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Integration of Wave and Offshore Wind Energy in a European Offshore Grid

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ABSTRACT

High wave and offshore wind energy potentials are located along the West and North coasts of Europe, respectively. In the near future, these resources should significantly contribute to the European electricity mix, but there is hardly any grid infrastructure available for large scale integration of offshore renewable energy sources. According to this, the paper covers i) public and private initiatives for offshore transmission networks, ii) the synergies between the wave and the offshore wind energy sector within an offshore grid, iii) power transmission options for offshore generation and iv) the challenges ahead of the realisation of an offshore grid.

KEY WORDS: VSC; HVDC; meshed; grid; offshore; wave energy; wind energy;

INTRODUCTION

In 2008, the European Union (EU) primary energy consumption was covered by oil (~39%), natural gas (~24%), coal (~16%), nuclear power (~12%), hydropower (~4%) and other renewable energy (RE) sources (~6%) (BP, 2009; EEA, 2008; IEA, 2009). Thus, 80% of EU primary energy consumption in 2008 was dependent on limited resources, such as fossil fuels and uranium, of which two thirds (about 1200 million tonnes oil equivalent) were imported resources. Additionally, the electricity demand in the EU is expected to grow at a rate of 1.5% in the period 2000-2030, the current interconnections capacities are insufficient to increase the power exchange (EC, 2006) and about 50% of the existing power plants in the EU are arriving to the end of their lifetime.

This scenario imposes two key energy requirements for the EU in order to secure a more independent, long term energy supply: i) increase the share of electricity generation based on RE sources in the energy mix and ii) reinforcement of the existing power grid. Except biomass, RE sources must be exploited at the origin sites (ECF, 2008) which, in turn, requires a grid infrastructure interconnected to different areas at the generation locations. In particular, offshore wind energy (OWE) from the North and West of Europe and wave energy (WE) from western oceans could play a significant role to fulfil i) but there are weak interconnections between EU member states (Van Hulle, 2009), the power market is inflexible and fragmented and there is a lack of offshore electricity grids (EWEA, 2009a). According to (EOEA, 2009), if grid connections issues are not solved by 2020, ocean energy scenarios as shown in Table 1 will not be achievable and offshore RE sources will compete for grid connection points.

Table 1. Ocean energy scenario in the EU (EUOE, 2010).

Year	2020	2025	2030	2035	2040	2050
GW	3,6	20	54	105	166	188
TWh/y	9	53	150	317	546	645

Grid integration of OWE and WE demands either direct connections to shore (i.e. radial connections), which require grid upgrades at every connection point onshore, or a comprehensive planned offshore grid within a European wide transmission network (i.e. meshed offshore grid). Van Hulle (2009) reveals that there is no optimal grid solution if every country implements its own onshore and offshore national power markets, which corresponds to the former strategy. On the other hand, if the grid is internationally designed, the overall costs are reduced because the cables can work as interconnectors (i.e. for power exchange between power systems) as well as for power transmission from offshore generation sites to onshore and offshore (e.g. offshore oil and gas platforms) consuming centres.

Furthermore, a meshed offshore grid within a wide transmission network brings several additional advantages. It provides cross-country access to energy storage facilities and redundancy in case of a system failure (Koldby and Hyttinen, 2009); it improves the national and international electricity exchange and it decrease the natural variability of some RE sources through regional diversification (Fig. 1) (Diesendorf, 2007; ECI, 2006). These reduces the need for base-load generation significantly, brings additional reserve capacity and allows

covering peaks of the demand with imports of power instead of running power plants at low capacity, which above all results in lower electricity power prices (Higgins, 2008; Kenitzer, 2007; Van Hulle, 2009). Nevertheless, the realisation of such network faces relevant technical, legal, timing and economic challenges.

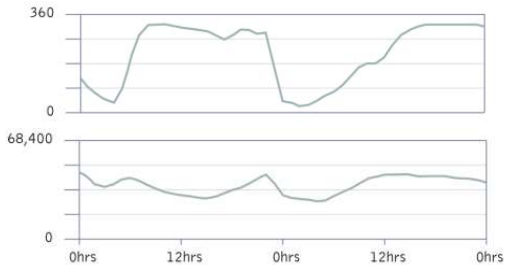

Fig. 1. Horns Rev I+II (above) and all OWE farms in the North Sea (below) power output (MW) on April 3-4, 2006 (Woyte et al, 2008).

This article is an overview of OWE and WE integration into the European electricity grid. Firstly, it reviews public and private initiatives for European offshore transmission networks; secondly, it presents the synergies between the WE and the OWE sectors within an offshore grid; thirdly, it describes power transmission options for offshore generation: HVAC (high voltage alternating current), line commuted converter (LCC) based HVDC (high voltage direct current) and voltage source converter (VSC) based HVDC; and lastly, it identifies the challenges ahead of an offshore grid based on the experiences from a small-scale version of it (i.e. Kriegers Flak).

