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Transmission solutions for connecting offshore power plants to the onshore grid

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Problem Description

The demand for renewable energy is constantly increasing and several offshore power plants, mainly wind power plants, are beeing planned. One of the challenges is how to transport the power from the offshore power plants to the onshore grid.

The data concerning the planned offshore wind parks in the North Sea are already set, concerning locations and planned installed capacity. The main object of this master thesis is to look into what kind of transmission solutions will be most reasonable to use, transporting the energy to onshore substations.

Assignment given: 31. March 2009
Supervisor: Arne Nysveen, ELKRAFT

Preface

This master thesis is carried out at the Department of Electrical Power Engineering at NTNU in collaboration with Siemens AG in Erlangen, Germany from spring until autumn 2009. The master thesis was proposed by Dr. Hermann Koch with Siemens AG, and changed in collaboration with Arne Nysveen, NTNU.

I would like to thank a number of people for their assistance and help during the study of this thesis:

Professor Arne Nysveen for being a helpful and competent supervisor.

Dr. Hermann Koch for helping with both practical and theoretical solutions for me in Germany.

Maria Lanig for supporting me at home.

Trondheim, 28.October 2009

Erlend Riise Engen

Summary

The European Union has set a binding target saying 20 per cent of their energy consumption shall come from renewable energy sources within 2020. Around 4 per cent of the total amount is planned to come from offshore installations (40 GW).

There total amount of planned offshore wind capacity is as of today 37 GW, mainly installations in the North Sea. The technologies that will be used for transporting the power to the shore are either HVAC technology using XLPE cables, transistor or thyristor based HVDC systems or an HVAC Gas Insulated Line (GIL) technology.

However, as the different technical solutions all have advantages and disadvantages compared to the other, the size of the power plants, distances from the shore and closeness to other wind parks will decide what technology will be used for the different cases.

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1. Introduction

1.1. The need for more offshore transmissions

Offshore transmission technology means more precisely cable solutions for transporting power through water. Submarine cables are used in order to connect islands to the mainland grid, crossing fjords and bays as well as powering supply for offshore installations and transporting the electricity from offshore power plants to the shore. For the latter, the main offshore power plants that will be considered in this thesis are offshore wind parks in Europe.

Submarine cables are needed in many situations, such as:

- Connecting islands to the mainland grid
- As power supply for offshore oil and gas platforms
- Connecting offshore power plants to the mainland
- For power exchange between countries (i.e. between Norway and Denmark)

The main situations that will be discussed here are the technology used to connect offshore wind parks to the mainland and interconnecting countries.

1.2. Offshore wind installations demand

As the climate debate is intensifying and the electricity demand in Europe is increasing, the demand for electricity production based on renewable energy sources is increasing correspondingly. The European Union (EU) has set a binding target where 20 per cent (1500 GW) of their energy supply is to come from wind and other renewable resources by 2020. Wind power is expected to deliver 12 to 14 per cent (180 GW) of the total demand, of thus at least 40 GW is set to be offshore wind power [1].

This is an ambitious goal, but not an impossible one. As of today there are only 1.5 GW offshore wind power installed [2], meaning the wind power industry, as well as the cable producers, will have their hands full the next ten years in order to fulfil this goal.

However, the total planned installed offshore wind power capacity within 2015 is as of January 2009 over 37 GW [2]. But even though this amount of installations is planned, it does not mean every projected wind park will be constructed.

The main parts of the wind parks are planned in the North Sea, at a range up to 200 km from the shore [2]. Some parks are planed standing alone, but most of them are planned in clusters close to each other, or do at least have the same planned cable route to the shore. This leads to challenges for the companies responsible for transporting the energy to onshore substations. They may not only have to consider what the best transmission solution is for each wind park alone, but may also have to consider a shared cable system for several wind parks together.

Although no one can know exactly when and where the wind is blowing, it is fairly reasonable to assume that many of the planned wind parks in the North Sea will be operating at maximum power at the same time. In order to transport the energy to where it is needed at the time, the different national grids must be expanded. Connecting the countries around the North Sea to each other with submarine cables will also be favourable.

2. General about offshore transmission technologies

2.1. General

As the offshore wind parks are increasing in size, power and distance to shore, the cable producers are facing challenges in order to meet the power suppliers' demands. The offshore cable alternatives are AC and DC transmissions. But as AC technologies today is considered to have a limited range of about 120 km in point to point transmission due to losses in the transmission and DC converters are expensive, the chosen alternative will vary from situation to situation[1].

In addition, all work and installations offshore are expensive and is best kept to a minimum. The choice of transmission technology will affect the size of the offshore substation. A platform has to be build in order to carry the transformer(s) and eventual switchgear or converter. The mechanical stress to the components placed at sea is high, so the less equipment on the platform, the lesser the maintenance and potential malfunctioning problems.

2.2. Transmission technologies for offshore wind parks under construction

Several offshore wind parks are planned, and we are looking at a potential extensive expansion of the number of wind parks and each parks total installed capacity within the next 10 years, especially in the North Sea. Three of the parks that already are under construction are:

- Alpha Ventus (Germany)
- NORDEon 1 (Germany)
- Sheringham Shoal (UK)

They do all use transmission technologies they consider best suited for the wind parks specifications.

2.2.1. Alpha Ventus

Alpha Ventus is the first offshore wind park in Germany that is close to completion. The construction work started in August 2007 with the work on the cable route, and is to be completed within 2009. The twelve 5-MW turbines have been installed, of which the six first have been producing electricity since July 2009. For the last six, the cable work within the wind farm is yet to be completed [3].

The wind park is with its 60 MW relatively small compared to the planned installations, but the undertakers look upon it as a very good possibility to get offshore experience testing out different installation solutions. Six of the turbines are delivered by AREVA using tripod foundations and the last six are REpower turbines with a jacket foundation. The depth at the site is about 30 meters.

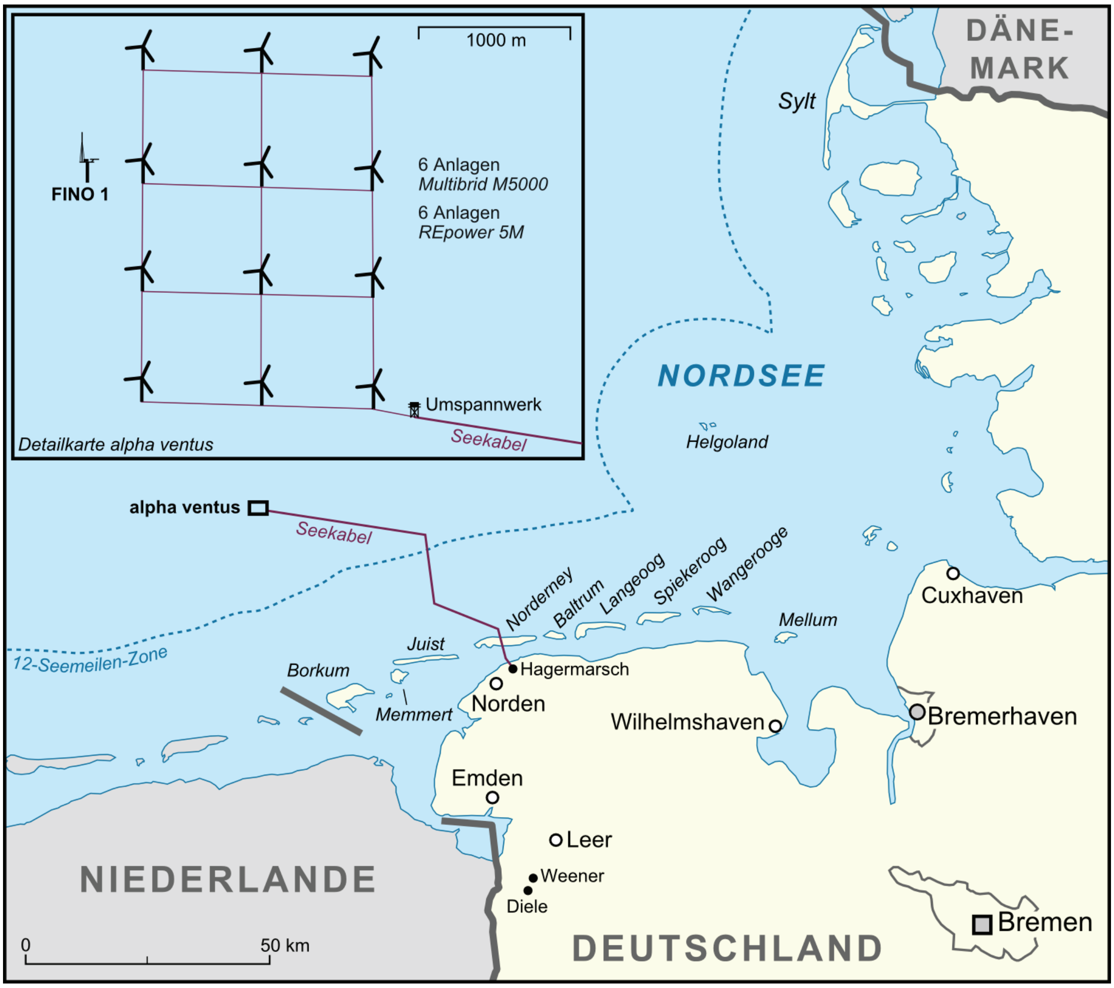

Figure 1: Alpha Ventus project. (Source: www.alpha-ventus.de)

For the Alpha Ventus project, the undertakers have chosen a 30 kV cable network within the park, transforming it up to 110 kV at the offshore substation connected to the mainland through a 60 km long AC cable. This is a medium distance, and well within the AC point to point transmission range. The 60 MW maximum transmission demand combined with the distance from the shore does also not represent a major challenge for the cable companies.

