining grid can return to operation.

The maintenance costs for the offshore grid will generally be higher than for the onshore grid, particularly due to small weather windows and a small number of capable firms.

At the aggregate level, offshore grid maintenance issues are regarded by OffshoreGrid consortium to be a small barrier for an offshore grid.

Timing of technology development

The timing of technology development has been found by the OffshoreGrid consortium to be a large challenge for an offshore grid. There is a variety of new technologies needed for safe and secure offshore grid operation, particularly with respect to power flow control mechanisms, security issues, increased capacity and reduction of energy losses.

The key issue to be tackled is multi-terminal operation. So far, fast DC breakers are not fully developed and multi-terminal operation is not possible. In case of an offshore grid failure the complete grid has to be de-energised, the fault has to be isolated, and only then can the offshore grid be loaded again. This can also have serious impact on the onshore grid stability due to frequency problems. Furthermore it should be highlighted that TSOs do not have any experience with multi-terminal operation based on HVDC VSC technology.

The timing of technology development will depend on the likely order value, which in turn depends on the connection method the offshore industry adopts. For example the adoption of a model whereby offshore wind farms are clustered around offshore transmission hubs may drive an increase in the capacity of individual VSC converter stations, whereas a continuation of the trend of individual wind farm connection may not.

Commodity prices

The overall cost of the offshore grid is largely influenced by the cost of the key raw materials, most notably the raw materials used in HVDC and HVAC subsea cables, as they form by far the largest component of the offshore grid. Two metals tend to be used to form the conductors in power cables, copper and aluminium. The superior conductivity of copper means that more electric current (and hence more power) can be passed down a copper conductor of certain cross sectional area than down an aluminium conductor of the same size. This means that copper cables are smaller than the equivalent aluminium cables which can make transport and installation easier, both important and expensive considerations in the offshore environment. The surge in global demand for copper however has not only driven the price of copper to peak levels, but also introduced significant volatility in the pricing (See Figure 5.1 below). Any manufacturer using significant amounts of copper as a raw material would obviously offset this price risk in the equipment quotes, potentially pushing up the price of many of the pieces of equipment required for an offshore grid. Indeed many recent subsea cable orders have been specified with aluminium, primarily because of the high copper price.

At the aggregate level, the future development of key commodity prices is assessed by the OffshoreGrid consortium as a medium barrier for an offshore grid.

FIGURE 5.1: PRICE OF COPPER ON THE LONDON METAL EXCHANGE OVER THE LAST TWENTY FIVE YEARS (SOURCE: WIKIPEDIA FROM LME SOURCE DATA)

Standardisation

The adoption of common standards across the European sphere or even globally, should result in more 'standard' designs. The standardisation should in particular focus on functionalities as e.g. for:

- fault behaviours
- system protection schemes
- control and protection

Standardisation can reduce costs and also facilitates interconnectivity offshore. In particular it allows offshore wind farm and grid connection developers to buy equipment from different suppliers instead of ordering from a small group of manufacturers that offer turnkey solutions, for instance for HVDC VSC connections.

At the same time it is important to keep the standardisation to the necessary minimum in order not to hamper innovation. Therefore OffshoreGrid recommends focusing on standardisation of functionalities of equipment rather than defining concrete technical specification. This allows manufacturers to develop different technical solutions while still facilitating the interoperability of equipment.

Standardisation has been assessed by the OffshoreGrid consortium as a small barrier.

Onshore bottlenecks

A strong onshore grid is needed for the safe transmission of offshore power from the coast towards the onshore load centres. For Germany this was worked out during in-depth assessments within the dena Grid Study I and dena Grid Study II [31], proving the need for huge transmission capacity from the north to the south[43]. But the need for onshore transmission is also crucial in other European countries. In many European countries the necessary onshore grid reinforcements are often delayed due to low public acceptance.

Without the timely development of a sufficiently strong onshore grid, offshore grid development is put at risk. Therefore, onshore bottlenecks are regarded by the OffshoreGrid consortium as a large barrier for an offshore grid.

5.1.2 Regulatory framework and policy

An offshore grid involves different countries and transnational markets and a variety of support schemes and regulatory frameworks. The large diversity across Europe is summarised in Figure 5.2. Further details are listed in Table 14.1 in Annex E[44]. The difference in national regulatory systems and support schemes and in particular their incompatibility can in some cases be a barrier for the construction of an offshore grid as outlined below.

Support scheme

Most countries use feed-in tariffs, but certificate or bonus systems as well as combined systems are also implemented. The difference of support schemes is not per se a hindrance for the construction of an offshore grid and in most cases specific national support schemes are adapted to the specific national needs.

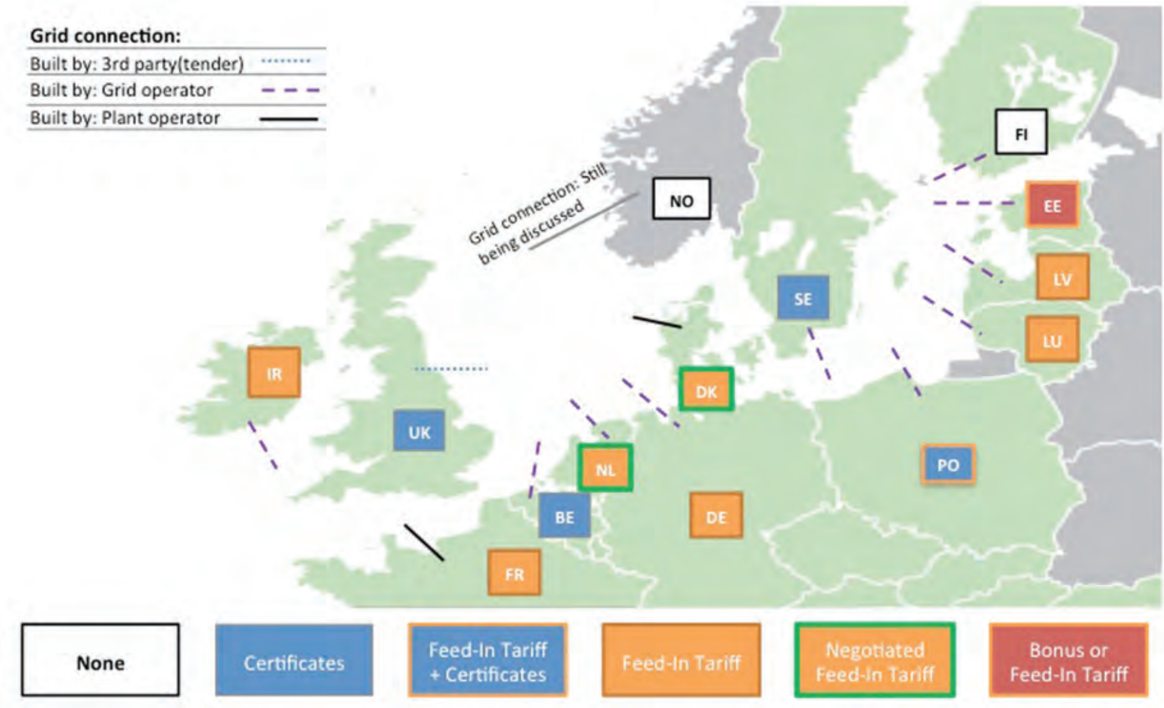
For the development of an offshore grid it is crucial to ensure their compatibility. The OffshoreGrid consortium understands the compatibility of support schemes as the possibility to allow offshore wind farms to be connected to two or more countries either directly or via an offshore grid without endangering the financial support for the offshore wind farm. The support should furthermore be guaranteed independently of the electrical power flows and whether the offshore wind power is sold across national borders.

The geographic scope of national offshore support schemes diverges considerably across Europe. In most countries support schemes are limited to the territory or the electricity system of the country. This

[43] The German decision on the nuclear phase-out might even enforce the need for north-south transmission, as most of the nuclear power plants are located in the south.

[44] A detailed overview over national support schemes, connection regulation and trade limitations is given in Deliverable 6.1 [29].

FIGURE 5.2: OVERVIEW ON OFFSHORE WIND SUPPORT SCHEMES AND GRID CONNECTION



hinders for instance the installation of wind farms outside national territories of one country while connecting it to this country. International agreement and consolidation on this issue is greatly needed.

It should be mentioned that besides the incompatibility of support schemes, also unaligned national offshore wind energy development goals can hamper the development of an offshore grid. This is because strategic cross-border coordination with compatible offshore goals, siting and timing can strongly support the offshore grid development with offshore wind farm clusters as major nodes.

Permitting

The permitting processes for offshore wind farms and their connection to onshore landing points differ widely across countries. This represents a medium barrier from the point of view of the OffshoreGrid consortium. There is a wide variety in the number of national executive authorities involved in each country, and not all countries carry out maritime spatial planning. This causes the national permitting processes to differ in level of detail, duration and costs, and they are largely unsynchronised between authorities.

In most countries however the grid connection responsibility lies with the national TSO who is obliged to provide connection to offshore wind farms. This facilitates a coordinated joint action among the responsible TSOs which can for instance be led by ENTSO-E.

Operational responsibilities and offshore grid codes

The clear allocation of operational responsibilities between national TSOs is seen as a medium barrier for an international offshore grid. Also, the harmonisation of offshore grid codes used represents a challenge. The possibility of setting up an internationally owned and operated offshore TSO is currently discussed [46]. The development of European network codes as initiated by the European Commission is a first step towards overcoming this challenge. For instance the grid code on the connection requirements for offshore wind turbines across Europe is planned to enter into force in 2011/2012. Additional network codes, for example codes for the grid operation or a network code on electricity markets may further enhance the coordinated planning of an offshore grid as well as its save operation.

5.1.3 Market challenges and financing

Economic barriers, due to market frictions or failures and unfavourable financing conditions, hinder the installation of an offshore grid in many ways.

Financing the large investments

As can be seen from the results of this report, the establishment of an offshore grid is going to be expensive. This is largely due to the large amounts of equipment required, but also to the high cost of both the equipment costs and the installation costs of this equipment in an offshore environment.

The overall (calculated) benefits of an international offshore grid from the system perspective cannot directly be returned to an investor. Still these huge investments are needed. Therefore an indication of long-term commitment and reliability in national offshore policies is needed to attract investors. Otherwise, investments in onshore and offshore grid infrastructure will not be made in sufficient magnitude. In addition, it may be the case that publicly funded securities are needed to give a break-through for pioneering offshore investments.

At the aggregate level, raising enough funds for an offshore grid is assessed by the OffshoreGrid consortium as a large challenge. The commission started to tackle the problem in the energy infrastructure package [23].

Capital attraction

The offshore industry faces ongoing up-front financing problems for offshore wind energy and grid projects due to the high risks that come along with it. Currently, the finance industry spreads its risk conservatively due to instability of credit markets and asks for high risk premiums.

Fundraising for offshore projects is additionally hindered by the long-term uncertainty over offshore wind farm development and the available locations for these projects. The risks of stranded investments remain comparatively high. Therefore, the barrier of capital attraction is assessed as large by the OffshoreGrid consortium.

5.1.4 Supply chain

There are relatively few manufacturers of some of the key elements that will be required to create an offshore grid, with correspondingly few manufacturing facilities and hence elevated demand for few manufacturing slots. An expected increase in demand for these technologies both in Northern Europe and globally means that prices will remain high and delivery times to projects constrained, unless the manufacturers have sufficient confidence in the market to justify investment to expand their manufacturing base. This conundrum remains one of the key barriers to not only reducing the cost of individual components, but also to achieving an offshore grid in the North and Baltic Seas.

Supply bottlenecks

Offshore wind energy is considered a cornerstone of European energy policy, however it still needs development and experience is needed in order to reduce risk estimations for investments. The envisaged 150 GW of installed wind capacity and the necessary transmission capacity needed to realise the proposed offshore grid design in 2030 is enormous, and the demand for equipment and trained personnel along the supply chain will be huge.

Currently it is noticed that there are supply chain bottlenecks for the main components of HVDC technology which can slow down the development of offshore wind farm connections. For singular cases it might be necessary to fall back upon AC connection concepts until the supply chain is fully able to deliver the requested equipment on time.

Due to today's uncertainties, some supply chain manufacturers are hesitant to carry out the needed investments to meet future demand. Therefore there is a risk that supply chain bottlenecks endanger continuous and steady development towards the envisaged efficient scenarios in 2030.

In particular, the development of appropriate harbour infrastructure and the number of laying vessels or ships capable of transporting offshore wind turbines are significant bottlenecks for an offshore grid.

Supply bottlenecks are regarded by the OffshoreGrid consortium as a medium barrier for an offshore grid.

5.2 Ongoing initiatives – policy – industry

First of all it has to be highlighted that apart from OffshoreGrid, there are few studies that analysed cost and benefits of an offshore grid.

- The PhD thesis by Gregor Czish [34] and the European IEE-funded project TradeWind [36] have briefly looked into the issue. Both studies outline first analysis, but no specific research was carried out.
- Greenpeace has developed a map of a possible offshore grid [35]. If it were to be built with 6,200 km of offshore electricity cables, the cost is estimated at about €15-20 bn.
- In February 2011, ENTSO-E published its views on offshore grid development in the North Seas [45]. Its initial view is that an integrated approach can deliver capital savings in the order of 10%.
- The initiative 'Friends of the Supergrid' has published a position paper on a first phase of the supergrid [44]. The design is based on connecting 23 GW of offshore wind from the Firth-of-Forth, Dogger-Hornsea, Norfolk Bank, German and Belgian Offshore clusters using technology expected to be available between 2015 and 2020. FOSG emphasises the need to connect to the large energy storage facilities in Norway. According to their estimates, the grid tariffs will need to rise by €0.0023 per kWh to recover the costs.

The OffshoreGrid study is clearly needed to advance the discussion and provide input for policy and industry discussion. Some of the ongoing initiatives are mentioned below.

Policy initiatives

Since 2009 the analysis of an offshore grid is a focus of attention on a European and national policy level. One of the European Commission's goals is to design a single integrated European market for electricity. An offshore grid in Northern Europe, interconnecting offshore wind and national power systems, is seen as vital in achieving this goal. The European Commission thus took a leading role by fostering discussion in different working groups. They also provide funding for a variety of projects to investigate relevant questions, such as optimal grid design (OffshoreGrid), questions concerning offshore wind potential (WindSpeed, [37]) and maritime spatial planning (Seanergy 2020, [38]).

Within the framework of the Trans-European Energy Networks for Electricity (TEN-E), a coordinator has been assigned to coordinate all activities related to Baltic and North Sea offshore wind connections. The coordinator, Mr. Adamowitsch, has started a well-frequented working group with regular meetings in which research, industry and policy representatives discuss barriers, challenges and solutions for a future offshore grid. The OffshoreGrid consortium actively follows this working group and provides input and presentations.

Furthermore, at the end of 2010, a new infrastructure package has been published by the European Commission. It involves a Communication on offshore grids [23], and sets the framework for further policy actions. In the Communication, the Commission defines 8 EU priority corridors for the transport of electricity, gas and oil. One of these priority corridors is an offshore grid in the Northern Seas. The OffshoreGrid consortium actively supported the European Commission in the policy making process. Specific questions were studied upon request and new results were exchanged proactively. The text and recommendations in [23] are based on the OffshoreGrid Draft Final Report [27].

There is also movement on the regional level. What originally started in the Pentalateral Energy Forum (Governments, TSO's and regulators of BE, FR, NL, LU and DE) under the initiative of the Belgian Minister of Energy, has evolved into a political initiative with all ten countries around the North and Irish Sea (BE, FR, NL, LU, DE, UK, IR, DK, SE and NO). The North Seas Countries' Offshore Grid Initiative (NSCOGI) aims at coordinating, on a multilateral level, offshore wind and infrastructure developments in the North Sea. It is more specifically targeted at achieving a common political and regulatory basis on offshore infrastructure development within the region. A common Memorandum of Understanding between all parties has been signed at the end of 2010 [39]. Much is expected from this initiative for the facilitation of real developments. In this framework, TSOs will carry out a cost-benefit analysis by December 2012. The OffshoreGrid consortium is in regular contact with Working Group 1 of the NSCOGI on Grid Configuration. The preliminary outcomes have been presented to this working group, and a session on the final results will be held in October 2011.

Industry level

As imposed by law under the Third Legislative Package on European Electricity and Gas Markets [40], European Transmission Grid Operators (TSOs) for electricity have united under ENTSO-E [41]. This organisation improves cooperation across national borders, and is thus crucial for the development of offshore electricity grids. Within ENTSO-E, two working groups are relevant in this respect:

- Regional Working Group North Sea under the System Development Committee,
- WG 2050/Supergrid under the System Development Committee.

The regulators cooperate voluntarily via the Council of European Energy Regulators (CEER). A key objective of the CEER is to facilitate the creation of a single, competitive, efficient and sustainable EU internal energy market that works in the public interest. The European Regulators' Group for Electricity and Gas (ERGEG) was set up by the European Commission in 2003 as its advisory body on internal energy market issues. ERGEG launched 7 Electricity Regional Initiatives (ERI, [9]), with the aim to speed up the integration of Europe's national electricity markets. Under the European Commission's Third Package [40], all European regulators are now united in the Agency for the Cooperation of Energy Regulators (ACER, dissolving ERGEG). ACER was created in 2010, as imposed by the 3rd package, to fill the regulatory gap on cross-border issues and should oversee the cooperation between the TSOs. Although there are various challenges to face on regulatory level (cost allocation and profit margins, compatibility in renewable energy support, etc.), action on offshore grid issues on the regulator's side is currently very limited.

Finally, the initiative 'The Friends of the Supergrid (FOSG)' [42] combines companies in sectors that will deliver the HVDC infrastructure and related technology with companies that will develop, install, own and operate that infrastructure. They have joined because of a mutual interest in promoting and influencing the regulatory and policy framework that is required to enable large-scale interconnection in Europe.

6 CONCLUSIONS AND RECOMMENDATIONS

- **Wind farm hubs**
- **Tee-in solutions**
- **Hub-to-hub solutions**
- **Overall grid design**
- **Overall recommendations**

The OffshoreGrid project provides concrete recommendations and guidelines on the topology and dimensioning of an offshore grid in northern Europe. Furthermore recommendations for policy, industry and the financing sector are also made in order to ensure that the offshore grid will be built quickly and efficiently.

Developing offshore grid infrastructure is a complex process. On the one hand there are the techno-economic issues assessed in OffshoreGrid, with a large amount of possible configurations and design options that influence each other and are heavily dependent on various factors[45]. On the other hand there are issues concerning the political and regulatory framework, financing, supply chain and operation to be resolved.

The development of an optimal grid design and modular planning is therefore only a first step. Further challenges are in store during the financing process, the grid construction as well as grid operation and maintenance.

OffshoreGrid drew up a design for an offshore grid and identified several case-independent conclusions that can provide insight and serve as concrete guidelines for specific cases.

The main results, conclusions and recommendations of OffshoreGrid study are summarised in this chapter.

6.1 Wind farm hubs

Key results on wind farm hubs

- Clustering of wind power projects is advantageous in many cases. The magnitude of the benefit depends on the hub distance from shore, and the distance between the individual wind farms (capacity concentration in the same area).
- A shared hub connection is most advantageous when a high amount of wind farm capacity is concentrated in a small area and when the cluster capacity is about the size of the standard available HVDC VSC systems.
- Integrating a wind farm into a nearby hub is economically advantageous for wind farm to hub connection distances of less than 20 km.
- In addition, a hub solution may be beneficial for reasons other than cost. Offshore hubs can help to mitigate the environmental and social impact of laying multiple cables through sensitive coastal areas and allow for more efficient logistics during installation. These benefits need to be balanced with the risk of stranded investments.
- Even if the construction of some wind farms within a hub is largely delayed, the hub solution can still be beneficial compared to individual connections. This even holds for some cases where some of the wind farms are not built at all (stranded investment). The impact of stranded investments or temporary connection over-sizing is limited, especially for big wind farm groups far from shore.

Recommendations on wind farm hubs

In view of the large potential benefits to be gained by connecting wind farm clusters via hubs, it is essential that political and regulatory strategies to foster their development are adopted.

- Where wind farm concession areas have already been largely defined, regulation should be designed such that hub connections will be favoured over individual wind farm connections wherever this is beneficial with regard to infrastructure costs. Today the economic assessment of hub connections is still limited to "obvious" cases. OffshoreGrid recommends extending the assessment scope of possible hub projects as far as possible.
- In countries where strategic siting and granting of concessions is not yet in place, policy makers should aim for fewer areas with a larger number of concentrated wind farms, with projects within an area scheduled for development at the same time rather than in more and smaller dispersed concession areas. In line with the expected development of HVDC VSC technology, the optimal installed capacity in an area should be around 1,000 MW

[45] Examples include price differences between countries, geographic parameters, market design, investments in new onshore power generation capacity, political decisions such as e.g. the phase out of nuclear energy, etc.

for areas developed in the coming ten years and 2,000 MW for areas developed after 2020.

- When differences in timing of construction exist between the wind farms in a hub or when delays occur, it should be investigated whether a hub is still beneficial. Short delays or delays of smaller wind farms generally do not impact the economics too much. However, governments should support simultaneous development as much as possible in order to reap the maximum benefits of the synergies of a combined solution. OffshoreGrid recommends assessing hub solutions even for projects that are built within time spans of more than 10 years.
- National borders should not be a barrier for a hub connection solution. If for instance a wind farm is built close to the border and close to a wind farm cluster in a neighbouring country, it is recommended to construct cross border hub solutions. Regulatory frameworks, support scheme issues should allow these solutions.
- In order to improve conditions for cross border meshed grid designs. European Member States have to discuss how to distribute costs or funding incentives for joint infrastructure measures. Furthermore it has to be agreed to which country the renewable energy generated is credited.

6.2 Tee-in solutions

Key results on tee-in solutions

- Connecting an offshore wind farm to an interconnector by means of an underwater tee-joint is technically possible irrespective of whether the interconnector itself uses HVDC CSC or VSC technology. For a configuration requiring circuit breakers on a platform, VSC technology will become the preferred solution.
- For reasons of operational security and fault handling, TSOs may generally prefer a solution with circuit breakers to reduce fault propagation. A full cost benefit analysis would be required to justify the additional cost and consequent reduction in net benefit incurred.
- Whether tee-in connection of offshore wind farms to interconnectors is beneficial depends on the associated constraints for international power exchange and the substituted infrastructure costs. When connecting an offshore wind farm hub to an interconnector, the availability of the interconnector for international exchange is reduced in the direction towards the country to which wind farm was connected originally (trade constraint). On the other hand, infrastructure cost savings incur as the tee-in is cheaper than the substituted individual connection, due to the fact that for the beneficial cases the cable length can be vastly reduced (wind farm is far from shore but close to interconnector).
- Tee-in solutions become more beneficial when:
  - Price differences between countries are low as trade between the countries would then be secondary,
  - The wind farm is far from shore and close to the interconnector[46],
  - The country where the wind farm is built usually has the lowest prices of the countries involved,
  - The offshore wind farm generation is inversely correlated with the price difference (high wind power, low price difference),
  - The wind farm capacity is either low compared to the interconnector capacity (low trading constraints), or double its size (large infrastructure savings); the economically worst case would be a wind farm and interconnector capacity of equal size,
  - A simple tee-joint is used instead of an additional platform (fewer costs but no ability to break faults).
- A special case, which can be considered to be a tee-in solution, has been identified for large wind farms far from shore. Instead of connecting the whole wind farm to one shore, the connection can be split and the wind farm can be connected to two shores.
- This way, a wind farm is connected and at the same time an interconnector is built that can be used when the wind farm is generating less than 50% of rated capacity, which occurs about 50-60% of the time.

[46] As shown in Chapter 4, actual numbers are greatly dependent on case-specific parameters.

- While the sum of the two cable capacities should be a little bit smaller than the wind farm size, the individual cable sizes should be decided based on the price levels in the connected countries. The connection to the country with a higher assumed price level across the project lifetime should be larger than the connection to the country with a lower price level.
- A detailed case study on the Cobra cable between Denmark and the Netherlands was carried out. Teeing-in a German wind farm to the Cobra cable is identified as beneficial from the point of view of European welfare. The case study also confirmed the conclusion on the split connection of the large wind farms: teeing-in a 1300 MW into the 700 MW Cobra cable proved to be the most interesting option.
- Concrete guidelines for pre-feasibility analysis on tee-in solutions have been defined and can be found on www.offshoregrid.eu.

Recommendations on tee-in solutions

- For large wind farms/hubs far from shore, the opportunities for splitting the connection to two shores and creating an interconnector at the same time should be investigated.
- For small wind farms that are considered to be far from shore (e.g. offshore wind to supply oil and gas platforms), it should be investigated whether they can be teed-in to an interconnector.
- When deciding between a tee-in solution and a split connection (one wind farm connected to two shores), the rating of the cable sections at either side of the wind farm should be carefully considered, based on an individual power market analysis. In order to reduce the constraints and maximise the benefits, the capacity should be highest at the side of the country which usually has the highest prices.
- Interconnectors that are required for international exchange or improving security of supply should not be delayed and they should be rated as optimal for these purposes. If future wind farms are considered to be installed close to one of these interconnectors, the technology and cable route should be anticipated to maximise the future benefits of the integrated solution.
- If a wind farm tee-in produces net benefits compared to the conventional connection of the wind farm to shore, no technology should be ruled out a priori. The decision on which HVDC technology to use and on which technical set-up to favour should be based on the analysis of all costs and benefits including operational implications (e.g. fault handling, redundancy, etc), costs of infrastructure, electrical losses and available capacity ratings.
- Tee-in connections are technically feasible and economically beneficial in many cases. However, incompatible regulatory frameworks and support schemes can hinder construction as the developer is confronted with large uncertainties, in particular in regard to the support or capital attraction due to difficult connection barriers. In particular when the wind farm in question is connected to an interconnector that does not start or end in the country in which the wind farm is built, national states might be reluctant to support the solution if the renewable energy generation is not credited to them.
  These political, support scheme and regulatory framework issues need special attention in the coming years in order to make tee-in solutions possible.