BACKGROUND

There are a considerable number of offshore grid plans covering the North and the Baltic Sea area due to the concentration of good potential sites for OWE development (Fig. 2). These plans come from policies at the European and national level along with initiatives from the academia, grid companies and various industries (EWEA, 2009a).

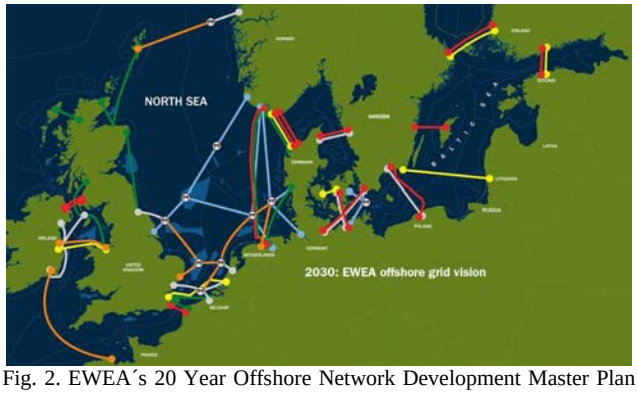

Fig. 2. EWEA´s 20 Year Offshore Network Development Master Plan and Europe OWE development and concession zones (in light blue). Lines in red are cables currently operating; in yellow, planned or under construction; in green and in blue, under study; and in white and in orange, proposed by EWEA for 2020 and 2030, respectively (EWEA, 2009a).

Plans at the European level

The European Commission (EC) coordinates the activities for offshore electricity interconnection within the Trans-European Energy Network (TEN-E) (EC, 2006). Particularly, TEN-E guidelines specify 42 projects of highest priority eligible for EU funding. Along with the Priority Interconnection Plan (EC, 2007), the European Economic Recovery Plan (EERP) (EU, 2008), includes support to TEN-E and RE projects. EC (2009) establishes the budget for EERP implementation in 2009-2010 for gas and electricity infrastructures, and OWE projects. It allocates 2.365 bEUR for the former and 565 mEUR for the latter.

The Second Strategic Energy Review sets the EU Energy Security and Solidarity Action Plan. It considers six priority infrastructures promoting EU's energy needs, four of which are electricity related: a Baltic Interconnection Plan, a Mediterranean Energy Ring, North-South gas and electricity interconnections within Central and South-East Europe, and a Blueprint for a North Sea offshore grid.

Research Programmes and Coordination Initiatives

Intelligent Energy Europe (IEE) from the EC has funded three projects relevant to OWE and offshore grid development in the North and the Baltic Sea. Tradewind developed a EU-wide power flow scenario including various offshore grid configurations; Windspeed is working on a decision support system tool for OWE deployment in central and southern North Sea; and OffshoreGrid will develop a scientifically-based view on an offshore grid in northern Europe along with a suitable regulatory framework.

Besides, EWIS, Power Cluster and ISLES projects are co-financed EU projects. EWIS looks into onshore and offshore grid reinforcements for wind energy integration, Power Cluster focuses on the challenges of the OWE sector in the North Sea; and the latter examines the feasibility of an offshore electricity network linking offshore RE sites in Ireland, Northern Ireland and Western Scotland.

Some coordination initiatives include: ACER (Agency for the Cooperation of Energy Regulators), ENTSO-E (European Network of Transmission System Operators for Electricity), ERI (Electricity Regional Initiative), NICER (North Sea Initiative: Centres for Excellences on Renewables), the North Sea Countries Offshore Grid Initiative and the Energy Grid Initiative.

Offshore Grid Proposals

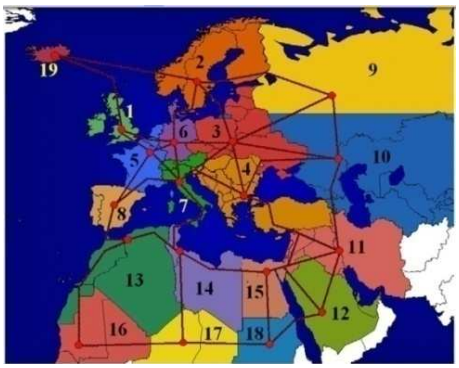

Fig. 3. Power system layout proposed in (Czisch, 2008). It is divided into 19 regions connected with HVDC technology to provide 100% RE.

