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HVDC Submarine Power Cables in the World

State-of-the-Art Knowledge

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HVDC Submarine Power Cables in the World

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Executive summary

"Offshore Transnational Grids - Technical and Geopolitical Implications" (acronym OTG) is a JRC Exploratory Research Project that runs from 1 January 2015 until 31 December 2016. The objective of the project is to identify and analyse the technical and geopolitical challenges for building an offshore electricity transmission interconnection between Europe and North America.

This science-for-policy report is the first deliverable of the OTG project. It provides an extensive study on the availability of the technologies required for the realisation of a High Voltage Direct Current (HVDC) interconnection between the European and North American Alternating Current (AC) transmission grids.

An introduction on HVDC transmission systems is given. This implies a discussion on the monopolar, bipolar and back-to-back configurations. Also the connection with AC grids, i.e. the converter station, is treated.

Further, attention is paid to the spatial context of laying a HVDC submarine power cable. Information is provided regarding geological and path surveys, subsea bed topography, geological structure and lithology. Geodynamic processes, sea currents, waves as well as temperature and salinity are also discussed.

Technologies and materials used to produce HVDC submarine cables are presented. Different cable types are shown.

Special attention is given to the installation of HVDC submarine cables. Techniques for laying a cable are discussed. Also issues such as protection measures and maintenance aspects are dealt with. The operation of HVDC submarine cable is treated as well.

Reliability and accident risk issues are discussed in a dedicated paragraph as well as environmental aspects.

A complete, comprehensive chapter is spent on existing and planned HVDC submarine interconnectors. Emphasis is given the longest and deepest examples. An extensive list of these cables with relevant data is given in Annex 1.

The report ends with a set of conclusions, primarily pointing at the following steps of the OTG project. Shortly, they are as follows:

- the HVDC submarine power cable technology is now mature;
- the experience in laying the cable on the seafloor is inherited and adapted from the much older technology of telecommunication submarine cables;

- Europe is the leading region in both the length and number of cables having the longest one, the deepest one and one of the most powerful cables; the majority of manufacturers and sea-laying cable operators originate here;
- mass-impregnated cables are the most used but a new generation of extruded cables are gaining field;
- first submarine power cables used a monopolar configuration but the newly built ones are predominantly bipolar.

1. Objectives of the report

Our world becomes more and more energetically hungry. Consumption tends to spread and level across territory but the main sources of energy are likely to remain localized. The growing integration of intermittent renewable sources of energy (wind) even increases the need for transferring electric energy over long distances, which may include sea crossings. One of the solutions available for bulk electric power transmission across large distances encompassing wide and deep water bodies is using submarine power cables. This technology can be considered as already mature with various examples of cables operating reliably for decades. However innovation and development have occurred at a high rate during last years. As more cable lines are under construction and many more are planned the landscape of submarine power cables is increasingly expanding and diversified. It certainly deserves a state-of-the-art study.

The report is the first deliverable of the "Offshore Transnational Grid" (OTG) work package, which is intended to identify and analyse the engineering and geopolitical challenges for building a transcontinental energy interconnection between Europe and North America.

The scope of the report is to examine the present-day technologies used for submarine power cables.

It is particularly intended to offer a picture of the state-of-the-art of the High Voltage Direct Current (HVDC) submarine cables in the world.

The report will not deal however with short distance HVDC power cables that connect off-shore wind farms or oil extraction platforms to the continent. The locations, number and length of these cables are not present in the lists or maps of the report. Nonetheless the lessons learned from building and laying the cable along with technical solutions found are presented in the report.

It is also out of the scope of the report to analyse the economics and power markets that make the cables workable.

2. The power system

2.1 AC and DC

Conventional electrical current may take two forms: Alternating Current (AC) and Direct Current (DC).

AC is produced by placing a coil of wire into a revolving magnetic field. This is the principle used in most of the power plants running today: hydro, thermal (coal, gas, nuclear), wind and tidal. Using one coil results in single-phase AC and using three coils results in three-phase current. Most of the power plants produce three-phase AC. AC flows in one direction for half a period and then switches direction for the next half a period. This continuous sinusoidal oscillation takes place with a certain frequency (the number of cycles occurring in one second). In European grids the standard frequency is 50 Hz.

DC always flows in the same direction. It is produced by batteries, solar cells and fuel cells. There are also DC generators working on the principle of electromagnetic induction but they are not the norm in power production. DC produced in photovoltaic panels (and parks) are turned into AC current and then fed to the grid.

The type of the current has influence on its transmission in respect to the voltage used, the capacity of the line (the amount of transferred power), the maximum length of the line and the intermediate electric equipment used. The advantage of AC over DC is that in AC transformers can be used to step up or down the voltage level. DC current is however more suitable for bulk transmission over long distances than AC where the losses are higher.

2.2 Generation, transmission and distribution

Electricity is produced in power plants and then carried over often long distances at high voltages by the transmission grid, which steps down at the level of the distribution network, bringing the electric power to the consumer (Fig.1).

This is the classical scheme that worked for many decades and still represents the norm for most of the regions in the world. As stated above most of the power plants produce electricity as AC and the entire system uses this current type afterwards since its voltage can be stepped up or down very easily by the use of transformers. Commonly there have always been a rather small number of power plants located close to the energy source (coal mines, rivers) or close to large human settlements, allowing local consumption. Gradually more generation units have been built and linked together using a grid of high voltage lines called the transmission system. Its role is to transfer large quantities of electricity sometimes over long distances in order to equilibrate and stabilize the power system in case of local increase of demand or sudden drop of generation. This management of this task is assumed by organizations called Transmission System Operators (TSOs), in most cases state-owned companies.

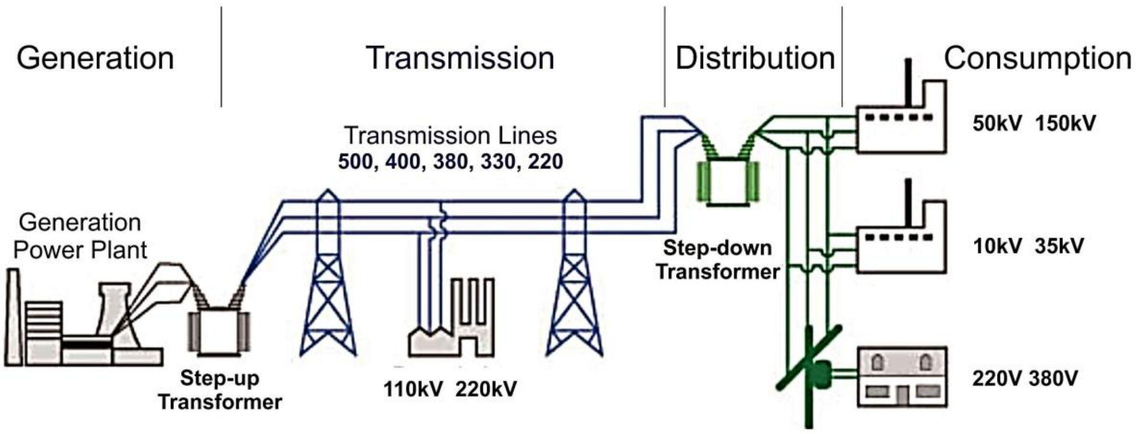


Fig. 1– Generation, transmission and distribution of electricity (Source: suptech.com)

As the consumer uses electricity at low voltage, stepping down the voltage and bringing the electricity in homes, offices or factories is done using a dense network of lines, which compose the distribution system. Distribution System Operators (DSOs) are in charge of operating this level. They can be of private, public national or municipal or shared ownership.

Lately this scheme has started to be challenged by the advent of new technologies and alternative spatial and functional layouts. The rise of renewable sources of energy with high intermittency (wind, solar) and the arrival of the concept of *prosumer* (producer and consumer at the same time) have changed the technical and market landscape demanding new adjustments to the grid. In this scheme large quantities of electric power produced from clean sources might be fed into the grid at moments when demand is low or the same unit (e.g. a house with PV panels) feeds but also takes electricity to/from the grid. For the first case the solution is building the infrastructure for transferring great quantities of electric power over large distances where they might be needed of (e.g. in another time zone or another climate area). For the second case the solution is strengthening the grid in order to cope with bidirectional flows of electricity.

As most of the power plants produce electricity as AC, in order to transmit the power as DC the current must be converted from one type into the other. This is done in converter stations placed at each end of the DC transmission line. The cost benefit of DC over AC is noticeable for lines over 600 km long.

The electric power system is a real time system. This means that the electricity produced is instantly consumed. Actually the need of electricity drives the pattern of generation so that the power plants must be turned on or off accordingly. Electricity cannot be stored "easily" like water or gas so a good management of the network is required.

2.3 Bulk electricity transmission with HVDC power systems

2.3.1 HVDC versus HVAC

There are two main ways for the transmission of large quantities of electric energy over long distances: High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC). High Voltage (HV, including here also Extra-High Voltage – EHV – and Ultra-High Voltage – UHV) is considered to cover the range of 35 kV – 800 kV and even beyond this in the future.

High voltages allow efficient transmission of large quantities of electric power over long distances. The higher the voltage is, the lower the dissipative losses are. These losses also depend significantly on the type of conductor used, the length and the cross section of the line and the type of current (AC or DC). DC flows through the entire section of the wire while AC tends to flow towards its surface, which causes the *skin effect* (Fig. 2). This reduces the "effective" cross section and thus increases the resistance and power losses.

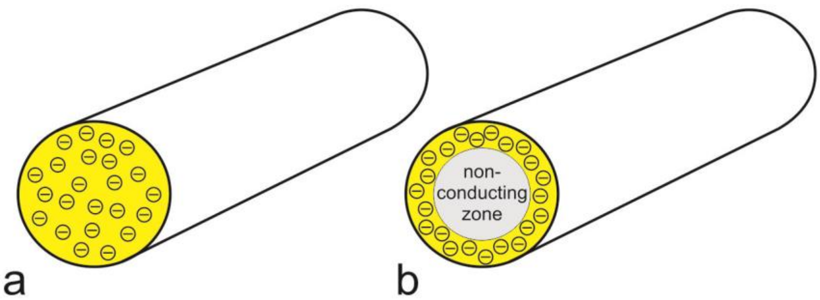


Fig. 2– DC (a) and AC (b) flow in a conductor; the *skin effect*

Two examples of HVAC and HVDC cable losses for comparable lengths and voltages are given in Table 1.

