



# OffshoreGrid: Offshore Electricity Infrastructure in Europe





# Offshore Electricity Grid Infrastructure in Europe

A Techno-Economic Assessment

3E (coordinator),

dena, EWEA, ForWind, IEO,

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3E is a global, independent renewable energy consultancy, providing full-scope technical and strategic guidance in wind (on & offshore), solar, grids and power markets.

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IEO: Institute for Renewable Energy is a Polish independent consultancy company and a think tank, linking research, technology and policy development activities in the area of renewable energy.

[www.ieo.pl](http://www.ieo.pl)



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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.

A handwritten signature in black ink, appearing to be 'GP', written over a horizontal line.

Geert Palmers,  
CEO, 3E



Photo: Vestas

## 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<sup>1</sup>. 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<sup>2</sup>:

- **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<sub>2</sub> 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.

<sup>1</sup> EWEA, Pure Power – Wind energy targets for 2020 and 2030, 2011 update, July 2011.

<sup>2</sup> 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.

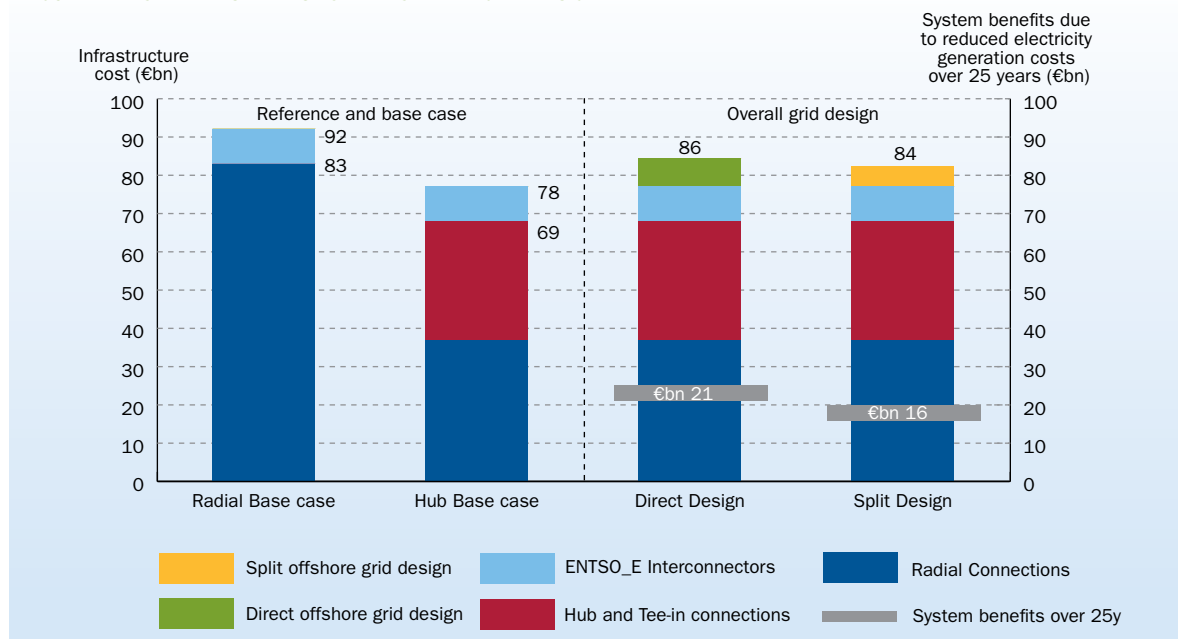
The overall investment costs are €86 bn for the Direct Design and €84 bn for the Split Design. This includes €69 bn of investment costs for the most efficient connection (hub-connections where beneficial as in the

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 yields 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].<sup>3</sup>

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

<sup>3</sup> 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.

### III a. 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 on-shore 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.