6.3 Hub-to-hub solutions

Key Results on hub-to-hub solutions

- Connecting countries via offshore wind farm hubs requires VSC technology and circuit breakers on a platform as fault propagation has to be limited. This is in particular necessary in order to maintain a high grid operation stability and security of supply level.
- Whether a hub-to-hub solution is beneficial over a direct interconnector depends on the associated constraints for international power exchange and the substituted infrastructure costs. While the integrated solution reduces the possibilities for trade (trade constraint), the infrastructure costs

are generally lower because the cable length can be vastly reduced: individual connection to shore is expensive, the wind farm to hub connection and the bundled hub-to-shore connection with a large capacity are cheaper.

- Hub-to-hub solutions become more beneficial when:
  - Price differences between countries are low,
  - Countries are far from each other but wind farm hubs are close (high cost savings),
  - The wind farm capacity, and thus its connection to shore, is high compared to the interconnector capacity (low constraints),
  - The wind power is inversely correlated with the price difference (high wind power, low price difference).
- In many cases the wind farm hubs will be built first to connect national wind farms. The interconnection between the hubs is then built later and should be dimensioned considering the price levels in the countries the hubs are connected to. This is because most of the time the power would flow from the hub in the country with the lower price to the hub in the country with the higher price. Of course it would be optimal to additionally dimension the hub connection cables according to these considerations, as in the case of the "split-cable-connection". But this is only possible in the ideal case when the hub-to-hub connection is taken into account at the very beginning of the project planning.
- Ideally, the hub-to-hub connection would be planned from scratch which allows the hub-to-shore and hub-to-hub connections to be dimensioned according to expected price levels in the interconnected countries. In general this would mean that the hub-to-shore connection should be dimensioned larger in the country with the higher price level. This is in line with the power flow as an additional power trade from the country with the higher price level would be beneficial.
- For meshed grid nodes with more than two lines coming together, similar conclusions can be drawn. The links to the country with the highest prices (over the lifetime) should be largest, and the other ones can be smaller in dimension. The most efficient solution would occur if the sum of all country connection cable capacities equals the sum of the connected wind farms. This way the additional investment in integrated platforms and joints brings interconnection between three countries. If larger interconnection capacity is needed, some of the cables can be oversized.
- Concrete guidelines for pre-feasibility analysis on hub-to-hub solutions have been defined and can be found on www.offshoregrid.eu.

Recommendations on hub-to-hub solutions

- When hub connections for offshore wind farms are developed, the plans should be reviewed by the TSO in order to identify possible connection options to other wind farms hubs or countries for which there is demand for international exchange.
- Equally, when developing interconnectors, TSOs should review the identified concession areas for offshore wind and consider the option of developing a hub in such an area as a starting point for the interconnector.
- If feasible options have been identified, the offshore grid developer should carry out a detailed feasibility and pre-design study in view of an optimal dimensioning of the integrated solution. This may include increasing the rating of the hub connection to shore in order to satisfy the required demand for international exchange. As for tee-in solutions, the focus should be on increasing the capacity on the side of the country which usually has the highest prices.
- Offshore grid development should be a joint or, at least, coordinated activity of the developers of the wind farms and their hubs connections, and TSOs.
- The North and Baltic Sea countries should adapt their regulatory frameworks to foster such a coordinated approach.
- When looking at the interconnection of two hubs in different countries: In the case that the hubs are built first and the hub-to-hub connection is added later on to the existing wind farm hubs, there is not much need of additional international coordination. In such a case the interconnection would be comparable to an onshore cross-border interconnection in terms of its legal, regulatory and political complexity.

- However the investigation has shown that the ideal hub-to-hub connection design takes into account hub sizes and the expected electricity price levels at the very beginning of the project planning. This way not only the hub-to-hub interconnection capacity can be optimally dimensioned but also the hub-to-shore connections can take into account electricity trade across the hub-to-hub connection.
- To achieve this ideal case, a significant coordination effort is needed and the compatibility of the support schemes and regulatory frameworks within the different countries needs to be checked. The reason is that such an ideal long-term planning would require strong political and regulatory continuity to reduce investment risks. If, for instance, the hub-interconnection is not realised in the end, the ideal hub-to-shore connection capacity would of course be different and thus the design of these hubs without interconnection would be suboptimal.
- Such coordination can be steered in bilateral processes with support at European level.

6.4 Overall grid design

Key results on overall grid design

- Building direct interconnections is valid and beneficial.
- Tee-in connections, hub-to-hub connections and the special tee-in case of split wind farm connections can significantly increase the cost-efficiency of an offshore grid, and together form important and beneficial building stones for any offshore grid design.
- The utilisation of offshore wind farm (or hub) connections is increased by building connections from the offshore wind farm (or hub) to other countries or an interconnected offshore grid.
- An offshore grid allows a shift to cheaper power generation. Renewable energy in particular benefits from the additional offshore transmission capacity.
- An offshore grid connects generation in Europe (in particular wind energy) to the large hydro power "storage" capacities in Northern Europe. This can lower the need for balancing energy within the different European regions.
- Two offshore grid methodologies were assessed and used to come to a final design. The Direct Design builds first on direct interconnections, and then integrated solutions and meshed links are applied. The Split Design starts by building interconnectors by splitting wind farm connections, then integrated solutions and meshed links are applied:
  - Splitting wind farm connections to combine the offshore wind connection with trade has proven to be more cost-effective than building direct interconnectors only for trade. The average reduction of the CAPEX by choosing a split connection over a direct interconnector is over 65%, while the reduction in system cost is only about 40% smaller on average. A comparison of the net benefit per invested Euro of CAPEX revealed that when splitting wind farm connections, each Euro invested is spent 2.6 times more effectively.
  - Although less extreme, the absolute comparison also proved that the Split offshore grid design would be more efficient than the Direct offshore grid design. For a CAPEX of €4 bn in both designs, the Split methodology leads to an extra reduction in system cost of 9% (€944 m over 25 years) compared to the Direct Design methodology.
- The overall costs for the overall offshore grid design (Direct Design or Split Design) are about €85 bn. This includes investment costs for the Hub Base Case scenario as a starting point which represents connection of 126 GW of offshore wind as well as the ENTSO-E TYNDP interconnectors.
- The costs for a further interconnected grid built on top of this Hub Base Case are only €7.4 bn for the Direct Design and €5.4 bn for the Split Design. These relatively small additional investments generate system benefits of €16 bn (Split Design) and €21 bn (Direct Design) across a lifetime of 25 years – benefits of about three times the investment.
- The total circuit length of the overall grid design (Split or Direct) is about 30,000 km (10,000 km AC, 20,000 km DC).
- Investments in offshore grid infrastructure have to be put into relation to the offshore wind energy

produced. The offshore wind farms considered in OffshoreGrid produce about 530 TWh annually which is almost the annual consumption of Germany. Over 25 years, this amounts to 13,300 TWh. Assuming today's average spot market price of €50/MW, the value of this electricity is €421 bn. In this relation the infrastructure costs only represent about a fifth of the electricity value that is generated offshore.
- Meshed grid designs with three- and four-leg nodes can result in high net benefits and large benefit-to-CAPEX ratios, as proven by the mesh configuration in both the Direct and the Split Design. In both designs, the mesh serves primarily as a North-South interconnection, which supports the conclusions that the North-South wind generation correlation was the lowest (see Section 4.1). Moreover, this also confirms the need for connection to the flexible and cheap Norwegian and Swedish hydro power resources.
- An offshore grid will be built step by step. Every new generation unit, interconnection cable, political decision or economical parameter has a serious impact on both the future and the existing projects, and thus influences the design of a future offshore grid. However, the two designs presented in this report bring useful understanding and conclusions that allow the grid development to be brought forward with modular steps in the best possible way.

Recommendations on overall grid design

- Any interconnector has a negative impact on the interconnectors that already exists because they reduce price differences between the countries. The business case for any new interconnector should therefore be very strong to withstand the negative impact of future infrastructure measures. Split wind farm connections are less dependent on the trade than a direct interconnector, and can therefore still be beneficial even with lower price differences.
- Following the same reasoning, the policy for merchant interconnectors which receive exemption from EU-regulation can be questioned. The merchant interconnector concept can incentivise investments that bear large risks. However, investors in and owners of merchant interconnectors are encouraged to obstruct any new interconnector, as this will reduce their return on investment. It is therefore absolutely necessary that there are no conflicts of interest, for instance with private investors that have key roles in grid planning, grid operation or political decisions process for these issues. Otherwise the endeavour to have a single EU market for electricity is put at risk.
- In addition to the techno-economic advantages, the Split Design has environmental benefits because it reduces the total circuit length. Moreover, it improves the redundancy of the wind farm connection, which improves system security and reduces the system operation risks, the need for reserve capacity, and the loss of income in case of faults. When doing detailed assessments for concrete cases, these merits should not be forgotten. These technical advantages also come along with tee-in and hub-to-hub connections and of course in particular for the mesh grid design (step 3 of the two design approaches).
- On the other side, tee-in solutions, hub-to-hub solutions and split wind farm connections are confronted with the unsolved problem of potential regulatory framework and support scheme incompatibilities between European countries. The reason is that renewable energy that is supported by one country can now flow directly into another country, so that the country paying for it cannot "enjoy" all the benefits. For split wind farm connections, this is even more difficult as the connection to the country in which the wind farm is located is reduced. As these complexities add risks to the development of integrated and especially split connections, they should be solved at international or bilateral level as soon as possible.
- The ongoing development of direct interconnectors should not be slowed down, as this concept can already be realised today without large wind farms far from shore. However it is advisable to anticipate tee-in connections for suitable future wind farms.

6.5 Overall recommendations

Developing integrated solutions requires suitable political, regulatory and market conditions. Concerted technology development and research is also needed. This is in order to provide a stable framework, within which both wind power generation and international exchange can be at least as profitable as when they are carried out independently.

- **Regulatory**
  - For solutions that involve two countries, for example tee-in and hub-to-hub, the operation of the grid can be managed through cooperation of the national TSOs, just as they manage onshore interconnectors. The grid up to the offshore wind farms can be seen as an extension of the onshore grid. The interconnector part can be seen as a normal cross-border point-to-point interconnector.
  - For multilateral solutions (fully meshed grid design), the operation is more complex and in particular in the case of grid faults the fault isolation and fault correction have to be well coordinated. Very good cooperation between the TSOs will be needed to efficiently manage the interconnections. A first step in such cooperation was already taken with CORESO[47].
  - Regulatory concepts for efficient ownership structures and profit allocation are needed to accelerate offshore grid development. If a wind farm is teed-in or split to two countries, the electricity it produces can be sent to the country with the highest price. Thus this would give additional benefits to the wind farm operator. At the same time the electricity from wind energy constrains trade and reduces trading benefits, leading to conflicts of interest between the parties involved. Thus, profit sharing concepts are needed that allow profitable operation of both the interconnector and the wind farm, and additionally return a significant share of the benefits to the consumer within a proper regulatory framework. If the latter is not the case, there is the risk of low public support (for example in the case of Norway where customers will have to pay higher prices).
  - Permitting procedures even for national offshore hub connections and single wind farms take considerable time and effort. The level of complexity increases strongly for international grid infrastructure.
  - Permitting procedures should be reviewed to facilitate international projects. Ideally, the offshore project can be handed in for approval in an identical form to the authorities of all relevant Member States.
  - Such a process should be fostered at national level and can be supported at European level or regional level, for instance by the NSC'OGI.

- **Political coordination**
  - Support for offshore wind energy should be made compatible with integrated solutions. The offshore wind power generation should receive its necessary support irrespective of which country the electricity is flowing to. To achieve this goal it is not necessary to harmonise the European support schemes, but it is necessary to make them compatible with one another.
  - Hub-to-hub interconnections, tee-in connections and split wind farm connections can be beneficial even when the infrastructure elements are added to already existent infrastructure, such as a tee-in to an existing interconnector or a hub-to-hub connection to existing wind farm hubs. When the interconnection is international, this requires bilateral arrangements, adaptations or exemptions to the national support schemes.
  - The offshore grid development depends to a large extend on a strong onshore grid that allows the electricity to be transported further. The system should always be considered as a whole and it should be emphasised that the development of an offshore grid can be supported by accelerating the construction of onshore grid reinforcements.
  - The optimal offshore grid design depends strongly on the timing and location of offshore wind farm development. Even though OffshoreGrid

[47] CORESO S.A. http://www.coreso.eu/

found that some meshed design and hub solutions are beneficial even if the elements to be interconnected are built within time spans of up to several years, simultaneous development in compact areas should be facilitated politically if possible. Ideally this coordination would be done at international level. The NSC'OGI could for instance support such a coordinated planning of offshore wind farm development.

- Market and financing
  - Market coupling with implicit auctioning is needed. Interconnection capacity needs to be traded day-ahead and intra-day to make optimal use of the infrastructure for trade and balancing purposes.
  - Market regions have to include offshore areas. It is necessary for the price levels between the market regions to give investment signals for further interconnection, including offshore.
  - Offshore wind energy and in particular a meshed international offshore grid lead to large infrastructure investments and high risks. Therefore investors are reluctant and capital attraction is low. The support of pilot projects has already been proven beneficial for offshore wind farms and should be extended to offshore grid infrastructure pilots. In order to put offshore grid development on solid ground it is necessary for offshore grid infrastructure investments to be supported at national or European level. The return on investment may further be supported by exemptions from regulatory framework rules which help to mitigate investment aversions. The possibility of such a merchant interconnector should however not entail conflicts of interest as described above (in the 'Regulatory' section).

- Technology Development and Research
  - The timing of technology development is crucial for the steady development of an offshore grid. Apart from the fast circuit breakers that would enhance multi-terminal development, larger cable capacities could boost the development of such a grid. This development would be driven by a growing offshore sector that can rely on a continuous offshore technology development. Policy makers have to ensure that the conditions for offshore wind energy development are stabilised in order to lay the grounds for long term project and equipment development.
  - Research in many aspects of offshore wind energy – such as offshore grid design, offshore equipment, offshore operation and maintenance concepts, and offshore wind farm control – has mostly been funded at national and European level throughout the last decade. The research carried out has significantly accelerated the development of offshore wind energy. It is absolutely necessary that this level of research support is maintained until offshore wind energy can be considered a mature and proven technology.
  - The standardisation of offshore grid equipment can open the market to further competitors and significantly reduce costs. At the same time over-standardisation can hamper further innovation.
  - The standardisation issues should be studied in detail at expert level in order to define the right moment to standardise and the optimal standardisation detail.

Political coordination is required to decide on and implement the recommended solutions. So far, the overall questions concerning the development of an offshore grid have been addressed by a variety of players such as the European Commission, the North Seas Countries' Offshore Grid Initiative (NSC'OGI) or ENTSO-E. Some questions need a European approach, while others can be better solved at national, bilateral or regional level. Nevertheless, it is important to further clearly assign responsibilities for certain aspects to different selected forums and entities.

Because the NSC'OGI brings all the relevant partners together, the OffshoreGrid consortium sees it as the ideal forum to coordinate the political, regulatory and market issues at international level.

Photo: Dong Energy

7 ACKNOWLEDGEMENTS AND FUNDING

The OffshoreGrid project is funded by the European Commission (EACI) within the Energy Intelligent – Europe Programme.

In addition to the principal funding by EACI and the consortium partners, the study was co-funded by ABB, Nexans, RWE Innogy, Amprion, Siemens, Vattenfall, the German Federal Ministry of Economics and technology and the Belgian Federal Public Service for Economy, SMEs, Self-employed and Energy.

The authors further wish to thank the members of the OffshoreGrid Stakeholder Advisory Board (as listed in chapter 1.4) and the participants of the two Northern European and Mediterranean Stakeholder Workshops for their constructive criticism and suggestions regarding methodology and interpretation of results. During the stakeholder workshops the following stakeholders were involved: ABB sa, AC Renewables, Acciona, AEE - Spanish Wind Energy Association, AES Tech Ltd, Belgian government, Bloomberg, BNetzA, CNI sa, CRES, Danish Wind Owners Association, DESMIE, Dong Energy, DTU, ECN, Ecole des Mines de Paris, EDORA, Elia, EMEU sa, ENBW Erneuerbare Energien, Enercon, Energinet, ENET sa, EON Climate & Renewables, Eurec Master, European Commission, FCM, Fraunhofer IWES, German Government, Green Evolution sa, Hellenic Cables, Hellenic Navy, Hellenic Wind Energy Association, Helleniki Technodomiki Anemos sa, Helleniki Technodomiki Energiaki, Iberdrola Engineering and Construction, IEEE, Irish Government, KAOL Energy, Lyse, Mainstream Renewable Power, Master D. Hellas, Mediascape Ltd, Metron Navitas, Mytilineos sa, National Offshore Wind Energy Association of Ireland, Netherlands Government, Nexans, Norwegian Government, OFGEM, OWEMES Association, Power India Magazine, PPC Renewables, Rokas Renewables, RTE, RWE Innogy, Siemens, Speed sa development consultant, Spok consultancy, Statoil Hydro, Stattnet, Strenecon and associates, Syndicat des energies renouvelables, Terna Energy SA, United Kingdom Government, Vattenfall, VDMA, Venergia sa, Vestas, VIP Swedish Wind Energy Association, Voreas Energy Consultancy, VWEA, WPD, wre hellas sa, WWF Greece


Photo: Vestas

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Photo: Vestas

ANNEX A – SCENARIO DETAILS

A.I Offshore wind power Scenarios

An important task in the OffshoreGrid project was the development of offshore wind power scenarios. They are mainly based on the latest EWEA offshore wind farms scenario [20] and on the onshore scenarios developed in TradeWind [24], however data have been verified and new records have been added according to the latest announcements of authorities and project developers. The database included 373 records (wind farm concepts) with a total capacity of over 180 GW in 15 countries (apart from Northern EU countries, also Norway and Russia has been considered). About 50 GW of them are well advanced projects, where developers and/or investors are clear and the permitting procedure is ongoing.

On the basis of collected data, medium (2020) and long term (2030) scenarios have been developed. The main assumptions were:

- The current proactive governmental policy towards the wind farms will be continued and joined by other countries,
- Wind farms licensed already (or well defined areas approved) and with advanced permitting procedure will be implemented before 2020, where the wind farms operating in 2030 will be located in already identified zones,
- Innovative concepts, like far (>60 km from shore) and deep (>60 m water depth) offshore, will not significantly contribute before 2030.

The resulting scenario is presented in figure 9.1 and Table 9.1.

FIGURE 9.1: GEOGRAPHIC DISTRIBUTION OF IDENTIFIED OFFSHORE PROJECTS

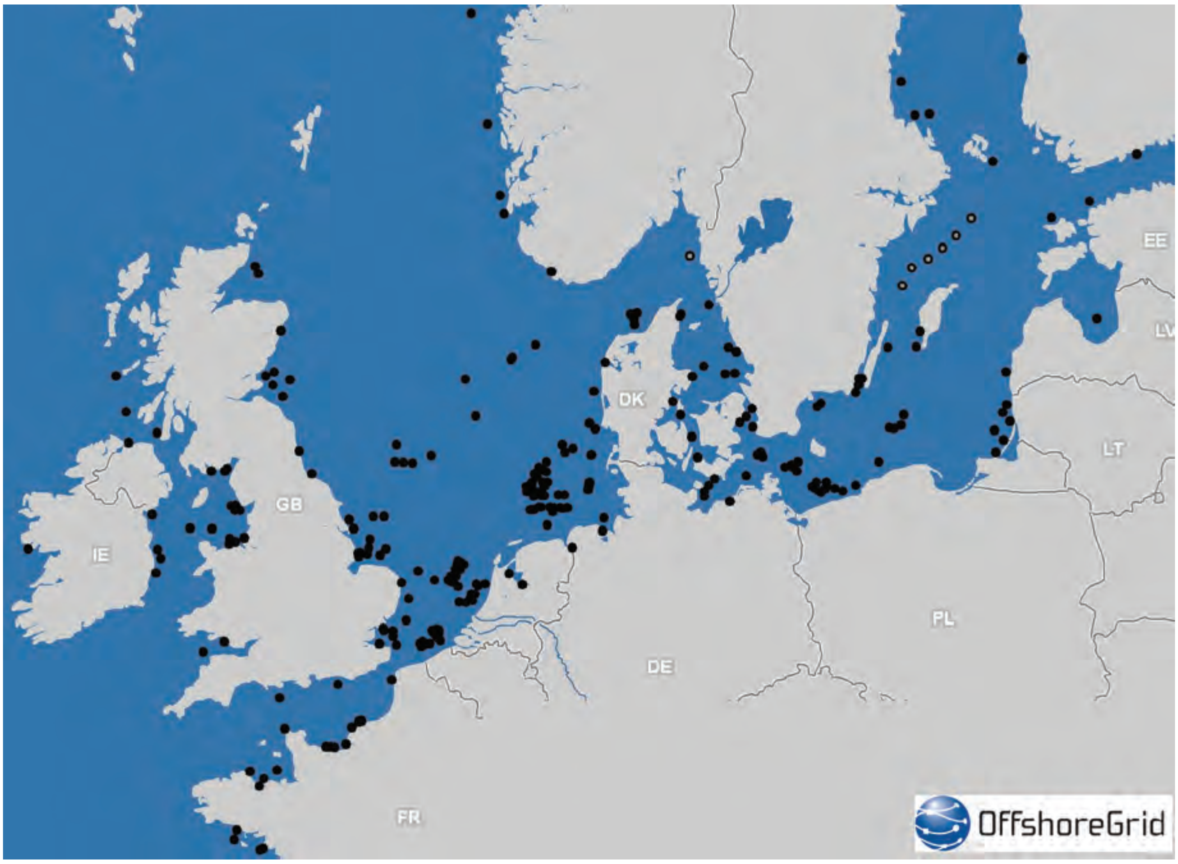


TABLE 9.1: THE OFFSHOREGRID OFFSHORE WIND POWER SCENARIO FOR 2020 AND 2030, COMPARED TO THE STATUS OF 2010 AND THE TARGETS IDENTIFIED IN THE NREAPS PUBLISHED AFTER THE DEVELOPMENT OF THE SCENARIO.

Country	Installed End 2010	OffshoreGrid scenario			NREAP's 2020 estimate[48]
		2020	2020-2030	2030	
Belgium	195	1,994	1,800	3,794	n/a
Denmark	854	2,329	1,470	3,799	1,339
Estonia	0	0	1,600	1,600	250
Finland	26	590	2,600	3,190	n/a
France	0	2,510	2,404	4,914	6,000[49]
Germany	92	10,249	16,304	26,553	10,000
Ireland	25	1 055	2,725	3,780	555
Latvia	0	0	900	900	180
Lithuania	0	0	1,000	1,000	0
Netherlands	247	4,622	7,500	12,122	5,178
Norway	2	957	8,710	9,667	n/a
Poland	0	500	4,800	5,300	500
Russia	0	0	500	500	n/a
Sweden	164	2,983	7,539	10,522	182
UK	1,341	15,303	22,843	38,146	12,990
Total Northern EU	**2,946**	**42,135**	**73,485**	**115,620**	
Total OffshoreGrid		**43,093**	**82,695**	**125,787**	

For offshore wind energy, the most important markets in the medium scenario will be UK and Germany. This leading group is followed by The Netherlands, France, Sweden and Denmark. The total installed capacity in Northern Europe is expected to be approximately 42 GW in 2020 and 116 GW in 2030. Until 2020, the major development is expected on the North Sea (63% of installed capacity in medium term, mostly in UK and Germany). In the Baltic Sea, the massive development of offshore wind farms is expected after 2020. Before this date the majority of the Baltic Sea implementations will be projects already started by Germany, Denmark and Sweden. Between 2020 and 2030 also Poland, Finland and the Baltic states will start large scale offshore wind development. In 2020 the majority of wind energy installed capacity will still be onshore in most Northern European countries, except for the UK and Belgium. In 2030 more than 40% of installed wind power capacity in Northern Europe will be offshore projects. In the UK, Belgium, the Netherlands, the Baltic States and the Scandinavian countries most of the wind power will operate offshore.

The OffshoreGrid scenario was developed in the beginning of 2010, and was then used as a basis for the rest of the project. In June 2010, following the requirements of the directive 2009/28/EC, the member states delivered their National Renewable Energy Action Plans (NREAP's) to the European Commission. For most countries, these include estimations of the total contribution expected from offshore wind energy to meet the binding 2020 targets. The member states projections of offshore wind capacity in 2020 (see Table 9.1) are in good agreement with the OffshoreGrid medium term scenario. Especially, it is confirmed that the majority of offshore wind energy development in the next 10 years is expected to take place in the North Sea. However, also on Baltic Sea the interest in offshore wind is growing, and member states (i.e. Poland and Baltic states) intend to join the offshore wind market. In conclusion, even though the OffshoreGrid scenario was developed before the publication of the intentions of the Member States, it is a valid scenario to be used as a basis for this project.

[48] Belgium and Finland did not specify the onshore/offshore split in documents sent to the European Commission.
[49] This figure also covers projects in the Atlantic Ocean, not included in the OffshoreGrid scenarios.