Similarly, there have been several discussions on possible offshore grid configurations. Already in the 1930s, Buckminster Fuller proposed a Global Energy Grid that would interconnect the world to supply all the energy needs from RE sources. Later proposals include: an Irish Sea grid (Watson, 2002); the Supergrid concept (Corbett, 2009; Veal, Byrne

and Kelly, 2007); Czisch study (Czisch, 2008) (Fig. 3); Greenpeace scenario (Woyte et al, 2008); EWEA´s 20 Year Offshore Network Development Master Plan (EWEA, 2009a) and the SuperSmart Grid concept (Schellekens et al, 2010).

It is remarkable that within the wide range of offshore grid proposals, none of them specifically considers WE electricity generation. They assume offshore RE electricity generation will be covered by OWE and on a later stage WE might become a secondary offshore contributor. Nevertheless, WE potential in Europe is large, the WE sector is close to reach the commercial stage and both the OWE and the WE sectors are facing similar grid connection challenges to become large scale contributors to the electricity mix. Indeed, studies indicate that it could be useful to create spaces combining OWE and WE, share the cost of grid connections and make it possible for more power to be harnessed from one site, thus making the project more economically viable (EOEA, 2010).

WAVE AND OFFSHORE WIND ENERGY WITHIN A COMMON OFFSHORE GRID

The offshore potential in Europe consists both of ocean energy and wind energy. The term ocean energy includes WE, tidal current, tidal range, osmotic energy and ocean thermal energy (Soerensen, 2009). High WE potentials are located along the West coasts of Europe (Fig. 4) and a large offshore wind resource can be found along the North and West coastlines (Fig. 5). Nonetheless, in areas with low WE potential like the North Sea, wave energy converters (WECs) can produce 10-75 TWh/y (Soerensen and Fernandez Chozas, 2010); in comparison to 125-169 TWh expected production in 2020 by offshore wind turbines (OWTs) in the same area. According to these, Europe has ambitious ocean energy (Table1) and OWE (Table 2) development scenarios.

Fig.4. WE in Europe in kW/m width of oncoming wave (CA-OE, 2006)

WECs are chosen according to the wave climate in the sea where are deployed. Since more than one solution can remain attractive for the market, the number of WE conversion concepts is very large. According to their location with respect to shore there are onshore, near-shore and offshore devices. The formers are placed on the coastline or integrated into fixed structures, near-shore devices are usually bottom-mounted at moderate water depths (20-30 m), and the latter are generally floating devices deployed at deep waters. Although there is hardly any WE commercial technology, there are several full-scale prototypes close to the commercial stage. On the other hand, the OWE sector has installed a number of bottom-mounted OWTs in the North and the Baltic Sea, where water depths increase slowly with distance from shore and allows deployment sites relatively far offshore. Nonetheless, there is an ongoing research on floating platforms to allow OWTs deployment at other potential sites with a steeper coastline.

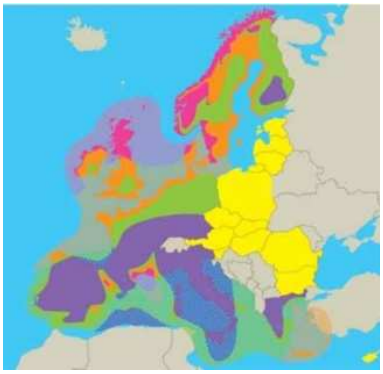

Fig. 5. Wind potentials in the EU, 1989. Pink coloured represents the strongest potential; orange, very high potential, green, high-medium potential; and purple medium/low potential (EC, 2008).

Table 2. Offshore wind energy scenarios

	Installed capacity (GW) 2015[1]	Installed capacity (GW), 2020 low scenario[2]	Installed and planned capacity (North Sea)[3]	
			GW	TWh
Belgium	1.446	1.8	3.85	13.1
Denmark	1.276	2.3	1.58	5.6
Finland	1.33	0.4	-	-
France	1.07	4	1	3.4
Germany	10.298	8	26.42	97.5
Ireland	1.603	1	-	-
Italy	0.827	0.5	-	-
Netherlands	2.834	4.5	12.04	41.7
Norway	1.553	NA	1.29	4.9
Poland	0.533	0.5	-	-
Spain	1.976	1	-	-
Sweden	3.312	3	-	-
UK	8.756	13	22.24	80.8
Total	37.442	40	68.42	247

[1] (EWEA, 2009a), [2] (EWEA, 2009b), [3] (Van Hulle, 2009)

Once OWTs and WECs are fully developed they will both harness offshore power and hence a conflict of use for the deployment area might be foreseen. Nevertheless, the sectors share significant synergies from which they can both beneficiate, and will barely compete.

