OffshoreGrid: Techno-Economic Model for Future Offshore Electricity Transmission

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Abstract—**OffshoreGrid is the first techno-economic study that carries out an in-depth analysis of how to build a cost-efficient grid in the North and Baltic Sea.**

The project investigated the most beneficial wind farm connection concepts for 126 GW in 321 offshore wind farms as expected for the year 2030. Based on this two highly efficient offshore grid designs were developed with modular building stones such as direct interconnectors, hub-to-hub connections, Tee-in solution.

It was shown that the final meshed grid design allows bringing offshore wind online in a cost efficient way while enhancing European electricity trade. This results in significant net benefits within the European power system.

The OffshoreGrid project results are a practical blueprint for policymakers, developers and transmission grid operators, to plan and design a meshed offshore grid. 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.

OffshoreGrid was carried out from 2009 to 2011 by under funding by the EU's Intelligent Energy Europe (IEE) programme. 3E coordinated the project consortium consisting of Senergy Econnect, SINTEF, dena, EWEA, ForWind, EC BREC IEO, NTUA

Index Terms—**Meshed offshore grid, offshore wind, unified European transmission system, hub connection, hub-to-hub connection, Tee-in connection**

I. THE OFFSHORE GRID PROJECT

OFFSHOREGRID is a techno-economic study funded by the EU's Intelligent Energy Europe (IEE) programme. It develops 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 paper summarises the key assumptions, the methodology and the results as also present in the consortium's final report published in October 2011.

The starting point of the project is Europe's 20-20-20 goals; in line with these goals, the coastal states will construct a large number of offshore wind farms in the North and Baltic Seas [1]. The system integration of these will not be possible without a reliable, modernised and efficient grid, both onshore and offshore. Connecting the wind farms at sea to the shore without building interconnection seems to be short-sighted, as there are many advantages to having an offshore grid connecting many Member States, as outlined in the North Seas Countries' Offshore Grid Initiative (NSCOGI) [3]. The primary advantages are:

- Increased security of supply
- Opening up of competition and the market
- Integration of renewable energy

II. MODELS AND SCENARIOS

OffshoreGrid developed scenarios up to the year 2030 that include commodity price, generation and demand development in Europe. In particular for offshore wind development, detailed analyses were carried out resulting in a 2030 scenario of 321 offshore wind farm projects in total. The number, location and size of the projects is based on the most recent national development goals and the latest EWEA offshore wind development scenario[4]. For onshore wind energy the TradeWind scenario was updated [5]. Of special focus in the study was the cost and future availability of infrastructure technology needed to build an interconnected offshore grid by 2030.

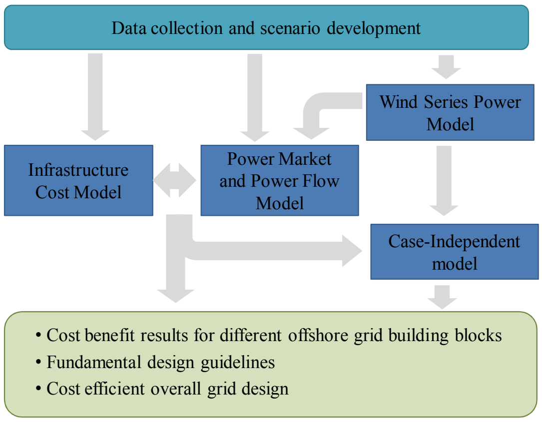

Figure 1:Combined model approach of the OffshoreGrid project.

In order to meet the specific requirements of the project, OffshoreGrid combined four detailed models:

- Wind Power Series Model [6]
  To develop detailed wind power time series for all grid nodes across Europe.
- Power Market and Power Flow Model [8]
  Grid (ENTSO-E Research Model) and market model for Europe including power exchanges with Russia.
- Infrastructure Cost Model [9]
  The model takes into account the cost of different offshore cable and equipment technology, cable length, sea depth, bathymetric data etc. to calculate grid infrastructure costs.
- Case-independent Model
  The model carries out vast sensitivity analyses in a simplified market and grid environment to draw general conclusions that can used for the step-wise development of a meshed offshore grid.