2.2.2. Sheringham Shoal

Sheringham Shoal is a joint venture between the Norwegian companies StatoilHydro and Statkraft. The offshore wind park is to be completed at the end of 2011. It will consist of 88 Siemens turbines, with a total installed capacity of 316 MW [4]. That is 50% larger then Horns Rev 2 which with its 209 MW currently is the worlds largest offshore wind park. However, at the time of completion there will be larger wind parks in operation.

The wind park is situated between 17 and 23 km off the English coastline and has a 20 meter average water depth. This makes an AC transmission favourable. Here, the undertakers have chosen a 36 kV cable network within the park, and two 145 kV three-core cables transporting the power from the offshore substation to the shore. Compared to the Alpha Ventus project that is used to gain experience from the tripod and jacket foundations, as well as from the AREVA and REpower 5 MW turbines, the Sheringham Shoal wind park consist of well tested components.

Figure 2: Illustration of Sheringham Shoal Wind Park. (Source: Statkraft)

The foundations are monopoles hammered into the seafloor, and the Siemens 3.6 MW wind turbine is a turbine well tested for offshore installations. With a site close to the shore, with shallow water and easy seafloor structure, using well known and well tested technology this is a very conventional wind park. It is very likely that many wind parks similar to the Sheringham Shoal wind park will be build in the near future, until these kind of available sites are used up.

2.2.3. BorWin 1

Compared to the Alpha Ventus and Sheringham Shoal projects, the BorWin 1 wind farm bring new challenges to the transmission company which is appointed to transport the power from the wind park to an onshore substation. The wind park BorWin 1 has been renamed two times, from BARD Offshore 1 to NordEOn 1 to BorWin 1.

The BorWin 1 is located about 125 km off the German coast, consisting of 80 BARD 5 MW wind turbines, leading to a total installed capacity of 400 MW at the end of 2010. This is the first offshore power plant using transistor based HVDC transporting the power to the shore [5].

Within the wind park there will be used a 36 kV cable system, which will be transformed up to 154 kV for the offshore converter station, BorWin Alpha, converting the electricity to DC using ABB’s HVDC Light technology. From that point it will be transported through a ± 150 kV DC cable pair 200 km to a substation in Diele, Germany. Of those 200 km, 125 km are submarine and 75 km are underground cables, minimizing the environmental impacts.

As the depth on the site is around 40 meters, jacket foundations have been chosen for the wind turbines and the substations.

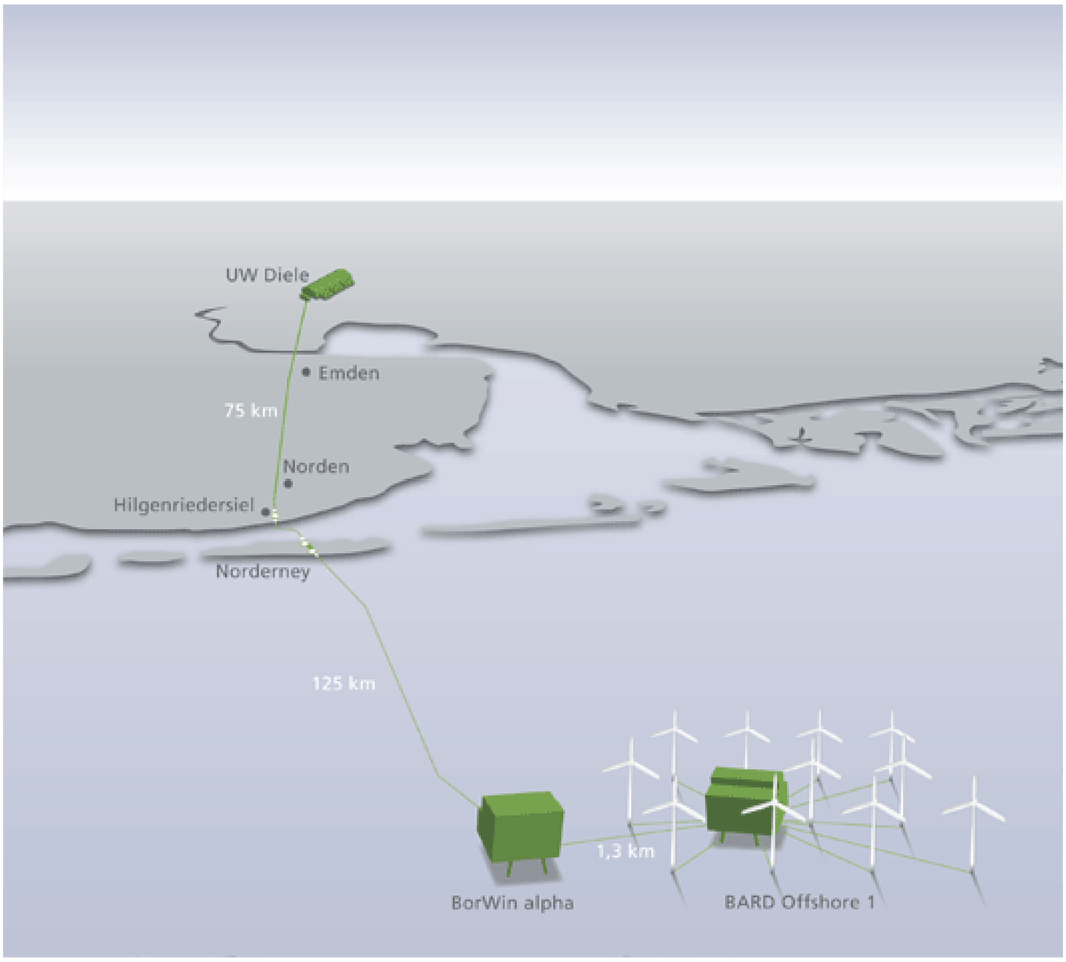

Figure 3: Illustration of BorWin 1. (Source: Transpower)

BorWin 1 is the first wind park with such a long distance from the shore, but more are planned, up to about 75 km further out at sea. The interesting part considering Germany, is that transpower stromübertragungs gmbh (former part of E.On Netz) has been appointed responsible for all offshore transmission lines in Germany by the German government in order to ensure quick progress in planning and laying the cables. This makes it easier for the wind park developers, which only has to install the wind turbines, laying the internal cable system leading to an offshore transformer. From that point, all responsibility lay on transpower.

The total planned offshore wind installation capacity in Germany within 2015 is almost 11 000 MW, 80 per cent of it in the North Sea. This makes it very interesting to see what kind of transmission solution that will be used to transport the power to the shore.

3. General about offshore renewable power plants

There are mainly three types of energy sources that are relevant considering offshore power plants:

- Wind power
- Wave power
- Tidal power

Of those three, wind power is by far the most mature technology. The first offshore wind park was installed of the Danish coast in 1991, consisting of eleven 450 kW turbines. Since then, the turbine sizes have increased exponentially up to the latest 5 MW turbines installed at the Beatrice field off the Scottish coastline, and a total of 1561 MW installed capacity was installed by January 2009.

In comparison does the largest wave power plant only consist of three wave converters, each with a 3 MW maximum output, and is situated off the Portuguese coast. The 3 MW wave power concept is called Pelamis, and is the only large-scale wave power converter that has been build. There are plans considering extending the power plant to 30 MW, installing 7 new converters.

Figure 4: Illustration of potential Pelamis wave power plant. (Source: Pelamis)

Tidal power is a very hot issue, primarily in the United Kingdom, as the tidal streams in certain areas along the Scottish coastline and between Ireland and Wales are strong enough to be reasonably exploited. (See Fig XX) But there are still no tidal parks in operation. Marine Current Turbines (MCT) have however installed a second generation tidal current turbine called SeaGen, which is a 1.2 MW prototype placed close to the Welsh island of Anglesey. They are planning on installing seven third generation turbines, each 1.5 MW, in the same area within 2011 and 2012 depending on governmental authorization [6].

Scottish Power Renewables are also planning on installing tidal turbines at three sites in the United Kingdom, each with between 5 and 20 Lànstrom HS1000 1 MW turbines. The turbine has been developed by Hammerfest Strøm AS, a company owned by Hammerfest Energi, ScottishPower Renewables and StatoilHydro [7].

Common for the tidal and wave installations that have been build and the planned installations, are the closeness to the shore (less than 20 km from the shore) and the relatively small installed power output (< 30 MW). This means there are no larger challenges for the transmission and cable companies considering connecting these power plants to the onshore grid.

In comparison, the wind park NordEOn 1 is under construction in the North Sea, 128 km from the German mainland with a 400 MW installed capacity. There is very likely that larger wind parks will be constructed at a distance up to 200 km from the German shore in near future. Therefore the challenges considering transmission technology will arise with the offshore wind parks and not the tidal and wave parks.