Firstly, WECs harness the available resource on the sea surface or below it, whereas OWTs harness the resource tens of meters above the sea level. Therefore, near-shore WECs can be deployed in the same site as OWTs, precisely in between them, as in any case there has to be a certain distance between the turbines to avoid shadow effects. Placed together, they can share the grid connection. Moreover, it has to be noticed that cable costing is not linear in function of the number of the cables as the same route and laying procedure might be applied for more than one cable (Ricci et al, 2009).

Secondly, the WE potential decreases close the coastline due to the interaction with the seabed. It is preferred to deploy offshore WECs at deep waters than at the shallow areas where OWTs are being deployed in the short term. In the medium and long term, due to higher energy potentials and large space demands, both OWE and WE farms will be located further offshore; nonetheless, it can actually be assumed there is enough sea for both.

Thirdly, WE and OWE encounter similar challenges on grid connection. A fundamental consideration for both sectors is that the deployment sites are dictated by the best locations for energy resource.

However, the majority of these is far from the main load centres and often has only a weak distribution network available, what can result in costly grid reinforcements and hence project costs may be prohibitive (Ricci et al, 2009). The project can turn economically viable if transmission capacity is shared.

Fourthly, a combination of the power output of both resources results in smoother variations of the generated power, better predictability and higher capacity credit (ECI, 2005), provided that WE peaks generally occurs 6-8 h later than wind energy peaks (Fig. 6) (Soerensen et al, 2005), and that WE has greater predictability and less variability than wind energy (Soerensen and Naef, 2008). Furthermore, this will reduce the spared capacity and the cost of the connection.

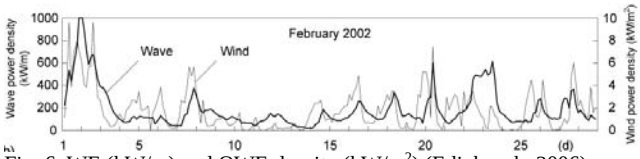

Fig. 6. WE (kW/m) and OWE density (kW/m^2) (Edinburgh, 2006).

According to this, ECI (2006) shows that a RE mix of tidal energy, WE and onshore wind energy (with the two latter accounting for ~45% each) reduces the long term variability of the electricity supply by ~37%, increases the capacity credit of the mix by ~20% and reduces the balancing costs associated with the variability by ~37%.

As a result, considering the synergies between the OWE and the WE sector, and that power transmission is a common challenge, efforts should be made to develop cost-effective offshore networks that are reliable and suitable for integration of farms of WECs and OWTs.

OFFSHORE POWER TRANSMISSION OPTIONS

Eventually, WECs will be connected in arrays (Fig. 7) to form parks using similar farm concepts and technologies as the OWE sector (Ackermann, 2002; Bresesti et al, 2007; Czech et al, 2009). The collection system can follow a string or a star configuration, where different voltage levels regions can be found: low voltage (LV), medium voltage (MV) and high voltage (HV). Above all, the number of collection voltage levels is a trade off between investment costs and power losses (Czech et al, 2009). Thus, it depends on the cables length and the rated power.

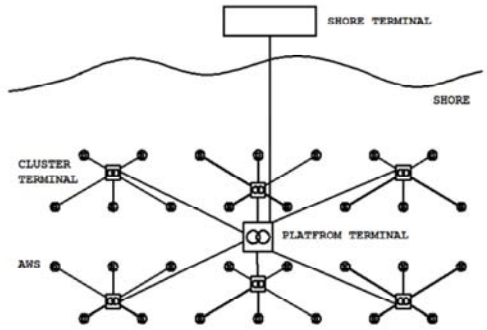

Fig. 7. Example of a star layout in a farm of offshore WECs named Archimedes Wave Swing (Czech et al, 2009).

For large farms (i.e. several MW) located far offshore the following configuration usually applies: in the LV region the converters (i.e. OWTs and WECs) are connected in parallel or in series, and likely to a cluster terminal; in the MV region the cluster terminals are connected to a collection point; and in the HV region the collection point is connected either directly to shore or to another common collection point that collects the power from different clusters. LV and MV levels use alternating current (AC). HV transmission can be either at AC or at direct current (DC). Considering that farms tend to be larger and transmission distances are increasing, HV levels are becoming useful in order to minimise power losses (Ackermann, 2002).

