Briefing Paper

Leonardo ENERGY

Ocean grids around Europe

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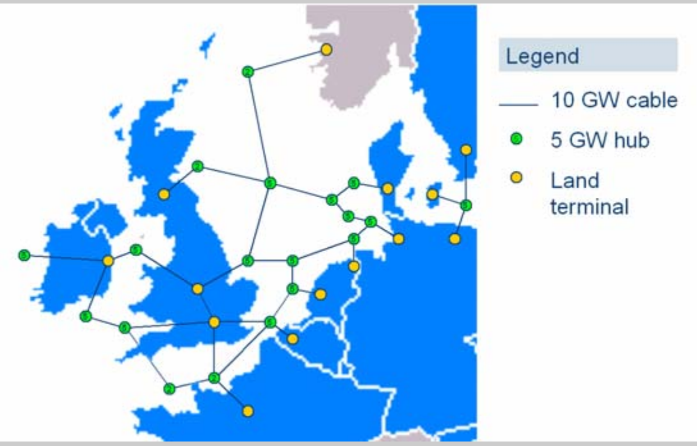

Renewable Energy

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1. Introduction

Several European countries have a policy to encourage the development of renewable en-ergy sources. This is identified in e.g. the European green paper Energy strategy for a sus-tainable, competitive and secure energy supply (March 2006). In the transition towards a European sustainable energy system for the future and to reduce the dependency of im-ported primary energy sources such as oil and gas, the development of offshore wind power is an essential element. EWEA assumes that almost 120,000 MW offshore wind power will be realized in the next two decades, amounting to 10% of the installed generating capaicty. Apart from offshore wind energy other offshore renewable energy sources such as wave energy, tidal energy and some experimental technologies of offshore energy have been considered.

Recent blackouts within Europe have shown that there is a need for increased European co-ordination regarding the transmission of electricity including aspects related to interconnections. In the EU technology platform Smart Grids[1], attention is paid to the networks of the future to ensure that they can accommodate and facilitate large amounts of renewable energy, both distributed and concentrated.

Following the European Smart Grids line of thinking, Airtricity has proposed a European offshore super grid (HVDC based on Voltage Source Converter technology), combining the grid integration of offshore wind farms with an interconnection grid between countries at sea. One could extend the role of this grid and connect all “ocean power” to it. The supergrid could then be part of the European backbone to connect and transmit bulk renewable power from remote generation sites, even as far as North-Africa (Desertec).
The goal of this paper is to discuss "Ocean Grids", grids at sea at a conceptual level. The idea behind Ocean Grids is to provide an offshore backbone for the mainland transmission networks on one hand, and connection points for offshore wind power stations on the other hand. This will include offshore wind energy and other potential energy sources at sea.

2. Renewable energy production trends

One of the reasons to explore offshore wind energy is the good wind resources (the wind blows harder in the sea and ocean), and space restrictions on the mainland for wind turbines. For this reason offshore wind power will be the most explored offshore sources of renewable energy. Second will be wave and tidal energy. Other sources could be so-called underwater turbines and the production of aquatic biomass at sea area to provide bio-energy. New interconnections in the Mediterranean Sea – to transport electricity generated by solar-PV in Africa – and in the north-western European waters (sea and ocean) to the hydro energy resources of Iceland, Greenland and the Scandinavian countries provide application possibilities, though not less interesting for offshore (ocean) grids.

