Survey of Offshore Wind Farm Project in EU and Their Connecting Grid Systems

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Table of Contents

Table of Figures

Abstract

Today the world is facing significant growth in energy demand. An increase of 50% in global energy demand is expected by 2030. The increase in energy prices (the price per barrel of oil hovers around $ 110), the depletion of fossil energy (more than 60 oil producing countries have already passed their peak production) also affect energy demand. In addition, strong regulations on emissions of greenhouse gases are being introduced, forcing states to change their energy policies and to switch to alternative energy.

The European Union (EU) has adopted the objectives of *3x20* Plan, which force its Member States to develop renewable energy sources (RES) and to give the objectives a more important place in their overall energy policies[1]. However, the potential production sites of production of electricity from renewable sources are often located far from consumption centers. Indeed, the EU has many energy resources (wind, solar, hydro) that are not-uniformly distributed among the Member States. The best areas for the production of electricity from renewable sources are often located in places where the electrical network density is low. Moreover, to achieve 20% energy from renewable sources in total energy consumption of each country, the *climate-energy* objective of the 3x20 plan allows member countries to rely, in part, on electricity produced outside the European borders.

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[1] *European Union 3x20 Objectives*, www.3x20.org

1. The Current State of Renewable Energy in EU

1.1 Distribution of the Wind Farms in EU

Europe is based on an *electric economy*. Indeed, electricity is becoming the dominant energy that will lead us toward a low carbon future. By 2050, most of our vehicles could function thanks to electricity, with the exception of some heavy commercial vehicles.

Europe is engaged in a transition to sustainability. Member States of the EU have committed to reduce their Kyoto Greenhouse Gas emissions by at least 20% below 1990 levels by 2020. To reach this point, Europe started to establish wind farms in offshore areas highly windy.

As we can see on the following chart, this implementation of wind farms was launched 2001 and it exploded beginning in 2007.

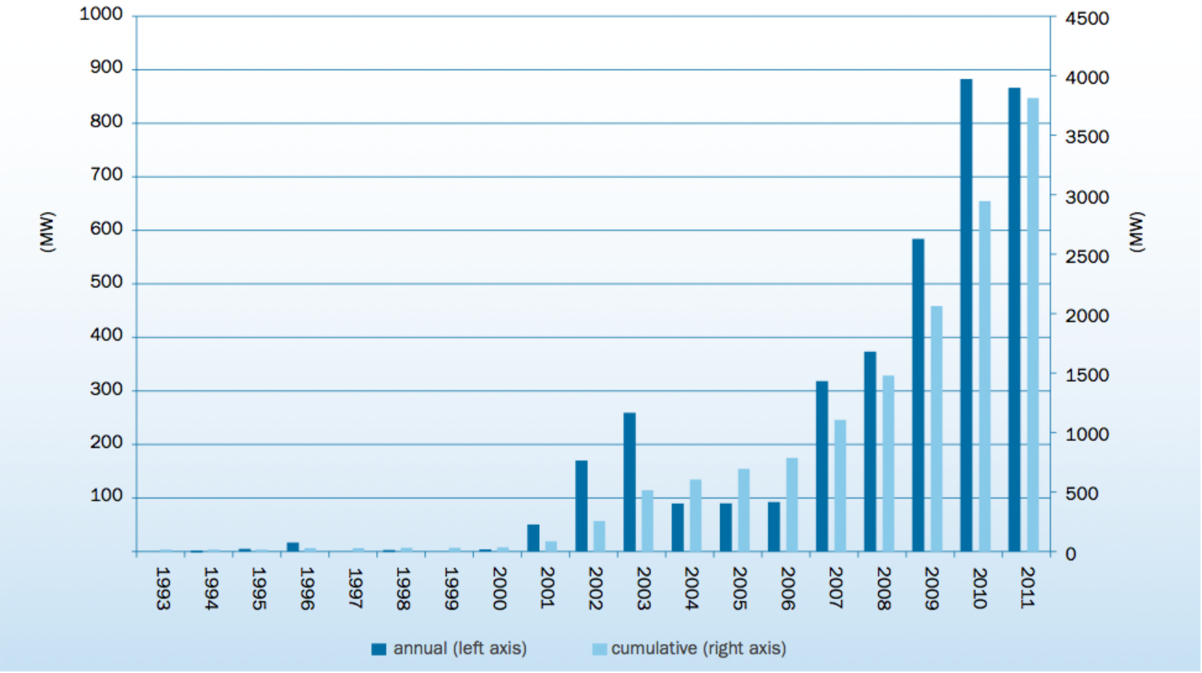

Fig 1: Cumulative and Annual Offshore Wind Installations (MW)

Source: European Wind Energy Association

A total of 1,371 offshore turbines are have been installed and connect to electricity grids in European waters totaling 3,812.6 megawatts (MW) spread across 53 wind farms in 10 countries. The offshore wind capacity installed by the end of 2011 will produce, in a normal wind year, 14 tera-watt hours (TWh) of electricity, enough to cover 0.4% of the EU’s total consumption.[2]

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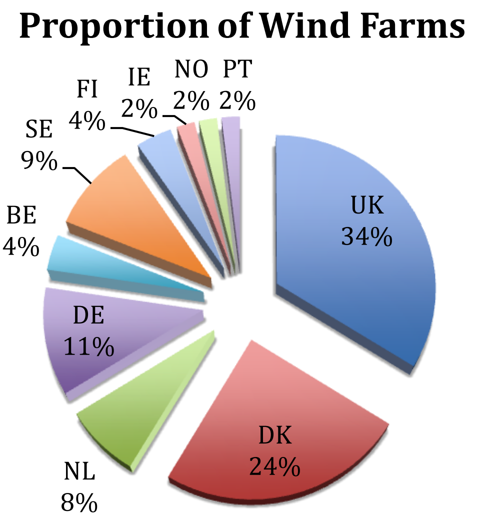
[2] According to the European Wind and Energy Association (EWEA) study

In 2010, Thanet, a 300 MW project in the United Kingdom (UK), was the largest offshore wind farm completed and fully grid connected in the world. In 2011, over 380 MW were installed at Greater Gabbard, also in the UK. Once completed, Greater Gabbard’s total capacity will be 504 MW. However, construction has also started on the first phase of the London Array project. Once completed, it will be 630 MW per year.

The UK is by far the largest market with 2,094 MW installed, representing over half of all installed offshore wind capacity in Europe. Denmark follows with 857 MW (23%), then the Netherlands (247 MW, 6%), Germany (200 MW, 5%), Belgium (195, 5%), Sweden (164, 4%), Finland (26 MW in near-shore projects) and Ireland 25 MW. Norway and Portugal both have full-scale floating turbines (2.3 MW and 2 MW respectively).