HVAC and HVDC for Offshore Power Transmission

There are advantages and disadvantages in using HVAC and HVDC connections for subsea power transmission. On one hand, HVAC connections are simpler and have lower costs than HVDC in short distances (about 50 km), since the HVAC offshore collection point does not comprise expensive converter valves. On the other hand:

- HVAC has limited transmission distances. The distributed capacitance of AC subsea cables is much higher than in overhead lines. Reactive power increases with voltage and cable length, and therefore transmission in long distances require large reactive power compensation devices at both ends of the cable. Thus, HVDC cable losses are smaller than in HVAC.
- HVDC needs less cabling than equivalent HVAC (Koldby and Hyttinen, 2009).
- DC transmission can asynchronously connect the offshore network and the main grid (Ackermann, 2002; Bresesti et al, 2007). This has three direct consequences: firstly, the connection barely contribute to the short-circuit power if a fault on the main grid occurs and it can decouple both grids to isolate the offshore network from onshore disturbances; secondly, the offshore DC terminal can collect the generated power at various frequencies from multiple generators and convert it to a common grid frequency; and thirdly, it can interconnect asynchronous regions for the exchange of power.

As a result, DC is becoming more interesting for remote offshore RE generation farms. There are two schemes of HVDC, line commutated converter (LCC) based HVDC and voltage source converter (VSC) based HVDC.

HVDC Transmission: LCC-HVDC and VSC-HVDC

HVDC enable large power transmission over long distances via submarine, underground or overhead lines; through two conversion stations connected by a DC link. The type of DC link depends on the application; LCC-HVDC uses monopolar, bipolar, tripolar or back-to-back, whereas VSC-HVDC transmission circuit is by nature bipolar (i.e. a pair of conductors each at a high voltage with respect to ground in opposite polarity). The conversion station is the terminal equipment in which DC current is converted to AC current (inversion) and vice versa (rectification). It includes the converter valves and the connection to the AC grid. The circuit of LCC-HVDC differs from the VSC-HVDC in the converter valves. The former is based on LCCs using thyristors as the switching element and the latter is based on VSCs using insulated gate bipolar transistors (IGBTs).

The advantage of LCC-HVDC technology is its proven track record in large capacity point-to-point transmission links over long distances and in interconnecting strong synchronous and asynchronous power systems (Zervos et al, 2008). Moreover, LCCs have fewer losses than VSCs and offer higher voltage and power ratings (Martínez de Alegría et al, 2009). Nevertheless, for low offshore transmission capacities this scheme has several limitations and undesirable characteristics which,

on the other hand, VSC-HVDC technology (ABB, 2010; Schettler, Huang and Christl, 2000) overcomes (Table 3):

- It can independently control the active and the reactive power over the complete operation range at each end of the line and thus, it can provide power system support capabilities (Sandeberg and Stendius, 2008). Active power control can be used for frequency regulation in the grid, so it can support the AC power systems at the ends of the DC link and be connected to weak AC networks (i.e. an offshore network) (Martínez de Alegría et al, 2009). Reactive power control can be used to regulate the voltage on the onshore side and to supply reactive power to the offshore generators. On the other hand, LCC consumes 50–60% of its active power as reactive power (Bresesti et al, 2007) according to the thyristors firing angle, which must be supplied externally.
- It provides start-up capability (Sandeberg and Stendius, 2008); thus, it can start a dead grid. LCC requires a receiving network of a strength exceeding the power of the HVDC link, thus, an auxiliary start-up system would be needed in the offshore farm (Koldby and Hyttinen, 2009).
- VSCs have very high switching frequencies in comparison to LCCs. Thus, the harmonic distortion of the AC voltage is much lower, fewer filters are required and the converter stations can be smaller and cheaper (Bresesti et al, 2007).
- VSCs do not need communication between stations during normal operation because the control is based on measurements of the DC voltage (Sandeberg and Stendius, 2008).

Table 3. Comparison between HVAC, LCC-HVDC and VSC-HVDC technology (Zervos et al, 2008)

		HVAC	LCC-HVDC	VSC-HVDC
Capacity distance dependent?		Yes	No	No
Power losses		Distance dependent	Total: 2-4% Converter:1-2%[1]	Total: 5-10% Converter:4-5%[1]
Start-up capability		(Yes)	No	Yes
Network support capability		Limited	Limited	Large range of possibilities
Substantion dimensions		Small	Capacity dependent. Twice that of VSCs [2]	Capacity dependent [3]. Larger than HVAC substation
Cost	Converter station[4]			0.11 mEUR/MW
	Cable[4]		132 kV, 3-core XLPE : 1.5 mEUR/km	At 150 kV, 350 MW: 0.445 mEUR/km - pair
	Installation of 1 cable[4]	0.1 mEUR/km	0.1 mEUR/km	0.1 mEUR/km

[1] (Martínez de Alegría, 2009); [2] (EWEA, 2009a); [3] A 600 MW, 400 kV VSC-HVDC converter station requires ca. 300x300 m^2; [4] (Lazaridis, 2005).