A.II Price scenarios

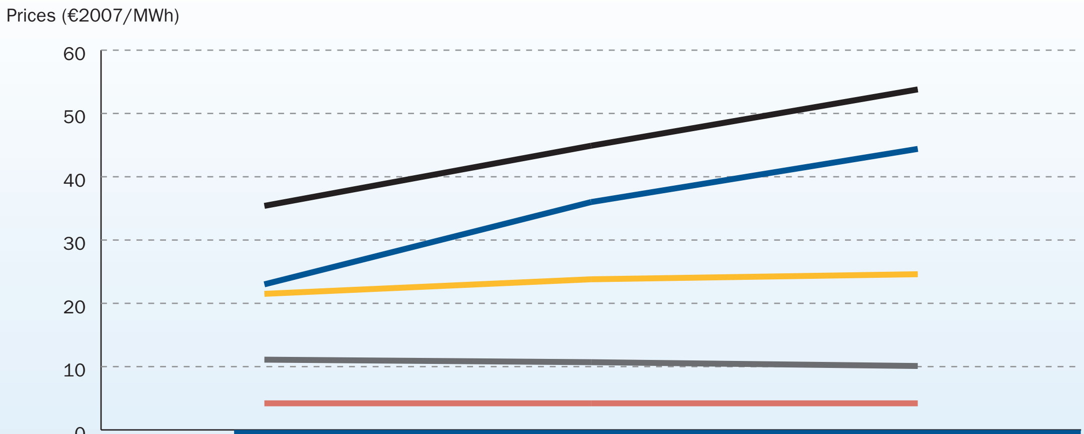
Figure 9.2 gives an overview of the chosen commodity price scenarios. Lignite and hard coal prices remain relatively stable until 2030. Gas prices increase slightly. The sharpest increase in prices is expected for crude oil and CO_2.

A.II.I Fuel price scenarios

While there are world market prices for oil, fuel costs differ significantly between continents, regions, and even neighbouring countries. The basis for these differences stems from variable taxation, delivery costs (e.g. geographical aspects), promotion and regulation systems or the different market designs. To estimate the development of fuel prices for power stations (coal, oil, gas) economic scenarios and outlooks have been analysed and evaluated.[50]

For the data analysis the different fuel types can be divided into two groups: fuel types with and without an existing European market. Fuel types with an existing European market are nuclear fuel elements, crude oil (and derived products) and hard coal. For these fuel types the same price scenario is used for all countries (one European price scenario). Lignite and natural gas are not traded on the European market. Price scenarios for these fuel types are defined on a by country basis. The following paragraphs contain the findings for the different fuel types. All prices are expressed as real prices. The base year for all fuel price calculations/ scenarios is 2007.

FIGURE 9.2: COMMODITY PRICES.



	2010	2020	2030
Crude oil	35,4	44,9	53,8
Hard coal	11,1	10,7	10,1
Lignite EU	4,2	4,2	4,2
Gas EU	21,5	23,8	24,6
CO_2 (€ 2007/t)	23,0	36,0	44,4

[50] These include the latest DG TREN scenarios calculated with the PRIMES model, the IEA World Energy Outlook, publications from the GreenNet project and scenarios proposed by different institutions (e.g. EWI/Prognos, Eurelectric).

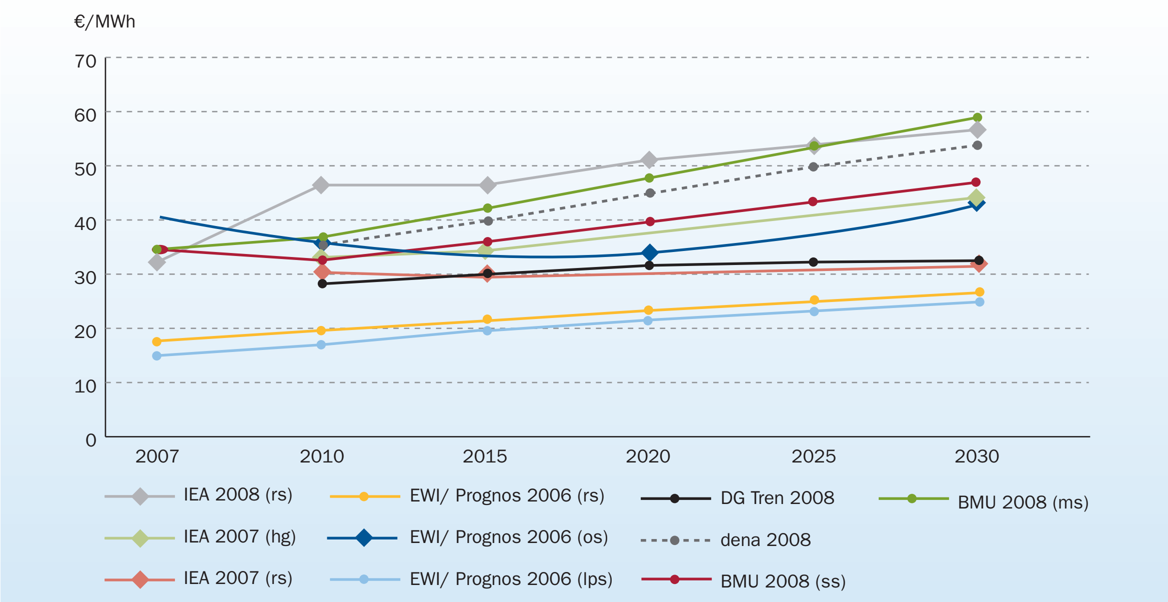
A.II.II European fuel price scenarios for nuclear fuels, crude oil and hard coal

To determine the prices for nuclear fuel elements two scenarios were analysed: DG TREN Trends 2008 and EWI/Prognos 2006 low price scenario. Both use the same prices per power station as displayed in Figure 9.3. In general, it can be said that due to the world market trade of nuclear fuels the same price can be used for all European countries.

The prices of crude oil already differ significantly within each study analysed. Prices range from €60 per MWh to €25 per MWh in 2030. In most of the reviewed studies different price scenarios are given. To illustrate these variations, Figure 9.4 displays some of the analysed crude oil price scenarios.[51] The dena

FIGURE 9.3: NUCLEAR FUEL ELEMENTS PRICE SCENARIOS (€/MWh)

FIGURE 9.4: CRUDE OIL PRICE SCENARIOS (€/MWH)



[51] ms= massive scenario, ss= slight scenario, lps= low price scenario, os= oil scenario, rs= reference scenario, hg= high growth.

2008 scenario displays the average of the two price paths within the BMU Leitszenario 2008 and has been broadly discussed and generally accepted among experts. For this reason it will be used as a basis for the price of nuclear energy in this study.

Hard coal, in contrast to lignite, is a product that is traded on the world market (Figure 9.5). In some studies the prices are basically constant, while in others they rise significantly until 2030. The IEA reference scenario (rs) displays the average price development across all studies, and is therefore used for modelling.

FIGURE 9.5: HARD COAL PRICE SCENARIOS (€/MWh)

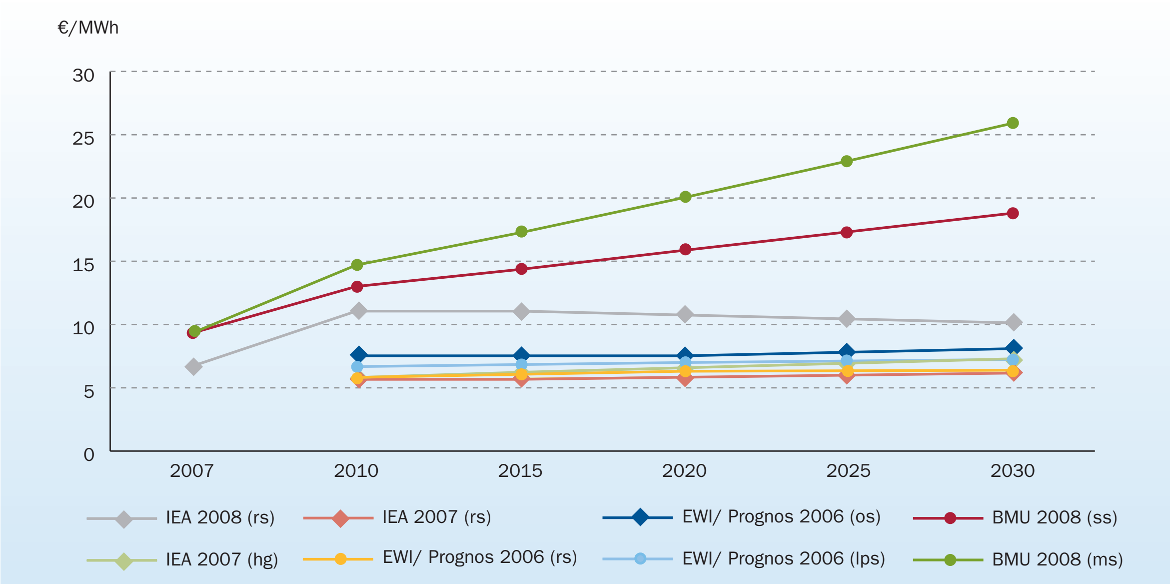
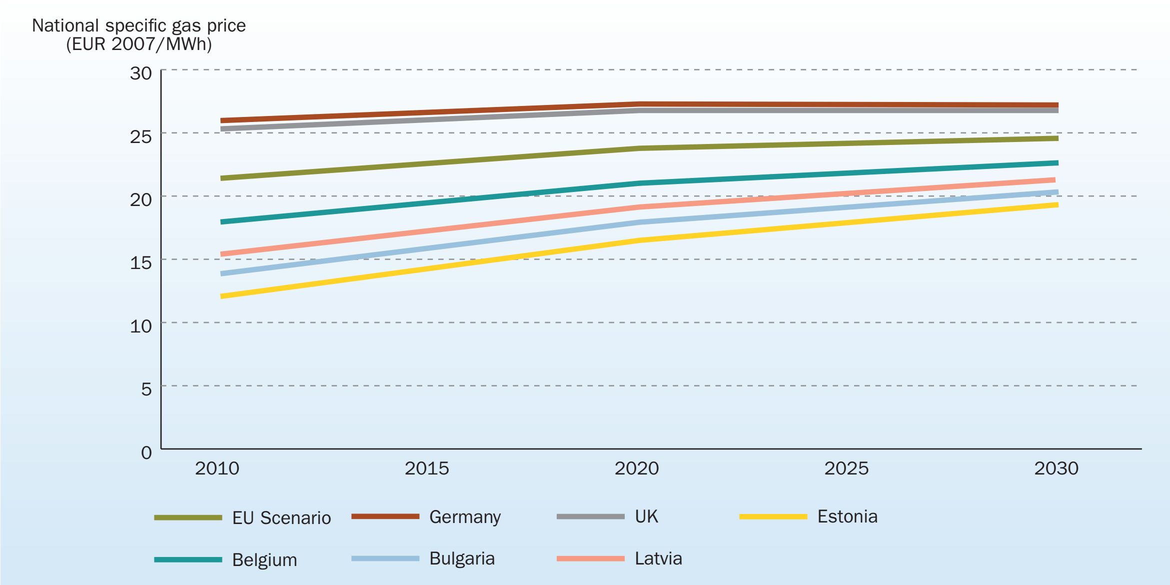


FIGURE 9.6: COUNTRY SPECIFIC GAS PRICE SCENARIO (€/MWH)



A.II.III National fuel price scenarios for gas

Gas prices play an important role in modelling the European energy market because of the following aspects:

- Due to the increasing share of fluctuating renewable energy, gas power plants will be operated more frequently and therefore set the price of the merit order[52] with rising probability.
- In contrast to nuclear fuel and hard coal, gas prices differ largely between countries.

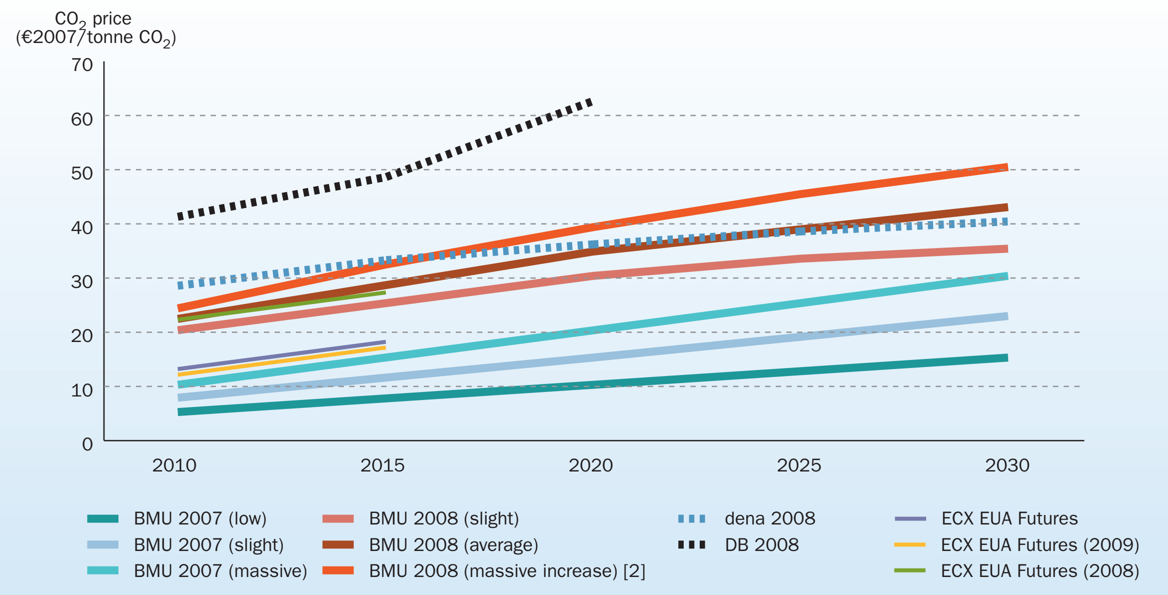
Thus, variable gas prices are one of the most important factors that determine country-specific energy generation costs. In order to model the European energy market, country-specific gas price paths were developed.

The results are illustrated in Figure 9.6. Gas prices differ strongly in 2010 and tend to harmonise towards 2030. In Germany and UK, prices are the highest (due to high gas prices for industrial consumers).

A.II.IV National fuel price scenarios for lignite coal

Due to the high transport costs (relatively low amount of energy per weight unit), lignite is not traded on national or international markets. Thus, there is no market price for lignite coal. This means that for all European countries in which lignite is produced, nearly the same amount which is extracted is also consumed for energy production.[53] Furthermore in most countries geological extraction and electricity production from lignite are conducted by the same company. The company will operate the lignite power plant as long as the variable costs are covered.[54] Hence, for modelling the merit order, the variable lignite extraction costs must be used instead of the price.

FIGURE 9.7: CO_2 PRICE SCENARIOS



[52] The merit order represents the supply curve of electricity generation. The generation units are ranked according to their marginal production price. Wind energy for instance has zero marginal production costs and is therefore one of the first units chosen for meet electricity demand.

[53] See Verein der Kohleimporteure: Annual Report 2009; EUROSTAT: Key figures on Europe 2009 edition; EWI, EEFA: Energiewirtschaftliches Gesamtkonzept 2030, 2009

[54] In the long-term both the variable and fixed costs must be recovered.

Due to the lack of public available cost data the merit order of lignite electricity production was calculated with the variable costs of extraction which equate to about 1/3 of the lignite price (scenarios).[55]

From interviews and studies the lignite price for five countries could be gathered (see Table 9.2). The lignite production in these countries accounts for more than 2/3 of the European lignite production and consumption. For the modelling process the country specific lignite prices were taken where available. For all other countries a European price scenario was developed.[56]

TABLE 9.2: SPECIFIC LIGNITE PRICES [€/MWH] [57]

Lignite Price [€/MWh]	2010, 2020, 2030
Albania	5.08
Germany	4.20
Greece	4.40
Kosovo	4.18
Poland	4.69
Price for rest of Europe	4.20

A.II.V CO_2 Price Scenarios

In 2005, CO_2 certificates were introduced in Europe via the implementation of EU ETS. The CO_2 price is an additional cost element for the use of fossil fuels. To estimate the price development of CO_2 certificates several studies have been reviewed. Furthermore, the trading prices for EU emission allowance (EUA) futures were analysed.

Figure 9.7 illustrates the different CO_2 price scenarios. The analysed scenarios differ widely. The diversity reflects the different assumptions for the oil price development.[58] The BMU 2008 average scenario has been validated by several experts and was chosen for modelling.

Secondly, it is evident, that the ECX EUA Future prices were located in between of the analysed price scenarios. The market participants did not share the expectation of sharp price increases due to future CO_2 certificate shortages.

[55] dena 2008; EWI, EEFA: Energiewirtschaftliches Gesamtkonzept 2030, 2009; Various telephone interviews with Jochen, Schwill, EWIS, October 2009.
[56] Based on Ewi/ Prognos 2006 low price scenario.
[57] dena 2008; Janusz Bojczuk, Poltegor Engineering, October 2009; Employer's Confederation of the Polish Lignite Industry, 2009; Marios Leonardos, Mines Planning & Performance Department.
[58] Increasing oil prices lead to high gas prices and comparatively low coal prices. Low coal prices indicate higher demand for coal, and therefore rising CO2 prices.


Photo: Vestas

ANNEX B – TECHNOLOGY ASSUMPTIONS

B.I Offshore technology assumptions

The 326 offshore wind power projects that fall within the geographic sphere of the OffshoreGrid project have a capacity range from as little as 5 MW to a maximum of 2,000 MW and have interconnection route distances between 1 km and 434 km. In this study, the total offshore wind capacity considered for the in Northern Europe scenario is 126 GW.

Obviously, to connect such a wide range of capacities over quite various distances will require different transmission technology solutions. It is the purpose of this section to briefly explain why certain transmission technologies have been selected for specific connections and also define what design building blocks have been used to build up the offshore power grid from the individual offshore substations through to the onshore connection points into the existing onshore transmission network.

B.I.I Offshore wind farm substations and platforms

The traditional voltage for connecting offshore wind turbines to the MV wind farm power collection system is up to 36 kV. However, due to the power capacities accumulated in many of the offshore wind farms considered in OffshoreGrid and the distance from shore it is not possible for the power to be transmitted to the onshore grid at this voltage for most of the projects. Hence, offshore substations will need to be established for many of the projects to accumulate the power from the internal wind farm cable array and step up the voltage to a level appropriate for transmission over distance.

The amount of power that can be accumulated at one offshore substation, and hence the number of offshore substations required for each wind farm, will be dictated by the power carrying capacity of the onward transmission medium, the power carrying capacity of the array cabling, and the number of wind turbines. The distance from the platform to the furthest wind turbine in the array must also be taken into consideration, as using excessive lengths of 36 kV cable to connect an array can lead to excessive power losses. Export cables then connect the offshore substation platforms (generally HVAC) either directly to the onshore grid or to HVDC converter platforms depending on the capacity and distance to shore.

Offshore platforms are required to house the substations which gather wind turbine connection cables and step up the voltage for transmission to shore. Platform topsides are supported on jackets (with anything from 3 to 8 legs) piled into the seabed. Monopiles can be used for smaller platforms, whereas self installing floating platforms are going to be used in the future due to the shortage of installation vessels and cranes. In addition to housing transformers, cooling radiators, fans, switchgears, and the associated control panels, the platform will typically include emergency accommodation and life-saving equipment, a crane for maintenance lifts, a winch to hoist the subsea cables, backup diesel generator, fuel, helipad, communication systems, and the means to support J-tubes which contain the subsea cables.

B.I.II Available transmission technologies

There are various transmission technologies for offshore wind farms available. In the following section the chosen technologies for the OffshoreGrid project are briefly reviewed.

High voltage alternating current (HVAC) solutions

The advantage of using AC cables as a connection medium is obvious when the requirement is to link an offshore farm or farms which are generating at AC with an onshore network that is supplying AC. However, the capabilities and limitations of AC cables are also well known, especially when connecting long distances. Due to needed reactive compensation, AC subsea cables have only been considered as a possible connection technology in this study where the total cable route length is less than 80km.

AC cables come in many types with variations possible on the metal used for the conductors (Copper or Aluminium), the type of insulation (oil mass impregnated (MI) paper or extruded cross linked polyethylene (XLPE)), and the type and need for armouring. These factors combined with the voltage and ampacity dictate the power carrying capabilities of a cable and ultimately its cross sectional area. The choice of which type of cable to use is very much project specific and depends on a whole host of economic and environmental factors, such as capital cost, losses, and the thermal resistivity of the medium in which the cable will be laid. Within the OffshoreGrid project the following offshore AC cable maximum size building blocks are regarded (Table 10.1). The infrastructure cost model selects cable sizes up to the cross sectional area shown below [27].

High voltage direct current (HVDC) solutions

In a HVDC system, electric power is taken from one point in a three-phase AC network, converted into DC by a converter station, transmitted to the receiving point by an overhead line or underground / subsea cable and then converted back into AC by another converter station and injected into the receiving AC network (Figure 10.1).

Traditionally, HVDC transmission systems are used for transmission of bulk power over long distances. The technology becomes economically attractive compared with conventional AC lines as the relatively high fixed costs of the HVDC converter stations are outweighed by the reduced losses and reduced cable requirements.

The following HVDC converter capacities (Table 10.2) will be used within the OffshoreGrid design.

FIGURE 10.1: OVERVIEW OF VSC HVDC TRANSMISSION FOR OFFSHORE WIND FARMS; IMAGE COURTESY OF ABB

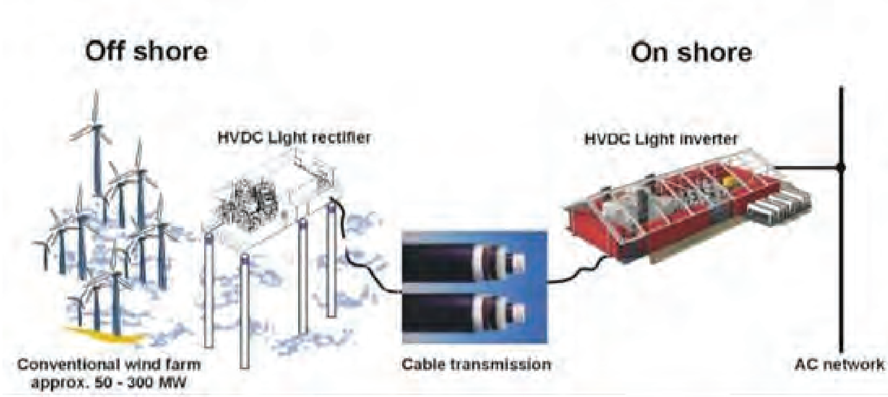


TABLE 10.1 OFFSHORE AND OFFSHORE AC CABLE DESIGN 'LARGEST BUILDING BLOCKS'

Nominal Voltage (kV)	Cores	Conductor	Insulation	Available Pre 2020		C.s.a (mm²)		Power Rating (MVA)	
				Offshore	Onshore	Offshore	Onshore	Offshore	Onshore
33	3	Copper	XLPE	Yes	Yes	1,200	2,000	52	65
132	3	Copper	XLPE	Yes	Yes	1,200	2,000	208	259
150	3	Copper	XLPE	Yes	Yes	1,200	2,000	237	294
220	3	Copper	XLPE	Yes	Yes	1,200	2,000	347.5	431
400	3	Copper	XLPE	Yes	No	800	2,000	491.7	739

TABLE 10.2 HVDC CONVERTER DESIGN 'BUILDING BLOCKS'

Type	Voltage (kV)	Configuration	Available Pre 2020	Power range (MW)
VSC	+/-150	Symmetrical monopole	YES	Up to 500
VSC	+/-320	Symmetrical monopole	YES	Up to 1,200
VSC	+/-500	Symmetrical monopole /Bipole	NO	Up to 2,000
CSC	+/-250	Bipole	YES	Up to 1,000
CSC	+/-500	Bipole	YES	Up to 2,000
VSC	+/-150	Symmetrical monopole	YES	Up to 500

TABLE 10.3 OFFSHORE DC CABLE DESIGN 'BUILDING BLOCKS'

Nominal Voltage (kV)	Conductor	Insulation	Available pre 2020	C.s.a (mm^2)	Max Sending Power (MVA)
150	Copper	XLPE	YES	2,500	600
320	Copper	XLPE	YES	2,500	1,280
500	Copper	XLPE	NO	2,500	2,000
500	Copper	MI	YES	3,000	2,000

HVDC cables

In order to reach the levels of power transfer required for the 2020 and 2030 OffshoreGrid designs, cables that can operate at high voltages will be required. As a result of conversations with cable manufacturers, the following DC cables in Table 10.3 have been specified within the OffshoreGrid design.

Superconductors

Superconductors are able to transfer large amounts of power using low voltages without the high electrical losses that are normally experienced using traditional conductors. However to maintain their superconducting state, they must be kept very cold and thus require cooling stations to be located approximately every 2km along the length of the cable. This is not practical for offshore applications as the cost of the cooling stations would outweigh any advantage gained from the superconducting cables. For this reason, superconductors have not been considered as a transmission technology for the modelling in OffshoreGrid.

Gas insulated transmission lines

Gas Insulated Lines (GIL) are a 3 phase AC transmission technology available up to 400 kV and 3000 MW. They are able to transfer large amounts of power over greater distances than AC cables because they use SF6 gas as the insulating medium between the live conductors and earth instead of XLPE. As a result the GIL has a lower capacitance meaning longer distances may be connected before the real power transfer capacity becomes limited by the charging current associated with AC transmission.

GIL has been installed onshore in transmission systems and is directly buried in the ground. For subsea applications the GIL must be installed in a pipeline to provide physical protection. GIL has been considered in the OffshoreGrid design, however due to the high costs of building and installing the GIL in subsea pipelines it remains more expensive than the alternative HVDC solution and has therefore not been used for any of the designs.

B.I.III Switchgears

Within the Offshore Grid design building blocks HVAC Gas Insulated Switchgears (GIS), HVAC Air Insulated Switchgears (AIS) and HVDC Switchgears have been considered. GIS has been found to have numerous advantages compared to AIS. HVDC switchgear, with the exception of circuit breakers, is similar to existing AC switchgear and may use either AIS or GIS design. The methodology used in the offshore grid designs has been to use DC fault isolation equipment (such as DC circuit breakers) to prevent any power infeed loss to onshore AC transmission systems exceeding the amount of frequency control reserve held by the onshore system.