Country	UK	DK	NL	DE	BE	SE	FI	IE	NO	PT	Total
No. of Farm	18	13	4	6	2	5	2	1	1	1	**53**
No. of Turbines	636	401	128	52	61	75	9	7	1	1	**1,371**
Capacity installed (MW)	2093,7	857,3	246,8	200,3	195	163,7	26,3	25,2	2,3	2	**3812,6**

Fig 2: Distribution of the Offshore Wind in EU – end of 2011.
Source: EWEA



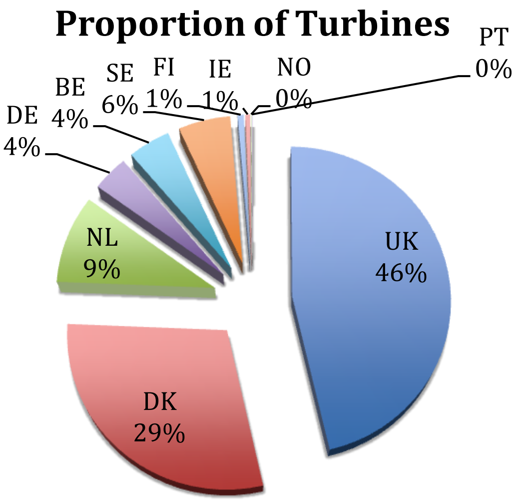


Fig 3: 2011 Distribution of Wind farms by Country
Source: Author

Fig 4: 2011 Distribution of Turbines by Country

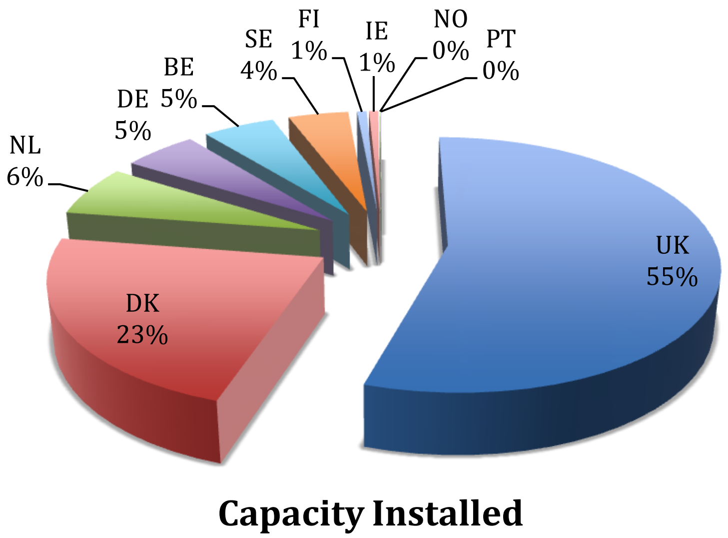


Fig 5: Distribution of Capacity Installed by Country – end 2011
Source: Author

1.2 Electric Power Consumption vs. Renewable Energy Production

An energy mix that varies according to the country provides electricity generation in EU. We can distinguish the low-carbon generation sources (hydro, renewable, nuclear) from the high-carbon generation sources (coal, oil or natural gas). The following chart shows the share of each source in power generation.

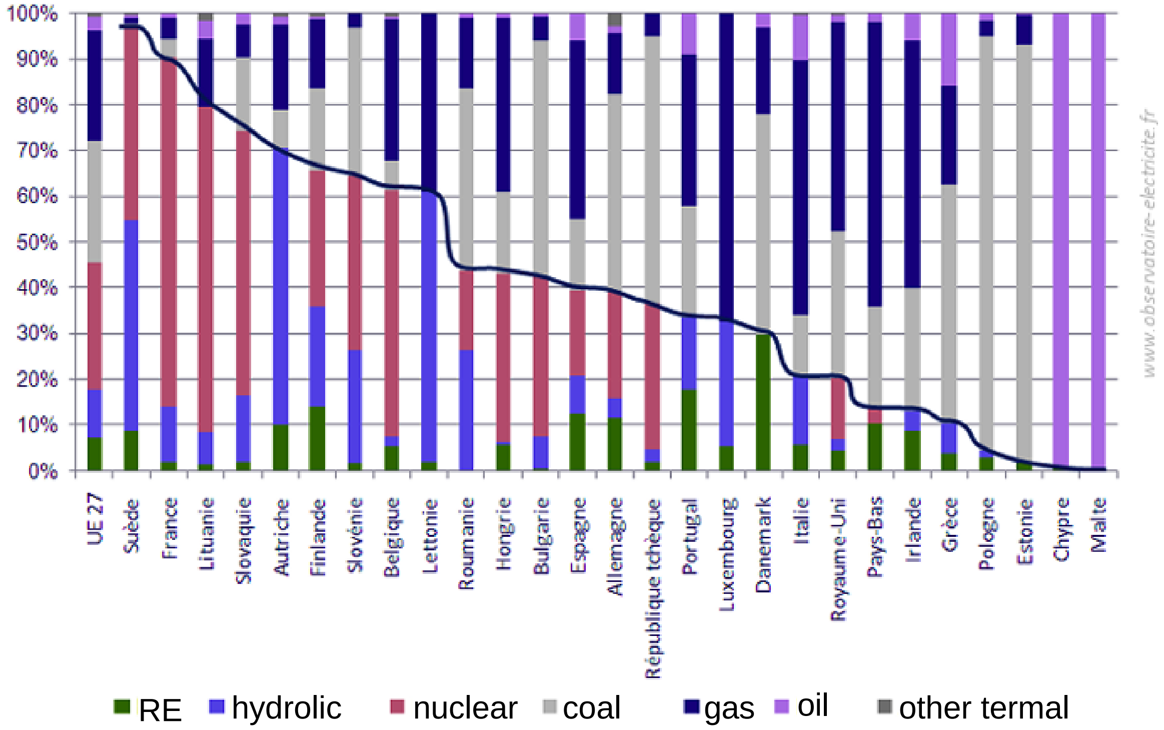


Fig 6: Energy Mix of Electricity Production in Europe – 2008

Source: Eurostat 2008

As shown in this graph, countries like Denmark and Portugal, possess the largest share of renewable energies in electricity production, nevertheless they have a low proportion of low-carbon generation sources. This shows the importance of harmonizing energy production among countries of Europe.

Now, we can look at the share of renewables energies in gross final consumption of electricity. According to figures collected by the statistical agency Eurostat, here is the histogram showing this distribution.

