An Introduction to High Voltage Direct Current (HVDC) Underground Cables

Brussels, 10 October 2011

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1. Introduction

Europe's electricity infrastructure is key to enable the European Union to deploy its renewable energy sources. In addition to upgrading and expanding the existing Alternating Current (AC) grid networks, there will be an increasing need to build "electricity highways", creating a powerful and reliable backbone structure for Europe's electricity supplies. Direct Current (DC) technology is appropriate when considering a long distance overlay net. With this paper, Europacable seeks to provide an authoritative source of information about DC underground cable technology.

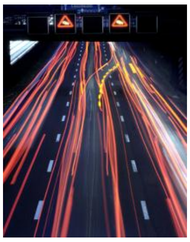
2. HVDC Transmission Technology

High Voltage Direct Current (HVDC) transmission lines are mainly applied when there is a need to transport high electrical power over long distances overland and/or in a controlled manner.

So far, HVDC transmission has mainly been used in submarine applications, either connecting offshore wind farms to land or transmitting electricity over long distance through the sea where overhead lines cannot be used.
This said, HVDC cables are beginning to be used also for land transmission projects. As higher power loads need to be transported over long distances across land, more and more thinking goes into creating HVDC "electricity highways".

Furthermore, HVDC is a proven technology for transmission projects that interconnect asynchronous networks.

Today, two HVDC land transmission technologies are used to carry electricity over long distances:



- HVDC overhead lines to carry high power (>1,000 MW) over distances above 200 km;
- HVDC underground cables to carry medium and high power (100 MW – 1,000 MW) over distances above 50 km.

These two transmission technologies are compatible and can be combined. The transition from the overhead line to the underground cable is realized via a transition connection installed in a transition yard.

HVDC undergrounding can safely transport high power loads over long distances with minimal losses. In addition to this transport efficiency, only a limited number of cables are required, hence allowing narrow trenches. Therefore, Europacable believes that undergrounding of HVDC transmission lines should be considered as a technology option available today.

While the cost factor for the HVDC cable is only to 2 – 3 compared to HVDC overhead line of the same capacity, the **converter stations** required to connect to the AC system entail significant investment costs. These need to be considered when seeking to integrate a DC link into the existing meshed AC systems in Europe.

The creation of a wider European HVDC grid system is today limited by the non-availability of circuit breakers, so called **switchgear**, which secure the operation of the meshed HVDC system. The development of this circuit breaker technology is currently being finalised.

2.1. HVDC Underground Cable Technology

High Voltage Direct Current (HVDC) underground cables have been in commercial use since the 1950's. Today, two HVDC cable technologies are available[1]:

- **Single core mass impregnated cables:**

This type of cable is currently the most used. It has been in service for more than 40 years, has proven highly reliable and can be provided by European manufacturers at voltages up to +/- 500 kV and 1600 A DC which corresponds to a maximum pole rating of 800 MW (presently in service) and bipole rating of 1600 MW. Conductor sizes are typically up to 2500 mm^2 (at transmission capacity of 2000 MW bipole).

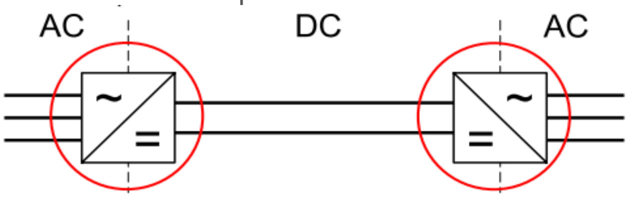
- **Polymeric cables, e.g. XLPE:**

Polymeric cables are only used in Voltage Source Converters applications that allow the power flow to reverse without reversing the polarity.
To date this technology has only been applied at voltages up to +/- 200 kV (in service with a power capacity of 400 MW). There are projects at an advanced construction stage at the voltage of +/- 320 kV and 800 MW power and ongoing projects at 1000 MW per bipole, but it is expected to increase the voltage and power in the near future.

2.2. HVDC/ HVAC Converter Technology

Due to the fact that the current electricity transmission and distribution networks in Europe are based on AC systems, converter stations are required to convert the DC current and voltage to AC and vice versa.