Photo: Stiftung Offshore Windenergie - Detlev Gehring

ANNEX C – DETAILS ON METHODOLOGY AND MODELS

The OffshoreGrid results are based on detailed generation modelling, market and grid power flow modelling and infrastructure cost modelling. Each of the aforementioned modelling tasks is already a great challenge on its own and there is no integrated end model that could solve the envisaged optimisation goal to determine an optimal offshore grid. The consortium therefore set up a stepwise methodology in which different models are combined in an iterative approach, as shown in Figure 12.1. All in all four major models were developed and applied:

1. Wind power time series model

Because of the predominant impact of wind power in-feed on the optimal grid design, special efforts have been made to generate appropriate wind power time series. A specialised wind power model (meso-scale numerical weather prediction model) has been used for this purpose. The resulting wind power time series are used as input to the power market and flow model described below.

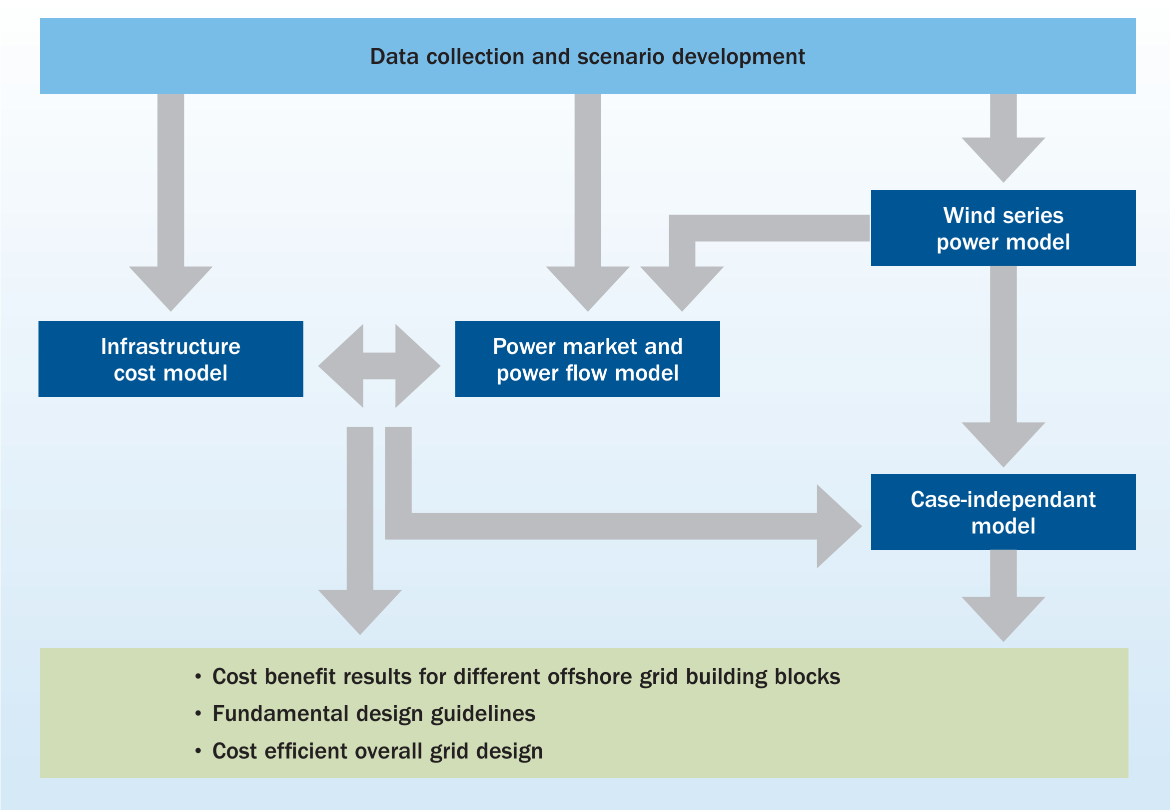
2. Power market and power flow model

Power plants generate when they can sell their electricity to the market if there is enough grid capacity to transport it. The power market and power flow model simulates the operation of the power system based on a detailed set of European generation data (capacity, costs etc.) and a detailed European grid model. Both conventional power plants and RES generation is modelled.

3. Infrastructure cost model

To build offshore grid infrastructure requires large investments. The extent of these investments is a key figure to be considered when determining the overall costs and benefits of the considered design. The infrastructure model takes into account costs of different offshore cable and equipment technology, the cable length, sea depth, bathymetric data etc.

FIGURE 12.1: SCHEME OF MODELS



4. Case-independent model

During the course of the study it became apparent that the appropriate wind farm connection design is very sensitive to the specific cases under investigation: distances to shore, wind farm capacities, price profile differences between the countries, etc. The results of the specific cases are useful but general conclusions are necessary for the optimal offshore grid design and also for clear recommendations, which is one central goals of the OffshoreGrid study. A case-independent model was therefore developed with inputs from the infrastructure model and the power system model. It allows developing general offshore grid design rules, which are then validated with the results of the specific cases of the model.

In the following sections, the key features of each of the mentioned models are described.

C.I Wind power time series model

Since on- and offshore wind power production is a crucial element in designing an offshore grid, OffshoreGrid builds on high-resolution time series of wind speed and power output of onshore- and offshore wind farms which served as input for the modelling power flows and power markets. For all single offshore wind farm locations of the input scenario, synchronous hourly time series of historical wind speed were calculated with a high-resolution weather model. These are then transformed into wind power production time series by using special power curves.

The applied Weather Research and Forecasting Model WRF [1] is a meso-scale numerical weather prediction model, able to simulate the atmospheric conditions across a wide range of horizontal resolutions from 100 km down to 1 km. The data input for WRF is provided by 6-hourly global weather analysis data[59]. The WRF-simulations dynamically downscale the weather analysis data from six-hourly resolution on a horizontal grid of 1° by 1° to one-hourly data on a 9x9 km² grid[60].

FIGURE 12.2: GEOGRAPHICAL DOMAINS FOR THE WRF-SIMULATION AS USED IN THE OFFSHOREGRID PROJECT

The region of the Northern European waters is modelled with a higher spatial resolution than the remainder of Europe (see Figure 12.2):

- Europe north of the Alps: 9 x 9 km² (including offshore regions in focus)
- Europe south of latitude 48°N: 27 x 27 km²

The wind speed time series were calculated for all relevant hub heights of turbines in today's and future offshore and onshore wind farms. Special attention was paid to the vertical wind speed profiles in different thermal stratifications of the local atmospheric flow, which were modelled with an improved, so called MYJ-Scheme for the atmospheric Planetary Boundary Layer (PBL) [7]. The model output is validated with real wind speed data at different heights, i.e. measurements from the German offshore platform FINO-1 [6]. Previous simulations with similar model settings were also checked with other meteorological observations, e.g. the met mast Östergarnsholm in the Baltic Sea. The model proved to be accurate and robust.

After the WRF model runs were performed and validated, the wind speed time series at more than 350 offshore sites and 16,000 onshore grid points as defined in the scenarios and models were determined.

[59] In this case: FNL Final Analysis from the United States' National Centre for Environmental Prediction (NCEP).
[60] In geographical coordinates, 1° corresponds approximately to 50-111 km.

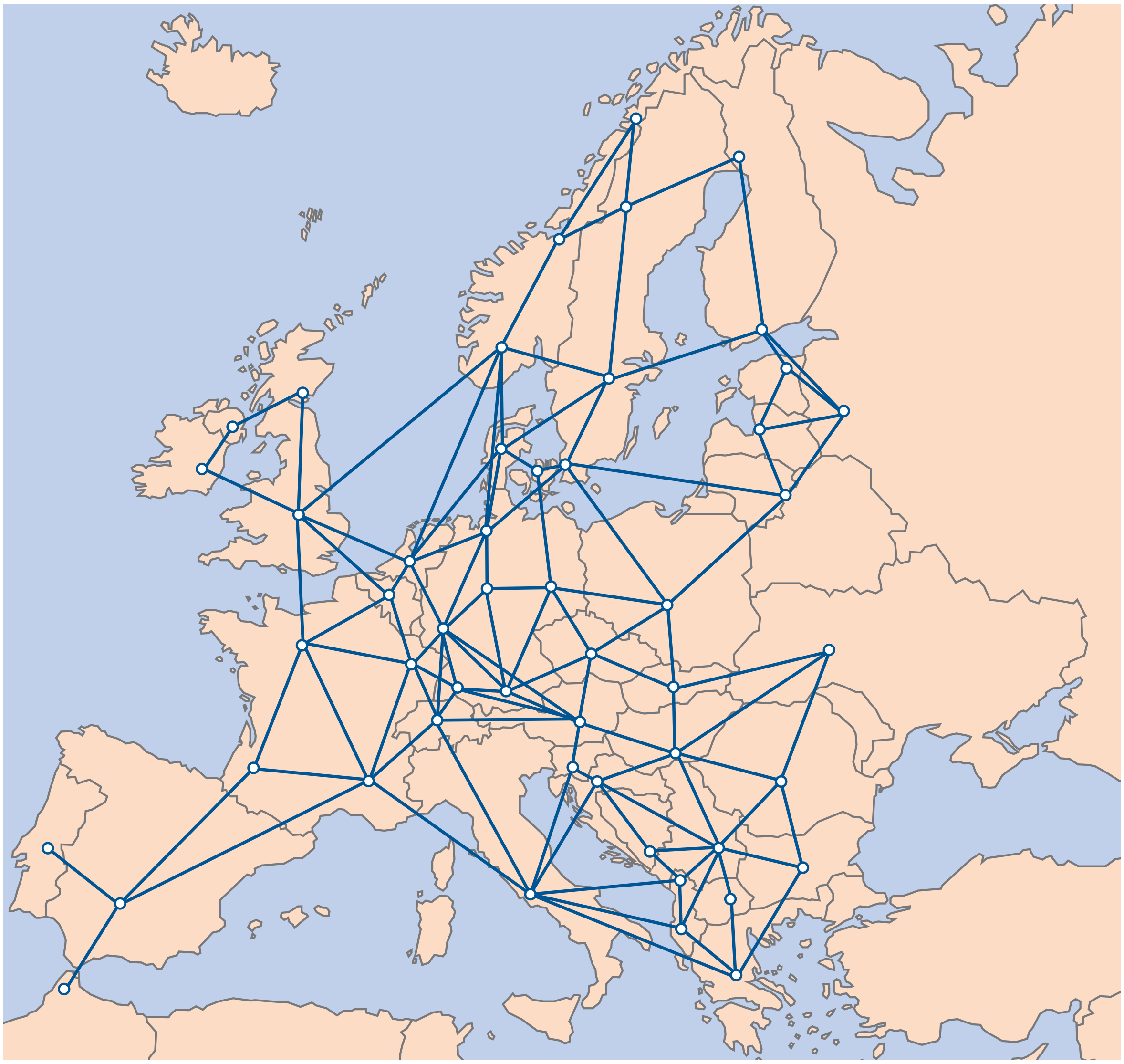
The wind speed time series were transformed to wind power with different types of power curve models for both onshore and offshore wind farms:

- For the identified offshore wind farms, aggregated wind farm power curves were derived by applying wind farm wake effects[61] to Multi-Mega-Watt power curves of future offshore turbines [9][10][11].
- In order to calculate the regional onshore power time series, the refined power curve model developed in the TradeWind project [2] is applied.

The time series reflect many relevant meteorological events, such as movements of storm fronts across large areas or large-scale calms. The dataset enables the evaluation of the implications of such events on the output of wind farms across a region, countrywide and for large offshore areas.

More information on this model can be found in the deliverable 3.2b [25].

FIGURE 12.3: OFFSHOREGRID ZONES IN THE EUROPEAN GRID MODEL FOR THE HUB BASE CASE 2030



[61] The wind that passes a wind turbine rotor is heavily impacted by the rotational force of the rotor. The area of influenced wind is called the wake of the wind turbine. When there are other wind turbines in this wake, their output is reduced. This is called the wake effect. The modelling of these effects is an important field of research.

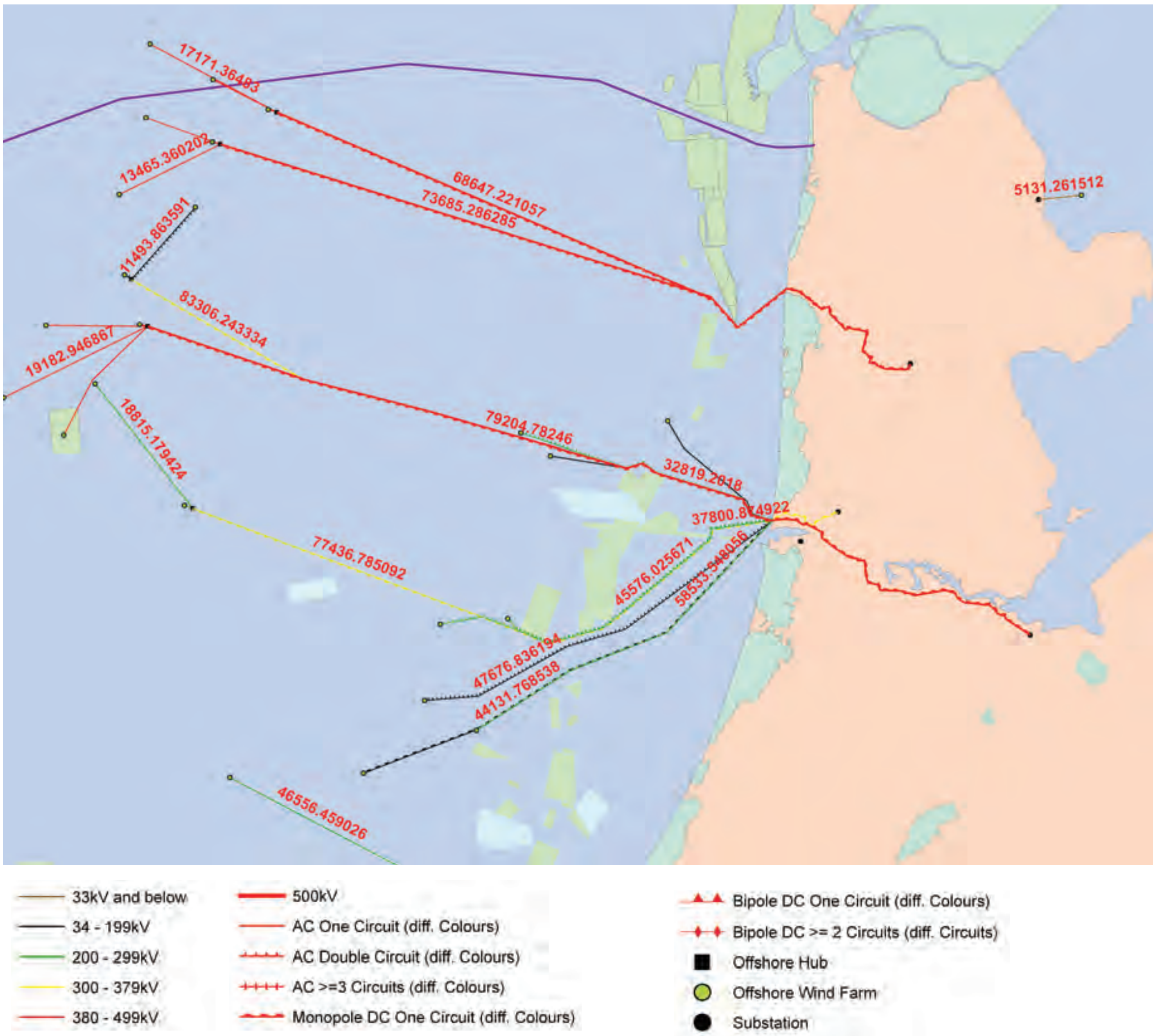
C.II Power market and flow model

The power market and power flow model simulates the operation of the power system based on a detailed set of European generation data (capacity, costs etc.) and a detailed European grid model. This allows the assessment of system operation costs, and the possible benefits by e.g. installing an extra interconnector.

The model used for the flow-based power market simulations is a Matlab-based collection of classes and functions referred to as the SINTEF Power System Simulation Tool (PSST) [2]. It is an updated version of the model used by SINTEF in the IEE project TradeWind. PSST combines a market model with a model of the European electricity grid. The model assumes a perfect market with nodal pricing. The socio-economic optimum for the overall European electricity production is found by minimising the total yearly generation cost. From the simulations both technical and economic parameters, such as generation cost, energy prices, price differences and grid utilisation (off- and on-shore) for different scenarios can be extracted.

The optimal generation dispatch is computed on hourly basis and the power flow through the electricity grid is linearly approximated (DC power flow [12][13]). In more technical terms, the optimal solution for each hour is found by minimising a cost function that essentially expresses the cost of generation, with different marginal generation costs for different countries and generator types. The power flow is constrained by the grid capacity on individual branch level and on international interconnections. This is fed as mathematical constraint into the optimisation problem.

FIGURE 12.4: GIS CABLE ROUTING



A detailed European grid model including the countries in Eastern Europe and power exchange capacities with Russia is the fundamental input for the power flow calculations. The inputs to the program are the grid model, the generation capacity forecast and cost for all generator types per country, hydro reservoir levels, and time series for demand, wind power production and hydro inflow.

For each hour the program updates the demand, wind production and marginal cost of hydro units based on reservoir levels, and runs an optimal power flow which determines the power output of all generators and on all lines. PSST keeps track of the reservoir level for hydro units by calculating the inflow and hydro production given by the hourly solution of the marked model. The power output of the generators is dependent on the minimum and maximum capacity, the marginal cost relative to other generators as well as the limitations of power flow on lines capacity and the impedances.

The European grid model used in this project is divided into five synchronous regions: Continental Europe (former UCTE), Great Britain, Ireland, the Nordic region (former Nordel) and the Baltic region. The countries included in the model are shown in Figure 12.3. The zones within the countries are indicated by white dots, interconnections are given as blue lines. As can be seen, France is modelled as 4 zones, while Germany is modelled as 6 zones.

By adding the network grid as constraints to the market model the effect of network constraints on both prices and bottlenecks is identified. Not only will it identify production and consumption but also the utilisation of individual branch and HVDC connections, showing where power flows through the system, identifying bottlenecks and main power transfer corridors. The results from the market model optimisation are given on a detailed level for individual branches and nodes, but it is also aggregated to area/zone totals to ease the analysis of the results for such a large model.

The total cost which is a direct output of the market model, is a good parameter for evaluating the benefit of introducing new capacities into the electrical power system[62], while the price difference between parts of the system is an indication of where to introduce such new capacities. In order to indentify the need for interconnectors between countries price differences between areas are required. However, the model will produce nodal prices which reflect the marginal cost of supplying power to a given node. The nodal prices are a good basis for computing the area price, i.e. the wholesale consumer price for power within a geographic area. Such areas are typically countries or zones within a country. Area prices in the PSST are computed from nodal prices as a weighted average, with weights given as the relative demand within the area. That is, the nodal prices at heavy load nodes are more important than the nodal prices at nodes with light load. In this way the model is able to find area prices, while still including the electricity network and having the high degree of freedom given by the nodal price model.

When comparing the infrastructure costs to the system benefits for two different design options, the system benefits are calculated as the present value of the difference in total cost between both cases over a lifetime of 25 years, and calculated with a discount factor of 6%.

More information on the market and grid model can be found in Deliverable D6.1 and D6.2 [29].

[62] Doing the analysis via the total system costs means that the optimisation is done from European welfare point of view.

C.III Infrastructure cost model

The infrastructure costing model is used to determine the capital costing of the entire OffshoreGrid infrastructure used in the modelling phases, including:

- Individual wind farm connections
- Hub connections of wind farms
- Wind farm Tee-in connections
- Direct interconnectors
- Meshed hub-to-hub, hub-to-shore interconnectors
- Split wind farm connections

The infrastructure cost model feeds directly into the net benefit model, together with the results from the power market model to assess the viability of links for arbitrage. The infrastructure cost model has two main stages, firstly incorporating a technical assessment of the required infrastructure to determine the required technology and then a costing exercise is performed to produce the capital costing for each wind farm connection.

TABLE 12.1: INTERCONNECTOR UTILISATION BETWEEN 2008 AND 2010 [41]

Interconnector	Utilisation
GB – France	60.3%
Moyle	55.9%
NorNed	74.9%
Average	63.7%

C.III.I Design assumptions

Offshore generation (GIS) locations

In order for the model to produce accurate costing the lengths of cable routes must be determined accurately. Initially all of the offshore projects and onshore connections points derived in WP3 were plotted in GIS software along with subsea obstacle data obtained from European oceanographic societies and governments. This allows accurate cable routes to be plotted to the projects around any subsea exclusion zones, (Figure 12.4) with distances for both onshore and offshore cable routes with the number of obstacles to be crossed.

Technology

The costs produced by the infrastructure cost model are determined mainly by what technology is required and the connection distance. Following the calculation of the route lengths a technical assessment is made to determine the topology for each link. For wind

TABLE 12.2: ENERGY PRICE DIFFERENCES AS DETERMINED BY POWER MARKET MODEL

	BE	DE	DK	EE	FI	FR	GB	IE	LT	LV	NL	NO	PL	SE
BE		4.64	9.69	6.39	23.72	10.12	9.42	8.17	6.92	6.38	7.00	17.46	6.03	25.89
DE	4.64		7.54	5.41	22.05	9.46	8.82	8.83	5.37	5.41	5.28	15.70	4.43	23.99
DK	9.69	7.54		6.20	16.21	7.55	8.92	11.43	5.83	6.20	6.28	10.11	6.88	17.04
EE	6.39	5.41	6.20		18.80	8.49	10.01	10.42	1.24	0.00	8.12	13.44	3.72	21.13
FI	23.72	22.05	16.21	18.80		16.48	20.30	23.36	18.95	18.80	20.70	9.90	20.92	7.29
FR	10.12	9.46	7.55	8.49	16.48		8.85	11.31	8.53	8.49	8.34	10.64	9.55	17.21
GB	9.42	8.82	8.92	10.01	20.30	8.85		6.06	9.89	10.01	6.46	15.04	10.04	21.16
IE	8.17	8.83	11.43	10.42	23.36	11.31	6.06		10.60	10.42	8.60	18.08	10.18	24.80
LT	6.92	5.37	5.83	1.24	18.95	8.53	9.89	10.60		1.24	7.75	13.39	2.75	20.53
LV	6.38	5.41	6.20	0.00	18.80	8.49	10.01	10.42	1.24		8.12	13.44	3.72	21.13
NL	7.00	5.28	6.28	8.12	20.70	8.34	6.46	8.60	7.75	8.12		14.66	7.21	21.21
NO	17.46	15.70	10.11	13.44	9.90	10.64	15.04	18.08	13.39	13.44	14.66		14.80	8.82
PL	6.03	4.43	6.88	3.72	20.92	9.55	10.04	10.18	2.75	3.72	7.21	14.80		22.13
SE	25.89	23.99	17.04	21.13	7.29	17.21	21.16	24.80	20.53	21.13	21.21	8.82	22.13	

farm connections and hub connections this could be either AC or DC depending upon the distance. All interconnectors for arbitrage have been assumed to be DC due to the distances involved in connection. The technology available is based on what technology is commercially available today and future technology established in section B.I.

Inputs to infrastructure cost model

The following parameters are used as inputs to the infrastructure cost model when assessing wind farm and hub connections:

- Connection distance (onshore / offshore)
- Project timing (pre / post 2020)
- Capacity (MW)
- Onshore network security criteria

Connection distance is used in the infrastructure cost model to determine the power transfer capability of AC and DC cables over the given distance. For DC cables the resistance creates a voltage drop which means the receiving power of the cables is less than the sending power. The voltage drop is reduced by selecting cables with larger and more expensive conductor sizes. If the losses are excessive then the cable is not used and the model selects a larger cable. AC cables have a technical limitation on the distance they can be used due to the charging current they generate. The infrastructure cost model calculates the power transfer capability of the AC cables in order to determine how many are required at each voltage level to transfer the power to shore if indeed it is possible to use an AC connection at all.

Project timing is used to determine the technology used on the project. Any wind farms built pre 2020 are limited to technology commercially available today with post 2020 projects allowed to use technology with increased capacities as defined in Section B.I.

Project capacity and network security criteria are used to determine the maximum capacity offshore link which can be connected to an onshore connection point. All links terminating to onshore connection points cannot exceed the current or future planned network security criteria. This limits the maximum amount of power which can be transferred over a single link due to the amount of reserve held by the onshore network to cater for an in-feed loss to the system. If the offshore grid link or project size exceeds the network security criteria then the link must be split into multiple smaller links or DC circuit breakers used to segregate the offshore grid network so for any fault or outage of cables or converters then the onshore network security criteria is not exceeded. This has an impact on cost, as potentially more equipment is required to achieve the same power transfer compared to larger onshore networks where larger in-feed losses can be handled.

C.III.II Costing process

The costing process assesses each AC and DC cable voltage in turn to determine the size, number and cost of cables required for the given distance and capacity. Following this the number of DC converters & switchgear is determined based on the number of cables, project size and network security criteria.

When costing wind farm projects or hubs the model selects the cheapest option whether it is AC or DC and outputs:

- Capital costing
- Technology
- Cable sizes
- Quantity of key plant (converters, offshore platforms)

When assessing interconnectors, such as direct interconnectors between onshore connection points or interconnectors between hubs the model defaults to DC as the technology choice and outputs the capital costing. Further information on the costing process can be found in deliverable D5.2 – OffshoreGrid Design Proposals Report [27].

C.III.III Direct interconnector justification formula

To assess the viability of direct interconnectors within Northern Europe a justification formula was used. This formula is used to identify direct interconnectors to study based on their estimated profitability. Following identification, the power market model was used with the identified potential direct interconnectors in order to produce the total generation costs, which in turn was then used to assess the net benefit of the interconnectors.

The power market model was used to initially create a reference case of energy price differences between the countries around the North and Baltic Seas. An example of the price differences is shown in Table 16. These price differences were based on the scenario with all offshore generation built using either individual or hub connections, and all of the planned interconnectors in the ENTSO-E TYNDP. The price differences are used to determine the potential interconnector revenue based on the following assumptions:

- 25 year payback period
- Interconnector utilisation of 63.7%
- 1,000 MW building blocks for each interconnector
- Interconnector receiving 60 - 100% revenue from the price differences

The interconnector utilisation figure was derived from the average utilisation of the England France (2,000 MW), Moyle (Scotland – Northern Ireland, 500 MW) and NorNed (700 MW) interconnectors using data downloaded from the ENTSO-E website from 2008 to 2010.