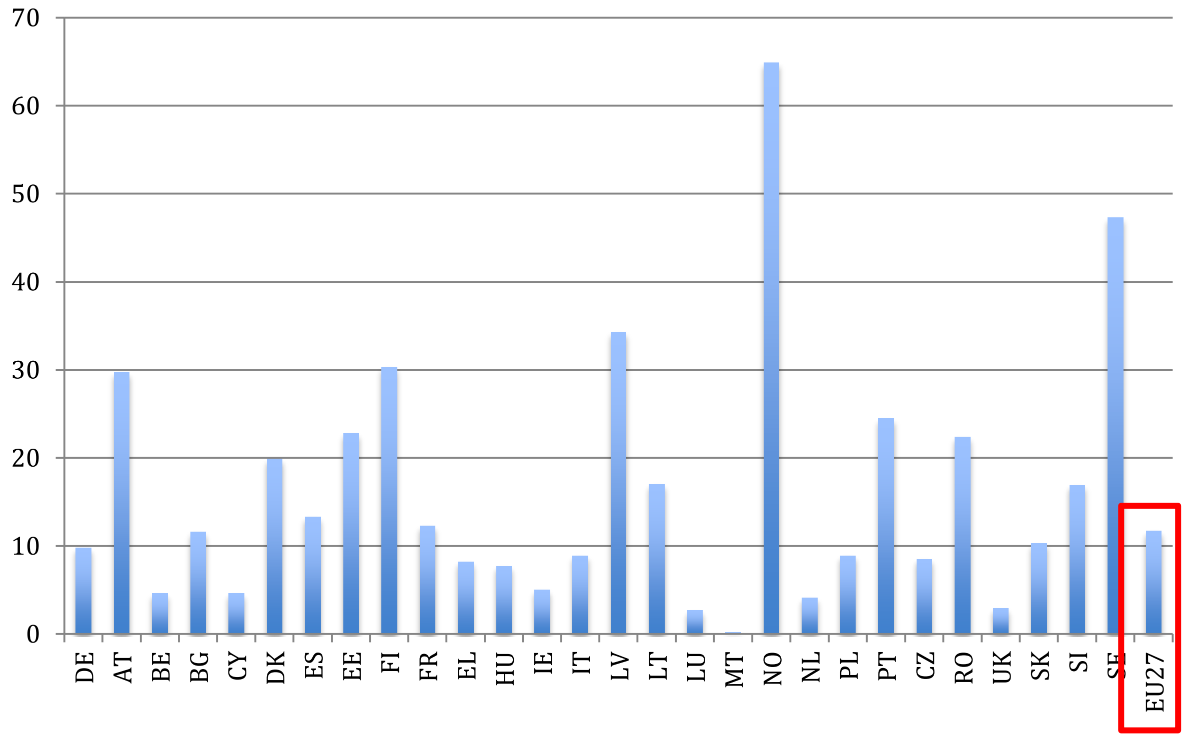


Fig 7: Share of Renewables Energies in Gross Final Consumption of Electricity – 2009
Source: Author

In the EU, renewable energy accounted for 11.7% of all energy consumption in 2009. The goal is to reach 20% by 2020.

The EU 3x20 plan of 2009 set a target of 20% renewables in total energy consumption by 2020. Between 2006 and 2009, this share grew from 9% to 11.7% of gross total consumption of energy. The European Union must maintain this rate of growth to reach the 2020 target.

2. The Supergrid Project

2.1 Project Background

2.1.1 The Concept

The concept of supergrid was initiated 10 years ago and it is defined by the Friends of the Supergrid (FOSG) as "a pan-European transmission network facilitating the integration of large-scale renewable energy and the balancing and transportation of electricity, with the aim of improving the European market"[3].

The Supergrid is not just an extension of the existing or planned point-to-point network among EU countries. Even the combination of these schemes will not provide the network with what is needed to route the marine renewable energy generated in the northern seas to load centers in central Europe. The supergrid is a totally different concept. Unlike point-to-point energy transmission, the supergrid involves the creation of *supernodes* to collect, integrate and deliver renewable energy to the best markets available. The supergrid is a trading tool that will improve the safety of the electrical supply for all EU countries.

There may be many forms of the supergrid. The offshore supergrid is based on the seas around north western Europe. There will be others, such as super-solar in the Mediterranean region. These schemes are ultimately connected to provide power throughout the EU.

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[3] *Friends of Supergrid* report, www.friendsofthesupergrid.eu

Fig 8: Schematic Representation of the Supergrid Project.
Source: FOSG

2.1.2 Policy Context

Europe must meet the environmental objectives accepted at the Kyoto agreement, that’s why the EU needs an energy policy oriented in an economical manner. The first task is to agree on economic policy that will transform the environmental objectives in a workable energy policy.

Then it will be necessary to develop an energy policy that limits, and preferably eliminates, the risks to the security of supply. It is important to note that two of the three founding treaties of the EU – the European Coal and Steel Community and (European Atomic energy Community (Euratom) dealt with energy. Jean Monnet, one of the founding fathers of the European Union, was himself concerned about the geopolitical consequences of unacceptable dependency of Europe on imported energy. It is even more important to note that Europe's dependence on imported energy has increased from 47.8% in 2002 to 56.2% in 2008 and is expected to reach 70% by 2020.[4]

At that moment, Europe is going to experience an "energy crisis". On the one hand, oil production has reached its peak. Even the most optimistic forecasts of the International Energy Agency agreed on this point. On the other hand, the Chinese and Indian demand for oil and gas will have increased six to eight times their current levels.

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[4] European Environment Agency, Net Energy Import Dependency, 2011

In this case it is inevitable that, with the depletion of stocks and intense global competition for resources between the United States, China and India, the EU will be marginalized unless the Member States act together in the global energy market. The costs of uncoordinated approach among European states, in these circumstances will be really harmful, both in economic and societal terms.

There are reasons to believe that Member States will establish a common policy on primary energy sources. The scale of ambition would not be greater than one to create a common currency with a common monetary policy and a supranational central bank.

It is inevitable that an internal market should complement a common external energy policy in electricity and by common standards in energy efficiency, as well as common measures to develop bio-fuels so as to bring transport into connection with power generation and building standards.

The European Union will either have a holistic energy policy a quarter of a century from now or it will slide into inevitable and irreversible decline. The history of the Union gives hope that the path chosen will be that of common action based on the pooling of sovereignty in accordance with the EU treaties.

It is with that expectation that the concept of a European Offshore Supergrid is offered for consideration by policy-makers throughout the EU.

2.2 Development Scenarios

The association Friends of the Supergrids offers a possible structure for the development of a Super grid in the northern seas in three stages. It is conceivable that the development scenarios of Super grids in the world could be modelled on this pattern.

First step: 2020

Fig 9: Supergrid Phase 1
Source: FOSG

The first step would be to build supernodes in the North Sea to collect the wind power generation. More generally, it would build concentration points for the energy generated by the production facilities to maximize their connection. The network would then distribute the electricity to existing networks via terminals on the mainland.

This proposal recognizes that:

- By 2020, the UK wants to add 25 gigawatts (GW) of offshore wind generation to its existing network.
- Germany plans to build 25 GW of offshore wind generation by 2025/2030 and using the existing grids in northern Germany.
- Norway wants to trade up to 25 GW of hydro generation in markets where prices are higher.
- Belgium’s Renewable Energy Plan includes at least 2 GW of offshore wind generation.
- The Netherlands’s Renewable Energy Plan includes at least 2 GW of offshore wind generation by 2020.

The design is based on connecting 23,000 MW of offshore wind energy from the Firth-of-Forth, Dogger-Hornsea, Norfolk Bank, German and Belgian Offshore clusters using technology expected to be available between 2015 and 2020[5].

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[5] According to the *Friends of the Supergrid Report*

Second Step: 2030

The second step would be to connect these nodes, via high voltage direct current (HVDC) cable, to terminals, which, in turn, are connected various existing national networks. This structure would seek to optimize the use of offshore networks with cross-border trade.

Fig 10: Supergrid Phase 2
Source: FOSG

Third Step: 2050

The electricity could then be used locally or transported to consumption centers further afield, through transport networks with high voltage direct current (DC), which have the capacity to transmit electricity over long distances with minimal losses. The third step would, therefore, consist of building high voltage direct current (HVDC) networks from terminals to centers of consumption further afield.