4. Offshore transmission technologies

4.1. HVAC technology

4.1.1. XLPE

4.1.1.1.Development of technology

Polyethylene (PE) was first discovered by accident in 1898, and then again in 1933. However, it was not until 1935 that PE was deliberately re-made by Michael Perrin at ICI (Imperial Chemical Industries) in the UK, marking the beginning of Polyethylene production {Wikipedia, 2009 #3}. The polyethylene production and development reached another phase in 1963, as Al Gilbert and Frank Precopio invented Cross-Linked Polyethylene, more commonly known as XLPE or PEX, in the General Electric Laboratory in New York [8]

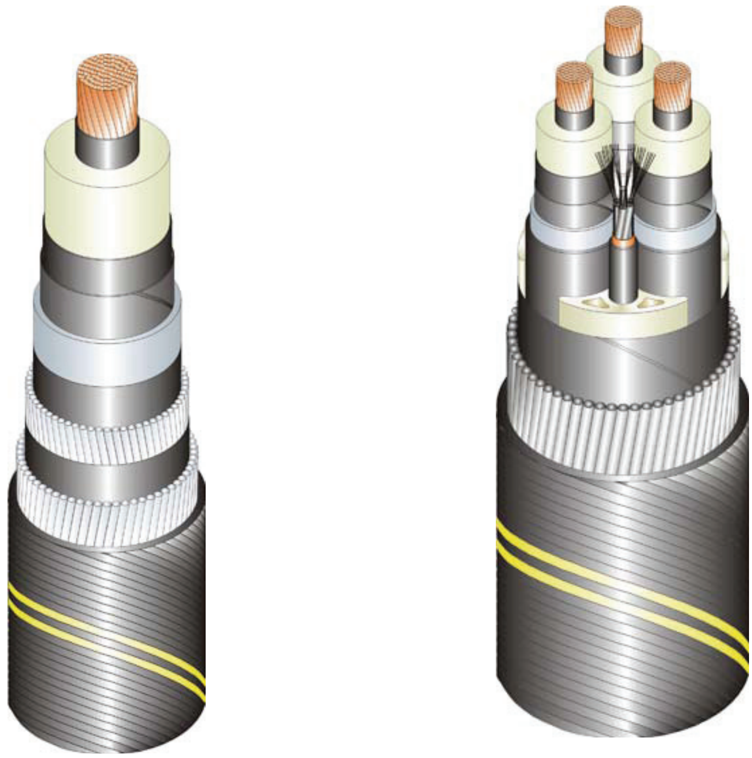

Figure 5: Single core and three-core XLPE cables. (Source: Nexans)

4.1.1.2.Technical specifications

The XLPE has got electrical properties similar to thermoplastic PE, but with better mechanical properties. The most important property of XLPE is its rated conductor temperature, which is 90 degrees Celsius, and an emergency temperature of 140 degrees [9]. As the power transmission capacity for a cable is dependent of the insulation temperature, an increase of 10-15 degrees in rated temperature is very favourable. However, the operators controlling the power flow in the cable may dimension a cable so that the operating temperature does not exceed i.e. 80 degrees Celsius in order to extend the cable's lifetime.

4.1.1.3.First submarine application

Due to these properties, it did not take long before XLPE was a widely used as cable insulating material. In 1973, 10 years after the development of XLPE, ABB installed the worlds first submarine XLPE cable, connecting the Finnish island Åland to the Swedish mainland. The cable installed was a 55 km long 84 kV AC cable. During 35 years in operation, not a single electrical failure has occurred [10].

Figure 6 First submarine XLPE cable. (Source: ABB)

4.1.1.4.Technology records

As a result of being a maintenance-free and reliable technology, XLPE cables rapidly became the preferable choice in stead of fluid-filled cables where it was possible. Today, almost every submarine power cable produced is XLPE-insulated. Therefore is the technology also steadily being improved.

In 2006, the cable producer Nexans beat their own record in voltage-level for a submarine cable as a 9 km long 420 kV XLPE insulated cable was laid from the Norwegian mainland to the island Gossen for power supply to the Ormen Lange gas processing plant. The cables are crossing a straight with a maximum depth of 210 meters [11].

The old voltage level record was made as Nexans produced and installed 170 kV XLPE cables for the Horns Rev Wind park project in Denmark in 2002.

Figure 7: Illustration of Horns Rev. (Source: Nexans)

The longest planned submarine AC XLPE insulated cable is going to be a 100.5 km long 115 kV 3-core cable which will supply the oil and gas platform Gjøa off the coast of western Norway with the needed power.

The cable will have a capacity of 40 MW, and is to be finished in 2010 as the platform is going into operation.

Another challenge associated with this cable, is that within the last 1.5 km the cable will stretch from the sea floor and 380 meters up to the floating platform. This makes the forces (mechanical and electrical) very high, so this part of the cable has to be extra reinforced.

4.1.2. Gas Insulated Transmission Lines (GIL)

Up to this date, no GIL offshore transmission line has been built. However, an EU financed GIL offshore project is currently running, looking into the possibility of using a GIL transmission line connecting most of the planned offshore wind power plants in the North Sea to the German shore. Therefore, this technology will be considered here.

4.1.2.1. Development of technology

The development of GIL comes as a result of Gas Insulated Switchgear development in the 1960's. As a result of using the very high insulating SF6 gas in stead of air or oil, the GIS can handle very high power needing a lot less space for the equipment. Also, having the equipment in an isolated environment makes it a lot less sensitive to pollution and other external influence. This reduces the operation and maintenance costs as well as increases the equipments lifetime.

The first GIS worldwide was delivered by ABB in 1967, with Siemens following in 1968. The first Siemens delivered GIS is over 40 years later still in service (12].

4.1.2.2. Technical description

Gas Insulated Transmission Lines (GIL) is high power cable transmission system using a SF6/N2 gas mixture as isolating medium. The conductor consists of an aluminium tube, and the enclosure, which retains the internal gas pressure, is made from an aluminium alloy. Between the conductor and the enclosure, there are regularly support isolators that keep the conductor in the centred in the tube. Up to 2001, every GIL system delivered used 100% SF6 gas as insulating medium.

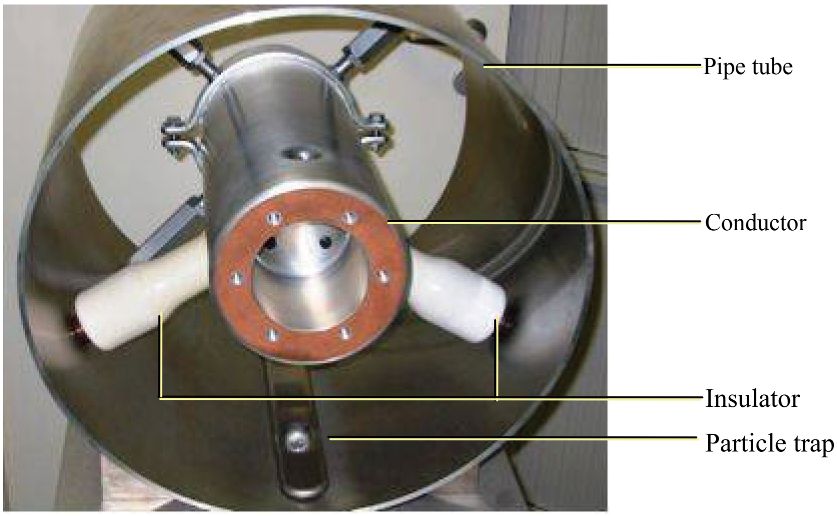

Figure 8: Overview of one phase GIL pipeline. (Source: Siemens)

While pure SF_6 offers the best dielectric performance at a given gas density, 10-20% SF_6/N_2 systems operating at a modest (0.7 bar) increases of pressure can perform with equal dielectric rating [12].

4.1.2.3. First applications

The first GIL installed in the US was the PSEG Hudson Generating station in New Jersey in 1972. The 242 kV, 1600 Amp GIL is direct buried connecting the Air Insulated substation to a transformer located remote from the substation. The GIL system is still in use today.

In Europe, the first installation came two years later in Schluchsee, Germany. It consists of two 420 kV systems, laid in a tunnel connecting a hydro pump power plant generator with overhead lines.

4.1.2.4. Technology records

The most powerful GIL system that has been delivered is a 550 kV and 4500 A system, installed at the Baxter Wilson Power Plant in USA. It has a total length of 1250 meters and was installed in 2001 [13].

4.1.2.5. GIL Offshore

Gas Insulated Lines have never been used in an offshore transmission system. However, there is an ongoing EU-financed project consisting of representatives from Siemens, ForWind, ILF and the Universities of Hannover and Oldenburg, which looks into the possibilities using GIL to transport the power from the planned offshore wind parks in the North Sea to the shore.

The wind power potential in the North See is very well, as the average wind speeds are between 8 and 11 m/s [14], the sea is relatively shallow (up to 30-60 meters) and the sea floor consists mainly of sand, enabling easy foundation anchoring.

Figure 9: Illustration of GIL tunnel. (Source: Siemens)

In the German part of the North Sea alone there is planned approximately 8000 MW installed wind power for the time being.
Many are planned to be placed relatively close to each other, having approximately the same cable route to the shore. This enables the building of a common high power transmission line/system from a platform at sea.

Figure 10: Overview of planned wind parks in the North Sea. (Source: Siemens)

Due to the insulating material, which in this case is a mixture of SF6 and Nitrogen gas, the ohmic and reactive losses are a lot lower compared to a regular AC cable. The usual commercial alternative to GIL offshore, transporting this amount of power over a medium to long distance, is HVDC cables, either with ‘old’ thyristor or ‘new’ VSC technology. Using an AC GIL system in stead of a DC system makes expensive converter stations unnecessary.

4.2. HVDC technology

4.2.1. Comparing thyristor and insulated-gate bipolar transistor (IGBT) converters

There are two types of converters that will be used for offshore HVDC transmissions:

- Thyristor based converters
- IGBT converters

Each of the converter types have advantages and disadvantages compared to the other, and the decision concerning which technology to use has to be reviewed for each specific project.

The thyristor based converters are able to handle a large amount of power pro system, today around 2000 MW. They are cheaper than IGBT converters, but a thyristor converter station require more filtering in order to gain a stable DC on the converter side and a smooth AC on the inverter side [15].

Each IGBT converter station is only able to handle a power around 1200 MW. However, it is only half the size of a thyristor converter at the same power rating. As a thyristor based converter station has to be specifically for each project, the IGBT systems are module-based therefore enable pre-assembly at the factory.