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[1] *www.smartgrids.eu*

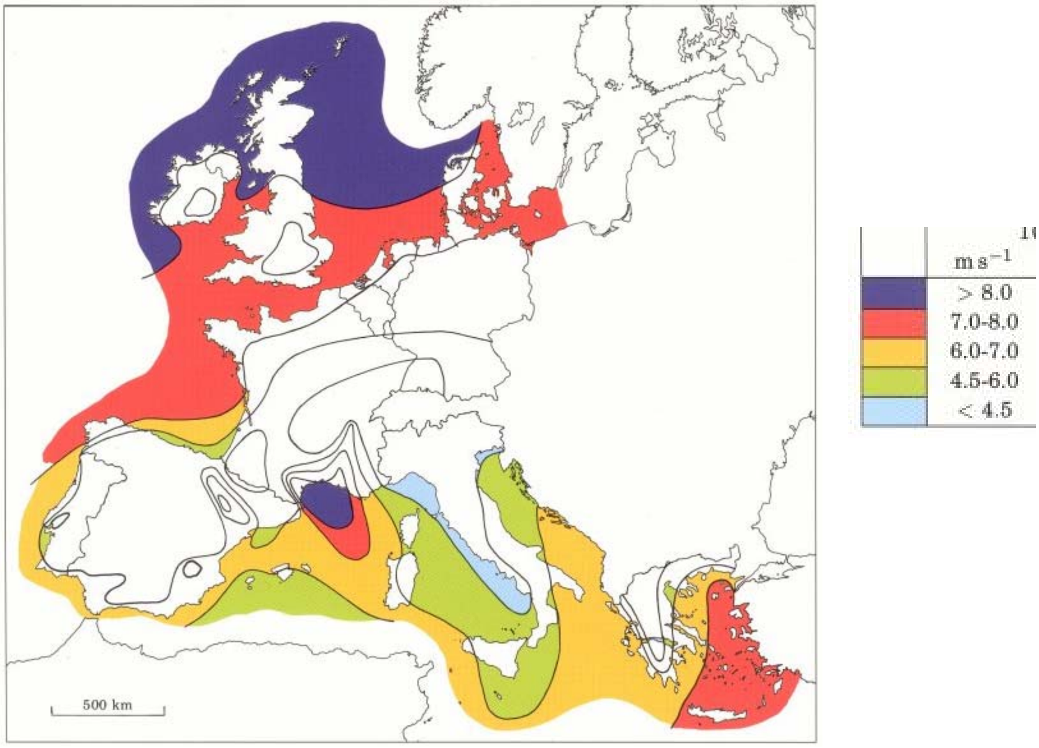

Figure 1: Average wind speed in and around the European continent

At present large schemes for deployment of offshore wind are being developed in the North Sea region of UK, The Netherlands, Denmark and Germany. Besides these, offshore wind farms are planned in Ireland, Sweden, France and Belgium. From the Wind Energy study 2006 by the German Wind Energy Institute (DEWI) the total installed European wind power in 2010 is expected to be around 75,000 MW and for 2014 around 115,000 MW, this corresponds with the 2004 EWEA study “Wind-Energy the Facts”. More recently EWEA published their No Fuel campaign in which they aim at 300,000 GW in 2030 in which 50% should be realized offshore. The presently installed wind power in Europe is approximately 41 GW of which 0.5% is offshore capacity. The location of offshore wind can be both in shallow water (up to 50 meters) or, as the new Norwegian[2] experience show, as floating windmills in ‘deep’ water, which makes it less dependent of the sea or ocean depth.

Exploitation of small gas fields can perhaps be made profitable when electrical power is generated locally (up to a few hundreds of MW) and supplied into a sea grid (instead of transporting the gas to the mainland). This is also possible for the existing almost exhausted (marginal) gas fields that are not connected anymore to the high pressure gas pipes.

Offshore oil platforms could also be connected as an electrical load to such a grid, resulting in reduced emissions at sea, but also savings on investment for power generation on oil platforms and thus more space for their core business.

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[2] *www.hydro.com*

Wave and tidal energy will most probably be applied at locations with strong currents and large differences between their low and high tides, e.g. Irish Sea and specific areas along the coastline of France respectively. The potential capacity of these sources are expected to be relatively low compared to offshore wind power. Nevertheless, if the European Commission will continue to support these types of new energy technologies in the coming years their contribution to a renewable energy supply can be significant on the long run.

Also new developments like a large "Energy Island", a multi-gigawatt offshore storage facility being developed in The Netherlands[3] can be connected to the ocean grid.

Figure 2 : Artist impression of an Energy Island[3]

3. Challenges for the European electricity grids

3.1 Single market and Trans-European Energy Networks (TEN-E)

In the 1980s, the concept of Trans-European Networks (TEN) was developed in view of facilitating a single European market. Within this single market, freedom of movement for goods, persons and services should be ensured by modern and efficient infrastructures. Both the interconnection of national networks and access to such networks are key items.

Trans-European Energy Networks (TEN-E) are the EU keyword for highly interconnected energy networks, mainly for electricity and gas. For electricity, the focus is mainly on establishment of significantly increased connection capacity between the high-voltage networks of the member countries.

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[3] *F.J. Verheij et al (2007), The Energy Island - an inverse pump accumulation station, EWEC 2007*

The development of an "ocean grid", i.e. a combination of large-scale offshore generation and load on one hand and strong offshore interconnectors on the other hand, would significantly contribute to the concept of a trans-European Energy Network.