Basic concept of HVDC Conversion:



Source: REALISEGRID, 2011

For the converters, two different technologies are available:

Source: Siemens HVDC VSC Converter Station

- **Line Commutated Converter (LCC) Technology**
  Also called CSC Current Source Converter, has been in existence for several decades. This technology requires the connection of two active power points at either side of the link;
- **Voltage Sourced Converter (VSC) Technology**
  This technology has been in commercial use since 1999. Contrary to LCC, it can also be applied for linking isolated networks to the grid, e.g. supply power from generation sources like wind power or to remote islands. Recently developed, compact VSC Multilevel Converters which have lower transmission losses are likely to be the converter type of the future.

[1] Self-contained fluid filled (SCFF) cables have also been used for very high voltage and short connections due to the hydraulic limitations.

History of HVDC Underground Cables:

- **1880**: Started what is known the "war of current" between George Westinghouse (supporting AC) and Thomas Edison (supporting DC) . DC survived for 10 years, with the first +/- 2 kV DC underground cable being installed from Miesbach to Munich, Germany, covering 57 km in 1882. However, the use of transformers in the late 1880's led to AC becoming the network concept in the world.
- **1950's:** Introduction of valves makes converters available and submarine paper cables come into operation at voltages < +/- 300 kV – many of which are still working today, for example
  - Vancouver Island Connector: 1969, +/- 300 kV, 156 MW, 3 cables 27 km each;
  - SACOI linking Sardinia, Corsica and Italy:1956, +/- 200 kV 100 MW, 2 cables each 118 km
  - Skagerrak 1 linking Norway to Denmark: 1976, +/- 263 kV, 250 MW, 2 cables each 125 km
- **1970's: I**ntroduction of electronic switch "thyristors" makes DC paper cables technology with voltages up to +/- 500 kV widely available
- **1998:** First XLPE DC cable in Gotland, Sweden connects an offshore windfarm +/- 80 kV, 50 MW, 2 cables at 70 km each
- **2002:** Murray Link in Australia covers 320 km underground at +/- 150 kV
- **2011:** France – Spain INELFE (Interconnection électrique France-Espagne), 2 circuits 2000 MW, +/- 320 kV, 4 cables 64 km each (under construction)
- Today, some 1,000 km of HVDC cables are in operation in Europe.

3. Use of HVDC underground cable technology

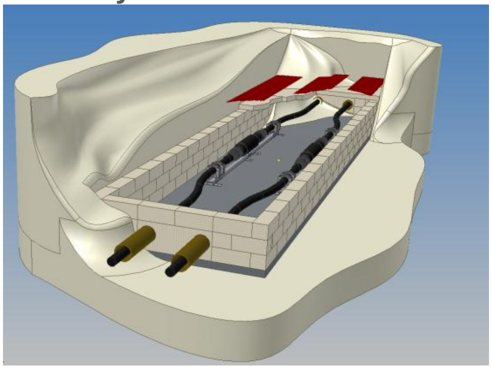
HVDC cable length and cable transport

- For land use, the HVDC cable length is limited by logistical constraints regarding transport, access and installation. Consequently, the maximum length is dependent on the cable diameter and weight. Typically, HVDC cables are delivered in a length exceeding 1,000 meters.
- HVDC cable drums are usually transported by road or by rail, with a common load capacity of up to 40 tonnes.

Installation of HVDC cables

- HVDC cables can be directly buried into the ground or installed in tunnels, ducts or pipes to respond to requirements from surroundings, and/or to enhance protection against external damage.
- The HVDC cable is surrounded by a sand blending, in some cases by a mixture of sand and weak cement.

Joint Bays



- Cable sections are linked by so called joint bays. These two phase joint bays typically are around 10m by 2.5m by 2.1m depth. The location of the joint bays is part of the design to allow access.
- Joint bays can be directly buried into the ground, surrounded only by a sand blending. If required, joint bays may be placed into an underground structure.
- There is no or only little visibility of these installations above ground.
- Developments in premolded joints and terminations technology make the erection of joints on site easier, shortening the time needed to complete the joint bay's installation.

Transition to HVDC overhead line

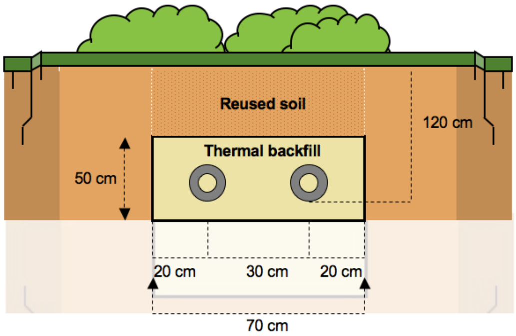
- The connection of the HVDC underground cable to the HVDC overhead line can be placed in a small transition yard.