Table 1 – Two examples of losses in HVAC and HVDC power transmission cables

	Length (km)	Power (MW)	Voltage (kV)	Losses (%)
AC	1000/2000	3000	800	6.7/10
DC	1000/2000	6400	800	3.5/5

HVDC cables require also less material since they need only one power line in order to transport electricity. An HVAC link needs three power lines to carry the same power. HVDC lines also use less space for their right of way on land in comparison with HVAC lines. The capacitance between the active conductors and the surrounding earth or water restricts the length of the HVAC cables. If the HVAC cable is too long, the reactive power consumed by the cable would absorb the entire current carrying capacity of the conductor and no usable power would be transmitted.

As most of the countries developed their own electricity grid the distances that must be covered by transmission were and still are in the range of few hundred kilometres. Larger countries (Canada, United States, Russia, Brazil, and China) developed rather regional systems that can function autonomously but having also interconnections between them. In these cases the bulk transmission of electricity is done using the HVAC technology. Overhead lines are used, which are easier to be integrated into existing grids both for constructive and functional reasons, e.g. link with the distribution network and downgrading the voltage. The DC and later the HVDC technology started to be used in power transmission at the end of the 19th century but only few lines and facilities were built, many of them experimental. The trend continued into the 20th century but only in the '70s they gained momentum and became commercially attractive. The improvement of methods and techniques, the advent of new materials and the need to transport electricity over very long distances from large (mainly hydro) power plants to big cities made this technology widespread all over the world, but until 2000 mainly as overhead lines.

The choice for using HVDC for power transmission usually appears in one of following situations:

- transmission of large quantities of electric energy where HVAC would be uneconomical or impracticable or when environmental restrictions apply;
- interconnection between two AC systems that operate at different frequencies or that are non-synchronous;
- improvement of the functioning and stability of an AC system.

Today the HVDC power transmission technology is developing at fast pace permitting transfer of large quantities of electrical power from big capacity power plants, mainly hydro, to big consumer regions across hundreds or thousands of kilometres. The latest examples of such projects include the overhead Xiangjiaba-Shanghai interconnector in China and the Rio Madeira HVDC system in Brazil. The Xiangjiaba-Shanghai line is the world's first UHVDC connection. It operates at ±800 kV and transfers 7200 MW from the Xiangjiaba hydropower plant in southwest China to Shanghai, which is 2000 km further away. It is a single overhead line. The losses are rated at less than 7%. The Rio Madeira HVDC system is the longest transmission link in the world. It carries 6300 MW from new hydro power plants on the Madeira River (Porto Velho) to urban centres in south-eastern Brazil over 2375 km, operating at 600 kV.

As already mentioned above, (U)HVDC is not only used to transport large quantities of electricity over long distances, but it has also other functions and advantages. It is the most reliable solution to connect two AC grids operating at different frequencies or phases (e.g. 50 Hz NE Japan and 60 Hz SW Japan, Nordel, Baltso and UCTE etc.).

2.3.2 HVDC configurations

There are two main configurations for HVDC interconnectors: monopolar and bipolar.

Most HVDC systems also have electrodes as part of their configuration. Electrodes are high capacity grounding systems allowing HVDC systems to still operate when one electrical conductor is out of service. They are an important system for the reliability and the safety of large HVDC interconnectors.

Monopolar interconnectors (Alstom, 2010) comprise a single conductor line while the return path is made through the ground or sea using electrodes (Fig. 3). At each end of the conductor there can be one or more six-pulse converter units in series or parallel. This configuration reduces the costs of a power (submarine) cable both regarding the material used and the work for laying down the cable. It can also represent the first stage of a bipolar scheme (see below). The return path through the earth or sea may raise the problem of corrosion on the metallic objects.

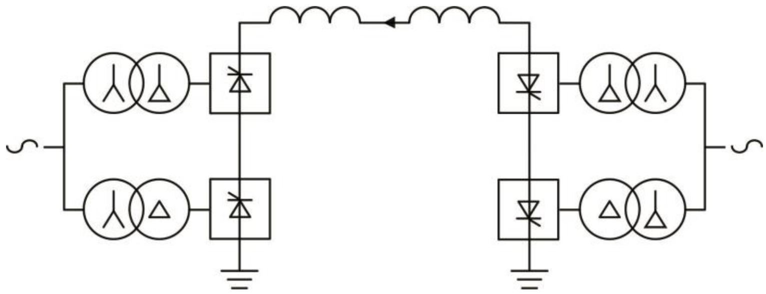


Fig. 3 – Monopolar configuration with earth return (Alstom, 2010)

Environmental conditions can influence the effectiveness of the return path. In some areas the sea salinity may not be high enough or there are fresh water crossings that influence the conductivity. On land there may be areas with high earth resistivity or ground currents that reduce drastically the transfer capacity. In such cases the solution is using as return path a metallic neutral or low voltage cable (Fig. 4). Using a metallic return cable increases the cost of installation and also the losses. It can also represent the first stage for a bipolar configuration.

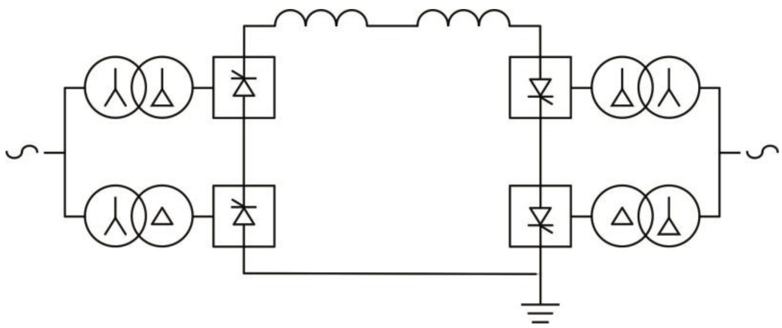


Fig. 4 – Monopolar configuration with metallic return cable (Alstom, 2010)

The bipolar configuration (Fig. 5) consists of two poles with opposite polarity: positive and negative. Each pole includes one or more twelve-pulse converter units linked in series or parallel and has its neutral point grounded. The direction of power flow can be controlled by switching the polarities of both poles.

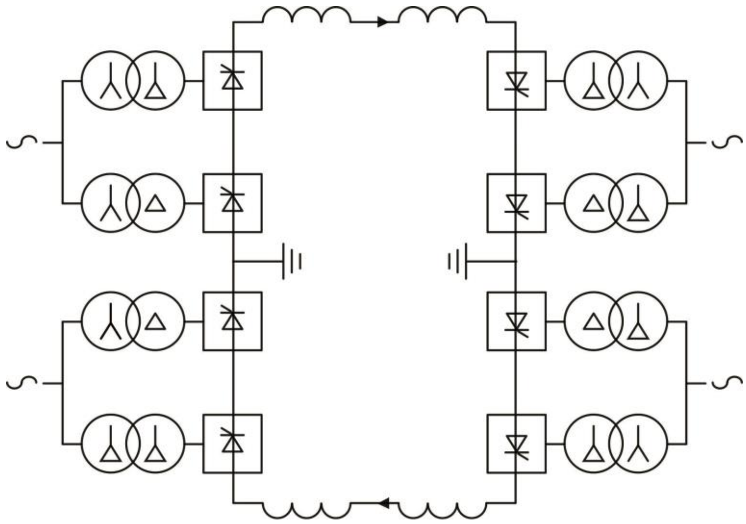


Fig. 5 – Bipolar configuration (Alstom, 2010)

In normal functional conditions the current flows in a loop and no current goes down through the ground so there are no corrosion issues. In case of a failure of one of the poles the other can still function in a monopolar configuration with ground path return. The amount of power transmitted through a bipolar configuration is double of its monopolar equivalent.

A special and more complex type is the multi-terminal configuration (Fig. 6). It consists of three or more convertor stations. It is used for cases when more than two landing points are required in order to enhance the reliability and functionality of the grid. At the moment there are only two HVDC systems in the world with such a design: the SACOI power cable between Italy-Corsica-Sardinia and the Quebec-New England Transmission in North America.

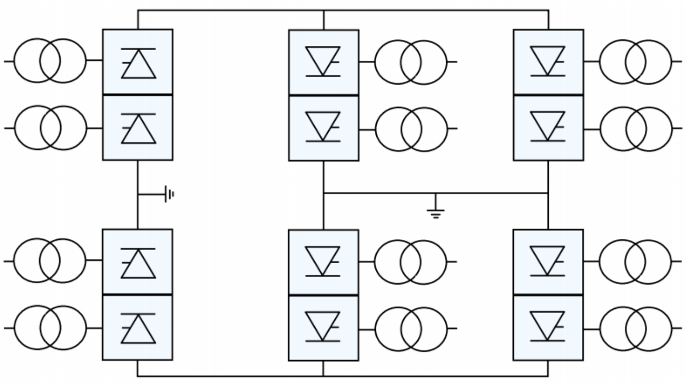


Fig. 6 – Multi-terminal configuration (Kjørholt, 2014)

There are also other configurations of HVDC systems that are used to couple two asynchronous AC systems or two networks operating at different frequencies. These back-to-back systems are special cases of a monopolar configuration with no DC transmission line. Both AC systems are close one to the other and do not necessitate long distance power transmission. The equipment for AC-to-DC-to-AC conversion is usually placed in the same area or building.

2.3.3 Link with the grid: the converter station

Power grids are mostly operating using AC. When there is a need to use DC to transmit power between two AC grids the conversion of AC to DC and back occurs in the so-called converter stations. There is one at each end of the DC line: one that transforms AC into DC to be used in cable (rectifier) and one that transforms DC from cable back to AC to be used in the transmission and distribution grid (inverter). A simplified sketch of such an interconnection is represented in Fig. 7.