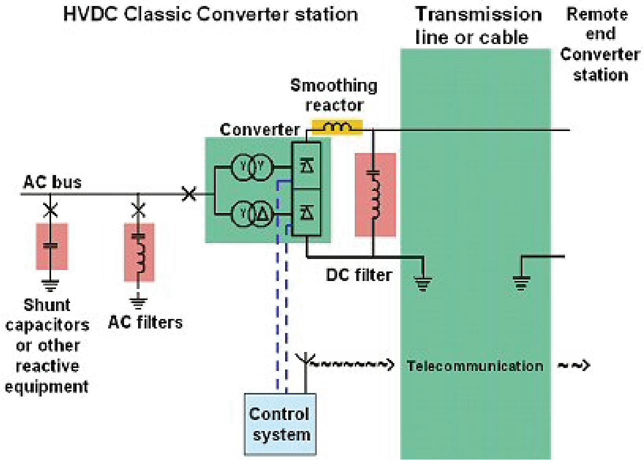

Figure 11: Schematics of a thyristor-based converter station (Source: ABB)

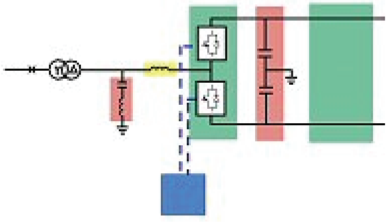

Figure 12: Schematics of an IGBT converter. (Source: ABB)

In comparison to a thyristor based systems, an IGBT system can be used for black starts and enables an easy independent control of active and reactive power

4.2.2. Thyristor based HVDC

4.2.2.1. Development of technology
The first long-distance power transmission using direct-current (DC) was demonstrated in 1882 at the worlds first international electricity exhibition in Munich, Germany.

A steam engine situated at Miesbach was used as source, and a 2 kV DC system transmitted 2.5 kW of power the 57 km distance to Munich, powering an artificial waterfall. However, both the steam engine and the pump powering the artificial waterfall were DC components, so there were no converters and rectifiers in use.

Figure 13: Map of the first HVDC transmission route. (Source: ABB)

In the 1920s and 1930s the mercury arc valve was developed, giving a boost in rectifier technology. In 1944, ASEA (later ABB) developed a rectifier and an inverter able to take 2 MW loads at a voltage up to 60 kV [10].

4.2.2.2. First submarine application

Not long after, the Swedish State Power Board placed an order with ASEA, building a HVDC transmission between the island of Gotland and the Swedish mainland. The 96 km mass impregnated paper insulated cables was laid in 1953, the link going into operation in 1954. It had a rated transmission capacity of 20 MW at 100 kV, using mercury arc valves and a vacuum tube-based control system.

Figure 14: First submarine HVDC route. (Source: ABB)

With the invention of the thyristor in 1957, improving the rectifier and inverter technology, new opportunities presented itself. In 1967 one of the mercury arc valves was at Gotland was replaced with a thyristor valve. After a one year long trial, a complete thyristor valve group was installed in both converter stations, improving the transmission capacity to 30 MW by increasing the voltage from 100 kV to 150 kV. The cable was taken out of service in 1987, after over 30 years in service without any major faults.

4.2.2.3. Technical specifications

The cables used for HVDC transmissions have been improved since the beginning, but no significant change of technology has taken place. The NorNed cable for instance is a mass- impregnated, non-draining, paper insulated cable.


Figure 15: Mass Impregnated Cable (Source: Nexans)

4.2.2.4. Technology records

With the developments of new converter technology and improved cable characteristics, the development in length and rated power of the cables has steadily increased. The longest submarine HVDC cable is today the NorNed cable from Norway to the Netherlands, being 580 km long with a 700 MW rated power. The Cross-Channel cable between France and England is with its 2000 MW (1986) the most powerful HVDC submarine cable system ever built.

4.2.3. Insulated-Gate Bipolar Transistor (IGBT) converter systems

4.2.3.1.HVDC Light

4.2.3.1.1. Development of technology

HVDC light is an ABB developed power system designed to transmit power underground and under water for medium and long distances. It is based on the development and use of voltage source converters (VSC's), using turn-on/turn-off IGBT power semiconductors that operate with high frequency pulse with modulation (PWM). This development of VSC's in the 1990s resulted in the building of a 3 MW test facility in Hellsjön, Sweden, in 1997.

The first full scale HVDC Light system was installed at the island of Gotland in 1999. The southern part of Gotland already had 40 MW installed wind power, and more wind parks were planned. As the island does not have any power production other than wind power, and the southern part of the island only had a peak load about 17 MW, the transmission capacity was already at its limits. With the already existing DC link from the centre of the island to the Swedish mainland, the possibility to control active and reactive power and the very satisfying results at the HVDC Light test cable installed on the mainland two years earlier, a 50 MW ± 80 kV HVDC Light system was chosen [16].

The cable used for HVDC Light transmissions are triple extruded polymer insulated cables. This insulating material makes the cables light and flexible, compared to the mass-impregnated paper insulated HVDC 'classic' cables

4.2.3.1.2. Technical specifications

The main difference between HVDC Light and conventional HVDC is the technology used in the converter stations. In classical HVDC, the valves used are regular Thyristors instead of IGBT's. This makes the converter stations a lot smaller in size, but limits the maximum convertible power.

The classical DC transmission is still the most cost effective solution in the high power range (above ca 250 MW). HVDC Light however, comes in unit sizes ranging from a few tens of MW to 1200 MW at up to ± 320 kV

The HVDC Light is bipolar by nature, disabling a zero ground return. This means that a HVDC Light system always consists of cable pairs.

4.2.3.1.3. First submarine applications

The first offshore HVDC Light project was commissioned by Statoil in 2002, connecting the Troll A natural gas platform in the North Sea to the shore. It consists of a dual set of a 68 km long bipolar submarine cable, having a rated power at 84 MW at ± 60 kV. It represented the start of the electrification of the Norwegian offshore platforms.


Figure 16: Kollsnes HVDC Light converter station (Source: ABB)

Due to the distance from the shore to the platform, power required and limited space on the platform, HVDC Light came up as the only reasonable alternative.


Figure 17: HVDC Light converter station at the Troll A platform. (Source: ABB)

4.2.3.1.4. Technology records

The largest offshore HVDC Link yet built (2009) is the Estlink cable, a 350 MW cable between Finland and Estonia. The submarine cable is 74 km long, and operates at +- 150 kV DC. Here, the main reason for choosing HVDC Light was the sea crossing and that the grid in Finland and Estonia operates at different frequencies.

However, the largest HVDC Light system that ABB is commissioned to build, is a 500 MW ± 200 kV cable between Ireland and Wales, to be operational in 2012. It will be the first HVDC Light system with over 150 kV DC voltage. With its 186 km long submarine cable it will be the longest submarine/offshore HVDC Light cable system yet built.

4.2.3.2.HVDC PLUS (Power Link Universal System)

4.2.3.2.1. Development of technology

HVDC PLUS is a Siemens developed power system, developed to transport power under ground or under water for medium to long distances. It uses a Voltage Source Converter (VSC) technology with a Modular Multilevel Converter (MMC) design. The HVDC PLUS is a relatively new system, as it was introduced to the market in 2007 [17].

4.2.3.2.2. Technical specifications

The MMC provides a nearly ideal sinus shaped waveform on the AC side and a smooth DC voltage. This technology has therefore a very limited requirement for high frequency and harmonic filters.

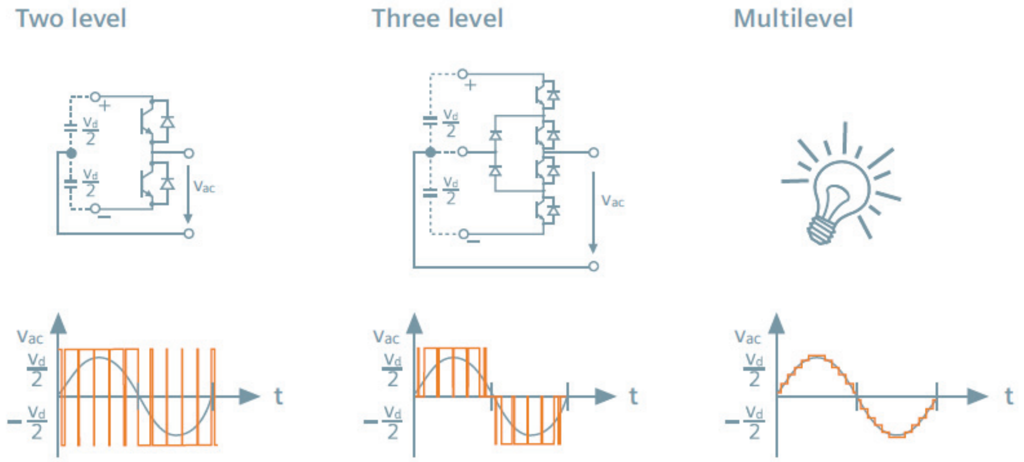

Figure 18: Overview of HVDC PLUS concept. (Source: Siemens)

As HVDC Light by ABB, the VSC does also here offer an independent control of active and reactive power, is module-based and requires a lot less space for the converters compared to classical thyristor based HVDC. Its transmission capacity is today about 1000-1200 MW.

4.2.3.2.3. First submarine application

As this is a quite new technology, no full scale system is yet operational. However, the Trans Bay cable in San Francisco is scheduled to be operational in March 2010. The converter stations are HVDC PLUS technology from Siemens, and the cables are extruded submarine cables provided by Prysmian Cables & Systems. With its ± 200 kV system, it will be the highest system voltage for an IGBT-based system yet build.