4. Environmental aspects of HVDC underground cables

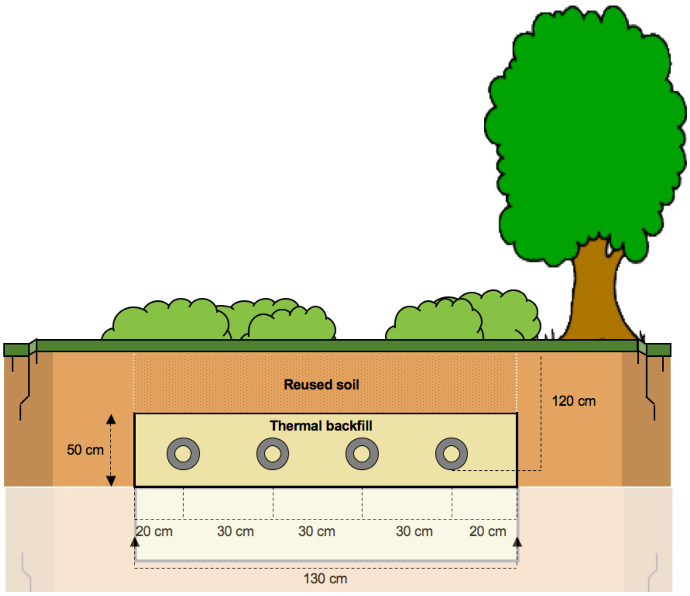
Trench width in directly buried cables

- HVDC underground cables are typically installed in a circuit comprising 2 cables (bipole installation).
- Each bipole is laid in a trench approx. 1 to 1.5 meters deep and 1 meter wide.
- If more bipoles are required, the distance between them would be of approx 4 meters in order to avoid any thermal interference. If two circuits are required the width would not exceed 10 meters.

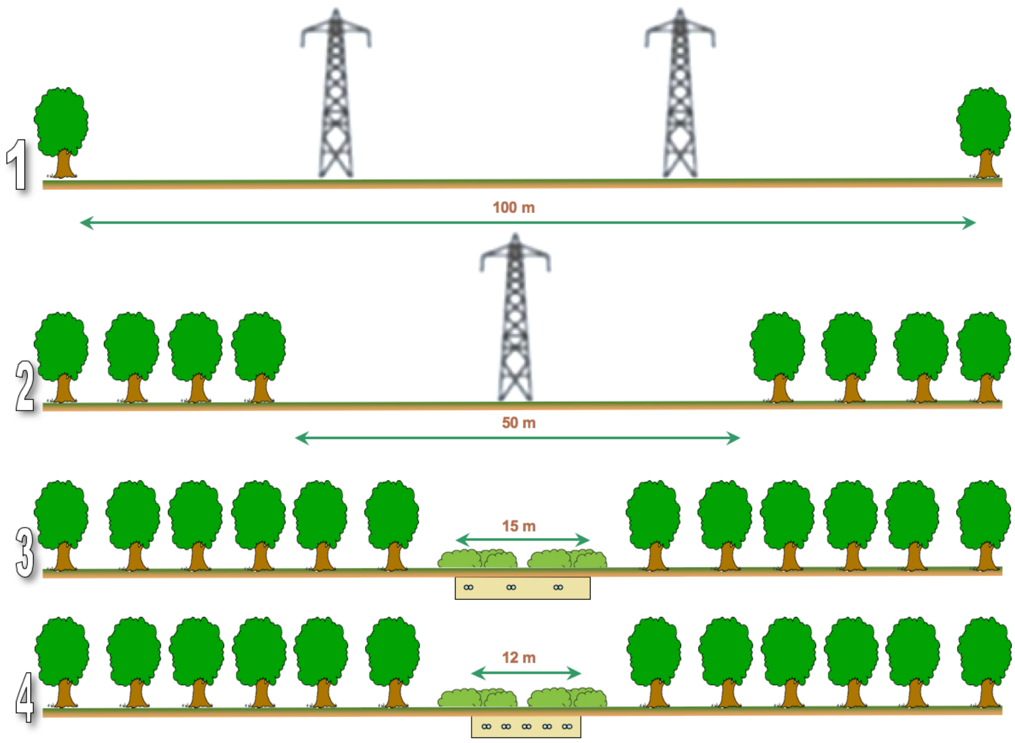
1) HVDC: 1 Bipole, 320 kV, 1 GW



2) HVDC: 2 Bipole, 320 kV, 2 GW



3) Possible layouts to fulfill HVDC 5 GW power transmission requirements



1) Overhead line at 600 kV - HVDC
2) Overhead line at 800 kV - HVDC
3) Mass impregnated cables and LCC technology: 3 bipoles at 500 kV - HVDC
4) Extruded cables and VSC technology: 5 bipoles at 320 kV - HVDC