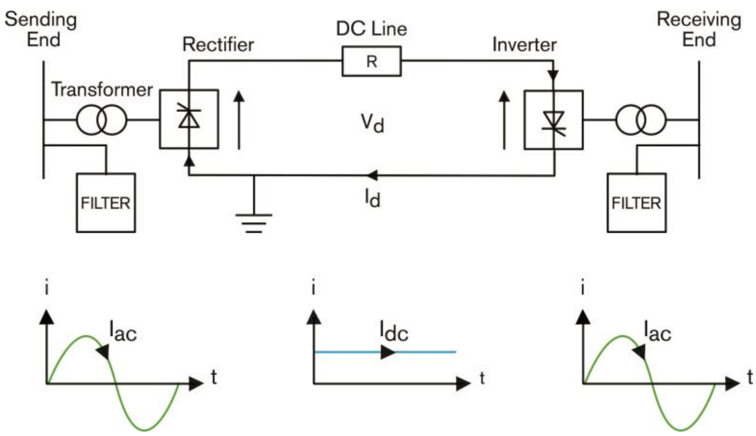


Fig. 7 – Simplified sketch of a converter station (Alstom, 2010)

The converter station can have different layouts depending on the technology, configuration and reliability/redundancy requirements. Its main components are:

- AC switchyard – a set of connectors between AC system and converter; together with the next two components they are usually placed outdoors. Its area depends of the configuration and complexity as well as of the AC voltage level (the higher the voltage, the larger the area).
- AC harmonic filters – circuits that limit the impact of reactive power and AC current harmonics
- High frequency filter – to limit the high-frequency interference that can propagate into the AC system from the converter bus.
- Converter transformer – the interface between the AC system and the thyristor valves.

- The converter – performs the AC to DC or DC to AC transformation; its building block is the six- or twelve-pulse bridge. For protection and safe operation this component is almost always located indoors, in a special area called the valve hall. It is built as a Faraday cage, having a metal screen casing the roof and walls in order to contain the electromagnetic field generated by the thyristor valve function. The thyristors valves are usually suspended from the ceiling with the high voltage at the lowest point of the valve and the low voltage at the highest point. The distance between the floor and the valve acts as an air insulator. The thyristor valves consist of many series-connected thyristors in order to control the voltage. The thyristors used for HVDC are amongst the largest produced and are the most expensive. Depending on the converter station complexity there can be thousands of thyristors needed.
- DC smoothing reactor – smooths the DC wave shape, reduces the losses and improves the performance.
- DC filter – limits the amount of AC harmonic current flowing in the DC line.
- DC switchgear – contains disconnectors and earth switches used in case of maintenance or reconfiguration.
- DC transducers – measure the DC voltage and current.

A simplified layout of a converter station is illustrated in Fig. 8.

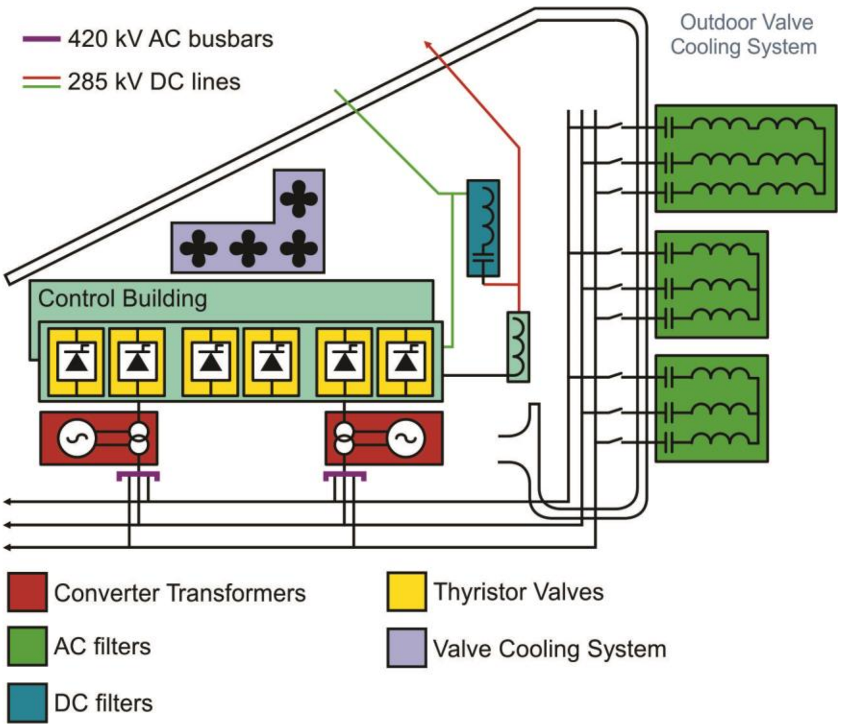


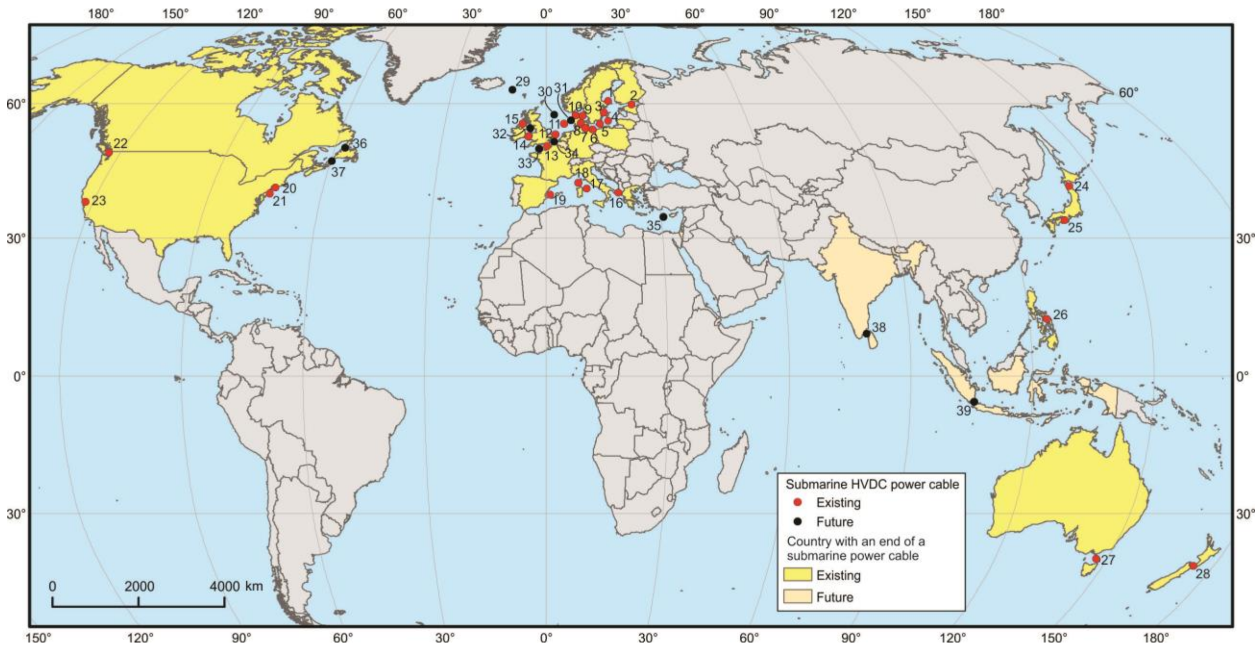
Fig. 8 – Simplified layout of a conversion station (Alstom, 2010)

The equipment inside a converter station produces a lot of acoustic noise under operation (>80 dB), so special attention is given to the insulation and equipment layout.

3. HVDC submarine power cables in the world

3.1 Geographical distribution

Expanding communication and ending isolation made sea divided regions to come into contact by laying down cables to connect their communication and power networks. At the moment there are almost 8000 km of HVDC submarine power cables in the world (Fig. 9) but the total length of cables laid down on the seabed reaches a staggering number of 10^6 km, i.e. mainly communication cables. However, with the continuous development at the present construction rate, submarine cables will become an ubiquitous element in the power transmission landscape.



Existing HVDC submarine power cables

1. Fenno-Skan 1 and 2
2. Eastlink 1 and 2
3. Gotland 1,2 and 3
4. NordBalt
5. SwePol
6. Baltic Cable
7. Kontek Interconnection
8. Storebælt
9. Konti-Skan 1 and 2
10. Cross-Skagerrak 1, 2, 3 and 4
11. NorNed
12. BritNed
13. Cross-Channel
14. East-West Interconnector
15. Moyle
16. Italy-Greece
17. SAPEI
18. SACOI
19. Cometa
20. Cross-Sound
21. Neptune
22. Vancouver Island
23. TransBay
24. Hokkaidō–Honshū
25. Kii Channel
26. Leyte-Luzon
27. BassLink
28. Inter-Island

Future HVDC submarine power cables

29. IceLink
30. MSNLink and NorthConnect
31. Nord.Link and NorGer
32. UK Western Link
33. IFA2
34. NemoLink
35. Euro-Asia Interconnector
36. Labrador-Island
37. Maritime Link
38. India-Sri Lanka Interconnection
39. Sumatra-Java

Fig. 9 – Submarine power cables in the world

More than 70% of the HVDC submarine cables in the world (both in terms of number and length) are located in European adjacent seas (Fig. 10). Islands close to the shore and archipelago nations are also places targeted by this technology. The vast majority of submarine power cables have a length of less than 300 km. They usually link countries separated by small to medium width water bodies on the same continent or at its fringes. There are a small number of intercontinental links like Spain-Morocco interconnection and the Red Sea Cable (Egypt-Jordan) but they are HVAC interconnectors and run on short distances (up to 30 km).