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III. APPROACH AND METHODOLGY

There are different interconnection methodologies that can be used to realise the benefits of an offshore grid, and several of these were investigated in this study.

The most efficient way to connect the wind energy to shore was first investigated, in particular examining the possibility to connect wind farms to hubs and bring the energy onshore en masse.

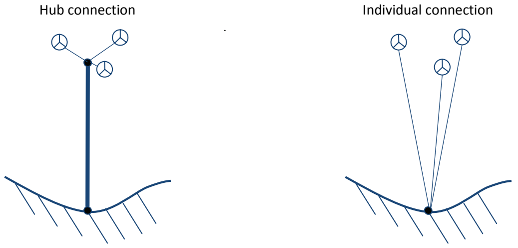
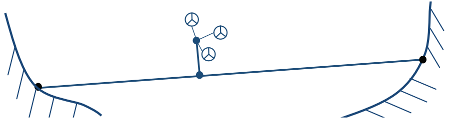


Figure 2:Hub connection and individual wind farm connection.

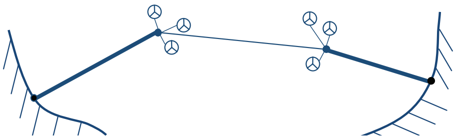
Based on the most efficient offshore wind farm connection scenario, an interconnected OffshoreGrid was developed in a step-wise approach. This was done by adding direct interconnectors, hub-to-hub and tee-in connections step by step. This was an iterative process where the economic viability of each additional connection considered was closely monitored, and the connection was accepted or rejected on that basis.

The main forms of modular interconnections considered were as follows:

- *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 transmission corridors between various countries (i.e. the wind farm hubs belonging to different countries are connected to shore, and also to each other).



Based on the various interconnection methods available, two overall interconnected grid designs were considered: the "Direct Design" and the "Split Design".

The **Direct Design Methodology** mimics the current evolution as it is envisaged today. First, direct interconnectors between countries are built to promote unconstrained trade, as average price difference levels between countries are high. Once additional direct interconnectors become non-beneficial, other connection methods (such as tee-in, hub-to-hub and meshed grid concepts) are added to arrive at an overall grid design.

The **Split Design Methodology** is essentially designing an offshore grid around the planned offshore wind farms. This is an approach where interconnections are built by splitting the connection of some of the larger offshore wind farms between countries, thereby creating a path for constrained trade. These offshore wind farm nodes are then further interconnected to establish an overall 'meshed' design, where this is deemed beneficial, as is done in the final steps of the direct design method.

IV. TECHNO-ECONOMICS OF GRID CONNECTION TYPES

As described above, various different kinds of connection configurations were investigated that serve as building blocks for the overall grid design. Each of these kinds of connections are beneficial under different circumstances, and the following paragraphs will help to outline what these circumstances are and how they differ from each other.

A. Wind Farm Connection to Shore with Offshore Hubs

Results have shown that 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 of these be clustered into hubs.

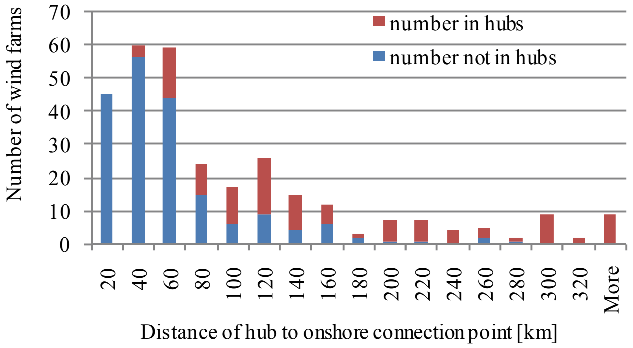


Figure 3: All 2030 wind farms in the Northern Sea Basins - Number of Projects (radial vs hubs)

The individual connection of wind farms results in costs of €83 bn. To connect with hubs where beneficial reduces these costs by €14 bn to €69 bn.