Use of land

- The only restriction on the use of land over an undergrounded section is that no deeply rooted trees may be planted within the corridor width plus a margin of about 2 meters to prevent root encroachment into the cable trench. Apart from that there are no limitations to cultivation, including agricultural farming.(see picture above)
- The laying depth of the cable systems has to be sufficient to avoid any damage to the cable trench and cables themselves by agricultural activities above the cables. The corridor must be kept free from any buildings.

Electro Magnetic Fields (EMF)

DC power transmission, via underground cable, generates very low frequency magnetic fields in the range of 50 micro-Tesla, which is in the same order of magnitude of the natural static magnetic field. The ICNIRP Recommendation "*Guideline on limits of exposure to static magnetic fields 2009*" recommends public exposure limited to 400 milli-Tesla. As the HVDC EMF value is 8,000 times lower than the accepted threshold, there is no risk to human health.

Possible heating of ground

- During operation, the temperature of the cable will rise dependent on the current carried and load factor. Heat distribution to surrounding soil depends on the backfill material.
- The impact of heat release on soil temperature is strictly local and very limited.
- An RTE Study 'Environmental impact of underground links across fields' (Jicable 2011), examined 2 lines of +/- 63 kV and +/- 90 kV under certain flow conditions, witnessing an increase of 1°C above the line at 1m depth. The study concluded that "*such little temperature increase cannot trigger a negative effect on crops growth. A slightly positive effect can even be considered. This result is consistent with the limited impact of the line on the crop yields*."
- From Europacable's view, this finding can be considered conservative if used as a reference for HVDC. However, it should be noted that at present, no specific scientific data is available for a HVDC cable installation.

Environmental impacts during installation

Installation of +/- 400 kV HVDC cable Italy Greece

- Civil works required to underground a HVDC line may have a considerable impact on the environment. Heavy machinery will be required for trenching as well as for delivery of cable drums. During the construction period, access tracks and haul roads are required to the site. These are removed following the completion of the works but there will be a need to consider on-going requirements for operational access.
- Waterways or particularly sensitive areas can be crossed by applying directional drilling techniques to install the cable. Distances exceeding 1 km can be crossed. These sections often determine the rating of the line or the size of the cable.
- In most cases, the cable system is directly buried hence 70% - 80% of the soil can be re-filled into the

trench. For the period of construction the soil can be stored alongside the trench. Up to 30% of backfill material has to be transported to the trench and the equivalent soil will be transported away from the site.

- Depending on the type of vegetation, the landscape is usually reinstated within 18 – 24 months. The surface vegetation above the installation is managed to ensure no root encroachment for the life time of the cable system.

5. Availability of HVDC undergrounding

Availability of technology
Today, mass impregnated HVDC cables are available up to +/- 500 kV at 2,000 MW and XLPE HVDC cables up to +/- 320 kV at 1,000 MW. Increases in voltage and capacity can be expected in the near future.

As regards other components required for an HVDC system, converter stations are fully available. The development of circuit breaker technology, so called switchgear, is currently in its final phase. It is expected that this last bottleneck, which will secure the operation of a future meshed HVDC system in Europe, will be removed in the near future.

Operational experience & Life expectancy
Generally speaking, the production process for extruded HVDC cables is similar to that of extruded EHV AC cables. Manufacturers have hence been able to build on the experiences gained in AC production over the past 40 years. What differentiate an extruded DC cable from an extruded AC cable are the materials used, the testing methods applied as well as the selection of the accessories. Also it needs to be stressed that every single HVDC project is unique and needs to be designed on a case-by-case basis.