Fig 11: Supergrid Phase 3
Source: FOSG

Whether in Europe or the rest of the world, the development of supergrids will require strong institutional support to be implemented.

2.3 Today's Situation

The North Seas Countries Offshore Grid Initiative (NSCOGI) constitutes the first stage of the European supergrid project. This is collaboration between the Member States of the European Union and Norway to create an integrated offshore grid for conveying the energy produced by wind farms and other renewable sources of electricity across the Northern seas of Europe (North Sea, Baltic Sea, English Channel, Celtic Sea and Irish Sea) and thus exploits the great offshore potential. The declaration of intent from participating countries in the initiative (Germany, UK, France, Denmark, Sweden, Netherlands, Belgium, Ireland and Luxembourg) was signed on December 7, 2009 at the European Union Council on Energy. The initiative was subsequently joined by Norway in February 2010. The European Commission, Agency for Cooperation of Energy Regulators (ACER), European Network for Transmission System Operators – Electricity (ENTSO-E) and the relevant Member State regulators participate in the work, including the design, regulation and procedures for authorization of a marine system.

The European power grid is, with the exception of a few submarine HVDC cables, completely based on alternating current technologies. The European power system is split into five synchronous grids: the Nordic, British, Baltic, Irish and Fifth grids.

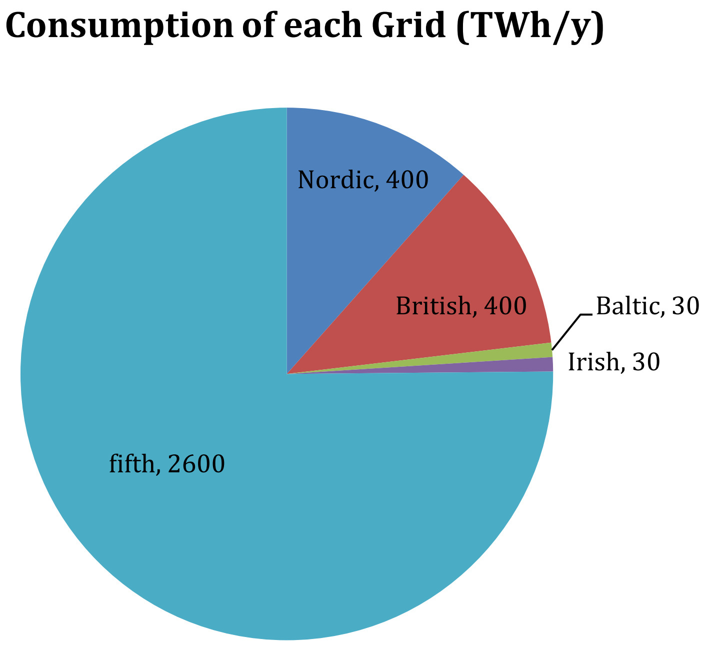

Fig 12: Consumption Share of Each Grid (TWh/y)
Source: Author

All these blocks are interconnected with HVDC back-to-back facilities or HVDC subsea cables. Currently, there are no significant HVDC connections to land in Europe, except some limited back-to-back connections to asynchronous areas, mainly to the Russian grid.

3. The Submarine Power Cables

Creation of a supergrid requires the establishment of an electric cables network over very long distances. The supergrids will allow, without significant loss of energy, the transport of electricity from one end to another of Europe. Currently, the DC technology stands out as being best suited to transport off-shore and on-shore electricity over long distances in excess of 500 kilometres (km.)

In this section we will explain how these cables work and how to install them.

3.1 How Does It Work?

3.1.1 Cables

Today we have two basic types of cable:

- High Voltage, Alternating Current (HVAC)
- High Voltage, Direct Current (HVDC)

These two types of cables have different properties; therefore, we use them in different conditions. The following table (Fig 13) summarized those properties.

Properties	HVAC	HVDC
Transmission distance	< 80 km	> 80 km
N° of conductors	3 conductors	1 primary conductor + 1 way back conductor
Current	Alternative	Direct
Power losses due to skin effect	+++	None

Fig 13: Comparative Table of HVAC and HVDC Cables

Alternating current (AC) is the main driving force in the industries and residential areas; but, for the long transmission line (more than 400 miles) AC transmission is more expensive than that of direct current (DC). Technically, AC transmission line control is more complicated because of the frequency. Because DC transmission does not have these limitations, transmission line construction has focused on HVDC lines over the last 40 years. HVDC technology makes possible the transferring bulk power over long distances.

Figure 14 shows the respective applications of AC and DC cables:

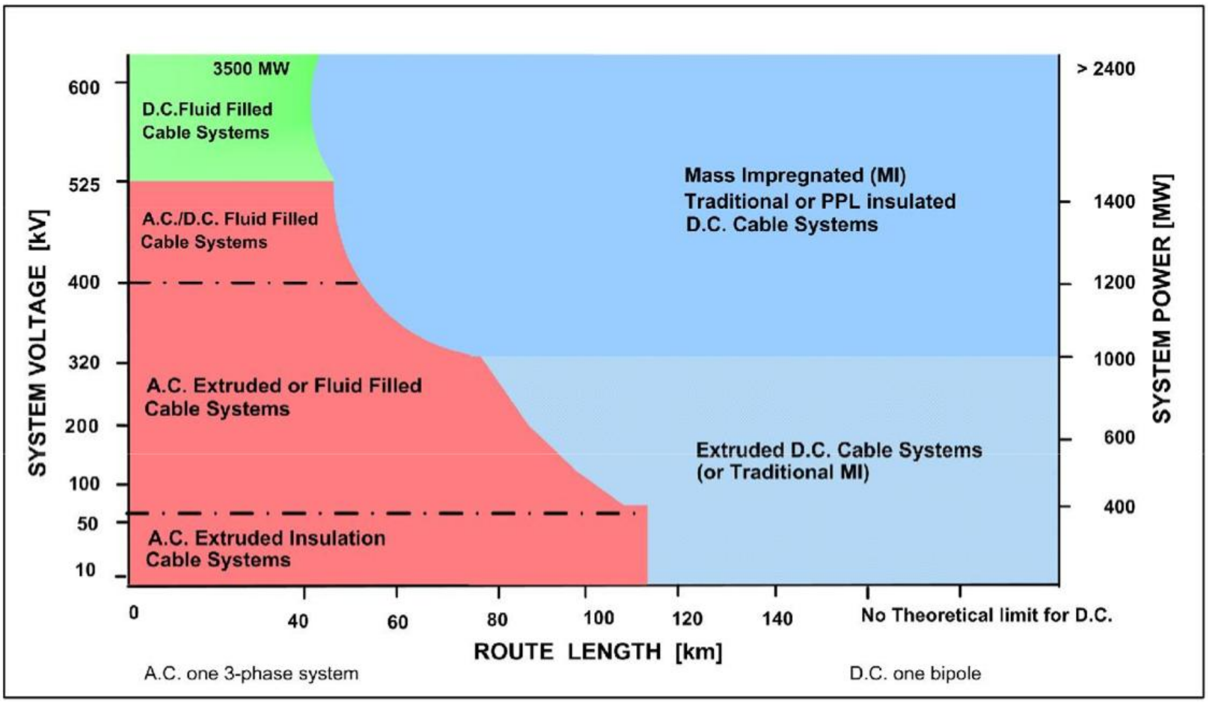

Fig 14: Typical Application of AC and DC Submarine Cables

Source: FOSG

AC transmission is they backbone of power transmission in Europe. This kind of transmission is easy to handle (e.g. transforming voltage, generating in rotating machines, driving motors, switching load currents or breaking fault currents).