3.2 Increased need for transmission and cross-border capacity to accommodate offshore wind

The changes in the generation portfolio described above imply several challenges for the European electricity transmission networks.

A main issue is the co-ordination of energy supply and demand, as the availability of wind power does not follow the demand pattern. This applies not only at different time scales, but also on both local and European levels. Moreover, wind power production cannot be scheduled and controlled as well as conventional generation. In the 1970s, the early days of modern grid-connected wind generation, this posed no major problems, as the variability of the relatively small wind power production was locally compensated for by the much larger conventional power plants in the regional transmission network.

In the 1990s, in many areas wind power exceeded 10% share in the generation mix, and could even reach 50% during low-load conditions. Under such circumstances, several conventional power plants are switched off and the remaining conventional generators cannot always maintain supply security in case of large variations in the wind power generated. In Spain, Denmark and Germany, among others, transmission system operators were worried that the system stability was at risk and put the effect of wind power on the system on the political agenda.

In principle, temporary excesses and shortages of power on a regional scale could be traded between countries. On a European level, it could be stated, "the wind is always blowing somewhere". However, there are several key reasons why the power cannot be balanced on a European scale: the interconnection capacities typically are relatively small compared to what would be needed to balance more than 50 GW wind energy across Europe. And even those interconnection capacities that are present today have limited capabilities because they are partly allocated for system purposes and/or to contracted power exchanges. Increases in transmission system losses are another aspect associated with long-distance transmission in heavily loaded networks.

Recent blackouts within Europe have shown that there is a need for increased European coordination regarding the transmission of electricity. Two large European research projects, TradeWind and EWIS, are currently investigating the effect of large-scale wind energy deployment on the European electricity networks.

In the EU technology platform Smart Grids, attention is paid to the networks of the future to ensure that they can accommodate and facilitate large amounts of renewable energy (both dispersed and concentrated). In some studies, a European super grid has been proposed, like depicted in Figure 3.

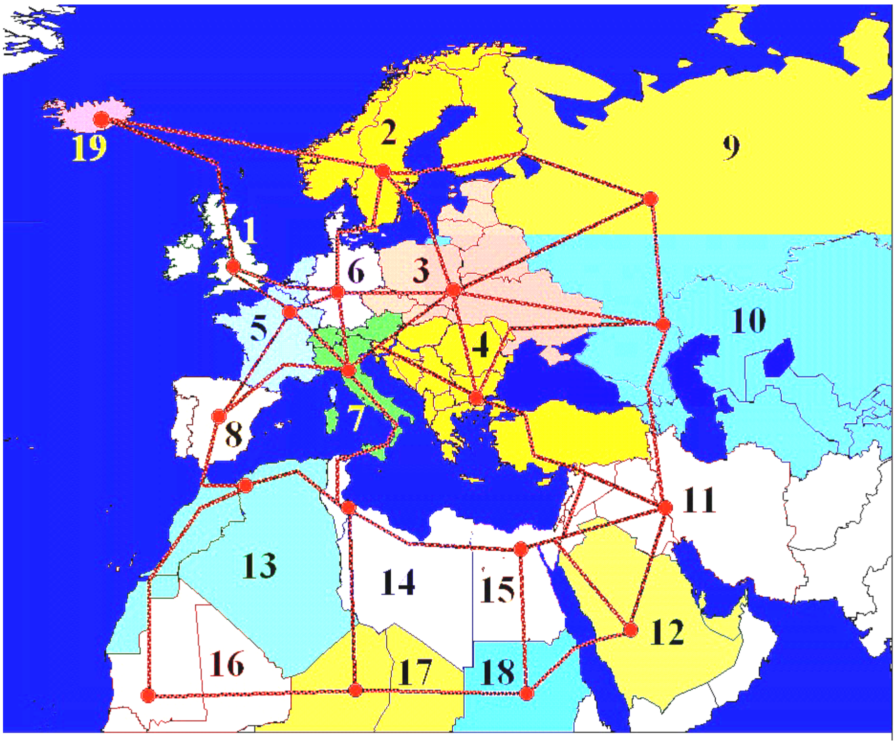

Figure 3 : Concept of an electricity superstructure in & around Europe (Czisch[4], 2005)

Apart from an increase of the interconnection capacity proposed in most, if not all studies, several complementary measures to integrate massive amounts[5] of wind energy should be mentioned:

- increasing the transmission capacity on the (main)land within the countries/areas controllability of wind farms, to partly control their output
- fast-acting generating units that can better adapt to rapid changes in demand and/or renewable energy production
- energy storage units, that can perfectly adapt demand and power production
- better sharing of power reserve between countries
- system-controlled curtailment of wind power production, among others to control the actual mix of conventional vs. renewable generation vs. interconnection capacity
- improved short-term forecasting methods for wind power production in order to improve dispatching of wind power.