The cable is being build to increase the energy reliability in the city of San Francisco. With its 400 MW transmission capacity, connected to a substation 88 km away in Pittsburg, the energy stability in the San Fransisco area will be considerably increased.

Figure 19: Cable route for the first HVDC PLUS system. (Source: Siemens)

5. Offshore power plants

5.1. Offshore wind power

5.1.1. About

As to reach the 20 per cent energy from renewable energy sources within year 2020, the eyes are looking to the sea for technologies to build renewable power plants using different energy sources. As wind power is the most mature renewable technology, except for hydro power, it is the technology that will contribute the most to fulfil the EU's goals.

The first offshore wind farm, consisting of eleven 450 kW turbines, went into operation in 1991 of the coast of Denmark in the Baltic Sea. Since then, the wind turbines have increased in size exponentially up to the latest 5 MW turbines installed at the Beatrice test field in UK. The turbine sizes are predicted to increase further, as the company Clipper Wind is developing a 7.5 MW wind turbine designed for offshore applications [18].

There are many reasons why to go offshore with the wind power. Some of the reasons are for instance:

- Wind stability. The wind blows faster and more stable over the sea, as the sea does not create as much wind turbulence as trees and grass.
- Less visual impact. The NOBY- effect (Not in My Back Yard) is becoming a larger problem for onshore wind parks. Almost everybody wishes wind parks welcome, as long as they cannot see them. As long as the wind parks are located a certain distance from the shore, there will not be a negative visual impact.
- Wind park layout. As the offshore wind parks are mostly located where the sea floor consists of sand, the topology is not important, enabling all turbines to have the same height over the sea. As a result, it is easy to plan where to locate the turbines, compared to onshore where several additional factors come into play.

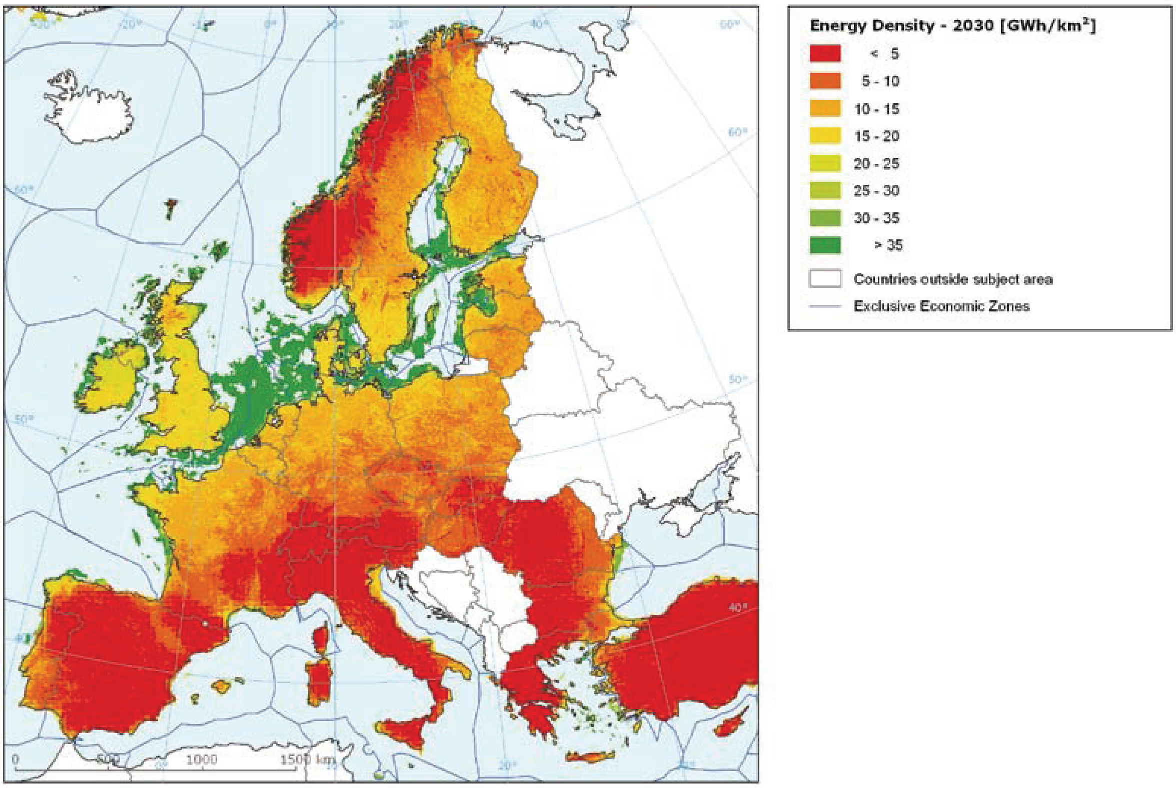

Figure 20: Overview of wind energy potential in Europe. (Source: EWEA)

5.1.2. In operation

Since the first offshore wind park in 1991, another 25 parks have been constructed, with a total of 1561 MW installed capacity.

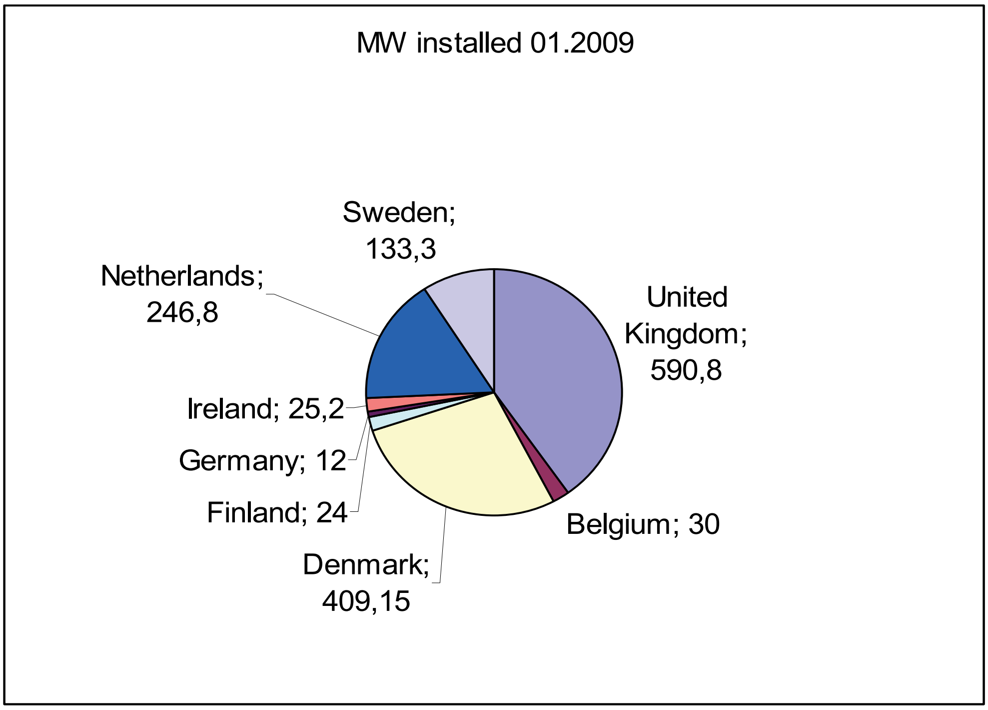

Figure 21: Installed wind power in European countries. (Source: EWEA)

Up to now, the offshore wind farms have been erected in shallow waters quite close to the shore. As the first floating full-scale wind turbine have been erected in south-west Norway, this might change in the future. The floating wind turbine concept, called HyWind, can be erected anywhere where the water depth is between 120 and 700 meters. This HyWind test turbine will be producing power for a two-year test period using a Siemens 2.3 MW turbine, starting autumn 2009.


Figure 22: Illustration of HyWind and the HyWind turbine during installation. (Source: StatoilHydro)

5.1.3. Planned

Except from an extensive building of hydro power, wind farms are the most mature technology with the largest energy potential in Europe. There has to be constructed a lot of turbines to fulfil the EU's goals, which states that 20% of the electricity produced and consumed in the EU shall by 2020 come from renewable energy sources. This leads to a massive construction of wind power. And as there is a lot of shallow water in the North and Baltic Sea and the technology for offshore wind farms is mature, quite a number of wind parks are planned in the North and Baltic Sea.

Compared to the today installed 1,561 MW, the total planned offshore installed capacity in Europe is 37,441 MW within 2015. Over half of these wind farms are planned in Germany and the UK. The main reasons for this are:

- Very good offshore wind strength in the North Sea
- Large offshore areas available
- Shallow waters enabling use of conventional foundation solutions.
- The EU goals and governmental feed-in tariffs [19].