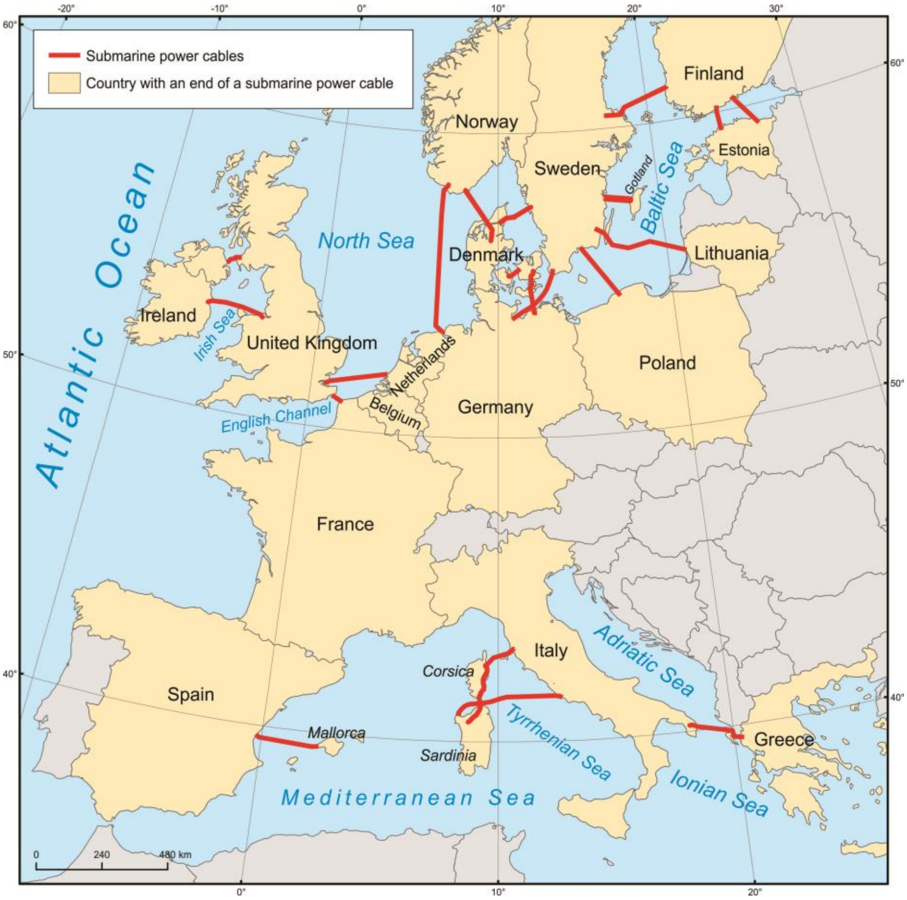


Fig. 10 – Submarine power cables in Europe

The first commercial HVDC submarine cable was built and laid down in 1954 in Sweden by ABB linking the island of Gotland with the mainland. Its voltage was 100 kV and the capacity 20 MW. The length was 90 km. Since then the technology evolved towards higher capacity and voltage as well as towards optimization of the flow control. A list with the main submarine power cables in the world can be consulted in Annex 1.

3.2 Spatial context

3.2.1 Geological and path survey

Prior to any decision for laying down a cable on the seafloor (power or telecommunications) a geological and path survey must be undertaken. This survey should offer a complete and complex image of the bottom of the sea in terms of bathymetry (depth of the sea), depth gradient (slope and topographical accidents), nature of the seafloor (lithology), environment conditions (temperature, salinity, pH and their variation) and dynamic processes that take places in the water body (waves, sea currents, icebergs) or affect the seafloor (turbidity currents and sediment flows, earthquakes, active faults, active submerged volcanoes, lava emergence). All these investigations are performed and assessed by geophysicists, geologists, oceanographers by using dedicated equipment. Since power submarine cables are big investments and long-lasting features a wrong assessment of these conditions would lead to an improper design of the cable and hence its malfunctioning or additional costs of maintenance.

3.2.2 Water depth and subsea bed topography

Most of the transmission power cables at the moment are laid in rather shallow waters, i.e. at less than 500 m depth. Only three cables go beneath this depth: HVDC Italy-Greece (1000 m), Cometa HVDC (1485 m) and SA.PE.I. (1650 m), which is the deepest in the world. The two deepest ones were both produced by Prysmian and are of mass impregnated (MI) paper type.

The routes chosen for cable laying try to avoid deep trenches or steep slopes while maintaining the shortest path possible. As most of the submarine power cables installed until now cross shallow and flat-bottomed seas covered with thick Quaternary sediments (Baltic Sea, North Sea, Irish Sea, English Channel, straits between islands of Japan, Philippines, US, Canada, Australia, New Zealand) the depth of the water and slope haven't been of a major concern. The threshold of 1000 m depth has been exceeded only in the Mediterranean Sea.

In water environments special attention must be paid to hydrostatic pressure exerted by the water column, which might become an important factor both in projecting the materials used and in manoeuvring methods for laying or repairing the cable. The pressure increases steadily with depth adding around one atmosphere (atm) at each 10 m depth (Table 2 and Fig. 11).
Although the cable sheath is built to resist to high mechanical stress and manoeuvres, special attention is paid when manufacturing segments for deep waters. This is important during cable installation when high tensile forces are applied to cables laid in deep waters.

As a recommended practice (DNV, 2012) the components in the cable cross section must be able to withstand to a pressure not smaller than 3.5 MPa or the pressure corresponding to the maximum water depth multiplied by a factor of 1.25. The casings for cable joints must be able to resist at least to 3.5 MPa or to the pressure corresponding to the maximum water depth multiplied by a factor of 1.5.

The latest generation of materials used for submarine power cables respond better to hydrostatic pressure action. The problem is more stringent for older oil-filled insulation power cables, still in use but generally in shallow waters. The new generations of mass-impregnated paper or XPLE insulations are made of high-density and high-viscosity compounds whose properties and function are not pressure influenced.

Table 2 – Water column pressure at different depths

Depth (m)	Pressure (atm)	Pressure (MPa)
1	1.10	0.11
10	1.99	0.20
100	10.92	1.10
200	20.84	2.11
500	50.60	5.12
1000	100.20	10.15
1500	149.80	15.17
2000	199.40	20.20
3000	298.61	30.25
5000	497.02	50.36
10000	993.04	100.61

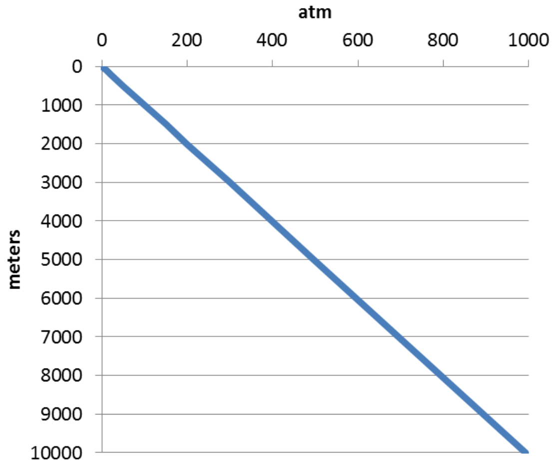


Fig. 11 – Water column pressure variation with depth

The power cables laid down until now cross continental seas (large bodies of salt water situated on the continental shelf marginal to an ocean). The continental shelf is characterized by shallow waters (up to 200 m, in some cases up to 400 m) dipping gently with an angle rarely steeper than 1° (0.1° in average) (Fig. 12).

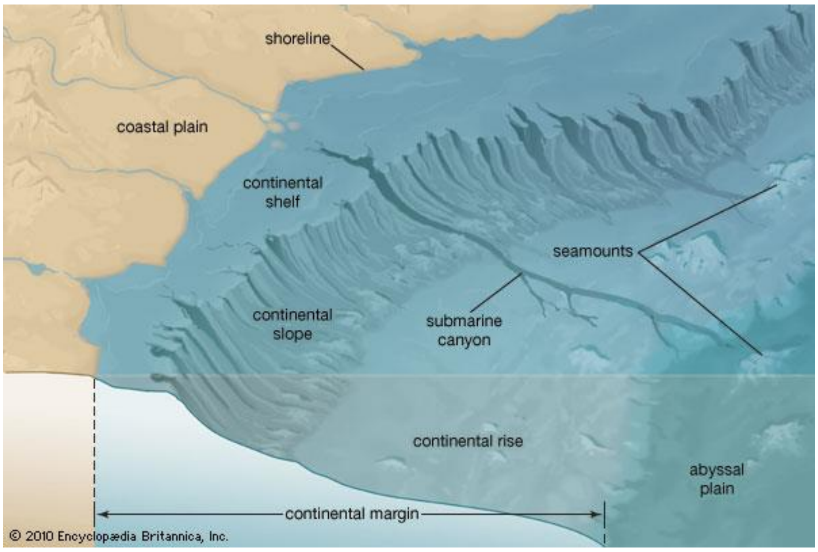


Fig. 12 – The main components and major submarine landforms of a continental margin

There are no major or sharp geomorphological accidents or asperities. In most of the cases the sea bottom is covered with a thick layer of Quaternary sediment which makes it rather flat. It is made up of recent deposited particles: sand, silt, clay, gravel or of biological origin (Fig. 13). Sometimes these can be loosely cemented which offers them a higher hardness. Most of the North Sea seabed, where a lot of submarine power cables are laid, has this composition. Due to the low depth of the water which can make the cable subjected to actions from above (vessels' manoeuvres, anchoring, dragging) the cable is buried in a sediment layer of 0.3-1 m depth. This operation is performed up to a depth of around 600 m.

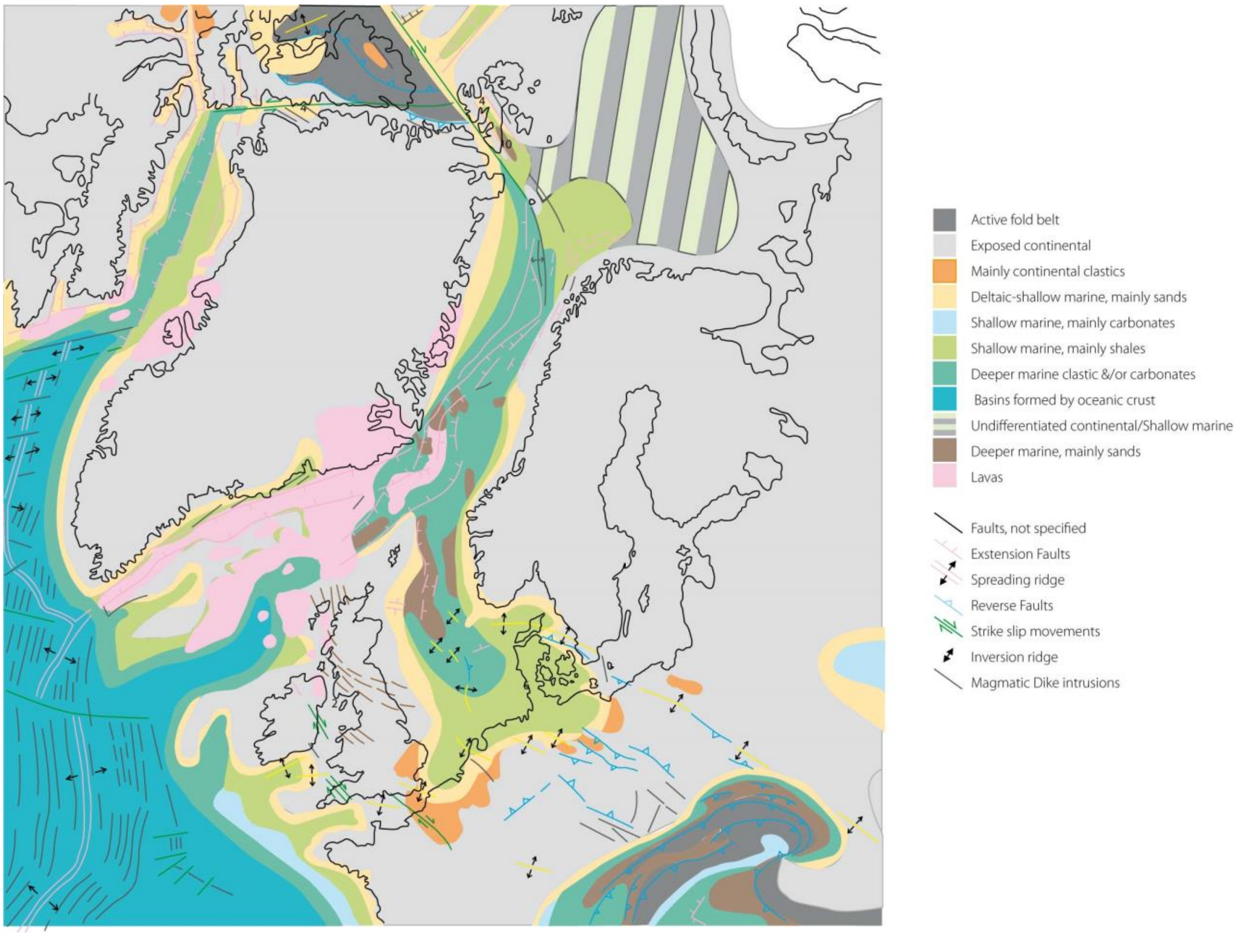


Fig. 13 – The main geological formations in the North-East Atlantic (Norlex, 2008)