### III b. 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.

### III c. 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.

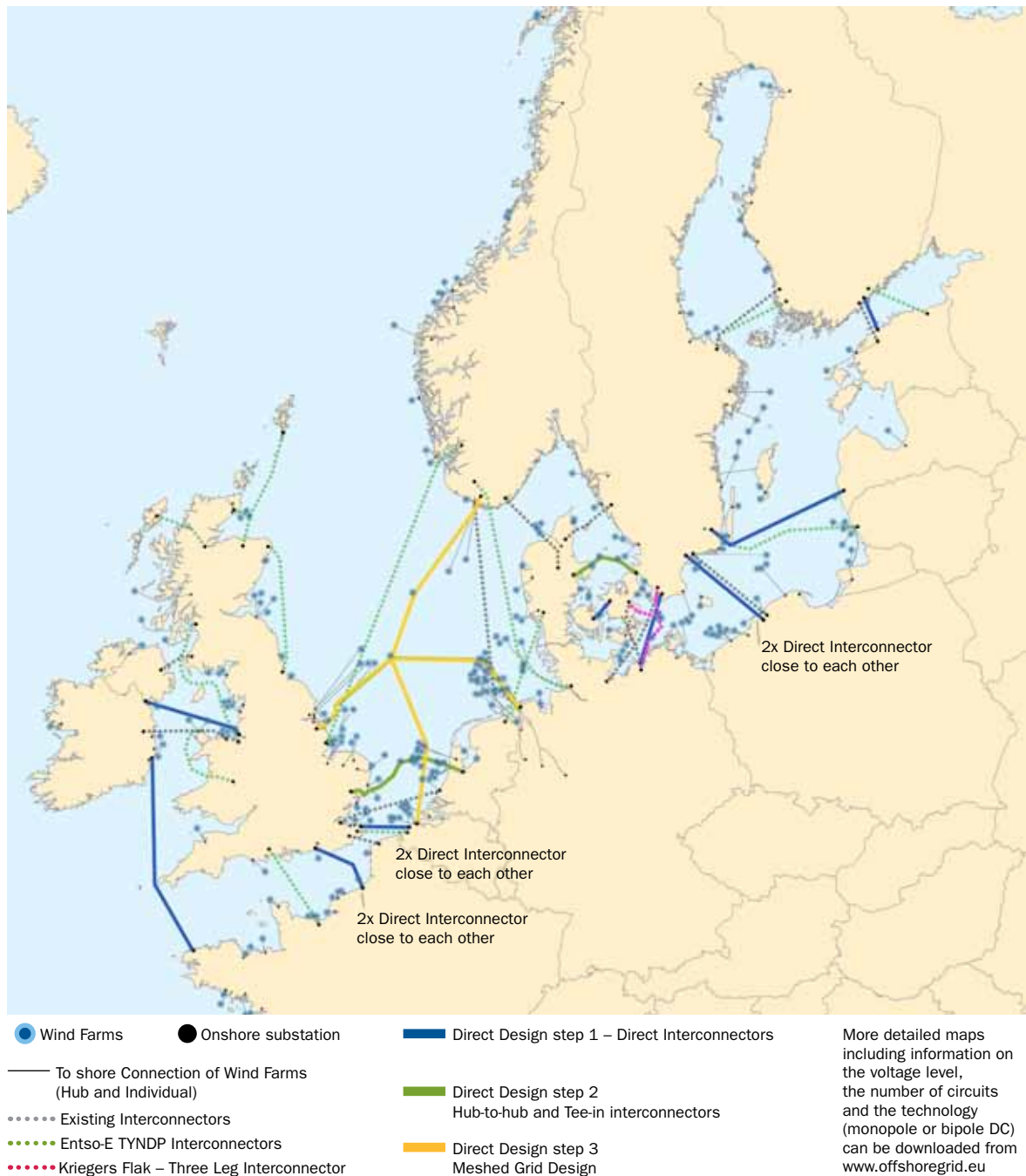
In general the hub-to-hub connection is more beneficial than direct interconnectors under the same conditions that make the tee-in connection beneficial: modest price difference between interconnected countries, the capacity of the wind farm and its connection is high compared to the interconnector capacity (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).