Specifically:

- HVDC mass impregnated cables have a long operational experience as they have been in use in submarine application for at least 40 years. On land, they are a proven and reliable transmission component.
- HVDC experience with XLPE cables is limited in service up to +/- 200 kV since 2002. This said, CIGRE recommendations are available to set stringent and validated criteria for the evaluation of the quality and reliability of XLPE cable systems up to +/- 500 kV. XLPE HVDC cable systems up to +/- 320 kV are currently under construction in the European TEN-E France – Spain Interconnector (INELFE).

Transmission system operators require a minimum life expectancy of 40 years. HVDC cables meet this objective complying with CIGRE recommendations.

6. Reliability of HVDC undergrounding

Reliability

As HVDC cable systems are a relatively new transmission technology, evidence based data regarding long term reliability is not yet available.

However, HVDC cables installed comply with the CIGRE Technical Brochure 219 which defines testing criteria for the qualification of extruded HVDC cable systems up to +/- 250 kV. The publication of a new CIGRE Technical Brochure for extruded HVDC cables up to +/- 500 kV is expected in early 2012. Mass impregnated HVDC cables are covered by CIGRE recommendation as reported in ELECTRA 189 up to the voltage of +/- 800 kV.

Generally speaking, HVDC cable systems are carefully checked before delivery and commissioning:

- Following production the HVDC cable and all system components undergo a thorough verification procedure, routine tests, to confirm compliance with homogenous quality according to international standards.
- Following installation, the cable system is subject to a commissioning test to confirm proper installation.

Once in the ground, the HVDC cable system is safely in place and well protected against any external weather influences. As any important infrastructure, undergrounding solutions shall be carefully designed to be protected against extreme weather conditions (e.g. floods, landslides, avalanches, etc). Monitoring systems allow close tracking of cable performance to ensure no overheating of the cable system.

Failure

As of today, there is practically no experience with failures of land HVDC cables due to the recent nature of their application. This said, in submarine applications, HVDC cables have proven to be a reliable technology: submarine paper mass impregnated cables have been in use for more than 50 years and XLPE HVDC submarine cables for 10 years. Compared to submarine applications, land applications will entail the same cable systems, with the key difference of more accessories such as joint bays.

In order to accompany the introduction of XLPE HVDC cable technology into the market, Europacable strongly recommends strict compliance with pre-qualification requirements as defined by CIGRE recommendations. As seen from experience to date, strict compliance with pre-qualification requirements issued by CIGRE expert committees will lead to the introduction of reliable transmission technology.

Repair time

In the absence of field experience, repair parameters will be similar to that of EHV AC cable installations.

Down times are consequently affected by:

- Safe access to site
- Time for TSOs and, if required, independent experts to undertake a thorough investigation to assess the reasons behind a failure; in exceptional circumstances this can last several months
- Decisions on counter measures to prevent future failures
- Availability / ordering / delivering of spare parts (recommended to hold stock)
- For XLPE HVDC land cables, repairs and testing itself can be conducted in less than 3 weeks. For mass impregnated HVDC land cables slightly longer times might be needed to insert joints.

7. Integration of HVDC undergrounding into AC transmission networks

Integrating HVDC cables into AC transmission networks offers the following advantages:

- Simple and efficient control of power flow
- No disturbance among the connected network in the event of failure
- No impact to short circuit current
- Interconnection of non-synchronised networks
- Additionally, VSC technology can feed load disconnected by any other network and can help to restart an AC network after a blackout.

8. Cost Aspects of HVDC undergrounding

Overall considerations

Respecting EU competition requirements, Europacable can only provide general statements regarding cost factors of HVDC undergrounding.

Also each project is unique and a full macroeconomic assessment of the cable system should be made that takes into consideration installation costs, life costs, maintenance costs, impact on land / property, environmental protection etc.

Experience of HVDC underground cabling and their cost is currently limited. Based on analysis conducted by Realise Grid[2] in 2010, the cost of HVDC underground cables (two cables, +/- 350 kV, 1,100 MW) is between 1 – 2.5 million euros per km. With that, the cost factor for HVDC underground cables compared to an HVDC overhead line is 2 – 3 times.

Whether HVDC cable or HVDC overhead line, the considerable investment cost for the converter stations required to connect the DC system to the AC transmission grid have to be taken into account.

Consequently, the cost factor for a HVDC cable system compared to a HVDC overhead line system will be considerably lower than the above mentioned factor of 2-3. Example:

Total Cost HVDC Overhead Line	Total Cost HVDC Underground Cable
• Cost for transmission technology: 100 • Cost for converter technology: 300 • **Total Cost: 400**	• Cost for transmission technology: 300 • Cost for converter technology: 300 • **Total Cost: 600**

- Cost factor for transmission technology only of a HVDC cable compared to HVDC overhead line: 3
- Cost factor for total system: 1.5

Principally, Europacable believes that the following two dimensions should be taken into account:

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[2] RealiseGrid footnote reference needed!!