In some areas old and much harder rocks are exposed at the seabed surface. The methods used for crossing these areas depend on the nature of the rocks and their arrangement. They can go from cutting a trench of 0.5-0.7 m deep into the rock and bury the cable in it to laying the cable over the rock and covering it with metallic mattresses.

The cables in the Mediterranean Sea dip beyond the continental shelf continuing on continental slope reaching in some parts the continental rise and crossing canyons and seamounts as in the case of the SA.PE.I. power cable (Fig. 14).

The continental slope increases the link between the continental shelf and the continental rise, from approximately 200 to approximately 3000 m. Its slope averages 4° but this depends largely on the local or regional geological setting. Pacific Ocean continental slopes are steep while the Indian Ocean ones are the flattest. Although it dips at a rather small slope, local geological faults or tectonically active margins can cause steep drops, which can be even vertical. These slopes are mostly covered by recent loose sediments but very often hard rock outcrops are present. In their upper part the effect of streams from the continent is visible by the prolongation of valleys forming submersed canyons.

Steeper slopes may determine a more accentuated rhythm of dynamic processes like submarine landslides or turbidity flows which can impact on the cable most of the time with serious consequences (Carter et al., 2014).

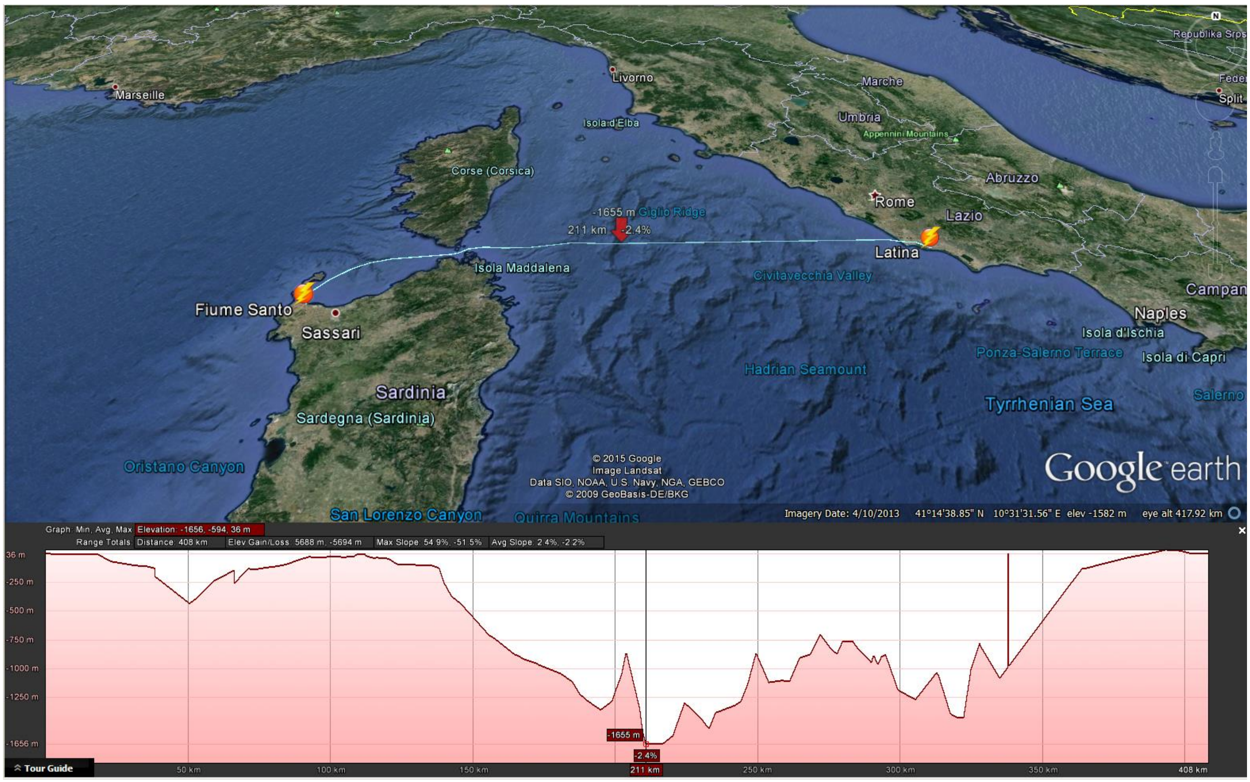


Fig. 14 – The bathymetric cross-section of the SAPEI power cable

Crossing these ups and downs would lengthen the cable, although by a small fraction. The depth swing will also require the cable with an optimal structure, the best tradeoff between depth and pressure related requirements, weigth and costs.

For long power cables crossing areas with great depths different materials in the cable's cross section were proposed for deeper and shallower segments. This is the case for NorNed in the North Sea and SA.PE.I. in the Mediterranean. For the SA.PE.I. cable the deep sea segment required a conductor made of aluminum while the shallow sea segment allowed for a copper conductor. The reason for this lies mainly in reducing the weight while being able to maintain the tensile force during installation but also in meeting the technical capabilities of the vessel used for this operation. As it is costly and time-consuming to operate cables at great depths having a small number of joints or even none would be advisable. That means longer one-piece segments or designing new cable structures in order to reduce the weight if the same vessels were to be used. Alternatively new vessels with more carrying capacity would have to be built in order to accommodate the longer segments.

With more ambitious plans in the Norwegian region and the Mediterranean Sea in the near future more diverse geological settings should be met. The experience gathered from telecommunication cables already laid in similar areas could be adapted and used to power cables.

3.2.3 Geological structure and lithology

As the submarine power cable is laid on the seafloor knowing the nature of the bedrock is of critical importance. The lifetime of a cable is longer and its operation easier if the cable is laid in a stable environment. The environment of the seafloor is very diverse due to its varied geology and processes that affect it. It is also depth dependent with the more dynamic processes acting close to the surface.

Seafloor geology can be as diverse as the nature of its structural setting (Fig. 15)

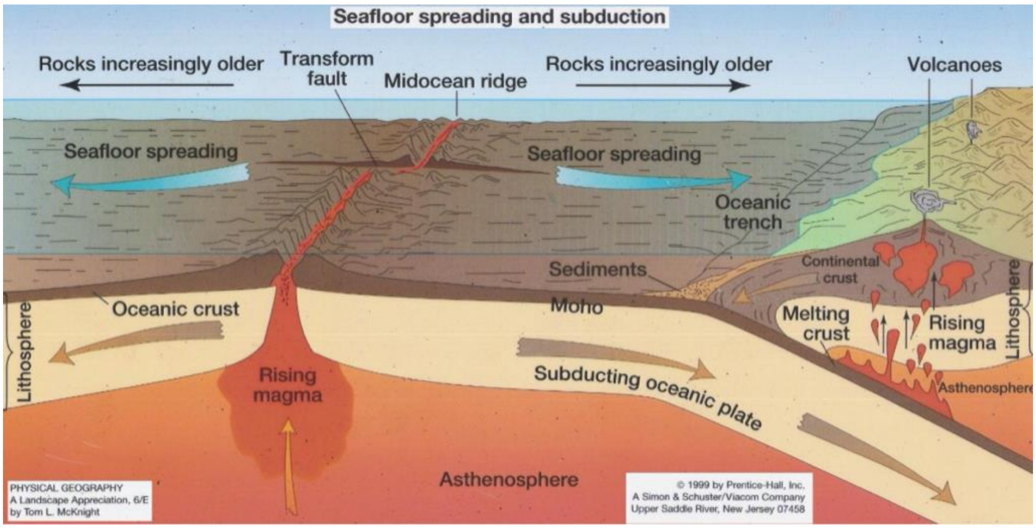


Fig. 15 – Seafloor spreading and the main geological structures

The major components of an ocean basin are:

- the mid-ocean ridge – a continuous mountain chain built by rising magma;
- the ocean floor – a vast expanse of older lava flows now solidified and covered by a thick layer of sediment that takes the form of an abyssal plain crossed by ridges and trenches;
- ocean trenches – deep trenches (≥ 5000 m depth) where two tectonic plates collide and with one subduct under the other.

While most of the seafloor environment is rather stable with few dynamic processes, there are places where changes take place at a higher rate. Mid-ocean ridges and ocean trenches are such places. Along mid-ocean ridges lava rises at places at the surface rendering these areas impassable. The Mid-Atlantic ridge forms a continuous subsea mountain chain of more than 10000 km length. Submarine volcanoes pose the same problems although their lava flows are more localized. Nevertheless the nearby accompanying phenomena (high water temperature, corrosive substances) represent a major threat to submarine cables. However, as the location of the volcanoes and lava eruption lines are well known this risk can be reduced by routing the path to avoid these areas.

Other areas are affected by active faults which might not be expressed in seafloor morphology since they might be covered by sediments but a sudden quake can cause landscape modifications or trigger landslides.