Interconnectors generate revenue by trading their capacity with energy suppliers and this is usually done through an auction process consisting of long and short term contracts. The interconnector is relying on the price differential between two countries or markets so that a supplier will buy energy outside of their domestic market and use the interconnector to transfer it. The supplier is looking to be able to buy energy and use the interconnector for a lower cost than buying it within their domestic market. To this end suppliers set up long term contracts with interconnectors and typically the interconnector will receive 60% of the price difference as revenue. This rises up to 100% of the price difference in short term contracts where energy suppliers choose to buy from foreign markets in order to meet their supply requirements.

Based on the price difference between all of the European countries around the North and Baltic Seas and the above parameters, the potential revenue of interconnectors was calculated between all countries which can be connected geographically. The capital cost of 1,000 MW interconnectors was also produced and to compare against the revenue to produce the profitability of all potential direct interconnectors. Ranking the profitability and selecting the 10 most profitable links initially produced the first 10 interconnectors to study in the power market model.

Following identification using the above described process the power market model was run with each interconnector added in turn to produce the total generation cost for the European system. Total generation cost and the capital costs of the extra infrastructure is then assessed to determine the net benefit, where if the total generation cost is reduced by more than the capital cost of the assets over their lifetime then the link is beneficial and kept in the model. Any links that were not beneficial were removed from the model. The process of adding links has the effect of reducing the total generation costs and also reducing the price differences between countries. Therefore an iterative process was performed where the updated price differences were used again in order to identify more interconnectors to study in the power market model until the price differences were lowed sufficiently so there is no more net benefit of adding direct interconnectors.

C.IV Case-independent model

The results of the combined power system and infrastructure models yield good insights in the design drivers for the specific cases investigated. As the results have proven to be very case-dependent, it was difficult to draw general conclusions which are useful for the European Commission, Transmission System Operators, and project developers. Moreover, such conclusions were needed as guidelines in the iteration process towards an overall offshore grid design.

The consortium has therefore decided to develop a case-independent model, which is an abstract model that can help to do extensive sensitivity analysis in an efficient manner. The results are cross-checked with the case study results from the real model. The case-independent model uses inputs from both the infrastructure and power system model. Instead of doing an optimisation process for each hour of the year, it aims at approaching the cost-benefit results based on average values and with simple straightforward rules. Consequently, it provides an approximate but robust result that allows quickly assessing whether it is worth to investigate the case in more detail.

As with the combination of the models of section C.II and C.III, the costs and benefits are compared for different designs, where costs and benefits are defined as:

- Infrastructure costs (depending on cable length and capacity)
- System benefits = present value of yearly trade benefits, which are defined as the sum of the product of hourly price difference between countries and the hourly remaining capacity for trade (interconnector capacity not used by wind power)

The model is built in Matlab and focuses on two design problems, namely the teeing-in of wind farms into an interconnector between two countries, and the interconnection of two countries via two offshore wind farm hubs in between. As inputs, it uses:

- Infrastructure cost tables (varying with distance and capacity) developed by SEL for:
  – individual connection of wind farms
  – teeing-in of wind farms
  – direct interconnector
  – interconnector between hubs
- Market price profiles and the difference between them for different countries (outcome of the power system model by SINTEF)
- Time series for the wind power production of a wind farm (data from Forwind model used)

The objective of the case-independent model is to have concrete design guidelines that are useful for various stakeholders. To this end, an extensive sensitivity analysis is done that looks into the impact of the price difference between countries, to the impact of cable or wind farm capacities, to the impact of cable lengths and reduced cable length, and to the direction of the price difference. The model can vary the following parameters:

- Average absolute price difference between countries
- Balance of the price difference between countries (balanced flow with 50% of price difference to either country or balanced more towards one of the two countries)
- Distance between onshore connection points (cable length direct interconnector)
- Distance between hubs and onshore connection points
- Distance between hubs (possible reduction in cable length vs. a direct interconnector)
- Capacity of the wind farm(s)
- Capacity of the cables

Photo: Detlev Gehring - Stiftung Offshore Windenergie

ANNEX D – DETAILS OF RESULTS

D.I Wind output statistics

D.I.I Spatial smoothing of wind power

There are several techno-economic benefits directly linked to an offshore grid as outlined in the introduction. One of these benefits is the additional interconnection of wind energy generation centres across Europe which smoothes the wind energy variability towards a more steady generation profile. This issue was already studied by the TradeWind study and was further elaborated within OffshoreGrid as more accurate wind power time series were available.

This smoothing effect is illustrated in Figure 13.1, displaying the gradients for three different sizes of regions in Denmark (a gradient is the percentage by which power goes up or down in one hour, or % fluctuation in an hour). It can clearly be seen that the gradient, or fluctuation in wind power, is much less when looking at a large region such as the whole of Denmark, when compared to the gradient of just one wind farm.

The effect is even more pronounced when aggregating on a European level, as shown in Figure 13.2. Whereas offshore EU wind power still exhibits hourly gradients of 8% during a noticeable time per year, total EU wind power (onshore plus offshore) hardly shows hourly gradients in excess of 5%.

The smoothing effect on wind variability is clearly visible in Figure 13.3 where it is clearly shown that the wind power generation of the OffshoreGrid 2030 scenario across a large area as EU27 (incl. Norway and Switzerland) exhibits a significantly lower variability compared to the wind power generated in e.g. Belgium alone.

A way of representing the beneficial effect of aggregation at power system scale is by plotting the load duration curve of wind power plants. This is a graph which shows how many hours the power plant is operating above a certain power output. Examples for a single wind turbine, a small country (Belgium) and the whole of the EU are given in Figure 13.4. Aggregating wind power flattens the load duration curve. A single offshore turbine in this example produces rated (100%) power for 1,500 hours and zero power during

FIGURE 13.1: FREQUENCY OF RELATIVE POWER CHANGES IN INTERVALS OF ONE HOUR FOR A SINGLE DANISH OFFSHORE WIND FARM, 25 DANISH OFFSHORE WIND FARMS EXPECTED IN 2030 AND ALL WIND FARMS (ON&OFFSHORE) THAT ARE EXPECTED IN DENMARK IN 2030. A POSITIVE VALUE REFLECTS AN INCREASE IN POWER AND A NEGATIVE VALUE A DECREASE

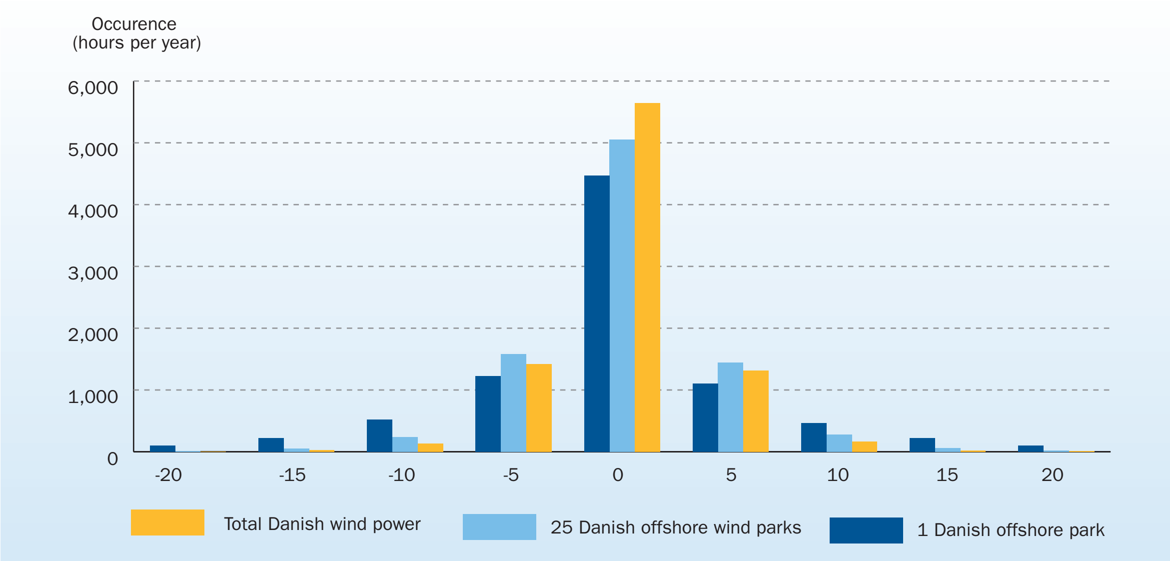
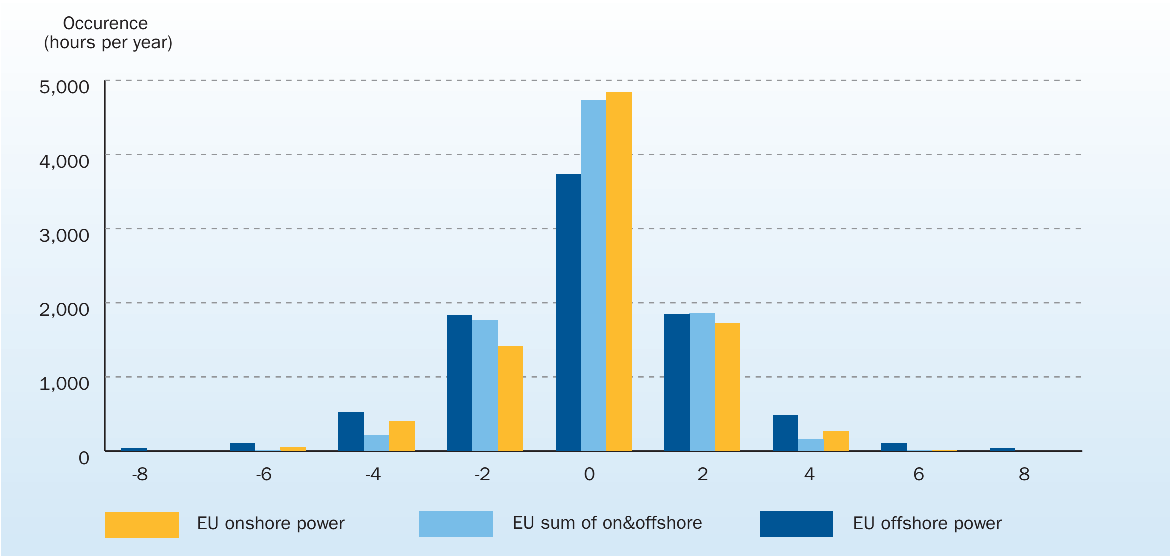


FIGURE 13.2: FREQUENCY OF RELATIVE POWER CHANGES IN 1 HOUR INTERVALS FROM ALL EXPECTED EUROPEAN OFFSHORE WIND FARMS IN 2030 (127GW), FROM ALL EXPECTED EUROPEAN ONSHORE WIND FARMS IN 2030 (267GW) AND THE SUM OF ALL EXPECTED ON&OFFSHORE CAPACITIES IN EUROPE IN 2030



1,000 hours, whereas at the EU level, the maximum wind power produced is 70% of the total installed capacity and the minimum wind power production is never below 10%. This demonstrates how aggregation at the European level results in increasingly steady wind power output, although there are still periods with low or high wind power production.

It is important to highlight that this large-scale wind smoothing effect is only possible if power exchange can be realised across large areas and if the power exchange is not restricted. The grids play a crucial role of interconnecting wind power plant outputs installed at a variety of geographical locations, with different weather patterns.

FIGURE 13.3: EXAMPLE OF SMOOTHING EFFECT BY GEOGRAPHIC DISPERSION. THE FIGURE COMPARES THE HOURLY OUTPUT OF WIND POWER CAPACITY IN THREE AREAS, INCLUDING ALL EXPECTED ONSHORE AND OFFSHORE WIND FARMS IN THE YEAR 2030

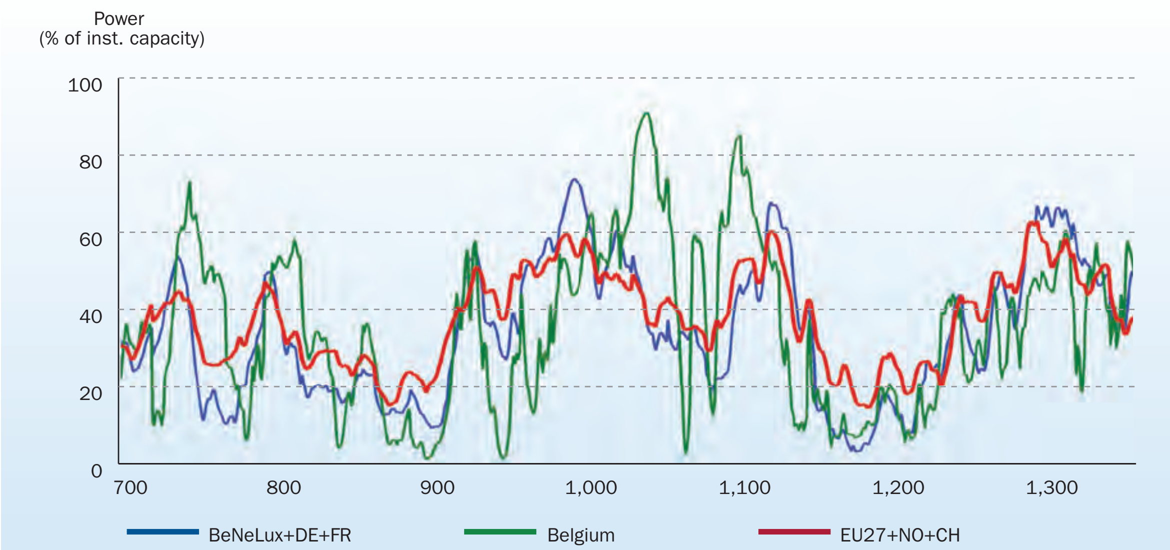
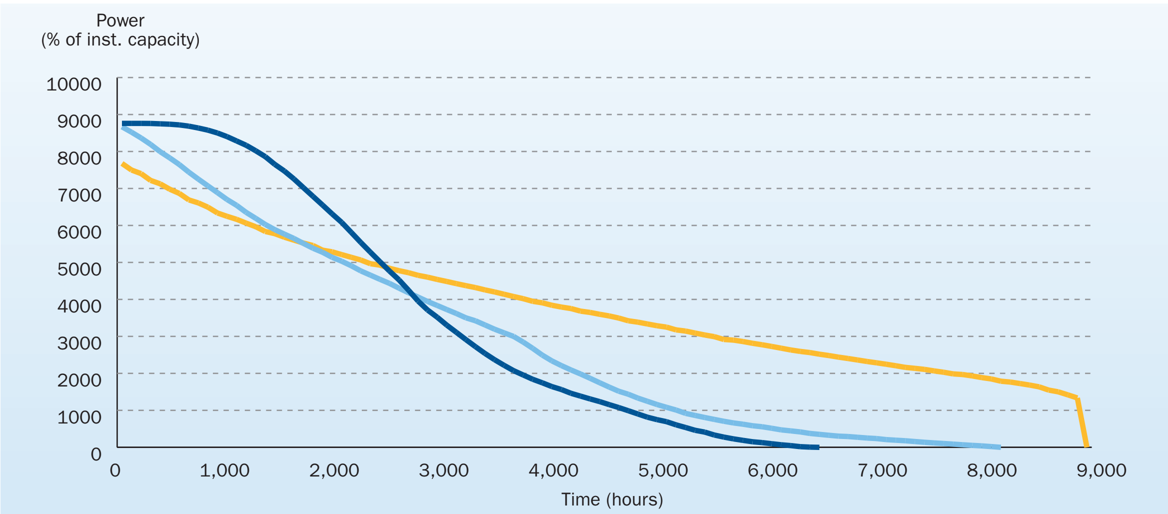


FIGURE 13.4: DURATION CURVES FOR THE 'WIND YEAR 2030', FOR A SINGLE OFFSHORE TURBINE IN FRONT OF THE BELGIUM COAST, FOR THE SUM OF ALL EXPECTED ON&OFFSHORE WIND FARMS IN BELGIUM IN 2030 AND FOR THE SUM OF ALL EXPECTED ON&OFFSHORE WIND FARMS IN EUROPE IN 2030



The larger the grid and the larger its transmission capacity, the larger the smoothing effect will be of wind energy. This effect of course also holds for aggregation of demand or other weather or resource dependent generation sources.

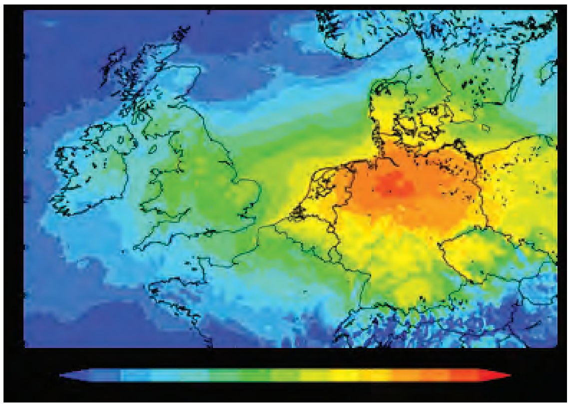
D.I.II Visualising spatial power correlations: von-Bremen-Maps[63]

A new way of identifying spatial correlations of wind power production is shown in Figure 13.5 and Figure 13.6. The simple idea is to calculate the correlation between a time series of a certain local variable, like local wind speed at a specific point in space, to a prescribed reference time series which is fixed. Then, all these correlations for a high number of geographical points, preferably for a high density of grid points, are plotted as a map. In this way, the map shows the spatial characteristics of a specific correlation.

The von-Bremen-map in Figure 68 shows the spatial correlation of local wind power time series and the German Wind Power Generation in spring 2007.

Figure 13.5 shows that the area which shows the highest correlation with the aggregated sum of the German

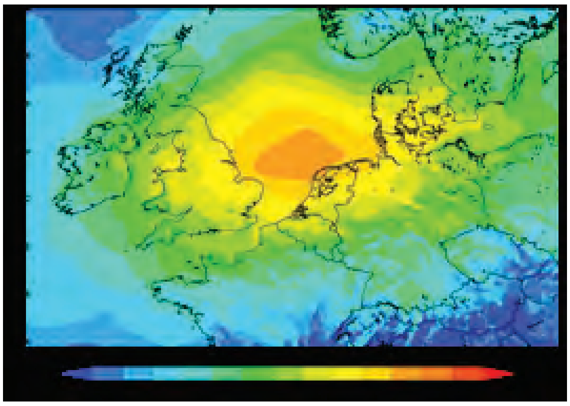
FIGURE 13.5: VON-BREMEN-MAP SHOWING SPATIAL CORRELATION BETWEEN LOCAL WIND POWER TIME SERIES AND THE MEASURED GERMAN WIND POWER GENERATION TIME SERIES IN SPRING 2007

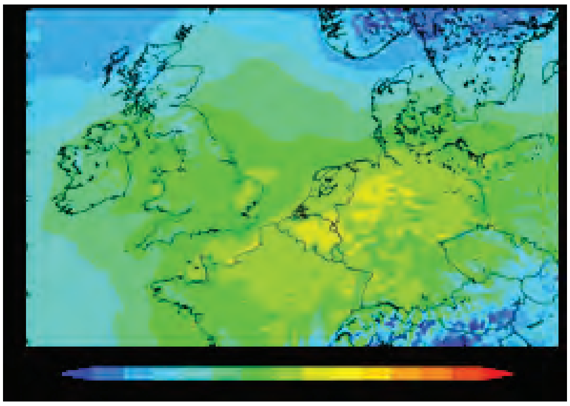


wind power generation is the region between Bremen, Hamburg and Hannover. This plausible result is due to the simple fact that the major shares of German wind power capacity are installed in the northern part of the country and the high density of turbines obviously results in a high correlation. The more interesting result is that the correlation shows a clear west-east pattern: The map reflects that the wind power production is strongly correlated from West to East (e.g. England, BeNeLux, Germany, Denmark and Poland), but less

[63] Developed by Dr. Lueder von Bremen (ForWind) in September 2010.

FIGURE 13.6: VON-BREMEN-MAP SHOWING SPATIAL CORRELATION BETWEEN LOCAL WIND POWER TIME SERIES AND THE SIMULATED TOTAL EU OFFSHORE WIND POWER (LEFT) OR ONSHORE WIND POWER (RIGHT), FULL YEAR 2007





between North and South (e.g. Denmark vs. France). Besides the fact that the main wind direction is from West to East, especially the low pressure weather systems with strong wind speeds also move mainly from West to East. This leads to a correlation between England and Germany of about 0.50, in contrast to only 0.18 between France and Germany.

Figure 13.6 shows the correlation of the local wind power time series with either the simulated offshore wind power (figure to the left) or onshore wind power (figure to the right) in Northern Europe, as assumed in the 2030 scenario of offshore grid. It reflects that most of the offshore capacities in the 2030 scenario are concentrated in the Southern North Sea. In contrast to this, the onshore wind power in the scenario is more or less evenly distributed over Northern Europe. In total, wind energy is clearly concentrated in the North. This concentration will pose considerable challenges regarding the power flows in the future European electricity grid.

To conclude, the analysis shows that grid interconnections between regions of low weather correlation can significantly reduce the variability of European wind power production. The North-South direction is the most interesting from correlation point of view.

TABLE 13.1: CORRELATION COEFFICIENTS BETWEEN COUNTRIES USING SIMULATED WIND POWER TIME SERIES FOR THE OFFSHOREGRID 2030 WIND POWER SCENARIO (ON- & OFFSHORE WIND TOGETHER)

	BE	DK	ET	FI	FR	DE	UK	IR	LA	LT	NL	NO	PL	RU	SE
BE	100%	45%	12%	2%	59%	67%	66%	37%	20%	21%	79%	12%	28%	20%	22%
DK	45%	100%	32%	17%	32%	76%	49%	20%	44%	48%	77%	44%	78%	48%	73%
ET	12%	32%	100%	51%	10%	18%	16%	12%	66%	66%	22%	13%	36%	45%	69%
FI	2%	17%	51%	100%	2%	6%	7%	4%	30%	34%	10%	23%	16%	19%	49%
FR	59%	32%	10%	2%	100%	37%	49%	43%	16%	18%	46%	5%	23%	17%	20%
DE	67%	76%	18%	6%	37%	100%	67%	26%	28%	30%	87%	40%	53%	32%	43%
UK	66%	49%	16%	7%	49%	67%	100%	62%	20%	21%	74%	37%	29%	21%	27%
IR	37%	20%	12%	4%	43%	26%	62%	100%	13%	14%	33%	14%	15%	13%	13%
LA	20%	44%	66%	30%	16%	28%	20%	13%	100%	89%	32%	15%	55%	74%	69%
LT	21%	48%	66%	34%	18%	30%	21%	14%	89%	100%	34%	17%	61%	88%	72%
NL	79%	77%	22%	10%	46%	87%	74%	33%	32%	34%	100%	36%	50%	34%	49%
NO	12%	44%	13%	23%	5%	40%	37%	14%	15%	17%	36%	100%	24%	16%	30%
PL	28%	78%	36%	16%	23%	53%	29%	15%	55%	61%	50%	24%	100%	65%	73%
RU	20%	48%	45%	19%	17%	32%	21%	13%	74%	88%	34%	16%	65%	100%	59%
SE	22%	73%	69%	49%	20%	43%	27%	13%	69%	72%	49%	30%	73%	59%	100%

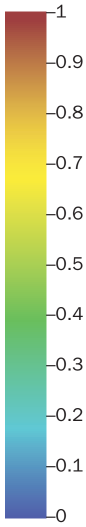
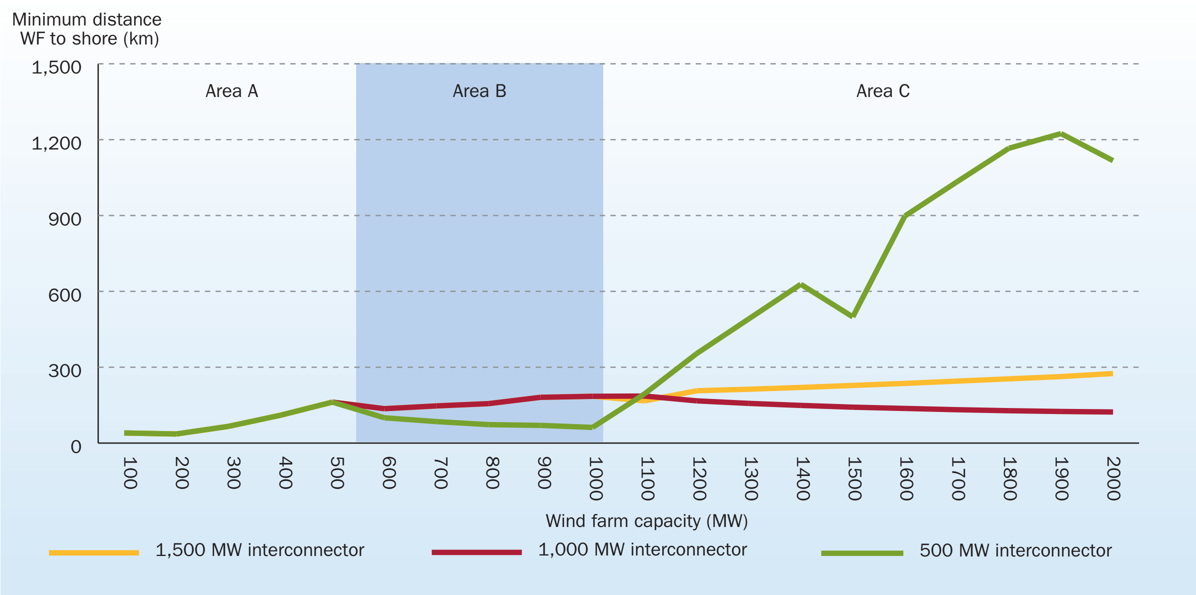


FIGURE 13.7: MINIMUM BENEFICIAL DISTANCE FROM THE WIND FARM TO SHORE FOR DIFFERENT INTERCONNECTOR CAPACITIES [KM]. (AVERAGE ABSOLUTE PRICE DIFFERENCE OF €7.5, DISTANCE WF TO INTERCONNECTOR OF 40KM, UNBALANCED FLOW WITH 30% OF PRICE DIFFERENCE FLOWING TOWARDS ONE COUNTRY)



Spatial correlations of wind power production between countries

With the simulated wind power time series, also the spatial correlations between individual countries have been investigated. The results are shown in Table 13.1, which confirms the findings explained above. These figures can be used in the preliminary assessment of new interconnectors that are meant for trading wind power.