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 in anticipation of the total capacity of all the farms, once they have been 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 a stranded investment, should some of the wind farms never be completed. However, OffshoreGrid shows that the costs of temporarily oversizing the hub and of stranded investments are limited, and that hub connections can still be beneficial even if wind farms are built across a lifespan of more than 10 years.

B. *Tee-in Connections*

Whether connection of offshore wind farms to interconnectors is beneficial depends primarily on the balance between two factors: 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 cost savings are generated due to the fact that 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 when:

- the electricity prices differences between the connected countries are not too large,
- the wind farm is far from shore and close to the interconnector,
- the tee-in to the country where the wind farm is built has the lower electricity price of the two countries (compared to the conventional connection, 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, and an interconnector is created by connecting the wind farm to two countries rather than just one (lower infrastructure costs). This is the same as splitting the connection of a wind farm and connecting it to two shores.

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

C. *Hub-to-Hub Connections*

Hub-to-hub connections are generally beneficial when the countries to be connected are far from each other, and when 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.

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.

Once more, 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. Advance 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).

V. OVERALL GRID DESIGN RESULTS

Based on all these design options, as well as using conventional direct country-to-country interconnections, an overall grid design was developed. 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.

Please note that the design only allows assumptions of the economic viability rom an investors perspective. In the analysis of offshore grid the economics of infrastructure were judged from a system perspective by calculating the system electricity generation costs. A beneficial interconnector reduces these due to higher trading capacities between countries.

A. *Identifying an Efficient Integrated Grid Design*

As previously mentioned, two methodologies were applied to find and compare highly efficient offshore grid designs: the Direct Design and the Split Design method. Each methodology builds on three steps. For the Direct Design Methodology these are:

Step 1) The construction of direct interconnectors, taking the large price difference between countries as guidance (blue boxes in Figure 4)

Step 2) Beneficial tee-in solutions or the interconnection of countries via hub-to-hub connections were identified (green boxes in Figure 4). Step 2 was only considered when there were no further beneficial direct interconnectors to be placed (i.e. step 1 was completed to the fullest).

Step 3) Beneficial meshed connections were identified (orange boxes in Figure 4). Step 3 was only started when neither step 1 nor step 2 could identify beneficial connection solutions.

For the Split Designs, the same step-wise methodology was applied; only step1 differed. Step 1 of the Split Design is based on Step 1 of the Direct Design, but where it was beneficial, the direct interconnectors were replaced by split wind farm connections (the variant of the tee-in connection, represented by red boxes in Figure 4). Direct interconnectors of step 1 of the Direct Design methodology were retained when the replacement of the direct interconnector with split wind farm connections was not beneficial. These offshore wind farm nodes are then further interconnected to establish an overall ‘meshed’ design, where beneficial.

This step-wise approach is reflected in Figure 4, along with the benefit-to-CAPEX ratio of the interconnector established. The benefit is obtained by calculating the power system generation costs over the project lifetime of 25 years. These power generation costs are even reduced to take into consideration the fact that the cost of generation is less when trade is between countries is increased, which is the case when considering these scenarios. The system costs are then compared to the reference case without the interconnector.

In Figure 4 each investment results in positive net benefits, as non-beneficial infrastructure was omitted.

The return on investment from a system perspective is best reflected by the benefit-to-CAPEX ratio, which reflects how many Euros are gained for one Euro of investment across the project lifetime. It can be seen in Figure 4 that generally speaking, the Split Design is equally if not more beneficial than the Direct Design.