Most of the seafloor is covered by a thick layer of sediment that averages 450 m in thickness (Fig. 16). It can be thinner on mid-ocean ridges where the bedrock formed by hard rock can be exposed, sometimes even lava flows.

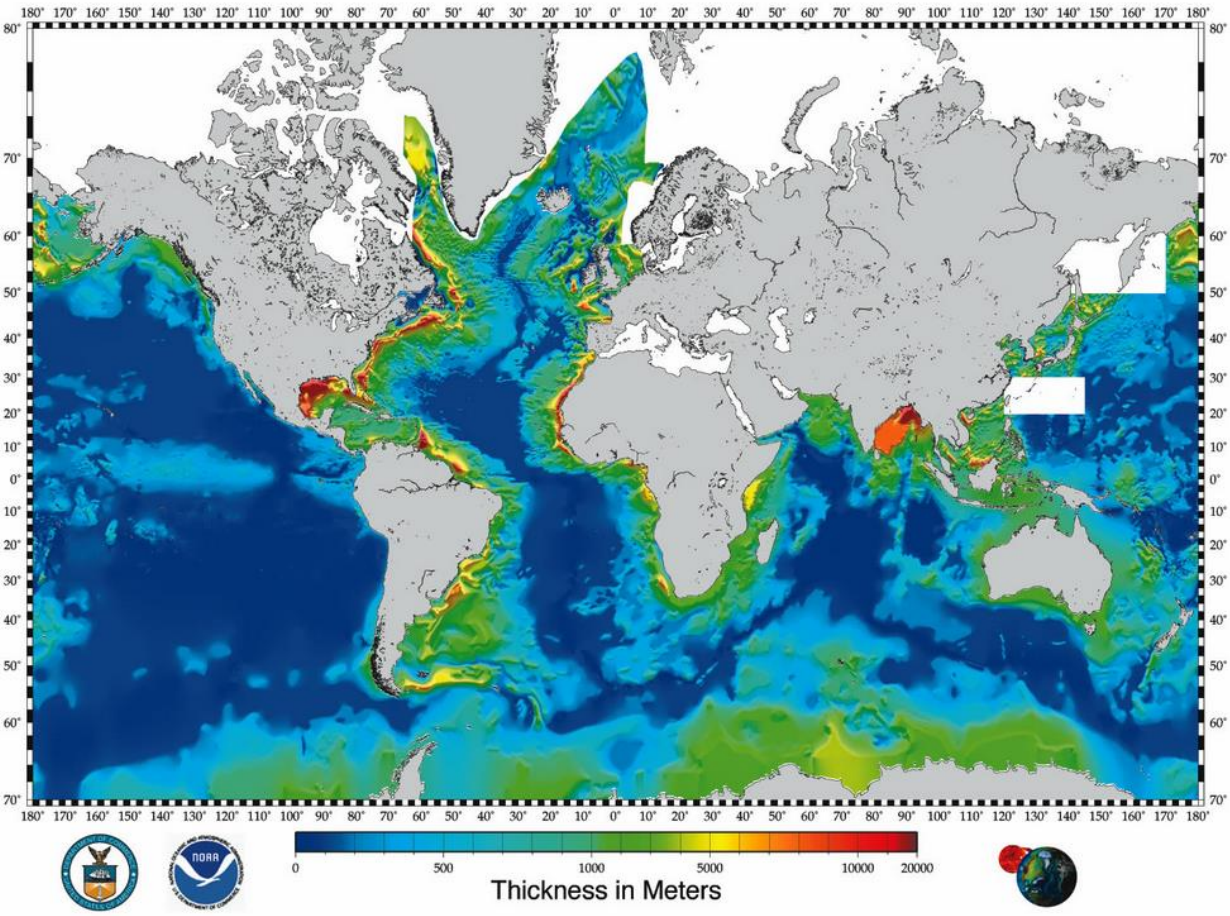


Fig. 16 – Total sediment thickness of the world's oceans and marginal seas (Source: NOAA)

Although the predominant process under the water surface is sedimentation the water movement can displace finer particles especially in the coastal areas causing the seafloor bathymetry to change.

Soft sediment (clay, mud, silt, sand) is easier to dig in to place a cable in a trench. However it is also easier to get the cable removed or displaced by waves and currents, making it prone to accidents. This threat is much reduced with increasing depth where the effect from waves and currents becomes lower or negligible. Harder sediments like gravel offer a better protection since they are heavier and less prone to displacement but more difficult to dig and hence resulting in higher costs.

3.2.4 Geodynamic processes

On the continental slope, where the value of the slope gradient is higher, the accumulation of fine loose sediments in large quantities might pose problems of slope stability. When this is combined with a burden of coarser sediments arrived with the streams discharge from the continent, their equilibrium might become instable. Water fills all spaces and pores in the sediment and can act as a lubricant. An event like an earthquake can trigger the slide of the sediment mass, which more often follows the path of the submarine canyons or other negative landforms. Sometimes, the own weight of the sediment might grow beyond the stability threshold and the landslide doesn't need an initial shake in order to initiate.

Much information about the processes affecting submarine sediments was obtained from cables' breaks (Carter et al., 2014). Since most of the submarine cables are telecommunication connections the experience assembled comes from this field.

In areas close to the shore the main dynamic processes are determined by waves and sea currents as well as sediment influx discharged by rivers. The magnitude of their actions depends on the local topography of the coast, the depth of the water, the inland petrography and the climatic pattern (rainfall, humidity, seasonal swing). In areas with high seasonal rainfall combined with softer rocks (sand, soft sandstone, clay) erosion can be strong enough to grind up to 10000 tons/km^2/year, which go into sea and build sediment deposits. This big quantity of material transported over hundreds or thousands of years builds the largest sediment accumulations on earth taking the form of submarine fans (Talling et al., 2013). Large accumulations of sediment (>100 km^3) can fail to remain still and start moving along the slope at high velocities (up to 19 m/s) reaching the deep ocean. Small volumes of sediment (0.008 km^3) found at canyon heads can also start moving at high speed (5 m/s) for hundreds of kilometres (Carter et al., 2014). If power or telecom cables are on their movement paths these swift displacements can break them or cover them with sediment which can exert additional mechanical stress.

A key lesson learned from previous submarine telecom cables is that active submarine canyons, fed by rivers with high discharge should be avoided. However this implies choosing an alternative route, which might be longer and results in a higher cost. When this is not possible due to cost restraints another option would be to place the cable at greater depths in the canyon where the landslides and turbidity flows begin to decelerate and have a lesser damaging potential.

Some cables are laid on a river bed before they enter the sea. A river bed may suffer important modifications in topography due to alternation of sedimentation periods with erosional ones. The difference in depth at the same place can be in some cases of a few meters. In order to secure the cable and avoid its exposure it must be buried at a higher depth than on the seafloor. For the NorNed HVDC cable laid in the Waddenzee area (North coast of The Netherlands), with a lot of moving clay sediment, a 3 to 5 m deep trench was dug in order to protect the cable against moving sediment (CEDA, 2005).

Prior to cable laying, during path survey a multitude of geophysical investigations are performed in order to have a clear view on the seabed properties and stability. These investigations are performed with specialized tools, which measure the water and sediment depth. Water depth is measured by echo-sounding. This has evolved into multibeam systems (Carter et al., 2009), which offer an image over a wider swath, which can be as much as 20 km wide.

The nature of the seabed and its structure is investigated by seismography. Waves at different wavelengths penetrate through water and seabed at variable depths according to their energy. The strength of the bounce sent back to the receiver gives data about the nature and depth of the reflection discontinuity. Sediment coring complements the image of the seabed and helps to assess its stability and suitability for cable burial.

Another geo-dynamic process which might affect the cables is the sea-bottom scouring exerted by icebergs. These are big chunks of ice loose from the inland glaciers when they reach the sea. They are more common and larger in the waters surrounding Antarctica and Greenland but not limiting at that. Their size depends on the behaviour of the ice and its internal structure (cracks, plasticity, temperature, tensional forces). Although they usually might be just few meters (sometimes tens of meters) tall, most of the volume lies below the water surface. The biggest icebergs can reach more than 200 m deep below the sea surface. In their drift they can reach shallower waters and come in contact with the sea bottom where they can plough more than one meter into the bedrock posing threats to the submarine cables. As most of the icebergs originate from inland glaciers a special attention must be paid to areas where these enter the sea on their permanent routes. In a study mentioned by Burnett et al. (2013) most cable (telecom) damages in western Greenland coasts occurred in water depths less than 25 m from impacts with fixed and floating ice. These potential hazardous areas can be identified through a preliminary study and avoided by the cables by rerouting or applying special protection measures (deep burial, metallic cases). Deep reaching wandering icebergs can however always be a threat that is hard to overcome.

3.2.5 Sea currents, waves

The movement of water can affect the cable in many ways. The most important movements of the sea water are represented by waves and currents. Waves are the result of wind blowing over a body of water maintaining a constant direction for a period of time. The kinetic energy of the moving air mass is transferred to the water surface forming undulations whose height and length depend on the wind intensity and duration. Sea currents are horizontal flows of water through the sea or ocean. They can be the result of predominantly blowing winds over large expanses of water or part of the pattern redistributing the heat in oceans and seas.

Both types of movements can affect submarine cables by the sole strength of water action or by redistributing the sediment. The depth of the waves and currents actions depends on the size and/or speed of these dynamic elements of the sea. Higher waves make their action felt at higher depths. Stronger and faster currents can displace and transport more sediment. The higher the wave or faster the current the more power they have to move coarser particles from the seafloor.

The action of the waves is stronger on the shore or in shallow waters fading with increasing depth. In general, the action of waves stops at around 30 m depth. Only exceptionally, during strong storms the waves' action is felt deeper. The coasts, especially the sandy ones suffer the most dramatic changes from the waves' action. When cables in such areas are not buried deeply enough the removal of sediment may expose them to the surface (Fig. 17). In such cases a deeper trench should be considered.

Fig. 17 – Cable exposure due to waves' action on a sandy beach in Great Britain (Source: aphotomarine.com)

In shallow rocky waters the waves' action pose a threat for the cable if the cable is not well anchored in case that a trench was not the option.

3.2.6 Temperature, salinity, corrosion

Sea water characteristics differ from place to place due to climatic zones, influences from inland waters, biotic activity and depth. These characteristics orient the HVDC cable manufacturing industry to using materials that have a neutral interaction with salt water.