Cost of installation:

- The cost of a HVDC cable system will depend on the specific requirements defined for the system. In addition to the cable itself, accessories like joint bays, transition station, converter stations etc. need to be taken into account. Generally speaking, due to the complexity of the technology, installation costs of an HVDC cable solution per km will always be higher than an equivalent distance of overhead line.
- Up to 60% of the installation costs can result from the civil works required for the installation. These depend on the type of soil that the cable is going to be placed in (sand, rocks etc.) as well as other existing infrastructure the route may cross. Europacable member companies will largely work with local contractors to execute the civil works. The installation of the cable system will be implemented by specially trained personnel.

Cost of operation

- The cost of operation of HVDC underground cable is negligible.
- Once in operation, a cable system itself is nearly maintenance free. As with any transmission corridor, the cable route requires regular inspection to prevent any encroachment. A test with +/- 5 kV DC voltage on the cable metal screen in order to check the outer sheath integrity may be performed every second year for precautionary reasons.

9. HVDC underground and submarine cable systems in operation

To date HVDC transmission has been used on more than 70 projects worldwide. The largest scheme with submarine cables in operation to date has a capacity of 2000 MW, the smallest scheme has a rating of the order of 50 MW.

- **Norned Subsea DC Interconnector**

This submarine cable between Norway and Netherlands uses a bi-pole LCC configuration and comprises two MI (mass impregnated) cables operating at +/- 450 kV with a rating of 700 MW and length of 580 km.

- **SAPEI: Italy – Sardinia Interconnector**

This cable connection between Italy and Sardinia is a +/- 500 kV MI bi-pole and is transmitting power of 1000 MW with LCC technology. The connection is 430 km long and the cable is installed in the sea at the maximum depth of 1650 metres.

- **Fennoscan 2: Sweden – Finland**

Fennoscan 2 is the most powerful MI cable installed today 500kV 800MW per pole. The link length is 200km.

- **TRANSBAY**

Transbay connection in San Francisco Bay and has been in service since 2009. The voltage is +/- 200 kV and the transmission capacity is 400 MW with a VSC bi-pole. The length is 83 km submarine and some 1.2 km land cable underground and is made up of XLPE cables.

10. Projects of HVDC underground and submarine cable systems under construction

- **France-Spain Interconnector (INELFE)**

This 65 km link will be made up of four XLPE cables two bi-poles carrying 2000 MW of power at +/- 320 kV with VSC technology. For the majority of the route the cables will be installed in a concrete trench with a tunnel where the route crosses the Pyrenees.

- **SYLWIN 1**

Is the connection of the largest offshore wind park in the German section of the North Sea. The connection will be a bi-pole with two XLPE cables +/- 320 kV for the transmission of 900 MW of power. The length is 159 km submarine cable and 45 km directly buried land cable.

- **SKAGERRAK 4**

This will be the first VSC connection at a voltage of +/- 525 kV with a monopole MI cable of 700 MW. The submarine part of the cable is 137 km long and the underground directly buried portions in Denmark and Norway are 92 + 13 km respectively.

- **Sweden: Barkeryd-Hurva connection (also called South-West Link phase 1)**

This connection forms part of a large project aiming to build a 3-point DC network between Sweden and Norway. This connection is part 1. The tendering phase is on-going and not too much information can be supplied for confidential reasons. The connection will be made of 2 bipoles carrying 660 MW each.AC/DC conversion will be VSC operating at +/- 300 kV.This connection is roughly 250 km long, 190 km underground and 60 km overhead. Part 2 of the project will connect Sweden and Norway and will be of a similar size.

For further information please visit our website www.europacable.com or contact:
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About Europacable

Founded in 1991, Europacable represents 90% of the European wire and cable industry. Our 42 member companies include European multinationals providing global technology leadership, as well as over 200 highly specialized small- and medium sized producers of energy, telecommunication and data cables. In 2009, the industry had a total consumption of €20 billion in wire & cables resulting in the manufacture in Europe alone of some 38 million km of cables. Europacable is listed in the European Commission’s transparency register under: 453103789-92.