But the important limitations of AC arise from:

- The reactive power component causing unwanted effects, such as voltage fluctuations, extra loading of system power components, and extra transmission losses.
- The need to keep the frequency exactly the same and close to its nominal high voltage (HV) bus value throughout an integrated system under all conditions (stability).

The key role of HVDC will be to provide higher transmission capacity over long distances than AC.

- Up to 7200 MW at ±800 kilovolts (kV) DC Line Commutated Converters (LCC)
- Up to 1000 MW at ±320 kV DC Voltage Sourced Converters (VSC)

Also, multi-terminal HVDC systems (Fig 15) can connect distant load and generation via one common DC circuit (e.g. “collection” of power from various power plants into one transmission line). This multi-terminal involves a minimum number of AC/DC conversions, which reduce the losses and the space requirement.

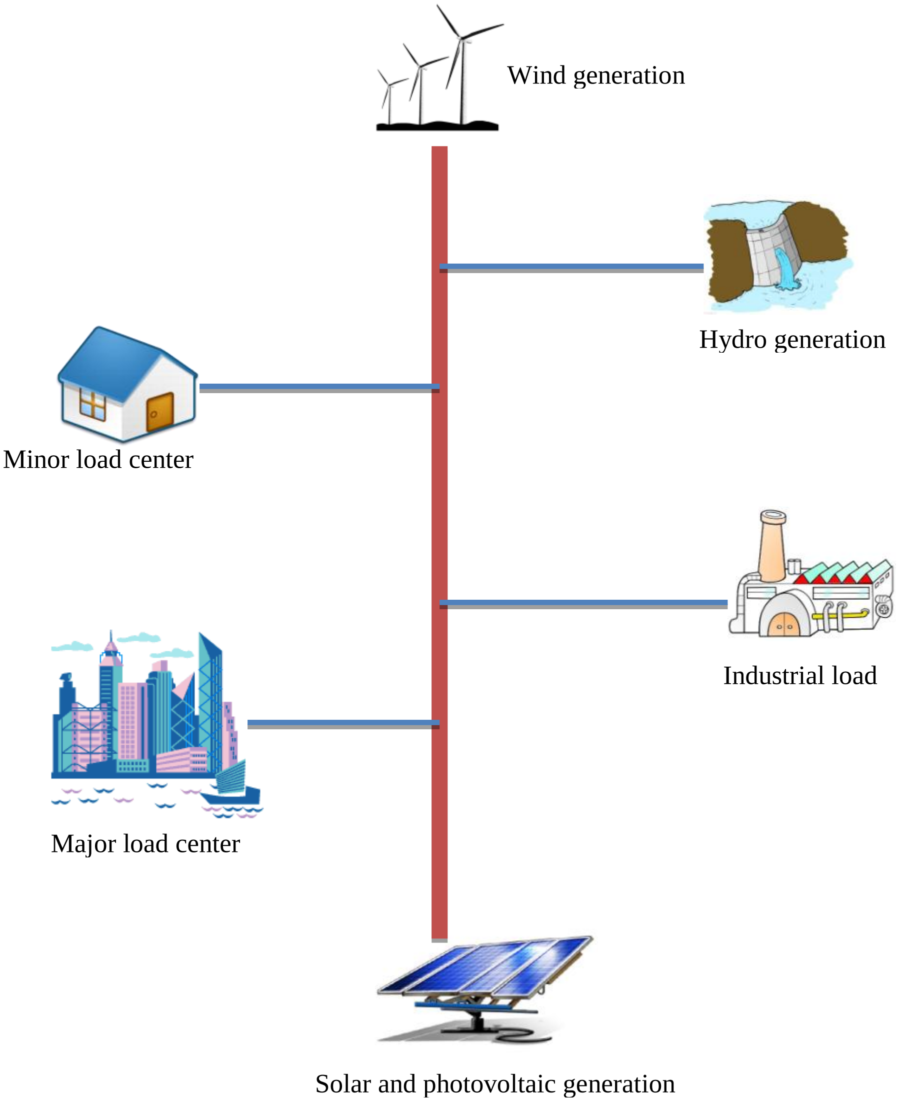

Fig 15: Multi-Terminal HVDC Systems
Source: Author

3.1.1.1 HVAC cables

Figure 16 shows a typical modern AC submarine power cable. Construction varies with manufacturer and seabed conditions; for example, more armor will be added to lines to be installed in areas with strong waves and currents.

1. Conductor – usually copper
2. Conductor screening – usually extruded
3. Insulation – XLPE or EPR
4. Insulation screening – semi conductive
5. Screen
6. Laminated sheath – aluminum tape and polyethylene
7. Optical fibers – optionally used for telecommunications
8. Fillers – as needed
9. Binder tapes
10. Armour Bedding – polypropylene strings
11. Armour – galvanized round steel wires
12. Serving – bituminous compound, hessian tape with polypropylene colored stripe

Fig 16: Modern Submarine Power Cable (AC)
Source: Nexans

An undersea cable designed to carry AC power consists of an inner electrical conductor surrounded by layers of insulating material within conductive and non-conductive sheathing. Typically, three cables are bundled together to carry three-phase currents.

3.1.1.2 HVDC Cables

The basic HVDC cable transmission scheme (Figure 17) is a mono-polar installation using the sea for the return current. The sea return (single wire ground return) reduces the cost of the interconnection since only one cable is necessary between the two converter stations. The sea return also keeps losses to a minimum since the return path has negligible resistance. The only losses are associated with the voltage drops at the anode and cathode. The electrodes have to be located away from the converter stations and the main HVDC cable in order to avoid corrosion and direct current pick up in transformer neutrals. The good conductivity of sea water makes it easy to design the electrodes.