The major advantage of VSC-HVDC over LCC-HVDC is its operation principle (ABB, 2010). It uses pulse width modulation (PWM) techniques to synthesise a sinusoidal voltage on the AC side (Sandeberg and Stendius, 2008). This fundamental frequency voltage (Ug) across the converter series impedance defines the power flow between the AC and the DC sides. By changing the phase angle between Ug and the voltage on the AC bus, it controls the active power flow between the converter and the network. The reactive power flow is determined by Ug amplitude, which is controlled by the width of the pulses from the converter bridge. PWM switching frequencies are in the range of 1-2 kHz, in comparison to LCC switching frequencies of 50-60 Hz (Martínez de Alegría et al, 2009). Thus, PWM technologies can control both the magnitude and phase of the voltage within certain limits, allowing independent and fast control of active and reactive power flows.

HVAC or VSC-HVDC for Offshore Power Transmission

Provided that VSC-HVDC technology offers better characteristics than LCC-HVDC, which are the determining factors to choose between VSC-HVDC and HVAC technology for offshore power transmission? These are mainly the cable length and the power capacity.

HVAC has lower cost with short cable lengths, but AC power losses are distance dependent and as the distance increases high charging currents appear (Fig. 8) using up much of the transmission capacity. In such cases, VSC-HVDC becomes a preferable and necessary option, even though VSC-HVDC conversion stations are more expensive than the transformer substations because of the transistors and filters (Ackermann, 2002), and have constant high power losses (i.e. dependent on the switching frequencies) (Bresesti et al, 2007). As a result, VSC-HVDC becomes more economically attractive than HVAC for large transmission distances (Ackermann, 2002; Bresesti et al, 2007; Sandenberg et al, 2008; Woyte et al, 2008).

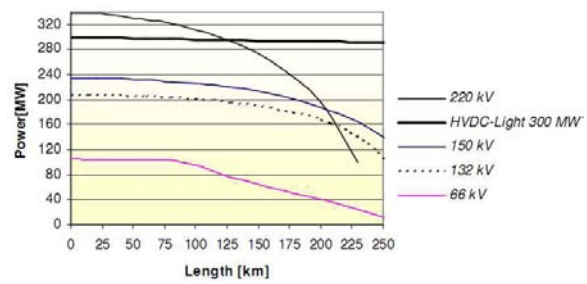

Fig. 8. Maximum lengths for HVAC with tuned inductive shunt compensation in both ends (Johannesson et al, 2009).

Besides, VSC-HVDC technology offers a wide range of applications and provides good control capabilities for an offshore interconnected grid. Trötscher and Korpås (2009) find that transmission lines built to form a meshed offshore grid not only optimise the capacity factor of OWTs from 45% to 70%, but also provide a higher utilisation of the grid infrastructure and facilitate the power exchange between power systems. In such a grid, VSC-HVDC would become more economical. What is more, Trötscher and Korpås (2009), and Trötscher, Korpås and Tande (2009), point out that a meshed power grid will seldom be built in one step but in several steps as demand for capacity materialises; thus, it requires flexible technology that allows to gradually build up meshed structures.

Nevertheless, there are several technical challenges related to VSC-HVDC technology:

- Multi-terminal VSC-HVDC systems are still new for the power system industry.
- VSC-HVDC has presently limited capacity. According to (Zervos et al, 2008) the upper limit for the converters is approximately 400-500 MW and for the cables 600 MW at ±150 kV; according to (ABB, 2010) the technology now reaches 1200 MW at ±320 kV.
- DC circuit breakers are in the development stage. Among others challenges, DC demands faster breaking times in comparison to AC, since the zero crossing makes it easier to break AC than DC (Koldby and Hyttinen, 2009).
- There is lack of standards on VSC-HVDC technology and connections (i.e. type of HVDC converter and DC voltage levels). Since the converter size is voltage dependent, comprises a significant cost and converters are currently being built, standardization is lagging

and already selected choices might become standards. However, there is lack of experience to base the standards on. IEC Technical Committee TC 115 and Cigré study committee B4 are carrying activities with HVDC, which can likely develop into standards (Koldby and Hyttinen, 2009).
- The technology for installation of submarine cables can reach about 1000 m, which does not hinder an offshore grid development in the North Sea but in e.g. the Mediterranean Sea (Martínez de Alegría et al, 2009).

Apart from this, there are other possible power transmission solutions but their development is less advanced than the presented technologies:

- Hydrogen generation. This alternative has two major drawbacks, the low efficiency of the conversion processes and that a market for hydrogen does not exist (Martínez de Alegría et al, 2009).
- Gas insulated transmission lines working with a low pressure mixture of air and SF6. Their application is in bulk power transmission at moderate distances. They offer high rating capacities and no power losses, but they need extreme temperatures.
- AC transmission system with low network frequency (Zervos et al, 2009).
- Four or six-phase bipolar HVAC systems (Zervos et al, 2009).