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[4] *G. Czisch (2005), Scenarios for the future electricity supply. Dissertation, Kassel University*

[5] *Tens of percents of maximum demand*

It may be expected, that at high levels of offshore wind and other renewable sources, an optimum will be found in a mix of measures.

4. A concept for ocean grids

The idea behind Ocean Grids is to provide an offshore backbone for the mainland transmission networks on one hand, and connection points for offshore wind power stations on the other hand. Figure 4 gives an impression of such an Ocean Grid on the North Sea. The contents and meaning of the dots (hubs & terminals) and lines will be discussed in the subsequent sections.

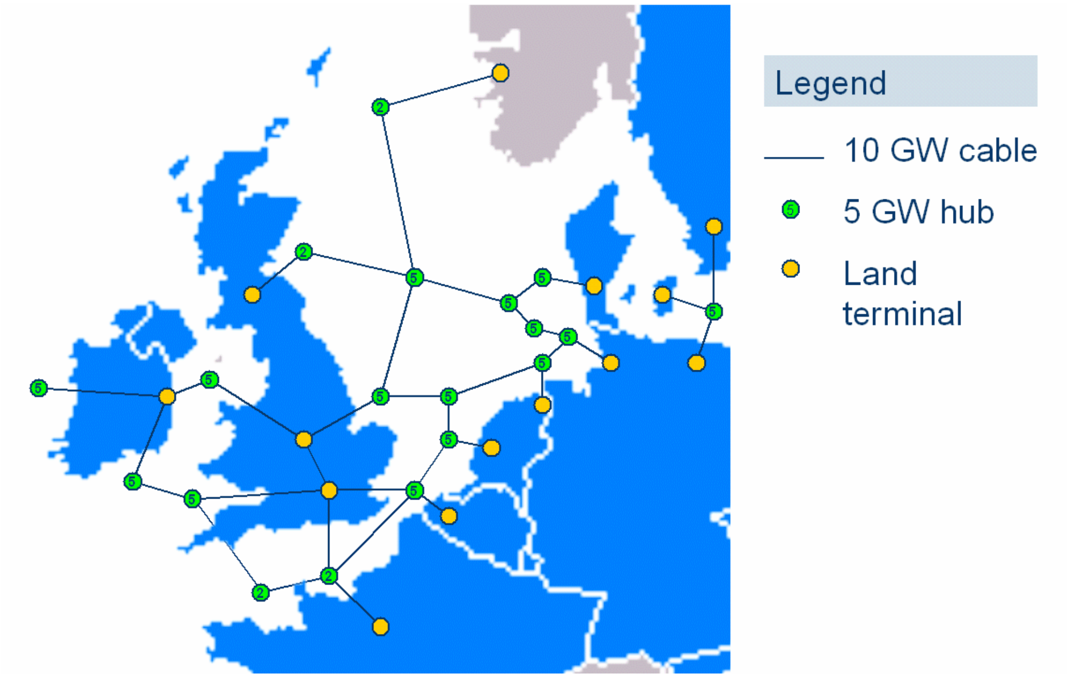

Figure 4 An Ocean Grid for the North Sea

All connections will be in HVDC (high-voltage direct current) technology. The reasons for proposing HVDC in this application are both length and power limitations of AC transmission through (submarine) cables: AC is unattractive for distances beyond 50..150 km.

The superstructure is formed by multi-GW rated HVDC cable connections running between the offshore hubs and the mainland points. In order to adequately serve as backbone(s), the connection rating is chosen as 10 GW – the cable connections are discussed in Section 5.

The green bubbles containing a figure represent 2 or 5 GW offshore hubs, in which locally generated offshore (wind) power (or from other sources) in the GW scale is collected and linked with the superstructure. These substations or hubs are discussed further in Section 6.

As the mainland networks are typically congested already, the ocean grid is envisaged to get close to the load centres. The yellow, empty bubbles show mainland terminals, located near load centres or at least strong points in the mainland network. See Section 7 for a discussion of the mainland connections and the relationship with the mainland network backbone.

Thus, the ocean grid combines the connection of offshore (wind) power with the realisation of strong interconnections between the countries. With the Ocean grid, the balancing and trading issue discussed in Section 3.2 will also be partly addressed for the countries concerned.