D.II Case-independent model – sensitivity analysis

The case-independent model was built in order to carry out pre-analysis of beneficial cases of hub-to-hub connections and tee-in connections. Furthermore the results of case-independent model can serve as quick guidelines for the modular offshore grid development and can give insight to policy decision makers, stakeholders, TSOs and interconnector and wind farm developers.

The case-independent model analyses the benefits of a project compared to the conventional solution. The model takes into account a variety of parameters that influence the results. If the parameters of the project are known, the reader can position his project within the field of parameters and read the economic viability of the project from the results given.

The model is explained below but the detailed results are available on www.offshoregrid.eu due to the large amount of data.

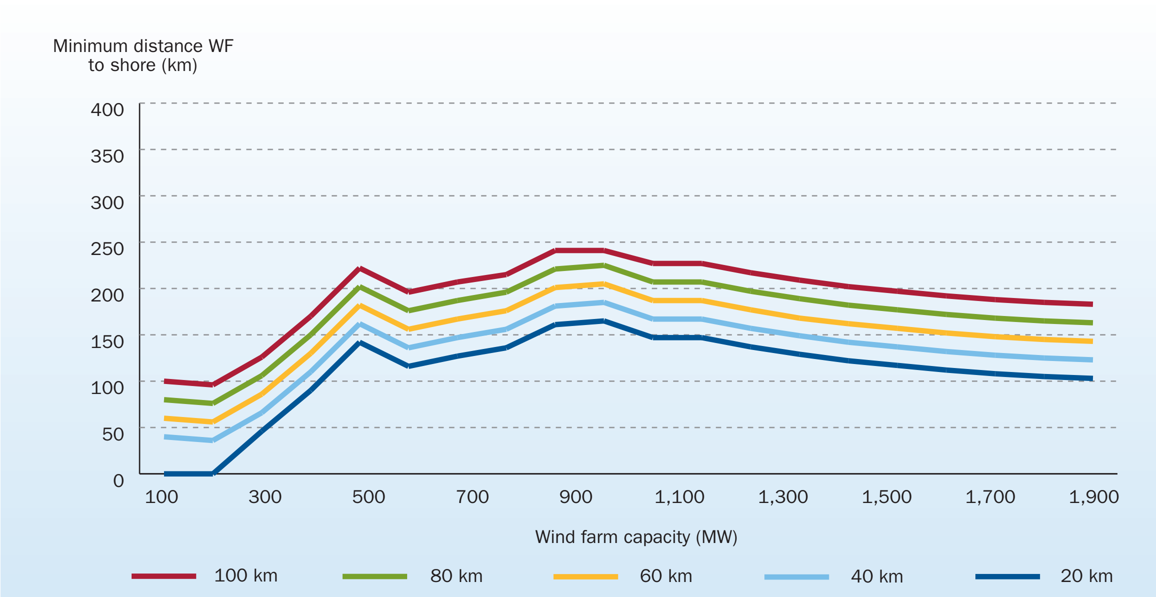
D.II.I Sensitivity analysis on the benefit of tee-in solutions

Impact of interconnector capacity

The impact of the interconnector capacity on the break-even distance is different for different wind farm capacities. These can be divided in three areas, as can be seen in Figure 13.7:

- **Area A: Wind farm capacities up to the interconnector capacity of 500 MW.**
  For wind farms with a small capacity, the break-even distances are equal for every interconnector capacity. The part of the interconnection capacity which is higher than the wind farm capacity is unconstrained in both the conventional solution as the tee-in solution. It does therefore not lead to a difference in the minimum beneficial distance.

FIGURE 13.8: MINIMUM DISTANCE FROM THE WIND FARM TO SHORE FOR DIFFERENT DISTANCES FROM THE WIND FARM TO THE INTERCONNECTOR [KM]. (INTERCONNECTOR CAPACITY OF 1000 MW, AVERAGE ABSOLUTE PRICE DIFFERENCE OF €7.5, UNBALANCED FLOW WITH 30% OF PRICE DIFFERENCE FLOWING TOWARDS ONE COUNTRY IMPACT OF DISTANCE WF TO INTERCONNECTOR)



- **Area B: Wind farm capacities between 500 MW and 1000 MW.**
  As described above, the minimum distance drops for wind farms larger than the interconnector capacity, until the wind farm capacity is double the size of the interconnector. This is shown in Area B for the interconnector capacity of 500 MW. For the larger interconnector capacities, the curves still coincide as in Area A.

- **Area C: Wind farm capacities larger than 1,000 MW.**
  As in area B, the break-even distance drops for wind farms larger than the interconnector capacity until double the size. In this area this is shown for the 1,000 MW interconnector curve. For 2,000 MW interconnectors, the break-even distance is larger than for the 1,000 MW interconnector and is still rising as the wind farm capacity goes to 100% the interconnector capacity. In Area C, the wind farm is larger than 200% the interconnector capacity for the 500 MW case. The break-even distance therefore rises steeply with WF capacity as the wind farm output would have to be curtailed due to too small cable capacity.

Impact of distance of wind farm to interconnector

The further a wind farm from an interconnector, the less beneficial it is to tee-in on that interconnector, and the higher the break-even distance (Figure 13.8).

Impact of absolute price difference

The higher the absolute difference of price levels in the connected countries, the more important the electricity trade becomes. Wind farms should then be smaller in order to not constrain "valuable trading capacity" of the cable. As a result the minimum distance increases with price level difference (Figure 13.9).

Electricity price profiles and wind-price correlations

- Unbalanced price profiles increase the impact of teed-in wind energy.
  If the price difference is not balanced, which here means that the price is most of the time (>50% of the time) lower in one country, the impact of wind power production becomes larger. This is because in case wind is blowing it blocks the possibility for trade. In this case one of the legs (the one connecting the country with lower prices) is not loaded and

infrastructure remains unused. A solution would be to dimension this leg smaller.

- Due to this large impact of wind teed-in to the interconnection, the minimum distance grows with the imbalance of the price levels.
- Correlation between wind and price imbalance is beneficial for a tee-in solution.
- If the price difference profile is correlated with the wind power production, this will have an impact on the minimum tee-in distance. If the price difference is lower when there is a lot of wind, the impact of constraining the cable will be less important and the minimum distance to shore will become shorter. If the price difference is higher at times of high wind energy production the effect is opposite.

FIGURE 13.9: MINIMUM DISTANCE FROM THE WIND FARM TO SHORE FOR DIFFERENT AVERAGE ABSOLUTE PRICE DIFFERENCES [KM]. (INTERCONNECTOR CAPACITY OF 1000 MW, AVERAGE ABSOLUTE PRICE DIFFERENCE OF €7.5, UNBALANCED FLOW WITH 30% OF PRICE DIFFERENCE FLOWING TOWARDS ONE COUNTRY IMPACT OF DISTANCE WF TO INTERCONNECTOR)

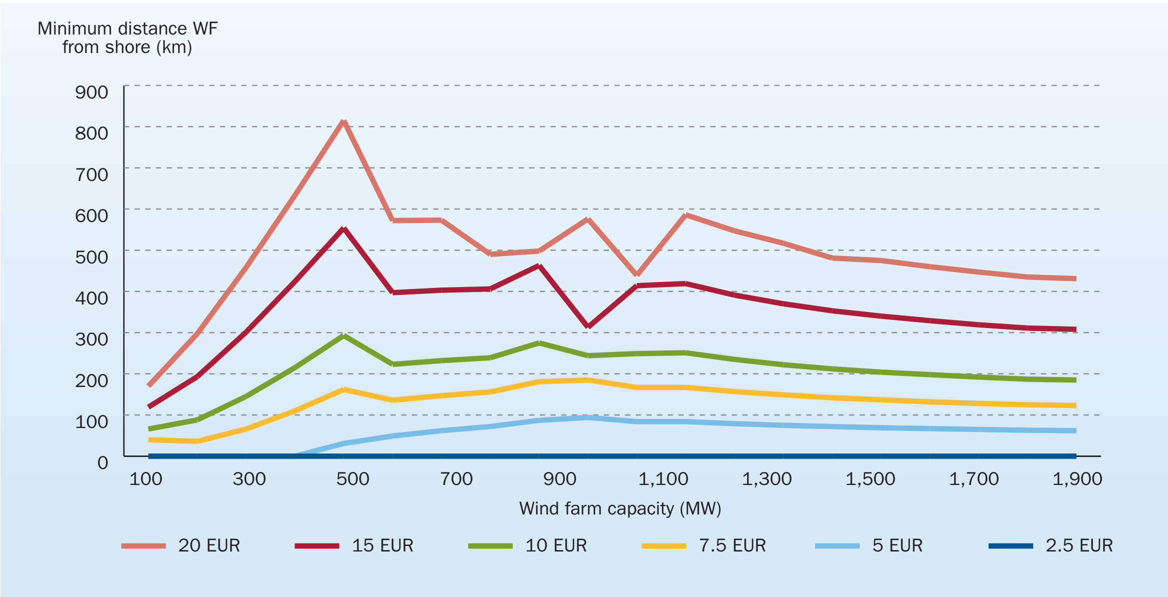
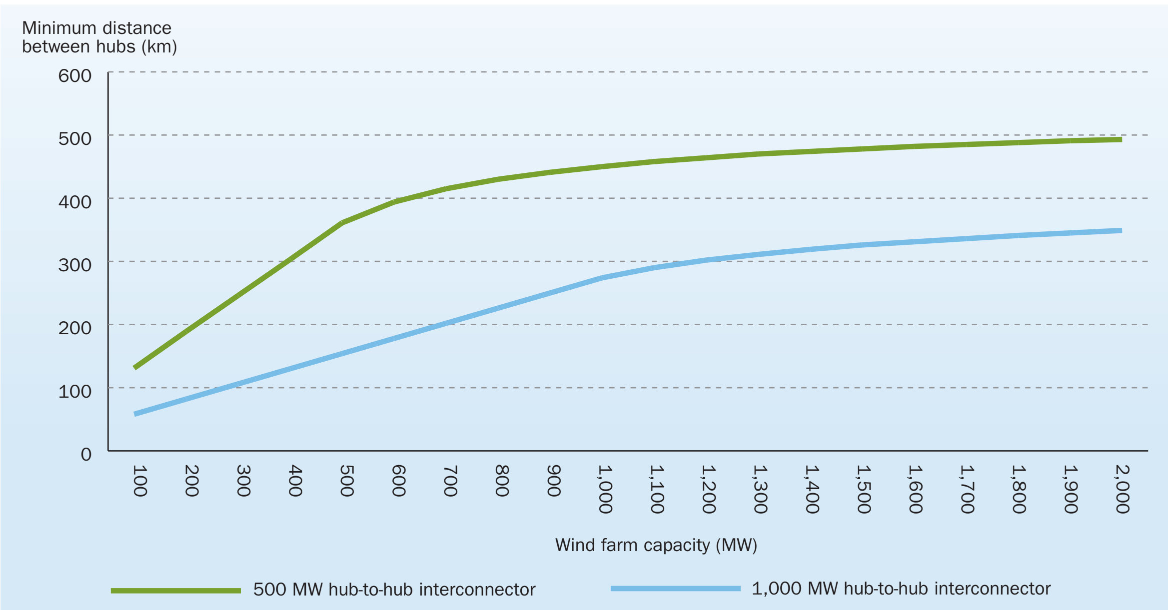


FIGURE 13.10: IMPACT OF INCREASING INTERCONNECTOR CAPACITY ON THE MAXIMUM BENEFICIAL DISTANCE FOR HUB-HUB INTERCONNECTORS. (DIRECT INTERCONNECTOR DISTANCE TO WHICH COMPARED: 500 MW, AVERAGE ABSOLUTE PRICE DIFFERENCE BETWEEN THE COUNTRIES: €5/MWH)



D.II.II Sensitivity analysis on the benefit of hub-to-hub solutions

Impact of interconnector capacity

For wind farm capacities which are smaller than the interconnector capacity, the wind farm connections are the constraining factor for the trade. Increasing the interconnector capacity further only leads to additional infrastructure costs and thus lowers the maximum beneficial distance between hubs (Figure 13.10).

Impact of distance between countries (direct interconnection length)

The larger the distance between two countries (and thus the larger the direct interconnector length to

FIGURE 13.11: MAXIMUM DISTANCE BETWEEN HUBS FOR DIFFERENT DIRECT INTERCONNECTOR LENGTHS [KM] (INTERCONNECTOR CAPACITY OF 500 MW, AVERAGE ABSOLUTE PRICE DIFFERENCE OF €5, UNBALANCED FLOW WITH 30% OF PRICE DIFFERENCE FLOWING TOWARDS ONE COUNTRY)

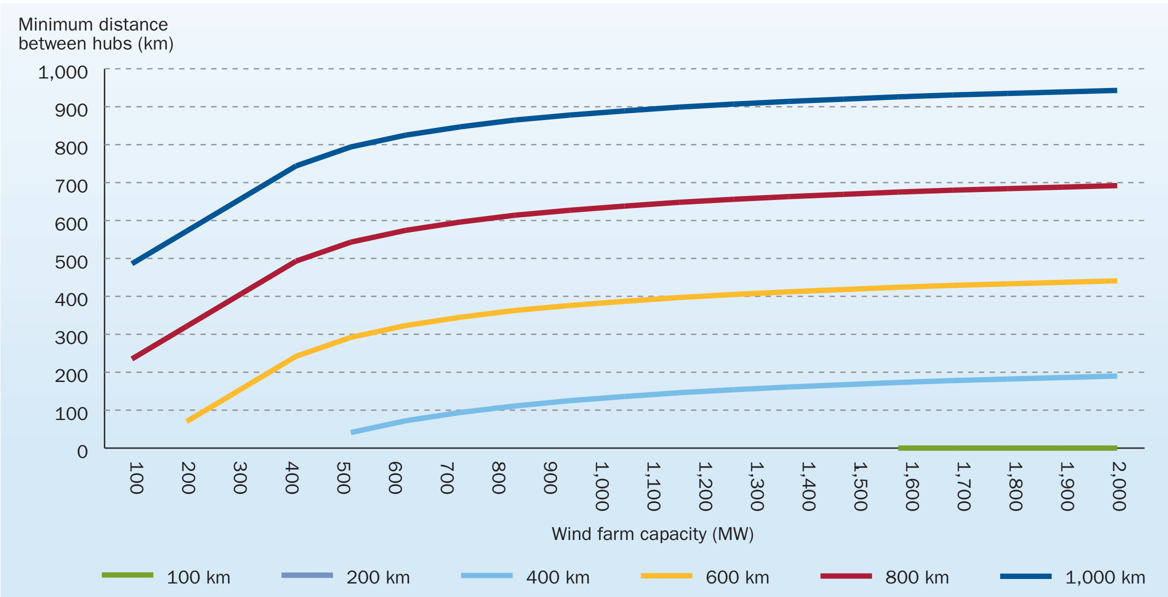


FIGURE 13.12: MAXIMUM DISTANCE BETWEEN HUBS FOR DIFFERENT WF CAPACITIES AND SEVERAL AVERAGE ABSOLUTE PRICE DIFFERENCES [€/MWH] (INTERCONNECTOR CAPACITY OF 500 MW, DIRECT INTERCONNECTOR OF 500 KM, UNBALANCED FLOW WITH 30% OF PRICE DIFFERENCE FLOWING TOWARDS ONE COUNTRY)

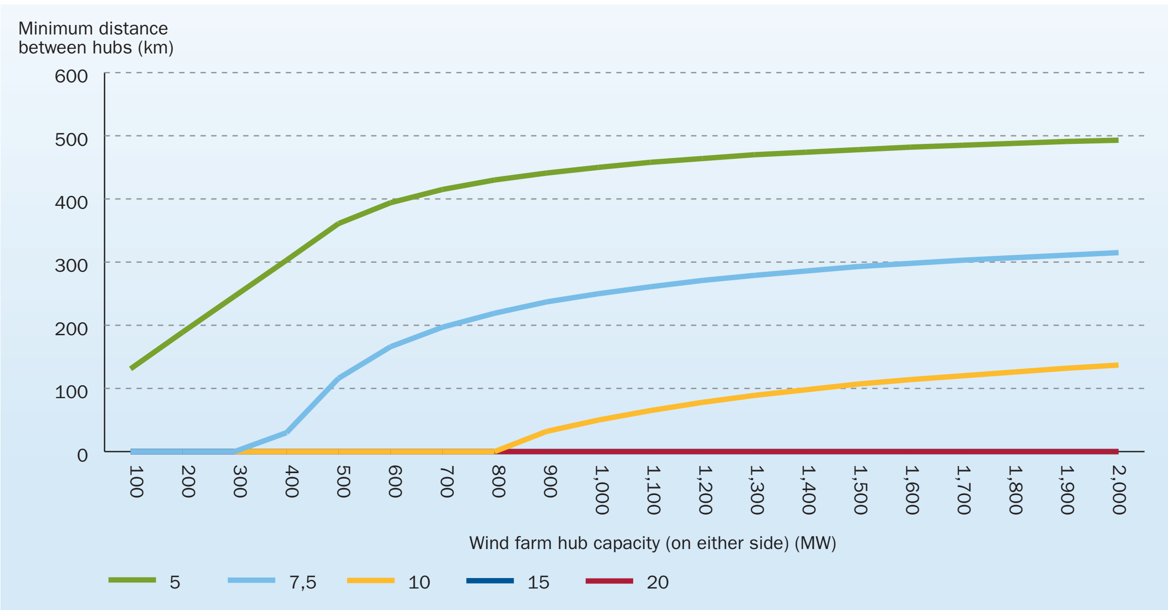
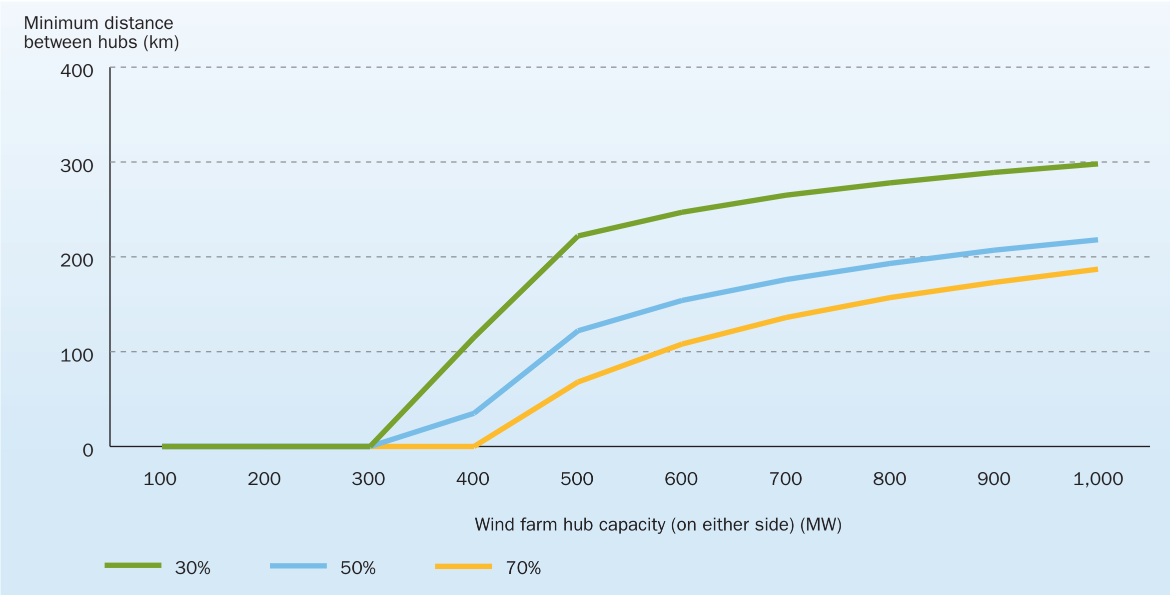


FIGURE 13.13: MAXIMUM DISTANCE BETWEEN HUBS FOR ASYMMETRIC WIND FARM HUBS CAPACITY - DIFFERENT PROFILES OF PRICE DIFFERENCE (30% TO COUNTRY A, 50% TO EITHER COUNTRY, AND 70% TO COUNTRY B) [€/MWH] (INTERCONNECTOR CAPACITY OF 500 MW, WIND FARM CAPACITY IN COUNTRY 2 IS TWICE THE SIZE OF THE WIND FARM IN COUNTRY A)



which is compared), the more infrastructure costs will be saved by interconnecting hubs. The maximum beneficial distance between hubs therefore increases with increasing direct interconnector length (Figure 13.11).

Impact of absolute price difference

The higher the absolute price difference between the countries, the more the trade of electricity becomes important and the less the interconnector cable should be constrained. For higher absolute price differences, the reduction in infrastructure costs due to the reduced cable length must be higher to cover the reduction in system benefits. The maximum distance between hubs in these cases is therefore lower (Figure 13.12).

Electricity price profiles and wind-price correlations

- Unbalanced price profiles have no impact
  If the price difference is not balanced, which here means that the price is most of the time (>50% of the time) lower in one country, one of the legs (the one connecting the country with lower prices) is not often loaded and infrastructure remains unused (the leg connecting the country with lower prices). However, as the constraints on the cables are independent on the direction of the price difference when the cable capacities are identical, this has no effect on the break—even distance. The constraints can be partly relieved by dimensioning one leg bigger and the other leg smaller.
- Correlation between wind and price imbalance increases the impact.
- As before with the tee-in solutions (paragraph 4.4.1), a correlation between the wind power production and the price imbalance has a negative effect on the economics of integrated solutions compared to the business as usual case. Similarly, an inverse correlation has a positive effect.

Impact of asymmetric wind farm hub capacities

In Figure 13.13 the effect of asymmetric wind farm hub capacities is analysed. The wind farm hub in country A is 50% smaller than the wind farm hub in country B. The wind farm connection cable in country B is thus double the size of the connection cable in country A so that wind power from both hubs can flow to the country with the highest prices most of the time (country B). Figure 13.13 confirms that when prices are more often higher in country B (30% of price difference balanced to country A), the trade is less constrained which leads to a higher maximum distance between hubs.

D.III Overall grid design

D.III.I Direct interconnectors

Table 13.2 shows the direct and hub-to-hub interconnectors that were identified as being beneficial and used in the first stage of the direct overall grid design.

D.III.II Split wind farms

Table 13.3 shows the interconnectors that were identified as being beneficial and used in the first stage of the split overall grid design.

D.III.III Tested meshed interconnectors

To give an indication of the number of simulations run, this paragraph gives an overview of all the interconnectors tested for the mesh (Table 13.4). This vast number of possible interconnectors was considered in order to assess the optimal meshed design in step 3 of the Direct and Split Design methodology.