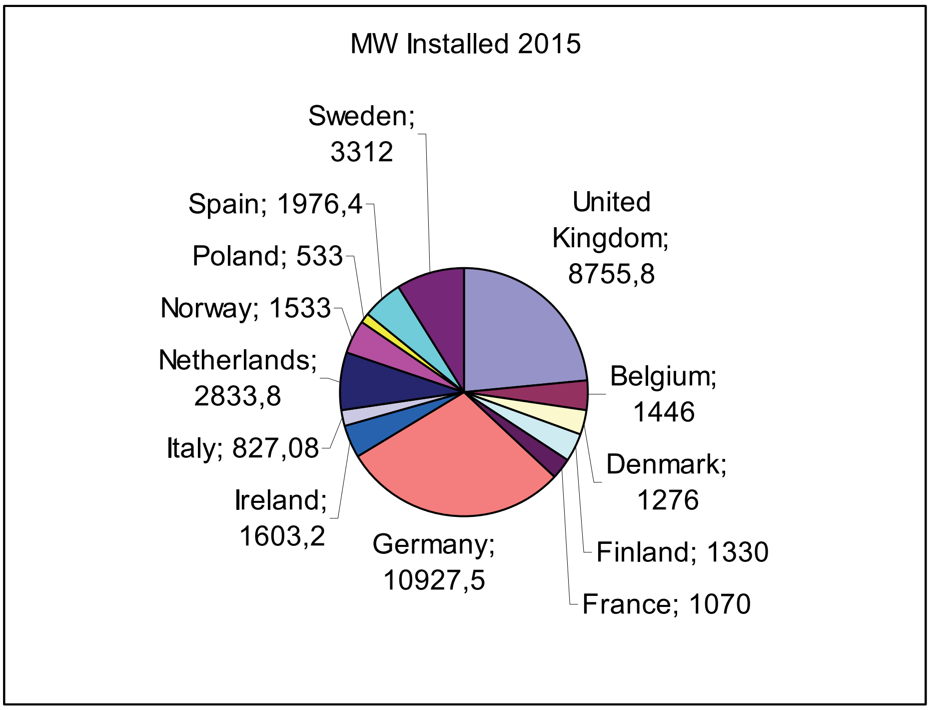

Figure 23: Planned installed offshore wind capacity within 2015. (Source: EWEA)

5.1.4. Potential

The EEA (Europe Environmental Agency) states in a technical report, that the raw offshore wind power potential is huge. Leaving all constraints aside, the technical potential can be around 25 000 TWh within 2020, which is around 7 times the electricity demand in 2020. However, this is a pure theoretical number. For offshore wind, the practical and economical constraints reduces the potential to 2600 TWh which still is enough to cover 70 % of Europe's electricity demand.

5.1.5. Special considerations

Even though the wind potential, both technical and in the future economical, is very high, there are other important aspects that also have to be considered before a wind farm can be build. Some of these aspects are:

- Distance to the shore – long distances make the power transmission expensive
- Fishing industry interests
- Ship traffic
- Sea depth – floating wind turbines will probably still be expensive in 2020
- Military areas – interference on radars from the wind turbine blades
- Natura 2000 areas (nature parks)

5.2. Wave power plants

5.2.1. About

The conversion of the wave motion into electricity is called Wave power. It is, once installed, a completely 'green' energy source, as wind- and tidal power.

Wave power constructions have different designs and ways of converting the motion in the ocean into electricity.

5.2.2. In operation

The first commercial large-scale wave farm is the Agucadora project off the coast of Portugal, which was commissioned in the second half of 2008. The wave farm consists of three 750 kW Pelamis Wave Energy Converters developed by the Scottish company Pelamis Wave Power, formerly Ocean Power Delivery [20]. With its 2.25 MW installed capacity, producing about 8 GWh/year, it is currently the world's largest wave farm.

Figure 24: Installed Pelamis Wave Energy Converter in Portugal (Source: Pelamis)

The Pelamis is a semi-submerged structure composed of cylindrical sections linked by hinged joints. It has hydraulic motors which drive electrical generators to produce electricity. It is designed for offshore locations with water depths of 50 – 70 meters, typically 5-10 km from the shore, where the high energy levels found in deep swell waves can be accessed. Each of the modules is 150 meters long, has a 3-meter diameter, and weighs 700 tonnes.

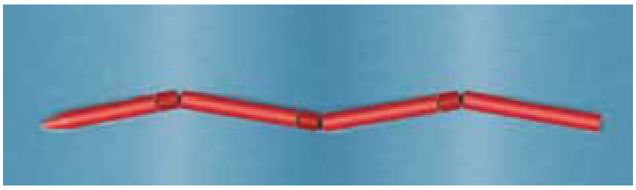
Figure 25: Top view of Pelamis Wave Energy Converter

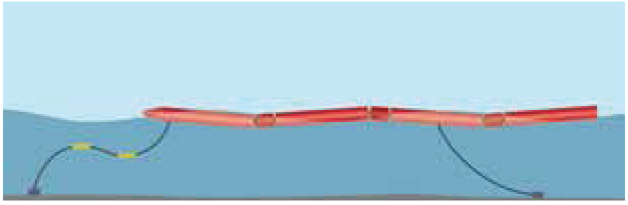
Figure 26: Side view of Pelamis Wave Energy Converter

5.2.3. Planned

5.2.3.1.Pelamis Wave Energy Converter

Scottishpower Renewables are planning a 3 MW wave test site off the Orkney Islands coasts, using four 750kW Pelamis Wave Energy Converters. The Agucadora wave farm is also considering increasing the installed capacity up to 30 MW. Both companies have however not set specific dates for when these wave farms shall be commissioned.

5.2.3.2.Ocean Power Technologies

Ocean Power Technologies has developed the PB150 PowerBuoy, which will be installed in 2010 at the European Marine Energy Centre in Orkney Isles, Scotland. It is meant as a test buoy, and is designed to generate power in wave heights between 1.5 and 7 meters. They are fixed to the seafloor, with one moveable part floating up and down with the waves.


Figure 27: PB40 Power Buoy test installation in Spain. (Source: Ocean Power Technologies)

5.2.4. Potential

The worldwide useful wave power resource has been estimated to be greater than 2 TW. However, generating electricity from the wave motions is still expensive, and the technology has to be more developed before we will see large wave parks (over 100 MW) in the oceans [21].

5.2.5. Special considerations

Wave power installations are subject to extreme conditions. Not only due to the mechanical stress due to heavy weather, but also potential corrosion problems due to the salty water. Other aspects that have to be considered are:

- Visual impact
- Impact on the marine life
- Fishing interest
- Ship traffic

5.3. Tidal power plants

5.3.1. About

Tidal power use sea currents much like wind turbines use the flowing wind to produce energy. The currents occur places where the difference between high and low tide is high, or where the tide has to go through a narrow strait to fill up a fjord or a bay within.

The two technologies that are most developed and ready for commercial installation are the SeaGen turbine from Marine Current Turbines (MCT), and the Lànström turbine (HS1000) from Hammerfest Ström AS.

One of the advantages with tidal power/energy is the possibilities to plan the production output. In comparison to wind power, it is known how strong the current will be at a given time on a given day. The visual impacts are low, as the turbines are fully or partly submerged.

However, tidal stream turbines need very good locations to reach an adequate power production. This makes the narrow straits in Scotland optimal, as they have a combination of high difference between high and low tide as well as narrow straits where the tide has to float through.

5.3.2. In operation

The SeaGen 1.2 MW prototype was installed in April 2008, going into operation in July the same year. MCT installed their first turbine, the SeaFlow, off the coast of Flynmouth, England, in 2003. It is a 300 kW single rotor tidal turbine which was developed for research purposes, improving the technology before full-scale tidal turbine parks may be installed.

In Norway, the prototype for the Lànström HS1000 turbine was installed in Kvalsundet in Finnmark, northern Norway, in 2003. It went through a four-year test period, before it was raised for verification in 2007. In 2009, it was reinstalled with some improved components, producing energy to the local grid.

5.3.3. Planned

As of today, there are planned two larger tidal current power plants, using the two mentioned turbines (SeaGen and HS1000).

5.3.3.1.ScottishPower Renewables

ScottishPower Renewables are planning and evaluating three sites in Scotland and Northern Ireland, where between 5 and 20 Lànström 1MW tidal turbines will be installed at each site. This makes it a total of 60 MW installed, which can provide electricity for up to 40.000 homes in the UK [22].

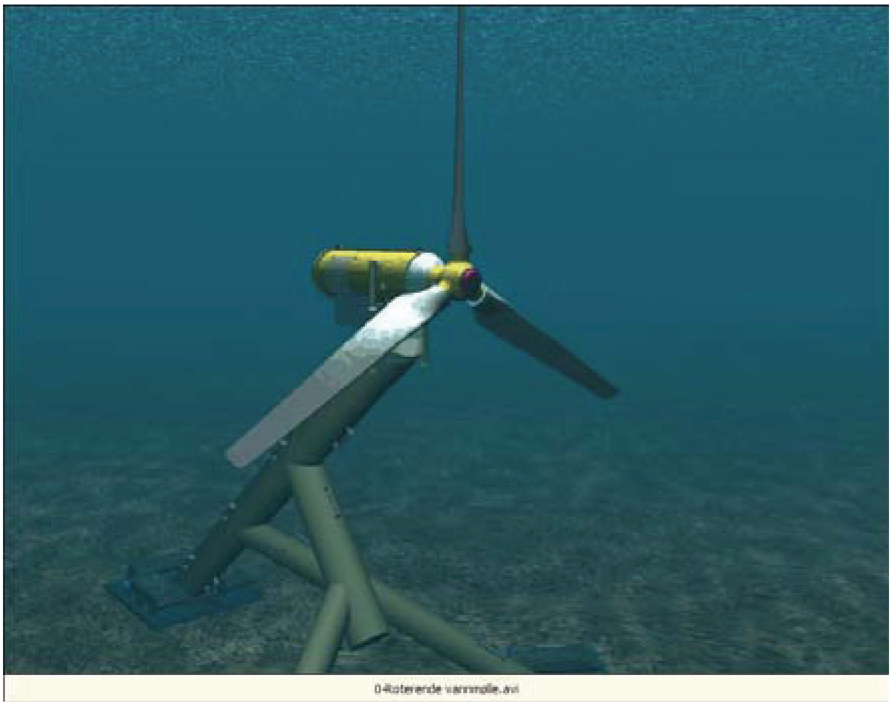

Figure 28: Illustration of one Lànström HS 1000 tidal turbine.
(Source: ScottishPower Renewables)

The turbines will be located in Pentland Firth and Sound of Islay, Scotland, and in North Anthrim, Northern Ireland (see figure 30).