Offshore oil platforms can be connected to this ocean grid (meaning no emissions at sea, but also savings on investment for power generation at oil platforms and thus more space for core business). On the other hand, non-profitable small gas fields and marginal gas fields can perhaps be made profitable when used as power generation (few hundreds of MW) connected to the ocean grid. There is also the possibility to connect the potential of ocean power (e.g. wave energy) to this grid and its role as part of the European supergrid backbone to connect and transmit bulk renewable power from remote generation sites, even as far as North-Africa (Desertec).

For southern Europe, Figure 5 gives an impression of the ocean grid around South-West Europe, and Figure 6 for South-East Europe. The hub size has been assumed much smaller in most cases (2 GW instead of 5), as the foreseen installed powers are lower.

Figure 5 : Ocean Grids for South-West Europe, including a link with Africa (Tunisia or Algeria)

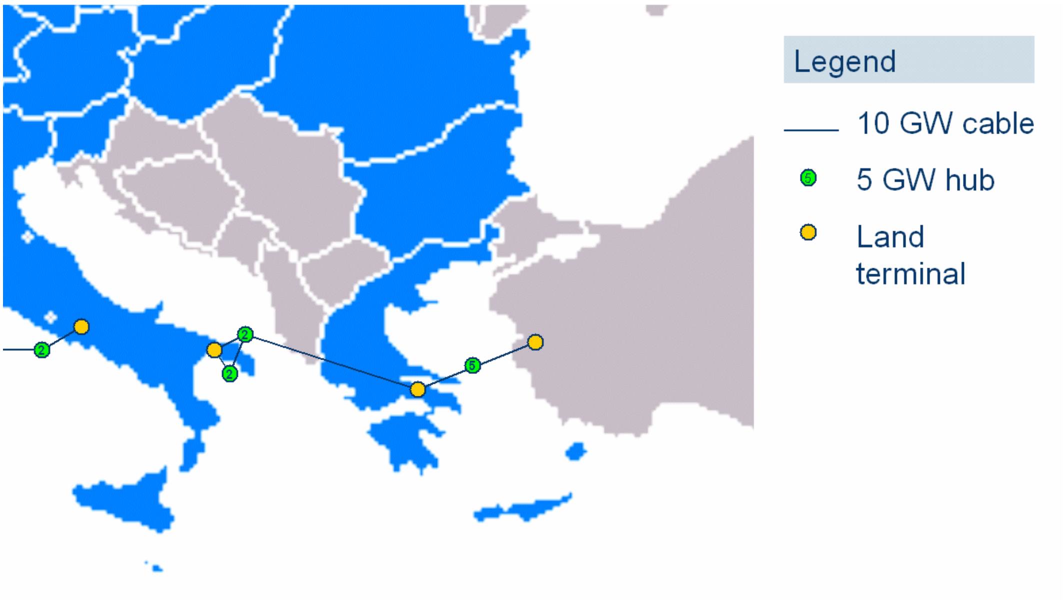

Figure 6 : Ocean Grid for the eastern Mediterranean Sea

In Figure 5, the ocean grid extends towards Tunisia as an extra connection between Africa and Europe, among others for large photovoltaic (PV) power plants in Africa.

The development of an "ocean grid" in combination with a European super grid, would significantly contribute to the concept of a trans-European Energy Network.
On the other hand, a unified European electricity market can be considered a prerequisite for a super grid to be able to be financed. Contrary perhaps to an individual wind farm connection, the cost of an ocean grid as part of the trans-European electricity networks are to be considered deep connection cost, and to be financed as such. This paper, however, focuses on the technology side of the issue.

Such an "Ocean Grid" would require development of sea-deployable transmission systems with large capacities as compared to the convential HVDC (across land) transmission systems that are being developed for China and India (up to 6.4GW and voltages up to 800kV DC).

5. Cables in the Ocean Grid

It is expected that the HVDC cable rating for the ocean grid will be in the range of 5-10 GW. This is about twice that of the largest HVDC overhead line connection and 5-10 times that of the largest HVDC cable rating available. Reasons to expect a significant increase in the rating up to 5-10 GW are:

- economies of scale
- congestion of cable routes at the cable landing areas and at the mainland
- shortage of available cable routes at sea where many areas are inaccessible for underwater cables or are to be avoided (e.g. fishing grounds, shipping lanes, military areas).