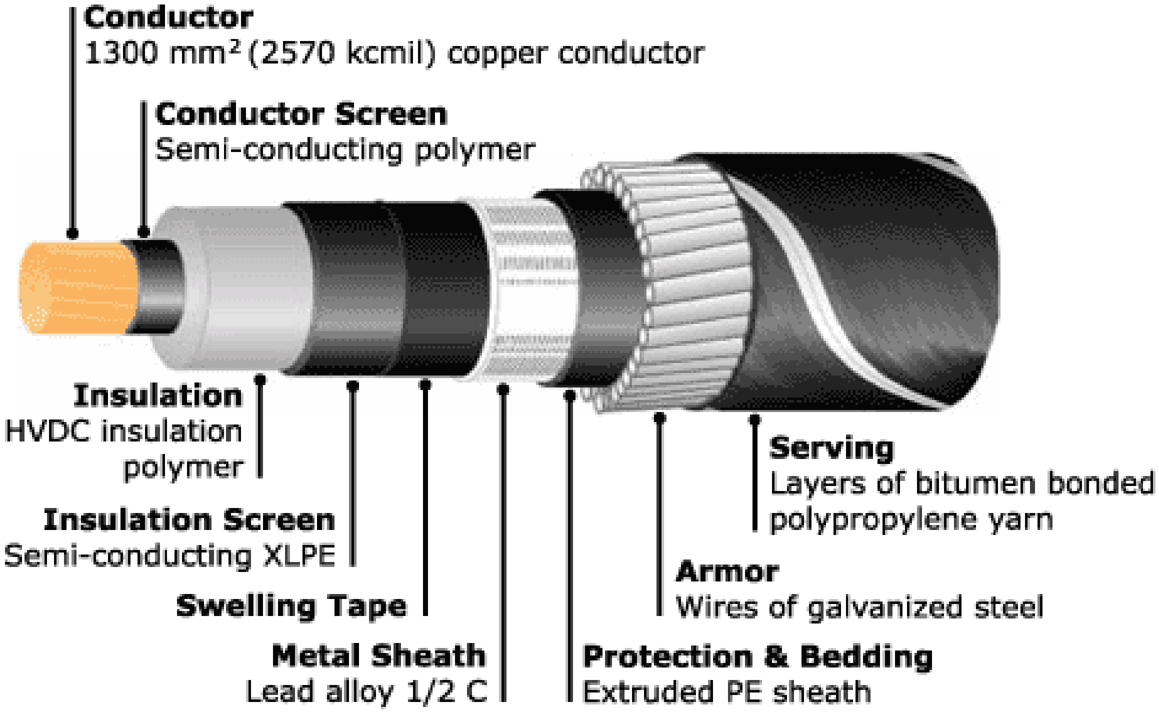

Fig 17: Modern Submarine Power Cable (DC)
Source: Nexans

A further development of the mono-polar transmission scheme is a bipolar configuration. In addition to the doubled transmission capacity, this arrangement also results in higher transmission reliability. The cost functions for the converter stations and the cable, as well as the transmission losses, need to be considered.

3.1.2 Supernodes

One other important technical aspect is the creation of supenodes that will interconnect and separate multi-terminal systems and point-to-point systems. A supernode interconnects a number of DC links together with wind parks via a small-islanded AC network (Node).

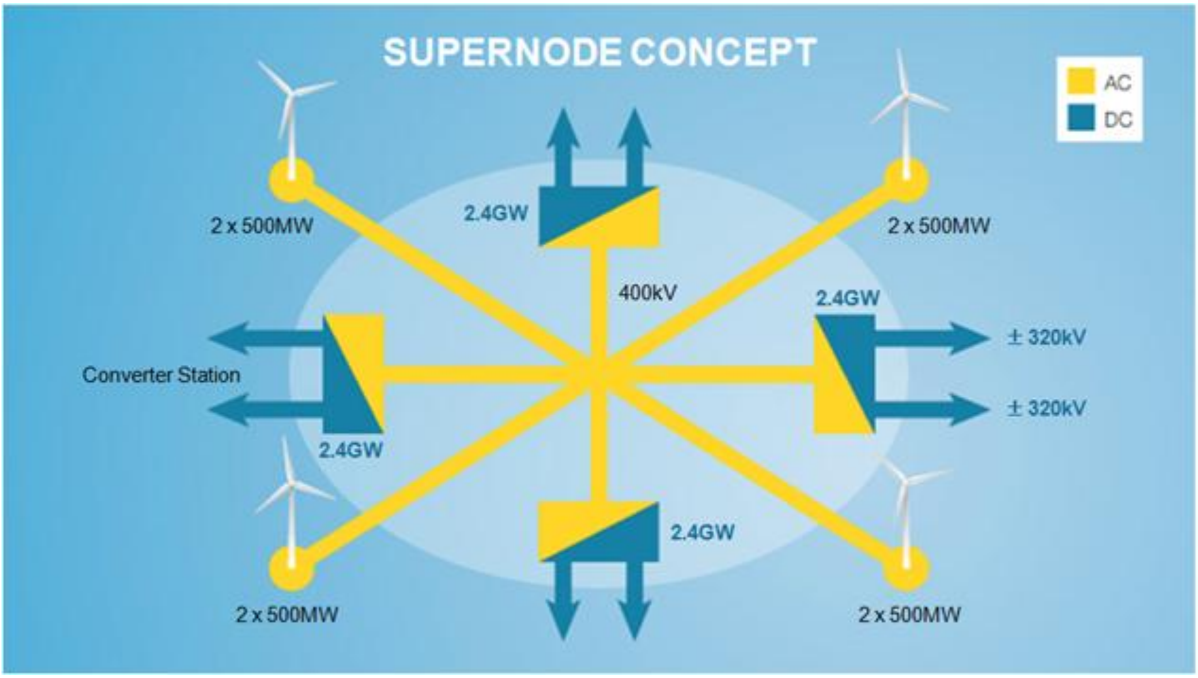

Fig 18: Supernode Scheme
Source: Mainstream Renewable Power

This concept is largely based on technology existing today and there of today there is much experience with DC links interconnecting two AC systems. Most of the existing DC links are equipped with Line Commutated Converters (LCC) based on thyristor semiconductor technology. However, there are a number of HVDC links operating or under construction, which are based on voltage sourced converter technology (VSC). The development needed to build Supernodes is mainly in the field of control and protection for the islanded AC network, which includes frequency control as well as fault detection and fault clearing strategies.

The preferred DC transmission technology for building Supernodes is VSC. This is because a VSC transmission system can generate and maintain the AC voltage at the node with respect to amplitude and frequency, a feature also referred to as black start capability. As long as there are VSC systems providing sufficient short circuit power available at the AC node, LCC based HVDC transmission can also be connected. The concept of VSC transmission controlling islanded AC networks will be demonstrated by the first HVDC connected wind parks in the North Sea, which are currently under construction.

3.2 How to Install Them

3.2.1 Cable route survey

Before installing cable, we have to be careful of where we’re going to lay them. That is why it is very important to make a cable route survey. Indeed, cable routes are selected to minimize the environmental impact and maximize cable protection. To do that, we use high technology boats (Fig 19) with seabed mapping systems that accurately chart depth, topography, slope angles and seabed type.