5.3.3.2.Marine Current Turbines (MCT)

Marine Current Turbines have developed the SeaGen 1.2 MW turbine (see picture above), and is in collaboration with the company npower (RWE) developing and improving the technology, and plan to install seven 1.5 MW SeaGen turbines in a 10.5 MW tidal power plant. The site is located off the coast of the Welsh island of Anglesey, a place called The Skerries (see figure 30). The power plant may go into operation between 2011 and 2012, depending on the governmental approvenments.

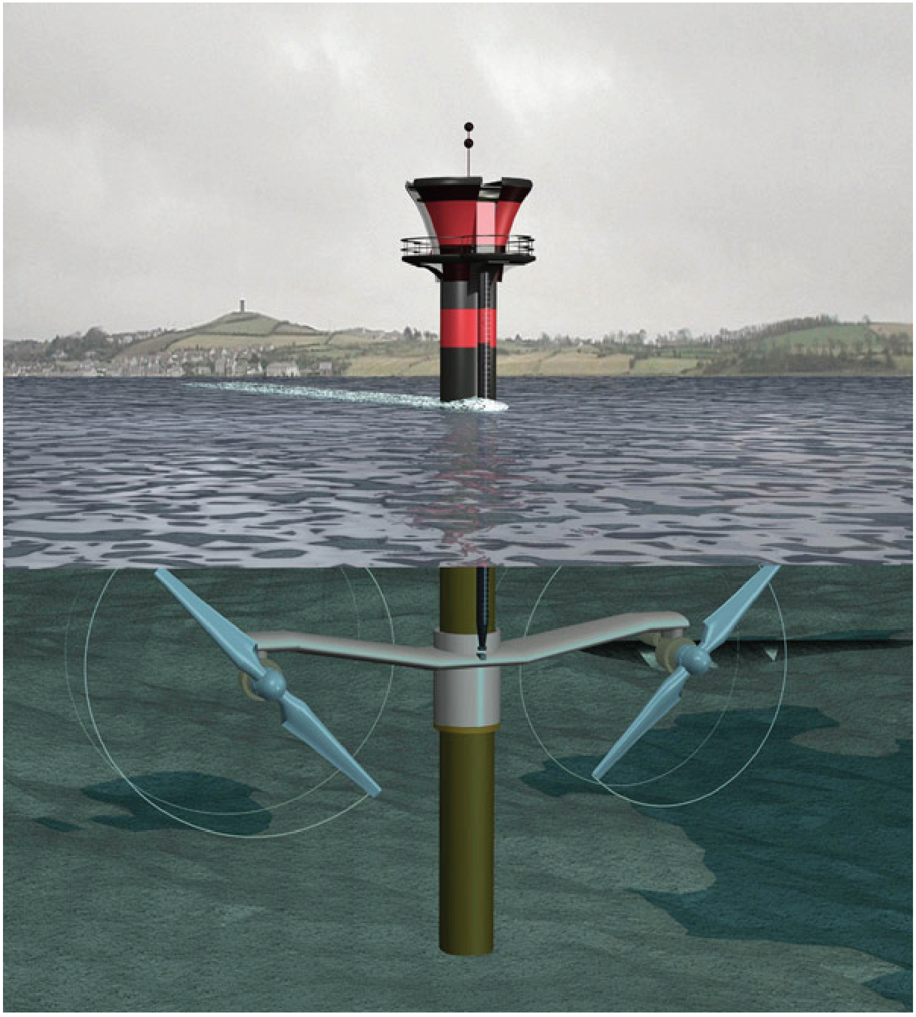

Figure 29: Illustration of the SeaGen tidal turbine. (Source: MCT)

5.3.4. Potential

According to a report from Marine Energy Group in 2004, the 5 sites in Scotland with the largest tidal current potential can have an installed capacity of about 2,3 GW within 2020, producing over 6 TWh/year. Pentland Firth is with its almost 5 TWh tidal energy production potential the most interesting site in Scotland [23].

As the UK has the most tidal stream potential in Europe and there is political will to subsidize renewable power, it is very likely that we will se larger tidal power plants in the near future here.

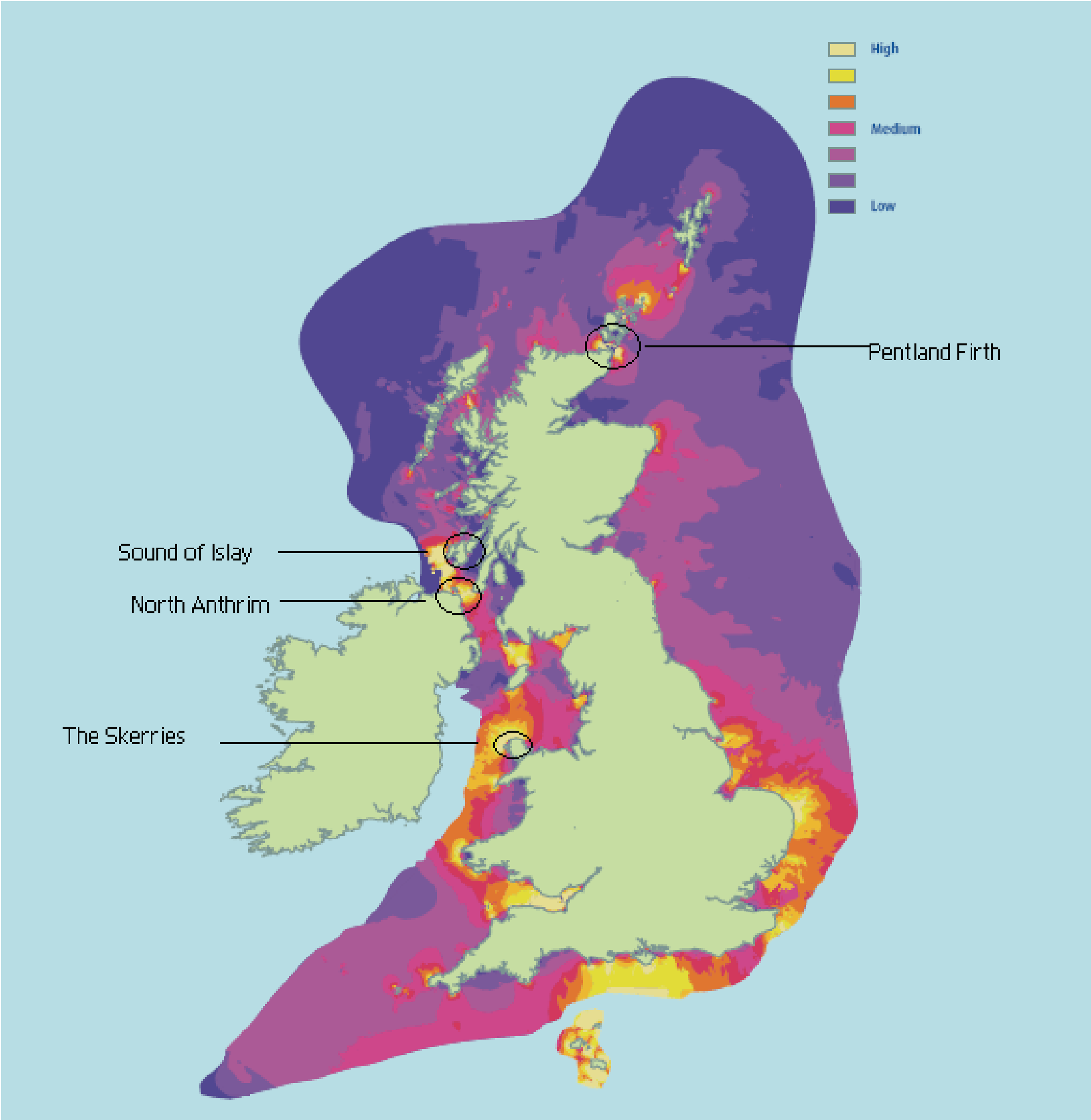

Figure 30: Tidal power potential in the UK, lighter colors show the best sites. (Source: 'Turning the Tide', 2007)

5.3.5. Special considerations

Even though the visual impacts are low, there are other aspects that have to be taken into consideration regarding tidal stream power:

- Current speed – a certain speed is needed to get some effect out of the turbines
- Impacts on the fishing industry
- Potential conflicts with ship traffic
- Impact on the marine life

6. Discussion

6.1. Planned offshore installations

Total planned wave and tidal power combined is still a lot less then one medium sized offshore wind park. However, it is important that the development continues, and every power plant contributes in a positive way. For the future, there may be developed floating wave and tidal energy constructions, which then may be installed close to or within wind farms, enabling use of the same cable system to the shore.

Wind farms however, are the major issue. The more the merrier. For future purposes, as the floating wind turbine constructions have been tested out, and may be competitive in price. Advantages are that they can be placed on deep water, regardless of seafloor structure and also may be placed exactly where the impacts for the fishing industry, as well as the ship traffic is low. They can be assembled close to the shore, shaded from harsh weather, and dragged into place. This might reduce the installation time and costs, as the weather only has to be fair as the turbine is dragged into place and anchored.

As the amount of planned offshore wind parks in Europe, especially in the North Sea, is so huge, there will be interesting to see what kind of transmission technology and solutions that will be used. Due to cable and substation costs, a contractor will usually not build and lay a cable system for a wind park with a larger capacity than needed. However, as transpower strohmübertragung gmbh in Germany is given full responsibility for all offshore transmission systems, they have to consider all planned installations and find the total optimal transmission solutions [24].

6.2. Offshore wind power transmission scenarios

6.2.1. Each power plant connected with own cable

This solution is likely to occur when the wind park developer is responsible for transporting the power produced to an onshore substation. For wind parks close to the shore, with a relatively short distance to an onshore connecting point/substation, this is likely to be the chosen alternative. This also goes for single wind parks where no other installations are planned in the area, regardless of the distance to the shore.