Technological development will be required in order to realize such large cable ratings. Technology options to increase the available rating for underwater cable connections to transmitting 5-10 GW could be:

- parallelling of multiple conventional polymeric or paper-insulated 1-2 GW rated cables, however this would partly cancel the economies of scale
- development of superconductive cables using high-temperature superconducting (HTS) cable technogy
- gas insulated lines (actually, large metal pipes in which bare conductors carry the electrical current).

Apart from the electrical cables themselves, technology will be required for appropriate joints and accessories, cable laying and cable repair/replacement after damage.

6. Offshore electricity terminals

This section discusses the concept of a 5 GWi[6] offshore terminal (hub).

Offshore wind turbines may, in the future, have sizes of 5-10 MW or even beyond, but some form of clustering is required to provide economies of scale. From an economical point of view, the wind turbines will be clustered in parks of e.g. 150 – 250 MW blocks (wind farms).

Due to similar economical considerations, it will not be economical to link each wind farm directly to the multi-GW grid. It is envisaged that multiple wind farms will be combined in strings rated 0,5-1 GW, like multiple wind turbines are combined in 20-50 MW strings within a wind farm.

Thus, the offshore collection and transmission system consists of three levels:

- a macro level, with HVDC cable connections rated ~10 GW (the super grid), containing the hubs
- a meso level, with HVDC cable connections rated ~1 GW (the hub power collection network), connecting the wind farms with the hubs
- a micro level, with AC or DC cable connections rated ~20-50 MW (the wind farm power collection network), connecting individual wind turbines with the wind farm collection stations.

For energy supply to or from oil/gas platforms, the same terminology can be used, with supply to individual platforms (order 20-50 MW) located at the micro level. Small, nearly-exhausted gas fields producing in the order of 100-500 MW could be directly connected to a large hub (feed-in at the meso level).

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[6] *The figures of 5 GW is not the result of an optimization but a ballpark figure.*

It is envisaged, that the cable networks at the meso and micro levels will not be redundant, i.e. in case of a technical malfunction or maintenance, the entire string or network part needs to be switched off. The macro level will need to be redundant, as even on a European scale, failure of a 10 GW transportation link will be problematic.

The connection from micro level to meso level in the wind farm collection stations can be realized using current technological concepts. The generator in a wind turbine always produces AC power. For the multi-MW wind turbines of the future, this AC power will be typically converted to DC within the wind turbine and reconverted to AC using existing technology. As the power produced needs to be converted to AC anyway, this is the most efficient option. One of the options could be, that the power collection network at the micro level will be AC, and the conversion to DC is carried out at the 200 MW wind farm collection stations. The technology for this ~200 MW conversion is also available. Possibly, the triple conversion AC-DC-AC-DC may call for other alternatives, e.g. eliminating the intermediate AC voltage. Technology development would be needed to connect the single multi-MW wind turbines to a park level using DC. This option is still in the research stage[7].

The 5 GW hubs connect the meso to macro level and perform following functions:

- switching and protection of the macro level 10 GW cable system
- insertion respectively extraction of the local 5 GW of power into/from the macro through-connection. If the local strings are operated on AC power, this insertion/extraction also encompasses AC/DC conversion. If the local strings are operated at HVDC power, this insertion/extraction may encompass some form of DC/DC conversion
- switching and protection of the local 1 GW strings
- communication between the meso and macro layers.

The hub can be visualized as an artificial island or (fixed or floating) platform, in which several collection cables come in along with two or more supergrid cables. Figure 7 shows the local collection network of a 5 GW hub.

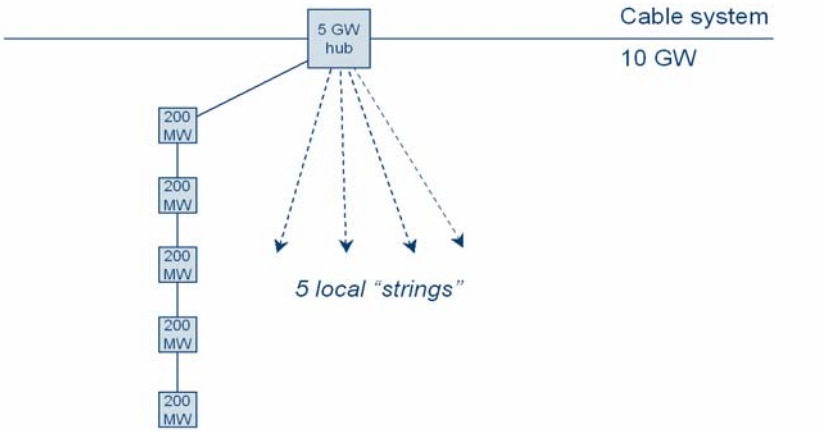

Figure 7 : Collection area around a 5 GW hub, containing multiple strings with multiple wind farms each

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[7] *S.Lundberg (2006), Wind Farm Configuration & Energy Efficiency Studies—Series DC versus AC Layouts. Dissertation, Chalmers University*

Technology to realize such a 5 GW hub does not exist yet. Areas to develop include equipment to switch ~10 GW safely and in a controlled way, and to insert/extract local multi-GW power feeders into/from these ~10 GW power flows.