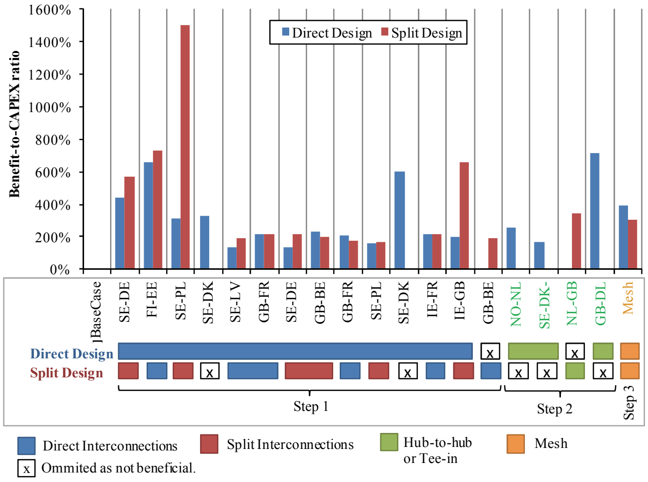


Figure 4: Benefit-to-CAPEX ratio for each modular step within the Direct and Split Design approach.

B. Economics of the Final Grid Design

When considering Direct vs. Split design methodology, the overall investment costs are €86 bn for “Direct Design” and €84 bn for the “Split Design”. This includes €69 bn of investment costs for the most efficient connection (hub-connections when beneficial) 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) [2].

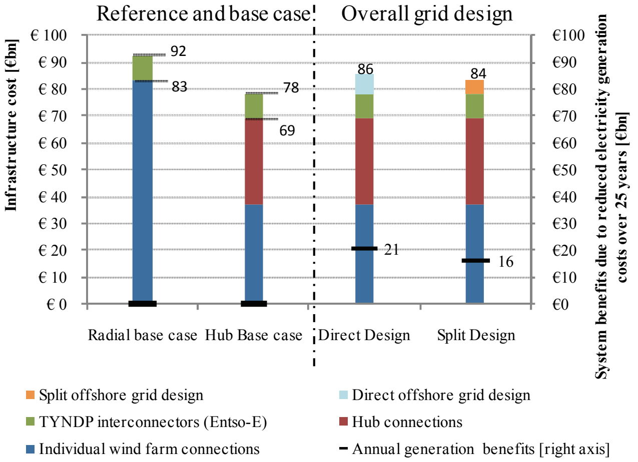


Figure 5: All 2030 wind farms in the Northern Sea Basins - Number of Projects (radial vs hubs)

The rest of the costs that make up the €85 bn for this interconnected grid, which would be built on top of the hub base case scenario, 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) over a lifetime of 25 years – benefits of about three times the investment. Both designs are thus highly beneficial. When comparing in relative terms by looking at the benefit-to-CAPEX ratio, split wind farm connections are in general more cost-effective than direct interconnectors and yield a higher return on investment.

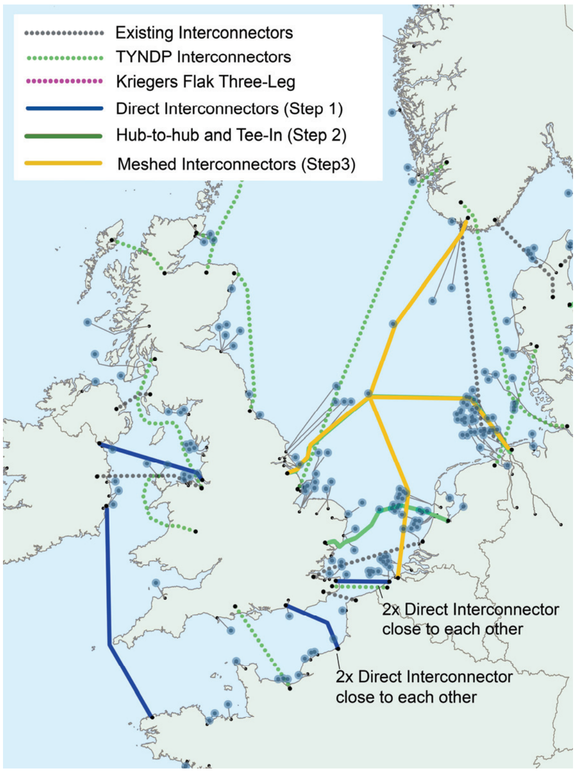


Figure 6: Offshore Grid overall grid design following the Direct Design Methodology (extract for the North Sea)