6.2.2. Clusters

Most of the wind parks planned in the North Sea are placed close to each other, within a designated area given by the responsible authorities. This enables the building of larger transmission systems, connecting the respective wind parks with an offshore substation and using a shared system to the onshore connection point/substation. Using shared cables systems to the shore is probably the best solution for this situation. It will reduce the total costs with cable production and installation, as well as costs regarding the offshore substation(s).

6.2.3. Clusters leading to one major transmission line

As wind parks close to the shore will have a certain distance between them, the most probable solution here is either building a new substation at a suitable location or laying each cable directly to an already existing substation further in on the main land. These wind parks will use AC transmission, so no converter stations will be needed.

Especially for the several wind parks planned a long distance from the shore, one solution in order to transport the power in a neatly to the shore is using cluster platforms between wind parks, transporting it to a mutual collection point. Setting up another substation at this point, making a 'power super highway' to an onshore substation might be the most effective total solution. In order to do this, the parts responsible for the transmission solutions to the shore in the respective countries will have to collaborate concerning where the collection point will be, the size of the installation, chose of technology and who will take the costs.

6.2.3.1. Transmission solutions

The transmission technologies that might be used for such a solution are:
- Thyristor-based HVDC
- IGBT-based HVDC
- Gas Insulated Lines (GIL)

6.2.3.1.1. Thyristor-based HVDC

Thyristor-based HVDC can handle the largest amounts of power pro system and has the cheapest system costs. However, as a thyristor based converter station require a lot of space, it is not likely to be used. Costs for offshore work and building the required platforms needed, makes the installation size important for the choice of transmission technology.

6.2.3.1.2. IGBT-based HVDC

This technology can today only handle about 60% of the power pro system compared to a thyristor-based system. The advantages using IGBT systems over thyristor-based systems are on the other hand significant. The main reasons for choosing this technology are:

- Half the size of a thyristor-based system, reducing platform size
- Less need for filtering components
- Can be used for black starts
- Can control and regulate active and reactive power independently
- Module-based system, reducing offshore installation work

All in all, the advantages using IGBT-based HVDC over long distances are so significant that there are reasons to believe this is the only HVDC technology that will be used for connecting offshore wind parks to the mainland. This goes for transporting power from a single wind farm, from a cluster or from several clusters connected together.

6.2.3.1.3. Gas Insulated Transmission Lines (GIL)

The GIL Offshore transmission system is planned to have a capacity of 4000 MW each, and two such systems will be enough to transport all the wind energy planned in the German part of the North Sea to the shore. The advantages are that it is an AC system, with losses far lower than AC XLPE cables. (Source: Siemens intern documents) The systems would be laid underneath the sea floor with concrete on top, minimizing the environmental impact and potential damages due to anchors from ships [25].

The largest disadvantage is that the investment costs are very high [24], and that the whole system would have to be build at once, before the planned offshore wind parks goes into operation.

6.3. HVDC transmission lines between countries with offshore connection point

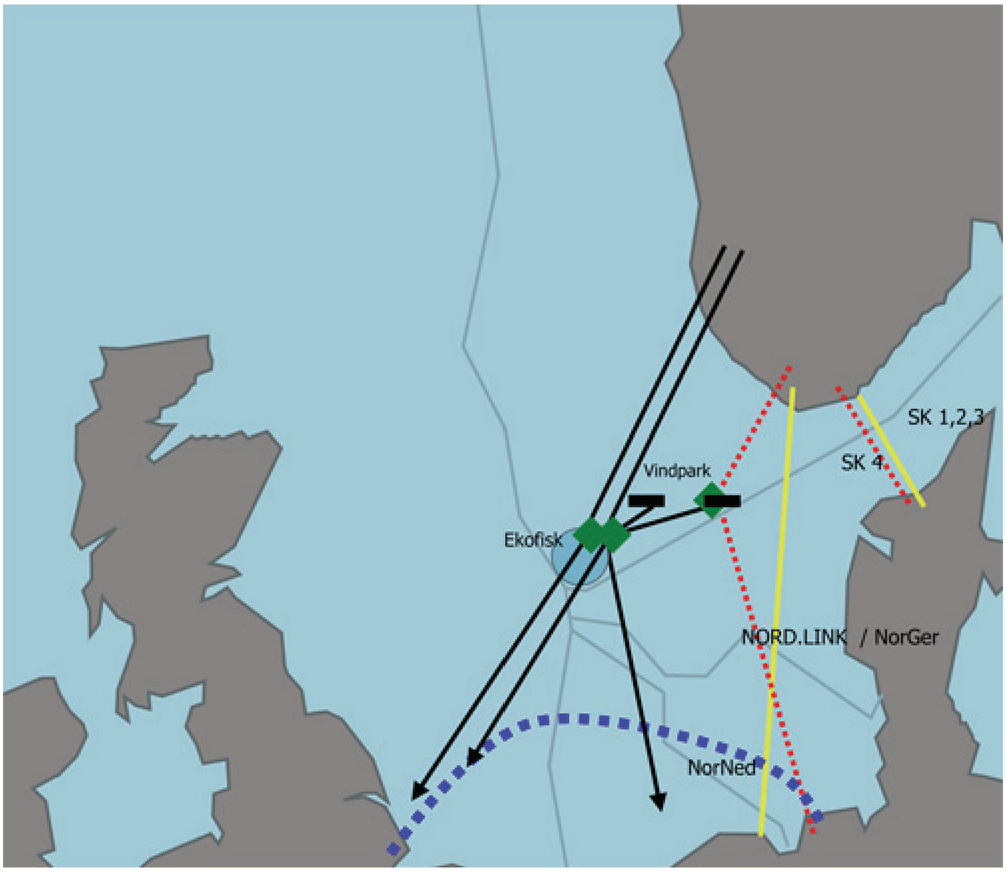

Figure 31: Illustration of potential offshore grid solution. (Source: Statnett)

There will be build more transmission lines between the countries surrounding the North Sea, and one solution in order to transport the wind power to where it is needed for the moment, is connecting the transmission lines with an offshore platform. This will reduce the length of cable from the wind park(s), and reduce the transmission length from where the power is produced to the country that imports the power at the time.

6.4. Potential development of transmission technologies

The transmission technology companies are always looking to improve their cables and systems in order to meet the future demands. For AC XLPE cables, it means improving both maximum voltage level and distances in point to point transmissions. For offshore wind parks, it means the future potential of using HVAC transmission at longer ranges than the technology of today can deliver. This will exclude the need for some expensive offshore and onshore converter stations.

Companies such as Siemens and ABB offer today IGBT-based HVDC solutions up to 1200 MW. It is not unlikely that within a five-year period the maximum capacity will increase to around 1500 MW, strengthening the already tight grip as the best offshore HVDC transmission solution.

7. Conclusion

Concerning the transmission technologies, HVAC will still be used for wind parks close to the shore, as the converter stations are expensive and give unnecessary losses. For wind parks further away from the shore, IGBT converter technology will be the only technology used for the HVDC transmissions. This is because of all the technical advantages it has over thyristor-based converter technology and will be used for both single wind parks and cluster solutions.

Building one large transmission system for transporting very large amounts of wind energy to the shore will most likely not be executed. The reasons are mainly the high investment costs and the uncertainty considering if all planned offshore wind parks also will be build.

The only country that has the potential to build such a transmission line is Germany, as transpower strohmübertragung gmbh has the complete responsibility for all offshore transmission lines, considering choice of technology, building the system and managing it afterwards.

Based on the amount of planned wind parks and their installed capacity, it is likely that the goal of 40 GW installed wind power capacity within 2020 will be reached. This is necessary in order to reach the EU's target that 20 per cent of their energy supply is to come from renewable energy sources within year 2020.

Wave and tidal energy installations will also be built, but the energy contributions compared to wind power are insignificant.

Figure 32: Photo of Horns Rev 1 Wind Park. (Source: Dong Energy)

References

[1] European Wind Energy Association. Wind Energy – The Facts 2009.
[2] European Wind Energy Association. Offshore Wind Statistics January 2009a.
[3] www.alpha-ventus.de Alpha Ventus Fact Sheet revised August 2009.
[4] www.sheringhamshoal.com .
[5] ABB. Grid connection of offshore wind farms – NordE.ON 1.
[6] Marine Current Turbines. Projects – The Skerries.
[7] www.hammerfeststrom.com .
[8] F.Precopio. The invention of chemically cross linked polyethylene (1999).
[9] H.Hampton. Long-life XLPE Insulated Power Cable (2007).
[10] ABB. The history of HVDC transmission.
[11] Nexans. www.nexans.no .
[12] Siemens AG. GIL Buch (Siemens internal document).
[13] IEEE Substation Committee – GIS Subcommittee. GIL Applications (2008).
[14] A.J. Brand. Offshore Wind Atlas of the Dutch part of the North Sea (2008).
[15] Mohan, Underland and Robbins. Power Electronics – Converters, Applications and Design, Third Edition (2003).
[16] ABB. It's Time To Connect – Technical description of HVDC Light technology.
[17] Siemens AG. The Smart Way – HVDC PLUS – One Step Ahead.
[18] Clipper Windpower. www.clipperwind.com .
[19] Deutsche Bundestag. Act on granting priority to renewable energy sources, section 1.
[20] www.pelamiswave.com
[21] World Energy Council. Renewable Energy Resources: Opportunities and Constraints 1990-2020 (1993).
[22] www.scottishpowerrenewables.co.uk
[23] Marine Energy Group. Harnessing Scotland's Marine Energy Potential, MEG Report 2004.
[24] www.transpower.de – Projects
[25] Siemens AG. GIL Offshore internal document