7. Mainland terminals

The mainland terminals will form the interface between the ocean grid and the mainland national networks. They will perform several functions, including:

- performing the conversion between 400 kV AC[8] (alternating current) and HVDC (direct current)
- controlling the power flow in the offshore network
- distributing the power flow to several 400 kV substations in the network
- providing ancillary services to the 400 kV network e.g. frequency control and reactive power control.

Figure 8 gives an impression of the network integration of such a terminal. The existing 400 kV infrastructure is given in red lines and circles. The hub should be located near a large load centre, in order to minimize the network reinforcements required.

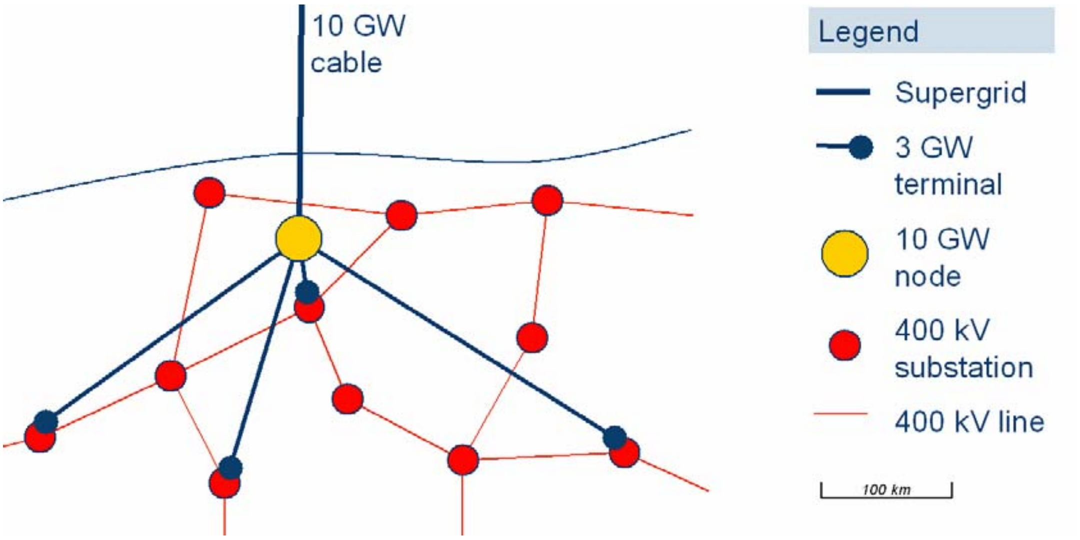

Figure 8 : Distribution area around a 10 GW mainland hub

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[8] *Like HVDC, the AC voltage is also high voltage. However, the term HVAC is avoided in order to avoid confusion with its usual meaning of heating, ventilation and airconditioning.*

Typical ratings of 400 kV lines (and cables) are 1-3 GW, i.e. one order of magnitude less than for the supergrid. In order to fit the 10 GW terminal in the existing system, many reinforcements are required around the terminal, depending on the situation. Such network reinforcements could be realized by spreading the power from the terminal to several geographically distributed 400 kV substations, each connected by a 1-3 GW DC/AC terminal. Thus, a kind of "pressure distribution" will be realized.

Another issue is the event of losing a 10 GW connection, whether importing or exporting.

In such a case, a significant redistribution of the power flow in the mainland network will occur. In part, the mainland generators and loads would need to find a different equilibrium, while remaining balancing should be realised by the mainland transmission networks. The redistributed power flows could well lead to overloads in the mainland transmission networks.

One strategy to overcome the issue of losing such a large connection would be to make the connection redundant, i.e. having such a structure (e.g. multiple cables) that single elements may fail with limited effect, and the probability of losing the entire connection is reasonably small. This would lead to a cost increase of such connections.