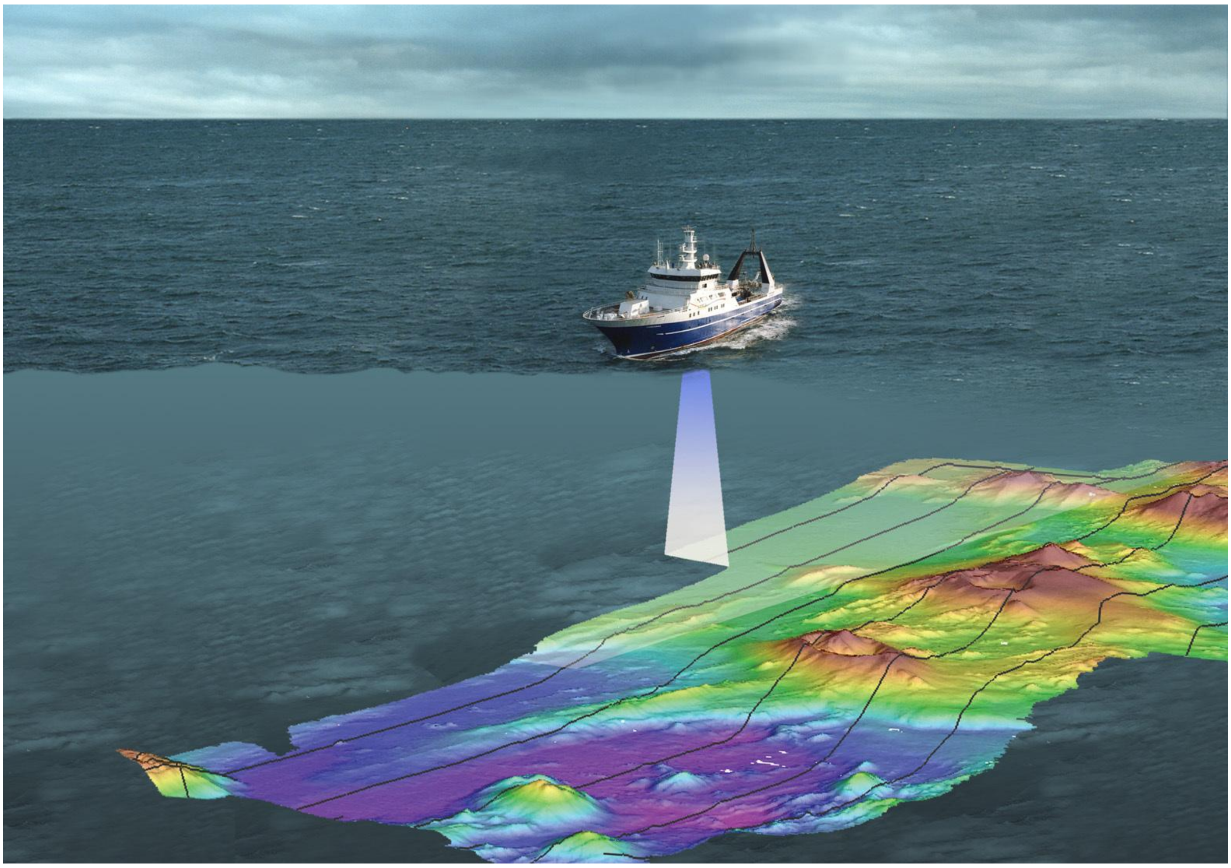

Fig 19: Boat Using a Seabed Mapping System
Source: NIWA

The seabed mapping systems consist in a multi-beam echo sounders that emit a fan of sound, beams to the seafloor to scan a wide swath of the seabed in great detail. The principle of the multi-beam transceiver is to send out a beam of sound waves that is reflected off the seafloor, back to a receiver on the ship.

3.2.2 Cables Laying

Specials equipment is needed to lay cables into deep water. These vessels (Fig 20) are capable of sailing in deep water and carrying kilometers of cables.

Fig 20: Cable Laying Vessels
Source: ABB Engineering

Also needed, special robots (Fig 20) are used to dig trenches to lay cables and bury in the seabed to avoid interfering with fishing.

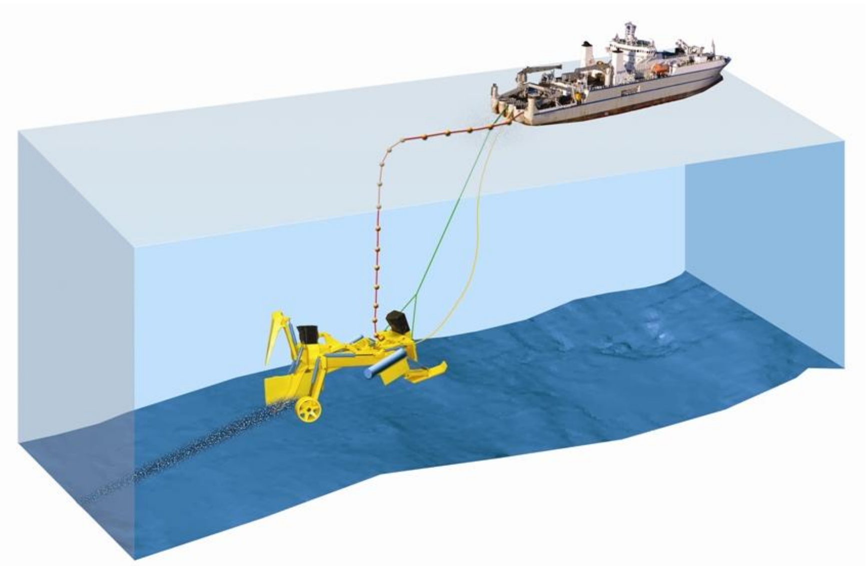

Fig 21: Cable Laying Robot
Source: QUORA

3.3 Supergrid Technologies Schedule

This table summarizes the future technological advances that will be created in the next few years.

Today → 2015	2015 → 2020	After 2020
Increased power ratings for VSC (1,000 MW at 320 kV DC)	DC cables with extruded insulation > 320 kV in operation	Further development of MI and MI-PPL cables
Demonstrators for DC side fault clearing (e.g. DC Circuit Breakers)	MI – PPL 600kV cable in operation	HVDC cables with new extruded insulation compounds in operation
DC 320 kV cables with extruded insulation in operation at different onshore and offshore projects (500 MW per cable)	MI > 500 kV in operation	Superconducting cables
DC Cables with extruded insulation > 320kV developed	Development of new extruded insulation compounds for HVDC cables	DC Gil
MI-PPL 600kV (1.1GW per cable) developed and higher voltages in development	System for fast selective fault detection in HVDC networks	AC/DC converter
MI > 500 kV cable developed	DC side selective fault clearing and system reconfiguration	
AC GIL in operation	Hierarchical control architecture for integrated AC and DC Grid in Europe	
Standardization work for HDVC grids in CIGRE, CENELEC started	Demonstrators for AC/DC converter	

Fig22: Schedule of the Next Technologies

Source: Author

4. The Financial Aspect

4.1 HVAC and HVDC Cost

HVAC transmission line costs more than a DC line for the same transmission capacity. In addition, in the HVDC case, it is necessary to have terminal stations that convert the AC to DC and vice versa which is more expensive. But passed a certain distance, the so-called "break-even distance", the HVDC will always be cheaper.