Electric current running through a conductor causes its temperature to increase. If the current becomes too high the conductor reaches a critical temperature at which parts of the insulation cannot function properly or even start to melt. Under normal operating conditions the cable's temperature should not reach those critical limits. The environmental temperature also plays an important role in keeping the functional parameters in their optimal range. As most cables are laid in rather cold regions the lower temperature has a cooling effect on the cable improving its efficiency.

Sea water temperature follows the general pattern of climatic zones with local influences caused by landmasses (Fig. 18). As a general rule temperature drops with depth (Fig. 21) reaching 4 °C at 1000 m depth (Fig. 19) maintaining this temperature down to the sea bottom.

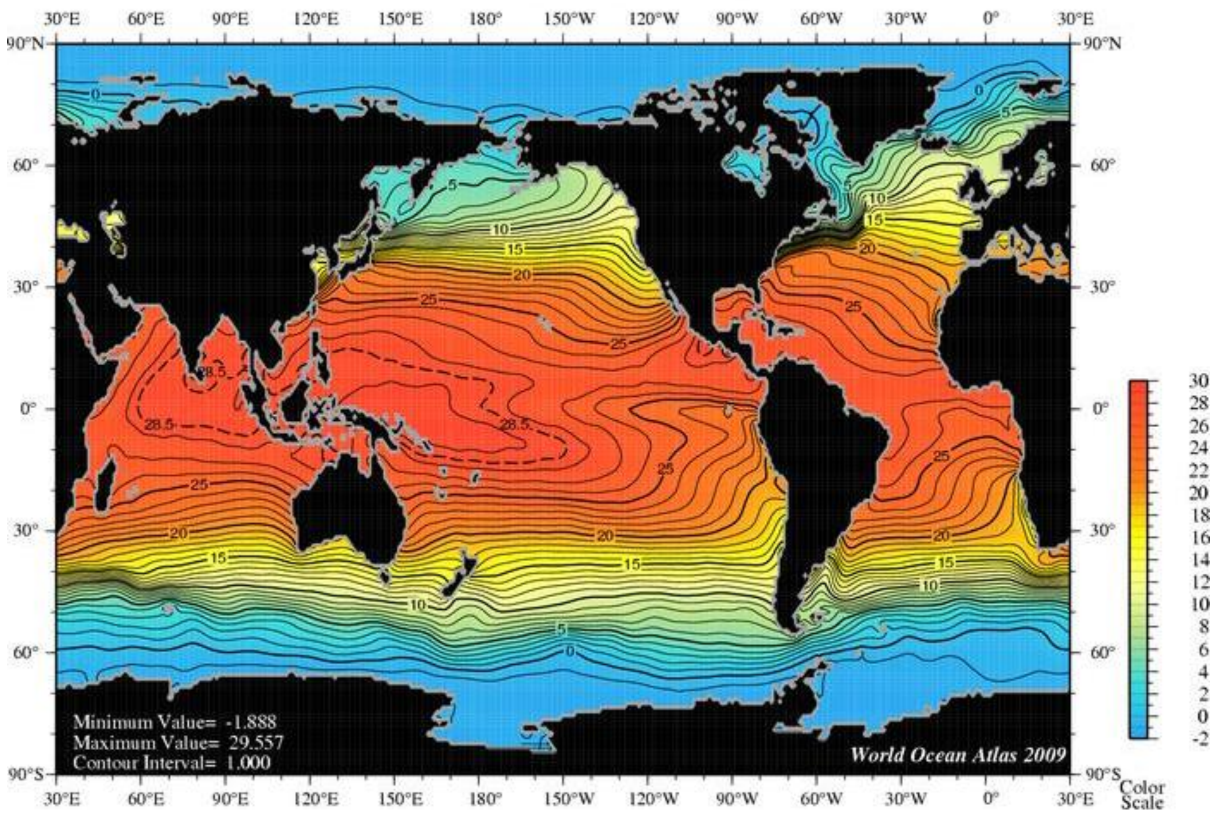


Fig. 18 – Annual temperature at the ocean's surface (Source: NOAA)

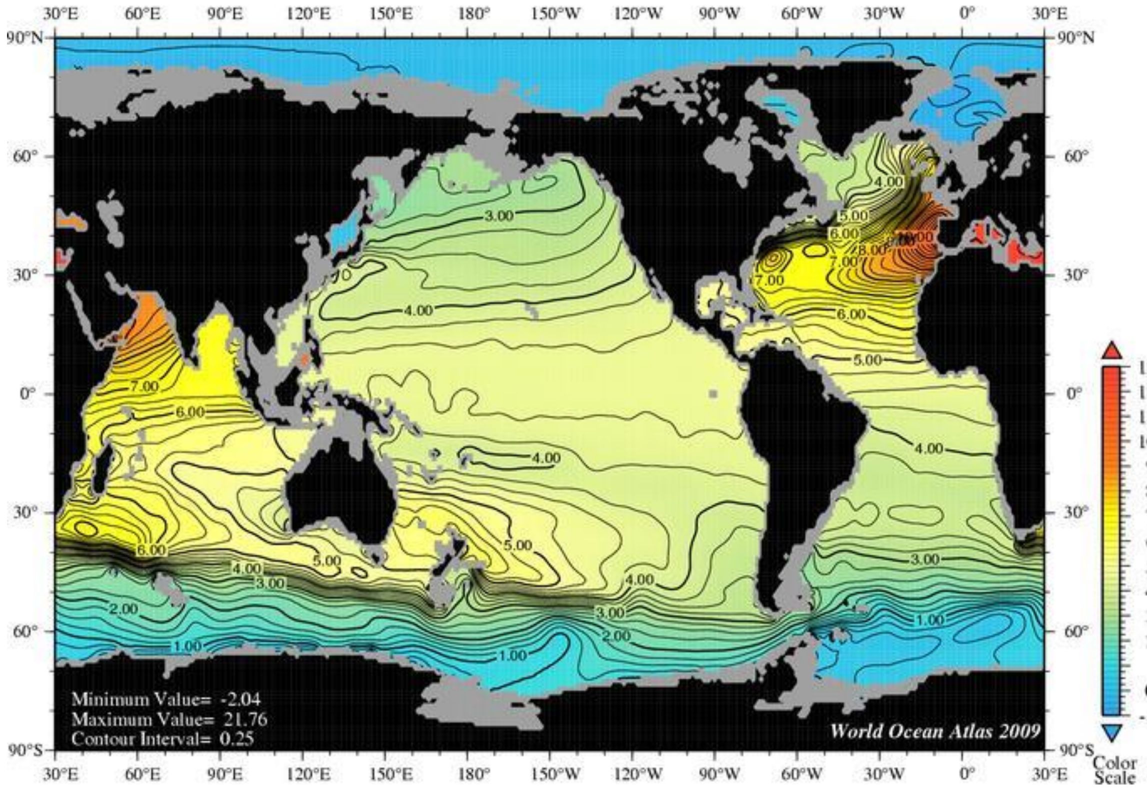


Fig. 19 – Annual temperature at 1000 m depth (Source: NOAA)

Salt water is a corrosive environment. Salt is present everywhere in the sea water in variable concentrations. The average salinity in planetary ocean is 33-36‰ with large variations (Fig. 20).

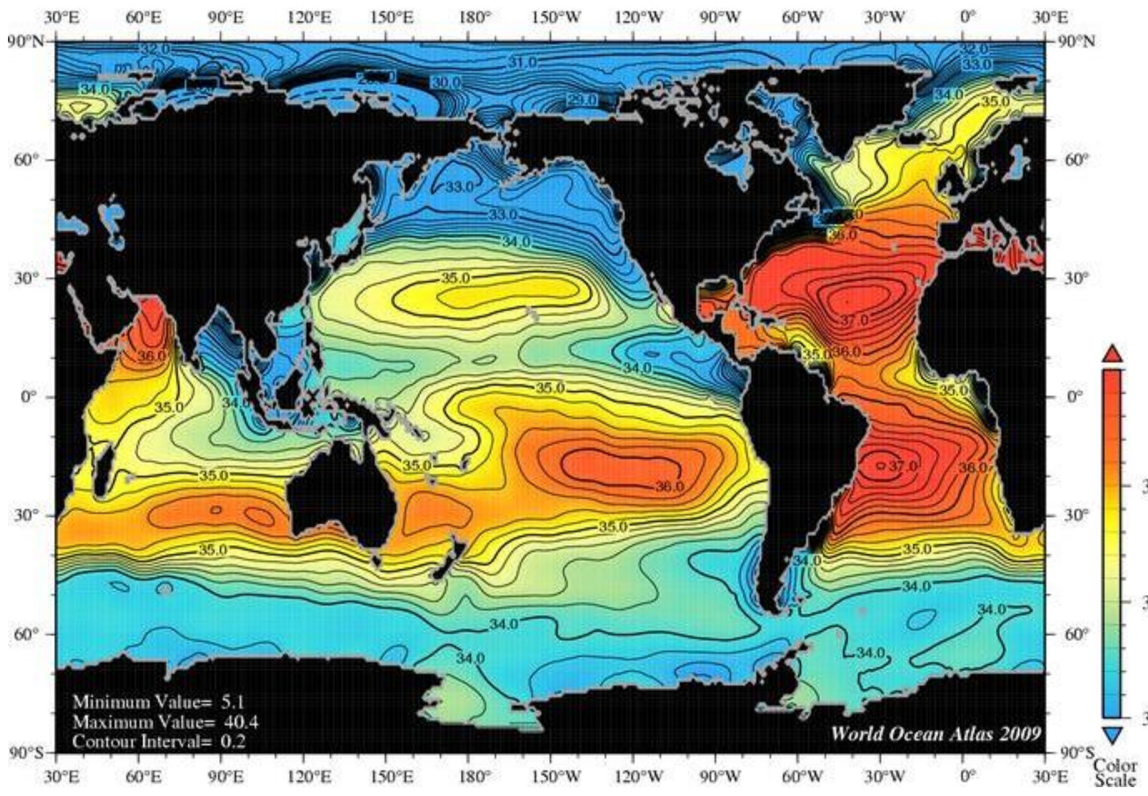


Fig. 20 – Annual salinity at the ocean's surface (Source: NOAA)

In shallow and/or closed sea located between tropics (but not only) with strong evaporation the salinity can reach 37-40‰ as it is the case for the Red Sea, the Mediterranean Sea, the Arabian Sea or the tropical Atlantic and Pacific. A major tributary river can lower the salinity of a sea or part of it as it is the case for the Black Sea, the Baltic Sea, the North Sea, the South China Sea and the Golf of Bengal. Salinity is lower along the coasts and higher in the open sea. The North Sea has a salinity of 32-36‰ in the open sea and 15-25‰ close to the shore.