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/MW. In this context, the infrastructure costs only represents about a fifth of the value of the electricity that is generated offshore. 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, of course, advantages and disadvantages to both the Direct and Split design methodologies.

Splitting wind farm connections to combine the offshore wind connection with trade has proven to be more cost-effective than building direct interconnectors used for trade only. 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% on average. A comparison of the net benefit per invested Euro of CAPEX revealed that in the Split wind farm design, each Euro is spent 2.6 times more efficiently. The absolute comparison also proved the Split offshore grid design to be more cost-effective than the Direct offshore grid design.

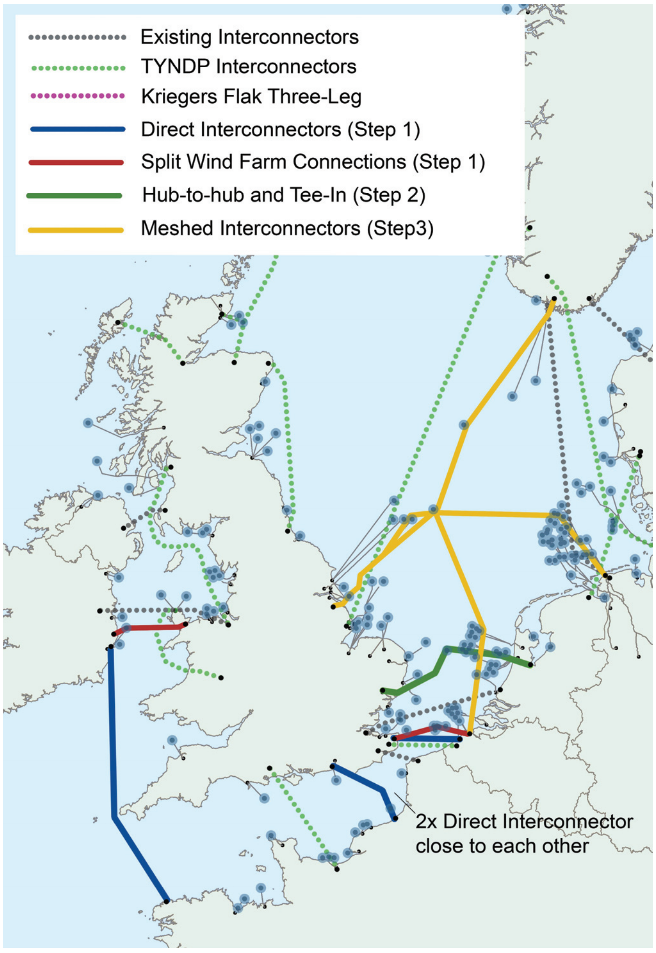


Figure 7: Offshore Grid overall grid design following the Split Methodology (extract for the North Sea)

In addition to its techno-economic advantages, the Split Design also provides environmental benefits because it reduces the total circuit length. Moreover, it improves the redundancy for 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.

On the other hand, tee-in solutions, hub-to-hub solutions and split wind farm connections are confronted with the problem of regulatory framework and support scheme incompatibilities between European countries. The reason is that renewable energy supported by one country can now flow directly into another country, so that the country paying for the renewable energy investment cannot enjoy all the benefits. For split wind farm connections this effect is even more pronounced, as the connection to the country which paid for the construction of the wind farm is reduced. As these complexities add risks to the development of integrated connections, and split connections in particular, they should be solved at the international level as soon as possible.