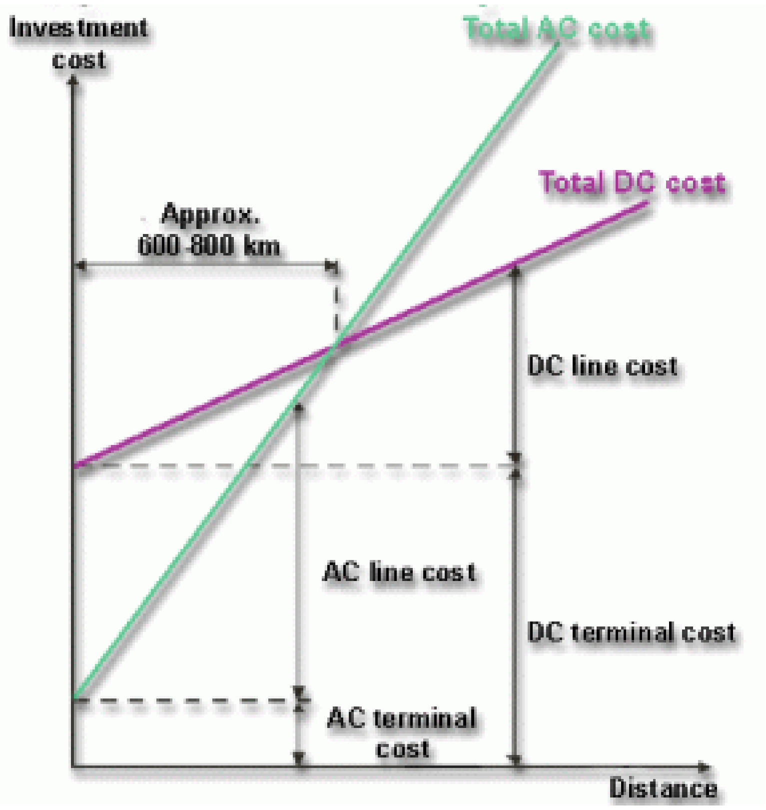

Fig 23: Typical Investment Costs for an Overhead Line Transmission with AC and HVDC.
Source: ABB Engineering

This point called "break-even-distance" is higher for overhead cables than for submarine cables. The distance depends on several factors (both for the underwater and overhead cables) and an analysis must be made for each individual case. That’s why the break-even-distance must not only be considered in the choice between AC and DC, since several other factors, such as controllability, are important.

4.2 Supergrid Cost

At European level, ENTSO-E is in charge of the network planning of electricity transmission through the development of the European Ten Year Plan network development. However, managers of the networks have not yet conducted a comprehensive assessment of the infrastructure related to supergrids and their cost. The 2050 Roadmap study conducted by the European Climate Foundation (ECF) is a first approach and provides a first measurement of the volume of interconnections that it would be necessary to develop in response to the scenarios of "decarbonization" of the electricity sector by 2050.

Studies have been undertaken on the development of offshore networks in the North Sea. These have helped to highlight the costs of about 75 – 90 billion euros for development of offshore networks in the North Sea to allow the reception of about 80 GW of offshore wind by 2030. This cost does not include enhancements that could be made necessary for terrestrial networks. Moreover, the level of these costs is highly dependent on available technologies, their level of standardization, and according the ECF, network structures that can be achieved. For example, for offshore networks, implementation of mesh networks in DC would optimize costs (optimization of marine energy connections) and the electrical system (development of interconnection capacity).

According to Eddie O'Connor, CEO and founder of Mainstream Renewable Power, the backbone of the creation of Supergrid is based on a fleet of ships capable of staying at sea in all weathers, 24 hours a day and 365 days a year, to build non-stop wind farms. The cost of each vessel is $250 million. O'Connor asked the EU to finance 80% of the assessed amount to nearly € 6 billion, while the European Investment Bank would cover the rest.

The Directorate-General for Energy of the European Commission estimated 1,000 billion euros cumulative investment needs for 2020, including 600 billion euros divided into three sectors (Fig 24).

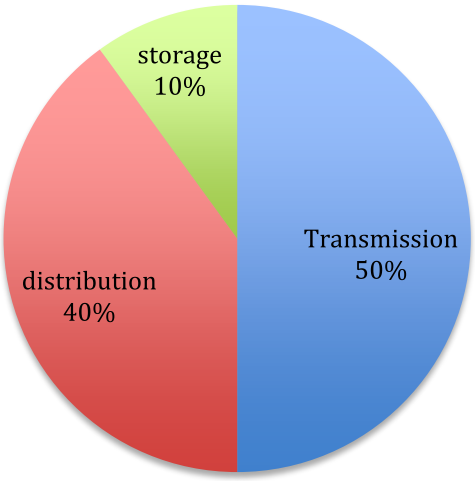

Fig 24: Share of Investment by Sector

Source: Author

Conclusion

In Europe, the development of supergrids meet several needs, such as the environmental goals set by the package "climate-energy" to improve security of supply and energy independence of Europe. This will strengthen interconnections and sharing among all European countries for electricity produced by plants and will optimize the efficiency of the electricity market by facilitating electricity trade between countries.

However, the reasons for the development of supergrids in other continents and other countries are not the same. Thus, in Asia, including China, the supergrids are being developed to transport electricity from large production facilities in the west to load centers mostly located in the east.

The supergrids fail to cater to the same objectives by region and the terms of their implementation will vary in different countries. In Europe, these networks may have parts in DC and offshore elements while in Asia or America, these networks, also called electricity highways, are ultra-high voltage networks, which can reach up one million volts. The only element common to these definitions is the transmission of electricity over long distances.

The concept of supergrids therefore covers multiple realities in different geographical areas and the objectives pursued and it raises many issues, including governance projects, estimation of development costs and duration of implementation of projects that need to be addressed if the projects are to be fully operational.

Some come to speak of a *Super Smart Grid*", a network that would combine the technologies of Smart grids with the assets posed by electricity highways to make an expanded intelligent network. The Super Smart Grid then would connect Europe to North Africa and the Middle East.

Bibliography

1. ABB, “HVDC Cable Transmissions”, www.abb.com.

2. Airtricity, “European offshore supergrid proposal”.

3. Bpp.tech, “Subsea umbilicals and power cables”, Darren Patel, 2008.

4. Friends of the Supergrid, “Position paper on the EC communication for a European infrastructure package”, www.friendsofthesupergrid.eu .

5. Friends of the Supergrid, “The roadmap to the Supergrid Technologies”, 2011, www.friendsofthesupergrid.eu.

6. International cable protection committee Ltd, “about submarine power cable”, 2006-2011, www.iscpc.org/publications/about_subpower_cables_2011.pdf

7. JRC, “Renewable Energy Snapshot 2001”, 2007.

8. KPMG, “Offshore wind farms in Europe”, 2007.

9. PRWeb, “Wind energy today: submarine cable O&M: cost critical strategies for offshore wind” July 2012, http://www.prweb.com/releases/2011/11/prweb8992345.htm

10. Quora, “How are major undersea cables laid in the ocean?” 2011, www.quora.com/how-are-major-undersea-cables-laid-in-the-ocean.

11. Smart Grids – CRE, “Dossier, les super grids”, 2012, www.smartgrids-cre.fr.

12. The European wind and energy association, “The European offshore wind industry key 2011 trends and statistics”, January 2012.

13. The UK parliament, “A European Supergrid”, 2010, www.publications.parliament.uk

14. The European wind and energy association, “Wind energy and the grid” http://www.ewea.org/index.php?id=196.

15. U.S Department of the interior, “Effect of EMFs from undersea power cables on elasmobranchs and other marine species”, September 2011.