Current Application of VSC-HVDC Technology

One of the existing VSC-HVDC links is BorWin 1 project. It corresponds to the first VSC-HVDC offshore connector and collection system (Johannesson et al, 2009). It names the connection from the OWE farm Bard Offshore 1 to the offshore collection point Borkum2 and the 400 MW, 230 km transmission link from Borkum2 to the mainland. Bard Offshore 1 is located 128 km offshore the German coastline in the North Sea at 40 m water depths. The farm has a capacity of 400 MW, comprising 80 turbines rated at 5 MW each. Each turbine delivers its AC power to an offshore substation (i.e. 36/170 kV). Then, a 170 kV, 1 km submarine AC cable delivers the power to Borkum2 offshore converter station, from where the power runs through a bipolar VSC-HVDC circuit to shore. This comprises two ± 150 kV, 128 km long submarine cables that run to a transition point onshore where they are connected to other 75 km long underground cables that transmit the power to the converter station onshore. The project cost is estimated to 400 mUSD (ABB, 2008).

Likewise, VSC-HVDC technology can be used for power transmission to offshore oil and gas platforms. Troll A transmits the power to an offshore North Sea platform via two bipolar 67 km long submarine cables, rated at 41 MW, ±60 kV each, that drive two 40 MW very high voltage motors. Similarly, a 292 km long submarine cable rated at 78 MW, ±150 kV, will power by 2010 the Valhall oil field in the North Sea from the Norwegian shore, replacing the current gas turbines.

The next section reviews a European attempt to integrate offshore RE generation and power exchange in the same project, named Kriegers Flak. It provides a good overview of the challenges ahead of and of the benefits of a joint project.

CHALLENGES AHEAD OF A COMMON OFFSHORE GRID

Kriegers Flak (KF)

Kriegers Flak (Berge, 2009; Christiansen, 2009) is an area in the Baltic Sea where the Exclusive Economic Zones from Sweden, Germany and Denmark met their borders. The area comprises a region with good wind energy potential, 15-40 m water depths and power transmission needs, which has resulted into plans of installing 1600 MW of OWE: 400 MW for Germany and 600 MW for Denmark and Sweden. Four possibilities have been considered to connect the OWE farms to shore: i) radial connections, ii) back-to-back connection using HVAC, iii) multi-terminal connection using VSC-HVDC, without KF 1 farm, and iv) multi-terminal connection using VSC-HVDC also connecting KF 1 with HVAC (Fig. 9). The three last options allow an exchange capacity of 400 MW, 600 MW and 1000 MW, respectively. The ultimate goal of KF project is to replace the single national solution by a common international one, hence allowing power systems interconnection.

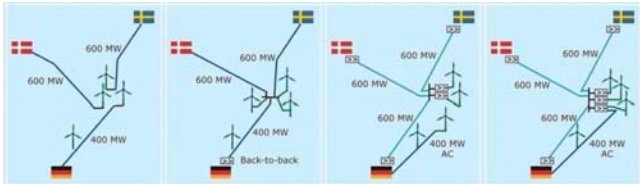

Fig. 9. Kriegers Flak connection possibilities (Christiansen, 2009)

The results from a pre-feasibility study (Kriegers Flak Pre-Feasibility Report, 2009) indicate a positive benefit for a combined solution compared to separate grid connections, but big challenges are ahead. These can be classified as technical, legal and economic challenges. Technical issues include the interconnection of two asynchronous power systems (i.e. North Europe and Central Europe) and the upgrade of the onshore grid to accept the planned power capacity. Legal issues comprises the differences among countries in the support schemes for wind power, in the regulatory frameworks and in the grid codes, grid access and grid connection rules, among others; besides a common power market does not exist. An additional challenge is the high cost of the project, mostly due to the interconnector investment. On top of these, the coordination is resulting complex[1] and there are still uncertainties on how much installed OWE capacity will be and when.

On the other hand, the main drivers of KF are the socio-economic benefits (i.e. increase security of energy supply, electricity generation based on RE sources, access to cheapest energy, job creation) and technology development. Furthermore, the learning experience of this project is considered crucial for further integration of interconnectors within offshore RE generation projects. Therefore, the EU is supporting KF by involving an external coordination group, i.e. Adamowitsch group, which coordinates Baltic and North Sea OWE transmission infrastructures and possible grid topologies; and with 150 mEUR, aimed to ensure a joint interconnection solution (EC, 2009).

Legislation, Timing and Economics of an Offshore Grid

Kriegers Flak provides a good overview of the obstacles that emerge on a project that involves more than one power market and legal system. Since it can be regarded as a small-scale variant of an interconnected offshore grid, the same challenges addressed above along with additional legislative, timing and economic issues, will eventually arise for a large scale development.