D.III.IV Price level differences between countries

As for any other good also for electricity, trade between regions follows the price level differences or in other

TABLE 13.2: DIRECT & HUB - HUB INTERCONNECTORS IDENTIFIED

Type	Country	From Name	Country	To Name	MW	Voltage	Technology
Direct	SE	Kruseberg	DE	Bentwisch	1,000	500	HVDC CSC
Direct	FI	Espoo	EE	Harku	1,000	500	HVDC CSC
Direct	SE	Stärnö	PL	Ustka	1,000	500	HVDC CSC
Direct	SE	Herslev (DK East)	DK	Starebaelt	1,000	500	HVDC CSC
Direct	SE	Selemåla	LV	Grobina	1,000	500	HVDC CSC
Direct	GB	Bolney	FR	Penly	1,000	500	HVDC CSC
Direct	SE	Kruseberg	DE	Bentwisch	1,000	500	HVDC CSC
Direct	GB	Richborough	BE	Zeebrugge	1,000	500	HVDC CSC
Direct	GB	Bolney	FR	Penly	1,000	500	HVDC CSC
Direct	SE	Stärnö	PL	Ustka	1,000	500	HVDC CSC
Direct	SE	Herslev (DK East)	DK	Starebaelt	1,000	500	HVDC CSC
Direct	IE	Knockraha	FR	La Martyre	1,000	500	HVDC CSC
Direct	IE	Woodland	GB	Deeside	1,000	500	HVDC CSC
Direct	GB	Richborough	BE	Zeebrugge	1,000	500	HVDC CSC
Hub - Hub	SE	Stora Middelgrund	DK	Djursland/Anholt	500	320	HVDC VSC
Hub - Hub	NL	IJmuiden Hub 03	GB	Norfolk_B_Hub	1,000	500	HVDC VSC
Hub - Hub	GB	Dogger Bank E	DE	Gaia Group	1,000	500	HVDC VSC
				Total	**16,500**		

TABLE 13.3: SPLIT DESIGN INTERCONNECTORS

Type	Country	From Name	Country	To Name	MW	Voltage	Technology
Windfarm Hub	DE	Ventotec Ost 2 Hub	SE	Kruseberg	436	320	HVDC VSC
Onshore Substation	FI	Espoo	EE	Harku	1,000	500	HVDC VSC
Windfarm	SE	Södra Midsjöbanken	PL	Lubiatowo	1,000	320	HVDC VSC
Onshore Substation	SE	Selemåla	LV	Grobina	1,000	500	HVDC VSC
Onshore Substation	GB	Bolney	FR	Penly	1,000	500	HVDC VSC
Windfarm Hub	DE	Arkona-Becken Südost	SE	Kruseberg	450	320	HVDC VSC
Windfarm Hub	BE	Belgium Zone 2	GB	Richborough	900	500	HVDC VSC
Onshore Substation	GB	Bolney	FR	Penly	1,000	500	HVDC VSC
Windfarm Hub	PL	P25 Hub	SE	Stärnö	450	320	HVDC VSC
Onshore Substation	IE	Knockraha	FR	La Martyre	1,000	500	HVDC VSC
Windfarm	IE	Codling Wind Park extension	GB	Pentir	1,000	500	HVDC VSC
Onshore Substation	BE	Zeebrugge	GB	Richborough	1,000	500	HVDC VSC
Hub - Hub	NL	IJmuiden Hub 03	GB	Norfolk B Hub	1,000	500	HVDC VSC
Hub - Hub	GB	Dogger Bank E Hub	DE	Gaia Group Hub	1,000	500	HVDC VSC
				Total	**12,236**		

TABLE 13.4: TESTED MESH INTERCONNECTORS

Case	Country	From Name	Country	To Name	MW	Voltage	Technology	Mesh Design
h_1	NL	IJmuiden Hub 03	DE	Gaia Group	1,000	500	HVDC VSC	-
h_2	NO	Idunn	DE	Gaia Group	1,000	500	HVDC VSC	-
h_3	NO	Idunn	SE	Skogssater	1,000	500	HVDC VSC	-
h_4	NL	IJmuiden Hub 03	BE	Zeebrugge	1,000	500	HVDC VSC	Direct + Split
h_5	NO	Idunn	DE	Gaia Group	2,000	500	HVDC VSC	-
h_6	NO	Lista	NO	Idunn	2,000	500	HVDC VSC	Split
h_7	NL	IJmuiden Hub 03	DE	Gaia Group	2,000	500	HVDC VSC	-
h_8	NL	Oterleek	BE	Zeebrugge	1,000	500	HVDC VSC	-
h_9	NO	Lista	SE	Skogssater	1,000	500	HVDC VSC	Direct
h_10	NO	Idunn	GB	Dogger Bank E	1,000	500	HVDC VSC	Direct
h_11	GB	Dogger Bank E	NL	IJmuiden Hub 3	1,000	500	HVDC VSC	Split
h_12	NO	Idunn	GB	Dogger Bank E	2,000	500	HVDC VSC	Split
h_13	GB	Dogger Bank E	NL	IJmuiden Hub 3	2,000	500	HVDC VSC	-
h_14	GB	Dogger Bank E	DE	Gaia Group	2,000	500	HVDC VSC	-
h_15	DE	Gaia Group	DE	Globaltech Group	1,000	500	HVDC VSC	-
h_16	NL	IJmuiden Hub 03	NL	IJmuiden Hub 2	1,000	500	HVDC VSC	-
h_17	GB	Dogger Bank E	GB	Dogger Bank C	1,000	500	HVDC VSC	Split
h_18	SE	Södra Midsjöbanken	LT	Klaipeda	1,000	320	HVDC VSC	-
h_19	DE	Arkona-Becken Südost	SE	Södra Midsjöbanken	1,000	320	HVDC VSC	-

words electricity is bought where it is cheapest and it is sold where it can be sold for the highest price. If interconnection capacity would be unlimited, the wholesale market price levels would be equal across Europe. However the limited interconnection capacity between countries limits the trade and the prices cannot be fully levelled. The price differences thus reflect the price for transmission capacity between countries.

If new interconnecting lines are built either on- or offshore, the trading volumes are increased and price levels differences are reduced. One could also interpret it as follows: the supply curve of interconnection capacity is increased and therefore the price for it is reduced.

In particular new transmission capacities allow the electricity to be produced where the production costs are lowest and therefore additional transmission capacity can lower the overall electricity generation costs. This system cost reduction is considered as the benefits of the transmission capacity that has to be compared with the infrastructure cost in order to determine the net benefits.

In order to assess this task the price levels between all countries were listed and the highest price levels were identified. This sorted list of highest price differences between countries was used as an indicator for the most beneficial interconnections. As detailed in chapter 4.5 the OffshoreGrid consortium tested two methodologies. The Direct Design approach and the Split Design approach:

- The Direct Design approach starts from the Hub Base Case scenario 2030 and adds direct interconnections between the countries. In the next step hub-to-hub connections and finally meshed grid elements are added.
- The Split Design equals the Direct Design, but in the first step the direct interconnections are mirrored with split wind farm connections (s. chapter 4.3.1) where beneficial.

At each of these steps the price levels between the countries are changed. This is displayed for the direct approach in Table 13.6 and for the Split Design approach in Table 13.5.

TABLE 13.5: DIRECT DESIGN APPROACH - PRICE LEVEL DIFFERENCES BETWEEN THE COUNTRIES AFTER DIFFERENT DESIGN REALISATIONS

		BE	DE	DK	EE	FI	FR	GB	IE	LT	LV	NL	NO	PL	SE
BE	Base Case		4,6	9,7	6,4	23,7	10,1	9,4	8,2	6,9	6,4	7,0	17,5	6,0	25,9
	Direct		4,0	6,7	8,4	11,9	7,6	6,2	7,1	7,2	8,1	5,0	15,5	6,1	11,0
	Hub-to-hub		4,1	6,8	8,3	11,7	6,4	5,4	6,5	7,2	8,0	4,3	16,3	6,3	10,9
	Meshed		4,1	6,3	8,0	11,4	5,8	4,6	6,0	7,0	7,7	3,3	15,6	6,2	10,5
DE	Base Case	4,6		7,5	5,4	22,1	9,5	8,8	8,8	5,4	5,4	5,3	15,7	4,4	24,0
	Direct	4,0		5,8	7,8	11,4	8,5	7,6	8,7	6,1	7,3	4,8	15,2	4,7	10,3
	Hub-to-hub	4,1		6,3	7,7	11,5	8,3	7,4	8,4	6,3	7,2	4,9	16,4	5,0	10,6
	Meshed	4,1		6,1	7,7	11,5	8,3	7,3	8,3	6,3	7,2	4,5	16,0	5,0	10,5
DK	Base Case	9,7	7,5		6,2	16,2	7,6	8,9	11,4	5,8	6,2	6,3	10,1	6,9	17,0
	Direct	6,7	5,8		4,7	7,2	6,7	7,1	8,8	3,0	4,1	4,4	10,7	3,7	5,6
	Hub-to-hub	6,8	6,3		4,6	7,0	6,5	6,7	8,6	3,0	4,0	4,3	11,3	3,4	5,5
	Meshed	6,3	6,1		4,6	7,1	6,4	6,3	8,3	3,0	4,0	4,2	11,1	3,3	5,6
EE	Base Case	6,4	5,4	6,2		18,8	8,5	10,0	10,4	1,2	0,0	8,1	13,4	3,7	21,1
	Direct	8,4	7,8	4,7		4,0	7,8	9,0	10,7	2,7	1,0	7,9	9,0	5,6	4,0
	Hub-to-hub	8,3	7,7	4,6		4,1	7,6	8,5	10,3	2,4	0,9	7,4	9,9	5,0	4,1
	Meshed	8,0	7,7	4,6		4,1	7,6	8,2	10,1	2,4	0,9	7,3	9,6	5,0	4,1
FI	Base Case	23,7	22,1	16,2	18,8		16,5	20,3	23,4	19,0	18,8	20,7	9,9	20,9	7,3
	Direct	11,9	11,4	7,2	4,0		9,0	11,0	12,9	6,3	4,7	10,6	5,7	9,1	2,1
	Hub-to-hub	11,7	11,5	7,0	4,1		9,0	10,5	12,5	6,1	4,7	10,2	6,3	8,5	2,0
	Meshed	11,4	11,5	7,1	4,1		9,0	10,3	12,4	6,1	4,7	10,2	6,1	8,4	2,0
FR	Base Case	10,1	9,5	7,6	8,5	16,5		8,9	11,3	8,5	8,5	8,3	10,6	9,6	17,2
	Direct	7,6	8,5	6,7	7,8	9,0		5,8	6,9	7,2	7,6	6,5	10,5	8,0	8,2
	Hub-to-hub	6,4	8,3	6,5	7,6	9,0		5,2	6,5	7,1	7,4	5,9	11,7	7,6	8,3
	Meshed	5,8	8,3	6,4	7,6	9,0		4,9	6,3	7,1	7,4	5,6	11,4	7,5	8,2
GB	Base Case	9,4	8,8	8,9	10,0	20,3	8,9		6,1	9,9	10,0	6,5	15,0	10,0	21,2
	Direct	6,2	7,6	7,1	9,0	11,0	5,8		4,1	8,1	8,7	5,3	13,0	8,2	10,0
	Hub-to-hub	5,4	7,4	6,7	8,5	10,5	5,2		4,1	7,7	8,2	4,6	13,6	7,7	9,6
	Meshed	4,6	7,3	6,3	8,2	10,3	4,9		4,1	7,4	7,9	4,1	13,1	7,4	9,3
IE	Base Case	8,2	8,8	11,4	10,4	23,4	11,3	6,1		10,6	10,4	8,6	18,1	10,2	24,8
	Direct	7,1	8,7	8,8	10,7	12,9	6,9	4,1		9,8	10,4	7,0	15,1	9,5	12,0
	Hub-to-hub	6,5	8,4	8,6	10,3	12,5	6,5	4,1		9,4	10,0	6,4	15,7	9,1	11,7
	Meshed	6,0	8,3	8,3	10,1	12,4	6,3	4,1		9,3	9,8	6,0	15,2	8,9	11,5
LT	Base Case	6,9	5,4	5,8	1,2	19,0	8,5	9,9	10,6		1,2	7,8	13,4	2,8	20,5
	Direct	7,2	6,1	3,0	2,7	6,3	7,2	8,1	9,8		1,8	6,3	10,2	3,0	5,0
	Hub-to-hub	7,2	6,3	3,0	2,4	6,1	7,1	7,7	9,4		1,5	6,0	10,9	2,6	5,0
	Meshed	7,0	6,3	3,0	2,4	6,1	7,1	7,4	9,3		1,5	5,9	10,6	2,6	4,9
LV	Base Case	6,4	5,4	6,2	0,0	18,8	8,5	10,0	10,4	1,2		8,1	13,4	3,7	21,1
	Direct	8,1	7,3	4,1	1,0	4,7	7,6	8,7	10,4	1,8		7,4	9,2	4,7	4,0
	Hub-to-hub	8,0	7,2	4,0	0,9	4,7	7,4	8,2	10,0	1,5		6,9	10,1	4,1	4,1
	Meshed	7,7	7,2	4,0	0,9	4,7	7,4	7,9	9,8	1,5		6,8	9,8	4,1	4,0
NL	Base Case	7,0	5,3	6,3	8,1	20,7	8,3	6,5	8,6	7,8	8,1		14,7	7,2	21,2
	Direct	5,0	4,8	4,4	7,9	10,6	6,5	5,3	7,0	6,3	7,4		13,3	5,8	9,2
	Hub-to-hub	4,3	4,9	4,3	7,4	10,2	5,9	4,6	6,4	6,0	6,9		13,9	5,6	9,0
	Meshed	3,3	4,5	4,2	7,3	10,2	5,6	4,1	6,0	5,9	6,8		13,8	5,4	8,9
NO	Base Case	17,5	15,7	10,1	13,4	9,9	10,6	15,0	18,1	13,4	13,4	14,7		14,8	8,8
	Direct	15,5	15,2	10,7	9,0	5,7	10,5	13,0	15,1	10,2	9,2	13,3		12,6	5,6
	Hub-to-hub	16,3	16,4	11,3	9,9	6,3	11,7	13,6	15,7	10,9	10,1	13,9		13,0	6,3
	Meshed	15,6	16,0	11,1	9,6	6,1	11,4	13,1	15,2	10,6	9,8	13,8		12,7	6,1
PL	Base Case	6,0	4,4	6,9	3,7	20,9	9,6	10,0	10,2	2,8	3,7	7,2	14,8		22,1
	Direct	6,1	4,7	3,7	5,6	9,1	8,0	8,2	9,5	3,0	4,7	5,8	12,6		7,6
	Hub-to-hub	6,3	5,0	3,4	5,0	8,5	7,6	7,7	9,1	2,6	4,1	5,6	13,0		7,2
	Meshed	6,2	5,0	3,3	5,0	8,4	7,5	7,4	8,9	2,6	4,1	5,4	12,7		7,1
SE	Base Case	25,9	24,0	17,0	21,1	7,3	17,2	21,2	24,8	20,5	21,1	21,2	8,8	22,1	
	Direct	11,0	10,3	5,6	4,0	2,1	8,2	10,0	12,0	5,0	4,0	9,2	5,6	7,6	
	Hub-to-hub	10,9	10,6	5,5	4,1	2,0	8,3	9,6	11,7	5,0	4,1	9,0	6,3	7,2	
	Meshed	10,5	10,5	5,6	4,1	2,0	8,2	9,3	11,5	4,9	4,0	8,9	6,1	7,1	

TABLE 13.6: SPLIT-DESIGN APPROACH - PRICE LEVEL DIFFERENCES BETWEEN THE COUNTRIES AFTER DIFFERENT DESIGN REALISATIONS

		BE	DE	DK	EE	FI	FR	GB	IE	LT	LV	NL	NO	PL	SE
BE	Base Case		4,6	9,7	6,4	23,7	10,1	9,4	8,2	6,9	6,4	7,0	17,5	6,0	25,9
	Direct		4,2	7,7	9,7	14,0	8,0	6,8	7,5	8,4	9,2	5,8	17,1	6,6	13,6
	Hub-to-hub		4,1	7,2	9,6	14,0	7,9	6,7	7,4	8,3	9,1	5,6	15,7	6,4	13,4
	Meshed		3,9	5,5	8,8	12,9	5,4	4,4	5,9	7,4	8,2	2,8	14,3	6,0	12,1
DE	Base Case	4,6		7,5	5,4	22,1	9,5	8,8	8,8	5,4	5,4	5,3	15,7	4,4	24,0
	Direct	4,2		6,5	8,9	13,3	8,8	8,0	8,8	7,2	8,2	5,3	16,5	5,1	12,8
	Hub-to-hub	4,1		6,2	9,1	13,5	8,8	7,8	8,6	7,3	8,3	5,4	15,3	5,2	12,7
	Meshed	3,9		6,0	9,1	13,7	8,2	7,1	8,2	7,4	8,4	4,4	15,4	5,2	12,9
DK	Base Case	9,7	7,5		6,2	16,2	7,6	8,9	11,4	5,8	6,2	6,3	10,1	6,9	17,0
	Direct	7,7	6,5		5,7	8,8	6,8	7,3	9,1	4,1	4,9	4,6	11,4	4,4	7,8
	Hub-to-hub	7,2	6,2		5,8	9,1	6,6	6,7	8,6	4,1	4,9	4,5	10,6	4,1	7,9
	Meshed	5,5	6,0		5,7	9,1	5,9	5,6	7,8	4,0	4,8	3,9	10,4	4,0	7,8
EE	Base Case	6,4	5,4	6,2		18,8	8,5	10,0	10,4	1,2	0,0	8,1	13,4	3,7	21,1
	Direct	9,7	8,9	5,7		4,8	8,2	9,7	11,2	2,7	1,2	8,9	9,4	6,3	5,1
	Hub-to-hub	9,6	9,1	5,8		4,9	8,2	9,4	11,1	2,7	1,2	9,0	8,5	6,4	5,1
	Meshed	8,8	9,1	5,7		4,9	7,9	8,7	10,6	2,7	1,2	8,2	8,4	6,3	5,0
FI	Base Case	23,7	22,1	16,2	18,8		16,5	20,3	23,4	19,0	18,8	20,7	9,9	20,9	7,3
	Direct	14,0	13,3	8,8	4,8		10,1	12,3	14,0	7,0	5,7	12,1	5,7	10,5	2,2
	Hub-to-hub	14,0	13,5	9,1	4,9		10,1	12,1	14,0	7,2	5,8	12,3	5,3	10,7	2,4
	Meshed	12,9	13,7	9,1	4,9		10,2	11,4	13,6	7,2	5,8	11,9	5,3	10,7	2,4
FR	Base Case	10,1	9,5	7,6	8,5	16,5		8,9	11,3	8,5	8,5	8,3	10,6	9,6	17,2
	Direct	8,0	8,8	6,8	8,2	10,1		5,9	7,0	7,6	7,9	6,7	11,6	8,2	9,6
	Hub-to-hub	7,9	8,8	6,6	8,2	10,1		5,7	6,9	7,5	7,9	6,5	10,5	8,1	9,4
	Meshed	5,4	8,2	5,9	7,9	10,2		4,7	6,2	7,2	7,6	5,3	10,4	7,6	9,3
GB	Base Case	9,4	8,8	8,9	10,0	20,3	8,9		6,1	9,9	10,0	6,5	15,0	10,0	21,2
	Direct	6,8	8,0	7,3	9,7	12,3	5,9		4,5	8,8	9,3	5,4	14,1	8,5	11,7
	Hub-to-hub	6,7	7,8	6,7	9,4	12,1	5,7		4,5	8,4	8,9	4,7	12,8	8,2	11,2
	Meshed	4,4	7,1	5,6	8,7	11,4	4,7		4,4	7,6	8,1	3,7	11,9	7,3	10,4
IE	Base Case	8,2	8,8	11,4	10,4	23,4	11,3	6,1		10,6	10,4	8,6	18,1	10,2	24,8
	Direct	7,5	8,8	9,1	11,2	14,0	7,0	4,5		10,2	10,8	7,3	16,0	9,6	13,5
	Hub-to-hub	7,4	8,6	8,6	11,1	14,0	6,9	4,5		10,0	10,6	6,8	14,8	9,4	13,2
	Meshed	5,9	8,2	7,8	10,6	13,6	6,2	4,4		9,5	10,1	5,8	14,2	8,8	12,7
LT	Base Case	6,9	5,4	5,8	1,2	19,0	8,5	9,9	10,6		1,2	7,8	13,4	2,8	20,5
	Direct	8,4	7,2	4,1	2,7	7,0	7,6	8,8	10,2		1,5	7,4	10,4	3,7	6,3
	Hub-to-hub	8,3	7,3	4,1	2,7	7,2	7,5	8,4	10,0		1,5	7,4	9,3	3,7	6,2
	Meshed	7,4	7,4	4,0	2,7	7,2	7,2	7,6	9,5		1,5	6,7	9,1	3,7	6,1
LV	Base Case	6,4	5,4	6,2	0,0	18,8	8,5	10,0	10,4	1,2		8,1	13,4	3,7	21,1
	Direct	9,2	8,2	4,9	1,2	5,7	7,9	9,3	10,8	1,5		8,2	9,6	5,2	5,3
	Hub-to-hub	9,1	8,3	4,9	1,2	5,8	7,9	8,9	10,6	1,5		8,3	8,7	5,2	5,2
	Meshed	8,2	8,4	4,8	1,2	5,8	7,6	8,1	10,1	1,5		7,5	8,5	5,2	5,1
NL	Base Case	7,0	5,3	6,3	8,1	20,7	8,3	6,5	8,6	7,8	8,1		14,7	7,2	21,2
	Direct	5,8	5,3	4,6	8,9	12,1	6,7	5,4	7,3	7,4	8,2		14,2	6,4	11,2
	Hub-to-hub	5,6	5,4	4,5	9,0	12,3	6,5	4,7	6,8	7,4	8,3		13,2	6,4	11,1
	Meshed	2,8	4,4	3,9	8,2	11,9	5,3	3,7	5,8	6,7	7,5		12,9	5,6	10,8
NO	Base Case	17,5	15,7	10,1	13,4	9,9	10,6	15,0	18,1	13,4	13,4	14,7		14,8	8,8
	Direct	17,1	16,5	11,4	9,4	5,7	11,6	14,1	16,0	10,4	9,6	14,2		13,5	4,9
	Hub-to-hub	15,7	15,3	10,6	8,5	5,3	10,5	12,8	14,8	9,3	8,7	13,2		12,4	4,3
	Meshed	14,3	15,4	10,4	8,4	5,3	10,4	11,9	14,2	9,1	8,5	12,9		12,2	4,2
PL	Base Case	6,0	4,4	6,9	3,7	20,9	9,6	10,0	10,2	2,8	3,7	7,2	14,8		22,1
	Direct	6,6	5,1	4,4	6,3	10,5	8,2	8,5	9,6	3,7	5,2	6,4	13,5		9,7
	Hub-to-hub	6,4	5,2	4,1	6,4	10,7	8,1	8,2	9,4	3,7	5,2	6,4	12,4		9,6
	Meshed	6,0	5,2	4,0	6,3	10,7	7,6	7,3	8,8	3,7	5,2	5,6	12,2		9,5
SE	Base Case	25,9	24,0	17,0	21,1	7,3	17,2	21,2	24,8	20,5	21,1	21,2	8,8	22,1	
	Direct	13,6	12,8	7,8	5,1	2,2	9,6	11,7	13,5	6,3	5,3	11,2	4,9	9,7	
	Hub-to-hub	13,4	12,7	7,9	5,1	2,4	9,4	11,2	13,2	6,2	5,2	11,1	4,3	9,6	
	Meshed	12,1	12,9	7,8	5,0	2,4	9,3	10,4	12,7	6,1	5,1	10,8	4,2	9,5	

TABLE 13.7: CORRELATION COEFFICIENTS

	Base Case	Direct design		Split design	
	Base case	Final design	Δ Base case	Final design	Δ Base case
All wind / all hydro	-0.29	-0.32	-0.03	-0.32	-0.03
All wind / all gas	-0.05	-0.04	0.01	-0.05	0.01
All wind / all lignite coal	-0.36	-0.30	0.06	-0.31	0.05
All wind / all hard coal	-0.41	-0.39	0.02	-0.40	0.01
All wind / all "other renewable"	-0.65	-0.64	0.01	-0.63	0.02
All wind / all nuclear	0.40	0.40	0.00	0.40	0.01
All wind / demand	0.29	0.28	-0.01	0.28	-0.01

Due to the price level changes and the immediate impact on the benefits of already existing infrastructure a large number of iterations had to be carried out in order to indentify the most beneficial interconnectors.

Please note that the absolute price levels in the countries might increase with further connections. Norway e.g. exhibits very low price levels in the Hub Base Case scenario 2030. If thus this low price electricity is sold to other countries the internal price level rises as higher priced generation capacity will have to be used.

Please note that Table 13.5 and Table 13.6 only show price level differences and not absolute price levels. These price levels decrease in general, but also here increasing price level differences are possible.

D.III.V Power system impact

Balancing of wind power variability

The offshore grid leads to the spatial smoothing of short term renewable energy variations and as such reduces the needs for balancing power in the system to a certain extent. This paragraph illustrates how the balancing of variable wind power is affected by the offshore grid, with a special focus on the hydro power in Scandinavia.

A priori, there are two competing hypotheses:

- the offshore grid enables cheaper generation units farther away from demand centres to momentarily replace more expensive generation units independently of Scandinavian hydro capability,
- the offshore grid improves the utilisation of Scandinavian hydro capability. At low price periods, Scandinavia will import cheaper power from the surrounding areas, and at high price periods, will export power. This makes more expensive generation units in the surrounding areas unnecessary.

Although it was shown in section 4.5.6 that there is an overall shift from hard coal and gas towards the cheaper category "other renewables" it is not immediately clear when in time this shift occurs. For example, it could be a shift that is evident hour by hour (first hypothesis), or a shift that occurs indirectly via hydro balancing (second hypothesis).

Measuring the balancing of wind power can be done by evaluating the correlation coefficients between wind power production and other power production. A generation type that balances wind power has a negative correlation with wind power. This means that it produces when there is low wind generation and it stops production when wind power is generated. Table 13.7 shows correlation coefficients between total wind production and total production of other generation types.

For the assessment of grid influence on wind power balancing, the interesting information in Table 13.7 is the change in correlation coefficients relative to the base case.

Both the direct and split grid designs have an increased anti-correlation between wind and hydro compared to the base case. This is interpreted as an increased balancing of wind by the hydro systems. For coal and gas, there is a decrease in anti-correlation. This result supports the second hypothesis presented above: With an expanded grid, hydro power replaces, to some extent, coal and gas in balancing variable wind power.

It should be noted that the model was adapted to the specifics need to identify highly efficient offshore grids. Balancing power was not in the focus of the study and due to the trade-off between practicality and detail, some technicalities like start-up time and costs, ramp-rate and minimum up- and down-times have not been included in the model. The model is already fairly detailed and takes about two hours to run one simulation. Introducing further details means that the optimisation takes even longer and fewer simulations can be performed.

In conclusion, the above discussion demonstrates that an expanded grid gives an increase in the balancing of variable wind power by hydro power and confirms the second hypothesis. Further development of the model would be needed to confirm also the first hypothesis and discuss the relative importance of the two effects.

ANNEX E – REGULATORY FRAMEWORKS AND SUPPORT SCHEMES

TABLE 14.1: OFFSHORE REGULATORY FRAMEWORKS

	DK	DE	SE	UK	NL	FI	PL	IE	NO	LV	LU	EE	BE	FR	Explanation
Support scheme	negotiated FT (see foot-note 1)	FT	CS	CS	negotiated FT (see foot-note 2)	0	FT+ CS (see footnote 3)	FT	0	FT	FT	B/FT (see footnote 4)	CS	FT	"CS = Certificate System FT = Feed-In Tariff FT+CS = Feed-In Tariff plus Certificate System B/FT = Bonus or Feed-In Tariff 0 = None"
Priority grid connection for offshore wind		✓			✓								✓		
Obligation on the TSO to provide connection to offshore wind park		✓	✓		✓	✓	✓	✓				✓	✓	✓	
Location of offshore wind farms outside territorial waters		✓	✓	✓									✓		Territorial waters are the waters included in the 12 nm-zone
Marketing options	DM	CDM	DM	DM	DM	DM	CDM	NDM	DM	CDM	n/a	CDM	DM	CDM	"DM = Direct marketing possible NDM = No direct marketing CDM = It can be chosen between DM or FT"
Geographical limitation for support schemes	S	S	T	T	O*	T	T	O**	O***	T	T	T	T	T	"T = country's territory on land and at sea (including EEZ)

S = electricity generated in the county's system

O = other"

Sources: discussion with experts, own analysis, findings of country surveys, http://res-legal.eu and CEER: Regulatory aspects of the integration of wind generation in European electricity markets, 2009

1) in other publications the term negotiated feed-in tariff is also referred to as bonus, premium or negotiated prices. However it is suggested not to use the term bonus in this case.