### III d. 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



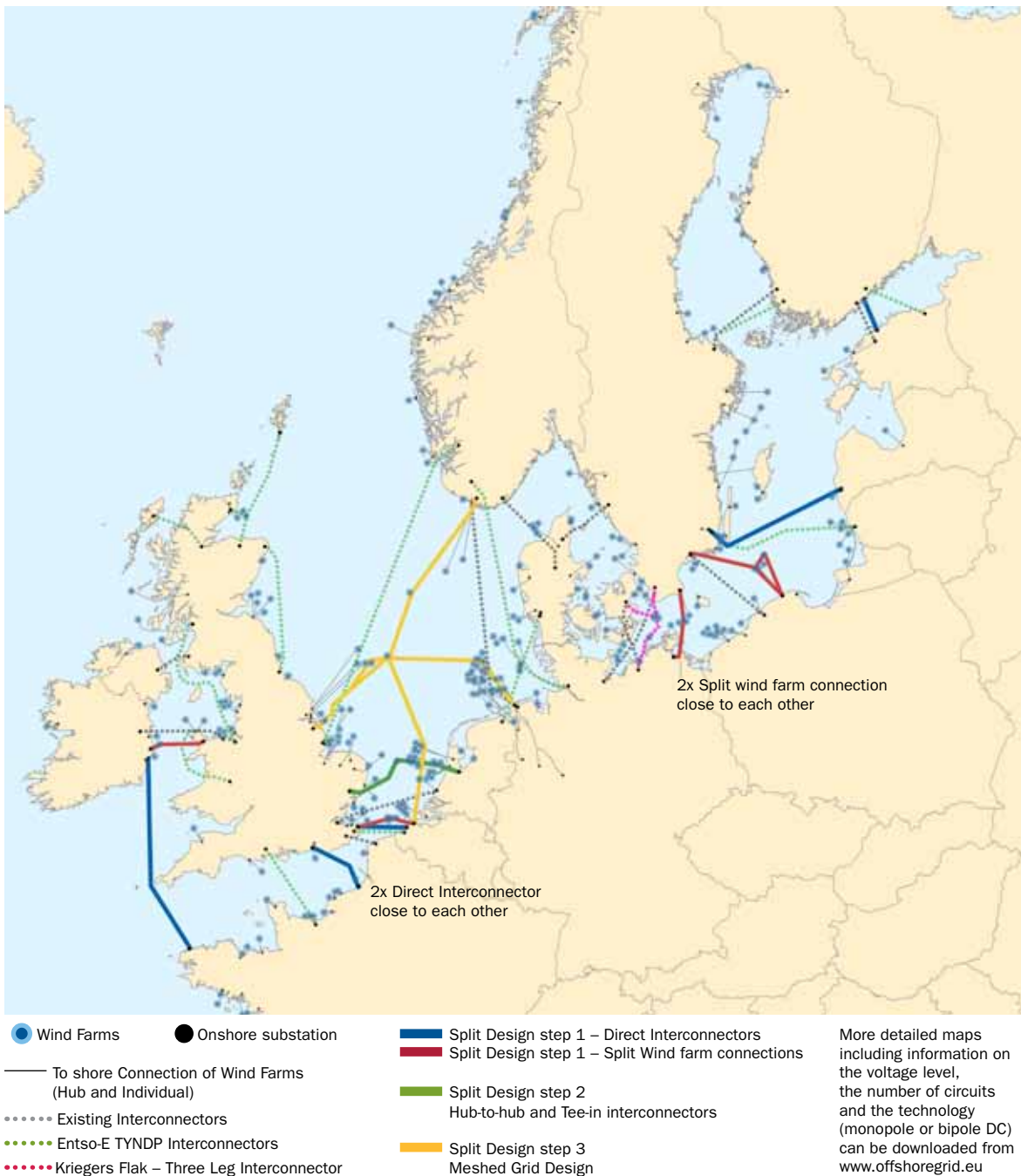
two different methodologies for the design of a cost-effective overall offshore grid:

- **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



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 frameworks. In particular, the compatibility of support schemes and the allocation of benefits should be addressed 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.





[www.offshoregrid.eu](http://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.