VI. Main Recommendations and Conclusions

To make the offshore grid more cost-effective and efficient, the innovative connection and interconnection concepts discussed above should be applied. The following 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 largely beneficial.
- In countries where there is not yet strategic siting or granting of concessions, policy makers should aim for fewer areas with a larger number of concentrated wind farms, rather than smaller, more numerous concession areas. The projects within one area should be scheduled for development at the same time. 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 connections 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.

- However, the ongoing development of direct interconnectors should not be slowed down, as this concept can already be built today within today's technological and regulatory framework, independent 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.
- Any new interconnector installed can have a negative impact on the economics of the interconnectors already in place, as they reduce the price differences between the countries. Integrated solutions are less dependent on the trade than a direct interconnector, and can therefore still be beneficial, even with lower price differences. Therefore where possible, opportunities for such 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 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 are encouraged to obstruct any new interconnector, as this will reduce their return on investment. It is therefore absolutely necessary that are no conflicts of interest, for example between private investors with a key role in grid planning and operation, and the political decision processes concerned with these issues. If these conflicts of interest propagate, 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-effective in many cases. Furthermore these grid designs can increase system security and reduce environmental impact. Policy makers and regulators should prepare to support such innovative solutions. In particular, the compatibility of support schemes and the allocation of benefits should be agreed upon as soon as possible on international level. The North Seas Countries' Offshore Grid Initiative is a good framework within which to coordinate the international issues surrounding the political, regulatory and market aspects.
- When considering international 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.

VII. ACKNOWLEDGEMENT

The authors gratefully acknowledge the contributions of the consortium partners of the OffhsoreGrid project, namely Simon Cowdroy[2], P. McGarley[2], L. Warland[3], H. Svendsen[3] , J. Völker[4], J. Tambke, L. von Bremen, K. Michalowska[5] and G. Caralis[6].

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Jan De Decker graduated in 2007 from the Katholieke Universiteit Leuven (Belgium) as a Mechanical/Electrotechnical engineer with specialisation in energy technologies. His thesis dealt with the optimal sizing of combined heat and power installations in applications with known heat load.

Jan De Decker joined the energy strategy and policy department of 3E in October 2007. He focuses primarily on the techno-economic modelling of electricity from renewable sources, in the integration of renewable energy in power systems and markets, and in everything related to offshore wind energy and offshore electricity infrastructure. At 3E, he has participated in a number of high level projects, including a CO2 mitigation study for the Belgian Region of Brussels and a wind power market integration model for the Belgian federal science policy department. Jan De Decker has extensive experience in offshore grid projects. He is co-author of the study 'A North Sea Electricity Grid Revolution' for Greenpeace and is currently managing a project on the development of a strategic roadmap on offshore grid development in the Pentalateral Energy Forum.

Paul Kreutzkamp studied Physics at the University of Freiburg, Madrid and Berlin and received his Diploma from the Humboldt University of Berlin with a diploma thesis on photoactive macro molecules.

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system integration of renewable energies. From 2009 to 2010 Paul directed the dena grid study II among others.

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Natalie Picot is a project manager in 3E’s wind technology team. She provides technical expertise and coordinates subcontractors and suppliers for the production of turbine components. Natalie has been working at 3E since 2010 and has previously worked for NKT Flexibles I/S in Denmark, one of the leading suppliers of flexible piping solutions to the offshore oil & gas and chemical & water industry. Initially starting out as a system design engineer, she became responsible for the approval of ancillary components and a point of contact for clients to the system design group on projects.

Natalie completed her bachelor’s degree in Mechanical Engineering at Queen’s University, Canada, in 2003, and went on to complete her master’s degree in mechanical engineering at McGill University in Montreal, Canada. She is currently enrolled in the part-time international MBA program at the Vlerick Leuven Gent Management School, in Belgium.