2) See footnote 1) and: existing offshore wind farms receive a fix feed-in tariff, new offshore wind farms a negotiated feed-in tariff.

3) The main support mechanism in Poland is a quota system is combined with a certificate trading system. The price for renewable electricity (feed-in tariff) is set every year by the regulator and equals the average electricity price of the previous year.

4) Plant operators have the choice to sell electricity to a supplier chosen by the transmission grid operator and receive a guaranteed price or sell electricity on the market and receive a bonus on top of the market price.

* Electricity generated within Dutch systems, tax reduction also for electrcity generated in other areas.

** Irish territory and European Union, if it does not contribute to the achievement of the member state's energy goals.

*** Currently no support scheme only grants, although no geographic limits, projects must be relevant for the Norwegian energy market.

n/a: no information available

ANNEX F – TRANSFER TO THE MEDITERRANEAN REGION

F.I Introduction and drivers

The idea of creating a European super grid is not new and the Mediterranean region will be a fundamental part of this grid. OffshoreGrid focuses on the integration of international electricity infrastructure and offshore wind energy, and therefore focuses on Northern Europe. This section provides a qualitative analysis for the Mediterranean region, and investigates how the results of the previous chapters can be interpreted in a Mediterranean context.

The Mediterranean context is much different from Northern Europe:

- In Southern Europe, the same drivers for developing interconnections exist[64]. However, where the economical trade of electricity and the integration of renewables can be seen as the main drivers in the North today, most of the power interconnections between countries and regions in the Mediterranean are (being) built for reasons of security of supply.
- Market integration is much lower in the Mediterranean region. Many electrical interconnections exist or are in development stage, but combining them with an integrated international power pool as in Northern Europe is today still unrealistic and very challenging.

At the same time, numerous benefits exist that make an interconnected (on/offshore) grid in the Mediterranean very interesting. Mediterranean countries fall within three time zones, have different climatic conditions and renewable energy resources, different living standards and habits. An interconnected grid would be very helpful for the stability of the system, the reduction of variability, the balancing of surplus electricity and deficits, the optimisation of the operation of the national power systems, and the economical trade between countries.

In the next sections, the Mediterranean countries are examined in three wider sub-regions:

- North Mediterranean
  - EU countries: Cyprus, France, Greece, Italy, Malta, Portugal, Slovenia, and Spain.
  - Non-EU countries: Albania, Bosnia Herzegovina, Croatia, former Yugoslavian Republic of Macedonia, and Serbia.
- South West Mediterranean
  - Algeria, Egypt, Libya, Morocco, and Tunisia.
- South East Mediterranean
  - Turkey, Israel, Jordan, Lebanon, Palestine, and Syria.

F.II General overview of the electrical system in Mediterranean

Energy profile

The Mediterranean region accounts for about 9% of the world's energy demand and will have an estimated total electricity generation of about 3289 TWh by 2030. Today most energy is consumed by the countries in the North of the Mediterranean Sea (70% of the total).

Generally, the South Mediterranean countries are facing rapid demographic growth combined with relatively low incomes, a rapid urbanisation rate, and important socioeconomic development needs. These characteristics translate into a rapidly growing demand for energy services and related infrastructure. By contrast, the North Mediterranean countries are generally more mature economies, characterised by much more stable energy demand projections.

[64] As discussed previously, the three main drivers are security of supply, the economical trade of electricity, and the large-scale integration of renewable energy.

Grid situation

Interconnection lines exist across the borders of all the Mediterranean countries exist, with the exception of Israel. Nevertheless, the power systems around the Mediterranean basin are still split into three or four separated asynchronous[65] zones [49]:

- The Northern Mediterranean countries are synchronously interconnected within ENTSO-E/SCR, which, since 1997, is interconnected with Morocco, Algeria and Tunisia after the first Morocco-Spain submarine interconnection was commissioned.
- Turkey officially requested a connection to ENTSO-E/SCR in 2000, but further improvements of the Turkish system are still required before it is in line with ENTSO-E/SCR standards.
- The Mashreq-Libya pool combines eight countries: Libya, Egypt, Jordan, Lebanon, Syria, Saudi Arabia, Palestinian Territories, and Iraq.
- Israel and Palestinian Territories, which is an island grid.

The most important existing bottlenecks are located between Greece and Turkey, Turkey and Syria, and between Tunisia and Libya. Additionally, the Net Transfer Capacity (NTC) remains weak across many borders.

Additionally, the inter-Mediterranean electrical exchanges are quite weak, especially between the Maghreb countries, despite the strong interconnections and a history of cooperation. The only link that is fully functional is the Spain-Morocco one.

F.III Mediterranean Offshore Grid to be driven by RES development

The analysis for Northern Europe assessed an offshore grid driven by the development of renewable energy sources (RES) (i.e. offshore wind). To interpret the results in the Mediterranean context, the expectations for RES development are investigated in this paragraph.

F.III.I Introduction

Large scale exploitation of renewable energy sources in the Mediterranean will be mainly based on wind power, solar photovoltaics (PV), and concentrated solar thermal power (CSP) plants. These three renewable energy technologies appear to have the greatest growth potential.

TABLE 15.1: OVERVIEW OF WIND POWER DEVELOPMENT AND SCENARIOS FOR 2020 AND 2030 IN MEDITERRANEAN

Region	New capacity in 2010 (MW)	Wind capacity in 2010 (MW)	Wind capacity (2020)	Wind capacity (2030)
North	4,143	37,195	101,480	139,684
EU countries	4,100	37,125	99,400	135,534
Non-EU countries	43	70	2,080	4,150
South East	528	1,339	9,250	20,400
Turkey	528	1,329	8,000	18,000
Other South East	0	10	1,250	2,400
South West	213	950	9,000	16,700
Algeria-Egypt-Libya	120	550	6,500	12,700
Other South West	93	400	2,500	4,000
Total	**4,884**	**39,484**	**119,730**	**176,784**

[65] Please note that only the Northern Mediterranean countries are synchronously interconnected. A true integrated market with all countries operating synchronously is not seen as realistic in the next 10-20 years.

Wind power has been the fastest growing RES, and its costs are competitive to conventional power plants in good sites. Although wind potential is lower in the Mediterranean region than it is in Northern Europe, most of the countries have perspectives for wind power development, particularly EU countries through their national action plans.

F.III.II Current status of wind power and prospects

The total wind capacity installed today (2010) in the Mediterranean is 39.5GW. In 2010 alone, almost 4.9GW of additional capacity was installed. Most of this capacity is installed in the countries in North Mediterranean[66].

Based on an analytical assessment of the industry development, the political situation in each country and taking into account previous studies on wind power development [24][20], long term wind power scenarios per country have been developed. The results are presented in Table 15.1. The total wind capacity is expected to increase from 39.5GW in 2010 to more than 119 GW in 2020 and 177 GW in 2030. The largest part of the development is expected in North Mediterranean countries, followed by Turkey. In the south western countries, south eastern countries and Northern Non-EU Mediterranean countries the development will be comparably much smaller.

Nearly all of this planned capacity is located onshore. Offshore wind is discussed in the next section.

F.III.III Offshore wind energy development in the Mediterranean Sea

Prospects for offshore wind development are rather low in Mediterranean. Deep waters are a significant obstructing factor.

There are no specific offshore scenarios for the Mediterranean Sea in literature. The lists of potential projects for offshore wind farms show that the majority of these plants will be very close to the mainland, playing a secondary role for offshore grid interconnections. Several uncertainties and challenges exist regarding offshore wind power development in Mediterranean:

- Water depth
- Complex orography
- Visual impact, environmental issues and public acceptance (e.g. tourism)
- Rather low wind potential
- Financing

Despite these uncertainties, North Mediterranean countries have set targets for offshore wind development in the Mediterranean Sea by 2020. France has set a target for 6 GW offshore, of which probably up to one third of this located in the Mediterranean (~2,000 MW). Italy and Spain have set a target for 1,000 MW and 1,500 MW, while Greece has (low) target for 200 MW. This offshore development mainly concerns conventional offshore wind farms. Floating concepts are not foreseen until 2020. Current cost estimates of floating concepts (€5,000-6,000/kW) combined with the rather moderate wind potential indicate that these systems will not be economically viable in the Mediterranean before 2030.

Offshore wind power is thus not likely to be the driving force for an offshore grid in the Mediterranean, although in some cases wind farms can probably teed-in to shore-to-shore interconnectors. Therefore, also solar thermal and other RES are investigated in this report.

[66] Spain, Italy, France, Portugal, Greece and Cyprus together represent more than 93% of the overall installed wind power.

F.III.IV Solar thermal power plants and photovoltaics

In the Mediterranean region, most is expected from solar photovoltaics (PV) and solar thermal power plants (CSP).

PV could supply a large share of the electricity needs in Mediterranean, but face two main constraints, which are the cost and the variability. The cost of PV is 3-5 times higher than the cost of wind power. PV will firstly be installed in small quantities and very distributed, mitigating the power transmission needs and thus the impact on any kind of offshore transmission grid.

CSP plants need more area for the installation and require direct sunlight. However, the cost is lower than for PV and is expected to decrease further in the near future, potentially becoming competitive with wind and conventional sources. Furthermore, significant economies of scale are possible for large plants, and the impact for the transmission grid is thus higher than for PV.

There are several discussions about the exploitation of the abundant solar resource in isolated areas in North Africa, and on its transmission to local consumption centres and to Europe via high-voltage direct current (HVDC).transmission lines to the consumption centres. The primary countries under consideration are Algeria, Egypt, Morocco, Tunisia and Libya. The capacity which can be hosted is enormous, but in short term only few projects are considered (10 GW by 2020).

F.IV Perspectives for offshore grid infrastructure in the Mediterranean

The DESERTEC concept was developed by a network of politicians, scientists and economists from around the Mediterranean. The idea is to exploit the abundant solar resource in North-African deserts and transmit the electricity through high-voltage direct current grid to consumption centres in Europe (Figure 15.1).

FIGURE 15.1: DESERTEC MAP - THE MEDITERRANEAN SOLAR PLAN (SOURCE: DESERTEC)

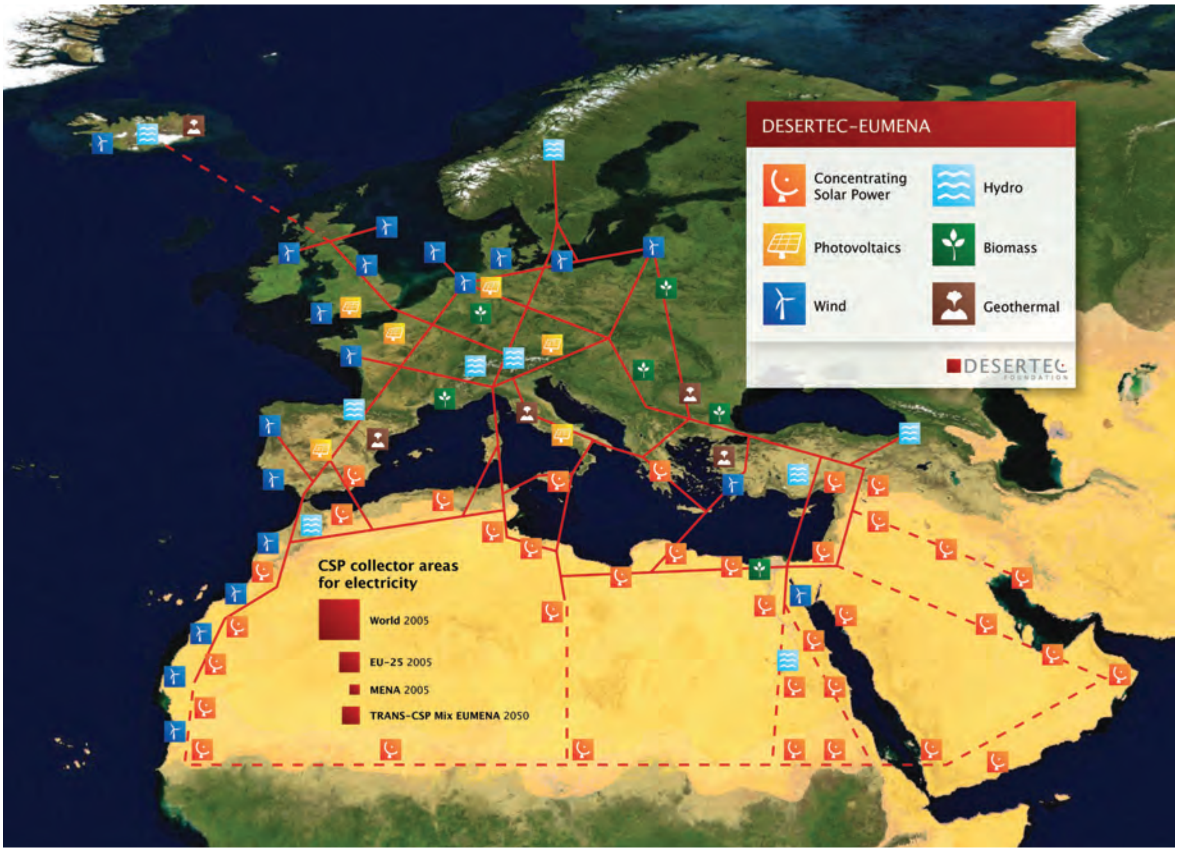
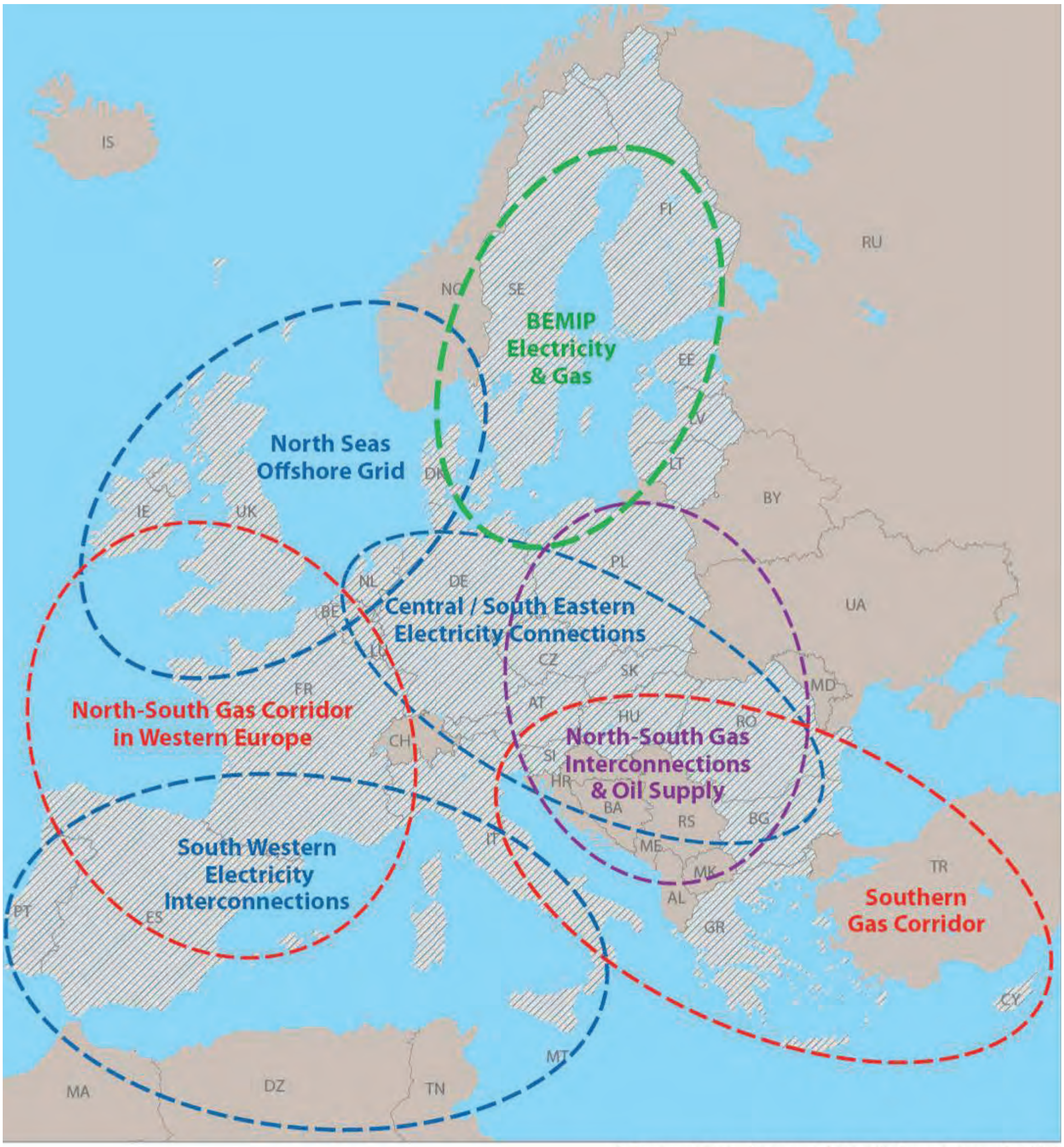


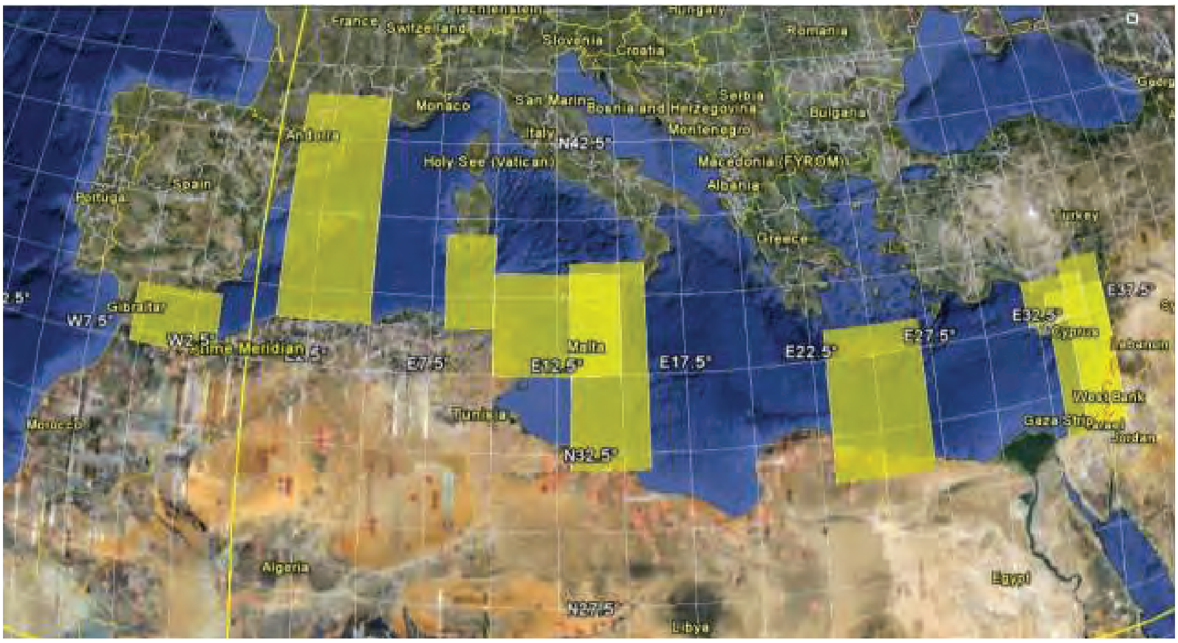
FIGURE 15.2: EUROPEAN ENERGY INFRASTRUCTURE PRIORITIES FOR ELECTRICITY, GAS AND OIL



The European Commission identifies the interconnections in South-Western Europe as one of eight priority projects in the field of energy [23] (Figure 15.2). The recommended key actions include:

- the adequate development of the interconnections in the Northern Mediterranean region and the accommodation of the existing national networks to those new projects,
- concerning connections with NON-EU countries, the development of Italy's connections with countries of the Energy Community, the realisation of the Tunisia-Italy interconnection, the expansion of the Spain-Morocco interconnector, the reinforcement, where necessary, of South-South interconnections in North African neighbour countries and preparatory studies for additional North-South interconnections to be developed after 2020.

FIGURE 15.3: SELECTED AREAS FOR ANALYSIS ON THE MEDITERRANEAN MAP (SOURCE [51])



In 2008, the Heads of states and governments of the European and Mediterranean countries have launched the Union for the Mediterranean, to improve the regional cooperation. In the energy field, the flagship project of the Union for the Mediterranean will be the Mediterranean Solar Plan (MSP). The MSP aims at two complementary targets: developing 20 GW of new renewable energy production capacities and achieving significant energy savings around the Mediterranean by 2020, thus addressing both supply and demand [49]. It will help to address the challenges of internal energy demand in the participating countries, achieve the objectives of the EU Energy and Climate Package, significantly contribute to the sustainable development of non-EU countries, promote investments and create jobs. There is a special interest for the promotion of electricity transmission infrastructure, with specific attention for the improvement of North-South interconnections in order to allow the export of green electricity from Mediterranean countries to EU countries. In follow-up of the Second Strategic Energy Review [22], several studies have been prepared, among which one on possible power corridors [51] (Figure 15.3).

An offshore grid in the Mediterranean Sea will mainly be built from direct shore-to-shore interconnectors. In some cases, tee-in solutions could be envisaged as well (e.g. Malta).

F.V Recommendations for policy, market and regulatory framework

The experience gained from Northern Europe shows that the driving forces for the development of an offshore grid is the development of RES, the removal of barriers and the regulation of the market [30]. Although the Mediterranean has abundant renewable energy resources, at present it is far from exploiting its full potential because of institutional, technical, political and market barriers. Moreover, not only the large scale development of RES but also further drivers such as the security of supply and economic issues will have to be considered when evaluating interconnections.

F.V.I Legislative framework for RES - national targets

Overcoming these barriers will require a strong political commitment as well as increased investments in the sector. A viable business climate in particular, based on stable and transparent investment frameworks with adequate pricing policies will be necessary for long-term investments to take place.

The increase of the RES penetration is the critical factor which drives the evolution of offshore grid development in Northern Europe. Together with the increase of RES, the need for balancing is increased and the security of supply requires further strengthening of interconnections. It is recommended also for non-EU Mediterranean countries to develop national goals for RES.

Development of RES, mainly wind power and solar thermal power in Mediterranean, requires parallel development of power interconnections for delivery to major load centres and maybe for transcontinental transfer. Implementation of long-term renewable energy policy programmes per country and national agreements for the development of RES and the reduction of greenhouse emissions are essential for the activation of the market.

The regulatory framework for RES in the Mediterranean presents a quite diversified picture. While the EU countries in the North Mediterranean have been setting policies supporting renewables for a long time, the South Mediterranean countries have a less structured regime. In addition, subsidies to conventional energies in these countries represent a relevant barrier that prevents renewables from exploiting their whole potential.

Additionally, RES development goals and their impact on an offshore grid vary considerably between countries. RES development goals have to be strongly integrated in the national and particularly the regional policy and stakeholder processes. This is to increase the social acceptance for grid enforcement or new RES capacity construction.

In the regulatory field, Mediterranean has a lot to gain from the experience in North Europe. However, currently it is more important to deal with the lack of regulatory framework in several countries (i.e. Jordan, Israel, Lebanon, and Syria). Although such countries do not affect wind development, they have a strategic position and affect the development of interconnections.

Economically, interconnections in Mediterranean could be incentivised by arbitrage possibilities between national power markets and can therefore improve market integration and power trading.

Therefore, the Mediterranean countries should work together towards international harmonisation and regular consolidation of national policies concerning RES. In parallel, the standardisation of grid codes is also important, since four unsynchronised pools exist and each pool is characterised by its own codes and standards.

F.V.II Market integration

Market integration of a large geographical area, such as the Mediterranean, is very important to reinforce system reliability, improve security of supply, reduce operational reserves in the whole system and enhance the diversity of the available sources.

Power interconnections and regional trading is considered as a mechanism for improving the economic efficiency of power systems. The value of the power interconnection is derived from the ability to achieve economies of scale, as individual smaller power systems can be operated and expanded as part of a larger regional system.

Successful market integration requires a common framework for transactions to take place, harmonised arrangements for system operations, a system of tariffs for use of transmission infrastructure, and agreed principles and procedures for dispute resolution.

To meet the challenge of market integration in Mediterranean, ways to finance extensions and harmonise the existing separated pools are required. For this purpose, economic and political improvements are essential, particularly in the weak countries of the region.

F.V.III Political issues

For the synchronised operation of the existing interconnections and the reinforcement with new onshore and offshore interconnections in Mediterranean, major technical and non-technical issues and concerns should be addressed. Political will and regional cooperation will become increasingly important as different parties, bodies and stakeholders work through these issues.
Political stability is another important obstacle, which represents one of the major causes of insecurity regarding the upgrading of grid infrastructure. Civil wars, social unrest and political instability make it very difficult t to attract foreign funds and investors.

OffshoreGrid

www.offshoregrid.eu

OffshoreGrid project

OffshoreGrid is a techno-economic study within the Intelligent Energy Europe programme. It developed a scientifically based view on an offshore grid in Northern Europe along with a suited regulatory framework considering technical, economic, policy and regulatory aspects. The project is targeted at European policy makers, industry, transmission system operators and regulators. The geographical scope was, first, the regions around the Baltic and North Sea, the English Channel and the Irish Sea. In a second phase, the results were applied to the Mediterranean region in qualitative terms.