Another strategy would be to reinforce the mainland network between the mainland hubs to some extent. European superstructures like in Figure 3 could provide relief for the underlying 400 kV connections.

Technology to realize the 1-3 GW AC/DC terminals is almost available. The 10 GW splitters do not yet exist. Areas to develop are equipment to switch ~10 GW cable connections safely and in a controlled way, and to insert/extract local multi-GW powers into/from these ~10 GW connections.

8. Transition towards Ocean Grids – modular design

Presently, the Ocean Grid only exists on a conceptual level. Not only is the technology not fully available yet, but realized offshore wind farms in shallow waters close to the coast lines can easily be connected to the existing AC grid using conventional AC cable connections. As long as there is sufficient space available in the mainland transmission networks, at the coast landing areas etc., this will remain the most cost-effective option. When the "inexpensive" solutions are depleted, the Ocean Grid will start emerging as a cost-effective solution.

One of the things happening when proceeding this way ahead is that we enter a “technology lock-in situation”. All the wind farms will be connected with separate AC cables and at a certain moment in time this is not possible anymore and than a “large installed” base is present that has to be “rewired”. From this point of view an ocean grid is more “future-proof”.

It is not possible to accurately predict the point of transition, but at some locations, trends towards an Ocean Grid are already visible: in 2007, German Eon Netz announced that it planned to connect several offshore wind farms in the North Sea through a 400 MW HVDC connection.

Given the significant investments required, in the order of hundreds of millions of Euros for each connection, it is not expected that parts of the Ocean Grid will be realized in their full capacity from the beginning. Rather it is expected that connections and substations will be built up in modularity.

"Power receptables at sea", substations that accept power from multiple offshore windfarms for transmission to the mainland, as being realized by Eon Netz in Germany and being under consideration in in other countries e.g. the Netherlands, by TenneT. It can be expected that these power receptables at sea form the first step in the realisation of (parts of) the Ocean Grid. In Figure 4, the Eon Netz link has been optimistically incorporated.

Modular (and sea deployable) design is crucial to allow for phased investments and mitigation of investment risks. Technological progress can also be implemented gradually in this way.

Cable connections may be realized by installing individual cables and expanding their number as needed. In the end, a cable connection would consist of multiple parallel connections, which would give the benefit of redundancy (no loss of 10 GW during a single event).

Both the offshore and mainland terminals could be built up of modular building blocks ("LEGO system"). Switchgear in substations typically already has a modular character. HVDC converters and associated gear, however, may require additional technological development to obtain the modularity required.

As usual for large international infrastructure investments, realising an Ocean Grid requires not only proper financing structures, but also:

- International agreements arranging for the establishment of the offshore network
- Adaptations in the European and national legal frameworks (laws, directives, regulation) regarding investments and exploitation of such interconnections
- Adapted market rules in order to better facilitate large energy transactions and system services on the common network.

9. Conclusions and future outlook

This paper describes the concept of a strong ocean grid to facilitate multi-GW deployment of offshore renewable sources. It combines the grid connection of such newables with the realisation of strong interconnections between the countries.

Ocean grids are seen as a key measure to implement significant amounts of offshore wind energy in the European networks. Also, a more transparent Europe-wide electricity market will be created, in line with the European Union's policy of "Trans European Networks for Electricity" (TEN-E), and the issue of variability of wind power output is mitigated.

Such an "Ocean Grid" would require development of sea-deployable transmission systems with large capacities as compared to the conventional HVDC (across land) transmission systems that are being developed for China and India (up to 6.4GW and voltages up to 800kV DC). Several issues, already under study, should be solved before ocean grids could fully develop:

- HVDC cable technology should be developed for redundant 10 GW cable connections. Apart from the electrical cables themselves, technology will be required for appropriate joints and accessories, cable laying and cable repair/replacement after damage.
- Modular HVDC substation technology should be developed for multi-GW hubs for meshed HVDC networks
- Sea-deployable techniques (platforms, floating)
- Development and realization of power receptables at sea, which in the future can be expanded or be part of the ocean grid
- Unification of the European energy market, already pursued in the EU policy on Trans-European Energy Networks, TEN-E
- International agreements should be arranged for the establishment of the offshore network. Market rules should be unified and adapted in order to better facilitate large energy transactions and system services on the common network. The TradeWind project will contribute to market rules harmonization in EU countries
- European and national legal frameworks (laws, directives, regulation) should be considered regarding investments and exploitation of such interconnections, among others the distinction betwee shallow and deep connection cost.