Firstly, regarding legislation, an optimal offshore grid requires a clearly defined legal framework in all the stages of the project (e.g. grid planning, grid construction and grid O&M) (Huertas-Olivares et al,

[1] The transmission system operator (TSO) in Sweden has recently decided to abandon the project due to the low feasibility of the wind farm project at Swedish ground compared to other wind farm sites in Northern Europe.

2008). At this stage it is essential to define and coordinate maritime spatial planning for offshore RE sites and grid infrastructures at national and international levels, aimed to create a central plan with milestones and binding targets. This will assure certainty for investment and lead to a stepwise development of the grid. Moreover, national policies should look beyond their national energy demands to improve Europe´s security of supply.

Secondly, the timing of the project is among others related to the supply chain. Overall estimations calculate that1000-2000 km of cable should be laid each year, which demands specially built vessels and submarine trenching robots. Currently, there is a limited number of those available (Martínez de Alegría, 2009) and it can be anticipated that there will be strong competence also from the OWE and WE sectors.

Furthermore, previous experiences show that timing and legislation are strongly related. In particular, the major reason for delay of electricity transmission projects is the complexity of application and authorisation procedures (EC, 2007). For instance, while the installation time of NorNed LCC-HVDC submarine link was 2 years, it took about 14 years from planning to project completion. Moreover, since a common offshore grid requires the integration of several power networks, a substantial number of entities might be responsible for permissions granting, hence resulting in time-consuming legal and licensing procedures.

In order to prevent these constraints i) authorization procedures must get simplified through the introduction of a single integrity consent regime (i.e. one-stop-shop) at national and international levels (DEA, 2006); and ii) a central government body not influenced by national policies has to be set.

In addition, several questions have been raised about the economic feasibility of an interconnected offshore project provided that the initial investment for radial connections is lower than for meshed connections (Trötscher and Korpås, 2009). Nevertheless, Trötscher and Korpås (2009) and Trötscher, Korpås and Tande (2009) prove that the total cost of an optimal grid (i.e. the cost over the entire lifetime of connecting OWE farms, oil and gas rigs and onshore power systems using meshed configurations), is hundreds million Euros lower than a radial one.

Furthermore, because a project of this nature brings several non-quantifiable contributions to e.g. the economic activity, securing long term supplies, access to RE sources and certainty about future energy prices and energy sources availability (La Regina et al, 2006); the project cost cannot be the solely decision parameter. Likewise, the externalities associated to the energy conversion processes and the energy resources (Soerensen and Naef, 2008), clearly decide in favour of large offshore RE utilisation and against conventional energy sources (i.e. imported resources in 2006 cost 350 bEUR to the EU). Last but not least, the IEA (2008) predicts an expenditure of 135 bEUR over 2007-2030 to cover electricity consumption growth, replacement of aging infrastructures and strengthen the integration of national markets, under a 'business-as-usual' scenario, in which coal and gas continue to dominate the electricity supply.

CONCLUSIONS

This paper presents an overview of a European interconnected offshore grid to harness high WE and OWE available resources.

It is highly recommended a joint collaboration between the OWE and the WE sectors to develop a meshed offshore grid. Both share common synergies in relation to governmental marine policies, marine stakeholders, spatial constraints and weak available grid connection points. Particularly, their cooperation brings two main advantages: firstly, share transmission cable costs, and secondly, smooth power output in time while reducing the spare capacity of the transmission lines.

Besides, a meshed offshore grid becomes cost-effective if planned i) to transmit the power generated offshore to the coast, ii) to exchange power between power systems, and iii) to transmit the power to offshore oil and gas platforms. Hence, cost-effective networks demand an overall optimized grid design that avoids suboptimal solutions based on individual and national projects. To achieve this, it is also recommended the cooperation among countries, harmonization of legal rules, simplification of authorization procedures (i.e. one-stop-shop method) and international spatial maritime planning.

VSC-HVDC is the most suitable technology to connect offshore RE generation and thus to create a meshed offshore grid. On one hand, it can collect the power from multiple non-synchronized generators, it can be connected to a weak AC network and it provides start-up and power system support capabilities. On the other hand, it can interconnect asynchronous systems (i.e. UK, Ireland, Northern Europe and Continental Europe are not united into a single synchronous network) through long submarine and underground cables and exchange power in two directions.

Even though there are still relevant technical, legal and economic challenges ahead of an offshore interconnected grid, to agree that organizations in different countries are planning to have such network is not a minor step (Koldby and Hyttinen, 2009). Last but not least, as other authors have stated a concept on this scale has already been realized for the gas industry, even including pipelines crossing continents.

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