Salinity is also a result of the global ocean circulation pattern which represents a complex movement driven by differences in water density and salinity and by heat accumulated and atmospheric influences (pressure, wind, temperature).

Since salt has a greater specific weight than water, a higher salinity causes heavier water which dips at greater depth. Generally the salinity increases with depth (Fig. 22) but the continuous movement of water leads to mixing.

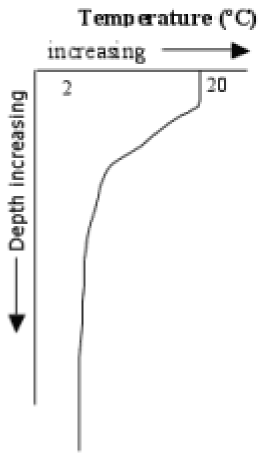


Fig. 21 – Temperature decrease with depth (Source: dosit.org)

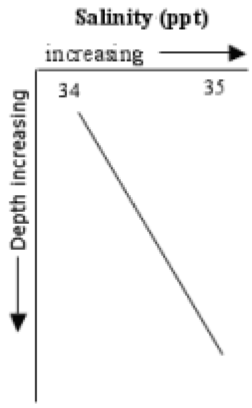


Fig. 22 – Salinity increase with depth (Source: dosit.org)

The cables must be protected against the corrosive effects of the salty water and this issue must be seriously tackled by the cable industry. The primary protective layer against the salty water is the armouring which is composed of zinc-coated steel wires (Worzyk, 2009). The zinc layer around steel wires is 50 µm thick. The secondary protective layer consists of a bitumen sheath, which might be eroded or removed during the installation process or afterwards. It is replaced lately by an insulation sheath of high density polyethylene. The zinc and steel remain as main barrier against the salty water. Their decay rates in natural submarine environments are 1-50 µm/year for zinc and 10 µm/year for steel. Burying the cable in the sediment reduces the amount of water in contact with the cable lowering the corrosion. Experience showed that aluminium must be avoided as component in the armouring.

As the cables are water proof and have a neutral interaction with salty water the natural salinity found in planetary oceans doesn't pose special problems (Carter et al., 2013).

3.3 Technology used and materials

3.3.1 HVDC cable

The submarine environment imposes some basic requirements to power cables that run through it (Zaccone, 2009):

- long continuous lengths
- high level of reliability with practical absence of expected faults
- good abrasion and corrosion resistance
- mechanical resistance to withstand all laying and embedment stresses
- minimized environmental impact
- minimized water penetration in case of cable damage

There are many companies producing power cables in the world but just few of them have experience in manufacturing submarine power cables for long distances and high capacity. ABB, Alcatel, Prysmian and Nexans manufactured most of the existing submarine power cables in the world. The latter two have also specialized vessels that allow them to install the cables at sea.

Prysmian is an Italy-based multinational company headquartered in Milan. Its main factory Arco Felice is located in Naples, Italy. It holds also the "Giulio Verne" vessel, which was specially built and equipped for laying power cables at sea.

Nexans is a French cable manufacture company headquartered in Paris. The submarine power cable factory is located in Halden, Norway. Nexans lays down the cables at sea with its purpose-built vessel Skagerrak.

If for an overhead HVDC power line a simple conductor is required, manufacturing a power cable for submarine use implies meeting the technical requirements stated above. A train of processes aimed at strengthen, insulate and protect the cable makes its manufacturing a high specialized skill (Fig. 23).

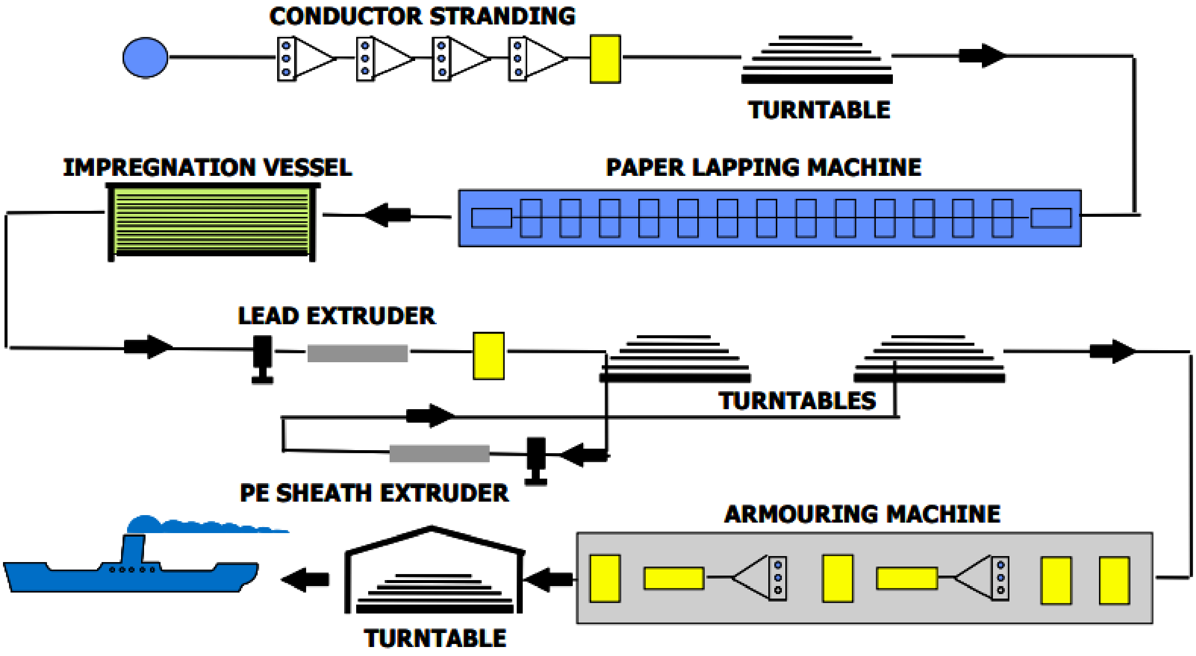


Fig. 23 – Sketch of the main processes for producing a power cable by Prysmian (Source: pesicc.org)

3.3.1.1 Cable arrangements

There are different possibilities to arrange the cables' layout depending of the system configuration (monopolar or bipolar):

- Two separate single-core cables
- Two single-core cables bundled
- Single-core cable with metallic return
- Two single-core cable with metallic return
- Concentric cable

The two first layouts are used in bipolar system configurations while the last three in monopolar configurations.

3.3.1.2 Voltage and capacity

Electricity transfer over long distances and for high power is made at high or very high voltages. By increasing the voltage the losses become lower and the capacity of the line increases (see above).

Over the years the voltage has gradually increased from 100-250 kV for the first commercial power cables in the '50s-'70s to 300-400 kV ten years later. Most of the newer submarine power cables in the world operate at 450-500 kV. Prysmian and Siemens are currently constructing the first submarine HVDC link with a voltage of 600 kV, i.e. the highest in the world between Wales and Scotland (UK Western Link).

3.3.1.3 Joints

It is preferable that submarine power cables consist of a minimum number of segments, ideally one. While for shorter cables this is possible, for longer ones more segments must be linked together into a longer piece. The segments are connected by using joints which are pieces of equipment that ensure the conductors, sheaths and armours on both parts are properly in contact (Fig. 24).

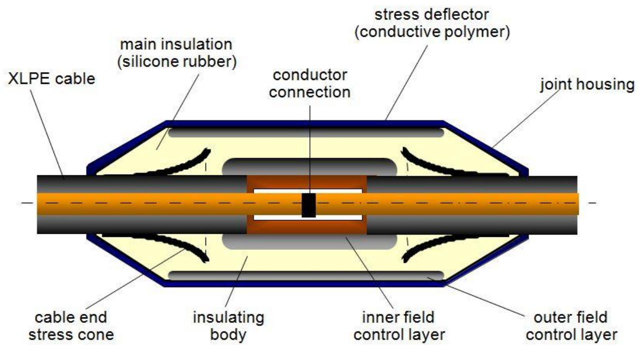


Fig. 24 – Sketch of a cable joint (Source: campbellwhite.com)

Joints can be rigid or flexible depending on the local environmental conditions.

3.3.2 Cable structure, materials and properties

The structure of the cable must ensure a high efficiency in electrical transmission, a good insulation and magnetic shielding along with a strong mechanical resistance. The structure may differ in materials and layout depending on manufacturers and environmental conditions.

The cables' structure includes a set of layers around the conductor – mainly copper to ensure the physical insulation, impermeability, mechanical strength but also flexibility and electrical and magnetic shielding.

HVDC submarine cables consist of one primary conductor by which the current is transmitted and a return path represented by another conductor or via seawater using an anode/cathode. In HVAC cables the current is transmitted using three conductors.

The conductors must be insulated against any external contact for the whole length of the cable. There are three main solutions for insulation that are widely used:

- Self-contained fluid-filled cables
    - SCFF/SCOF (self-contained fluid-filled / self-contained oil-filled)

- HPFF/HPOF (high-pressure fluid-filled / high-pressure oil-filled)
    - HPGF (high-pressure gas filled) and GC (gas compression)
- Paper insulated (lapped insulated) cables
    - MI (mass-impregnated) or PILC (paper-insulated lead-covered); it consists of mass impregnated paper with high-viscosity insulating compound
    - PPL (paper polypropylene laminate)
- Extruded cables
    - EPR (ethylene propylene rubber)
    - PE (polyethylene)
    - XLPE (cross-linked polyethylene); it consists of a network molecular structure suited for high temperatures

Self-contained fluid-filled cables (Fig. 25) are used for very high voltages, usually up to 500 kV. They are suited for conditions where there are no hydraulic limitations and for short distances. Their diameter spans between 110 and 160 mm and their weight is 40-80 kg/m while the conductor sizes up to 3000 mm^2.

Fig. 25 – The structure of a self-contained fluid-filled cable (Zaccone, 2009)

Mass-impregnated cables (Fig. 26) are the most used since they have proved to be highly reliable for more than 40 years since they are in use. They are used up to 500 kV and operate up to a maximum temperature of 55 °C. With the new PPL insulation the cable can safely operate at 85° C and a voltage up to 600 kV. The conductor sizes up to 2500 mm^2 while the external diameter spans between 110 and 140 mm with a weight of 30-60 kg/m, which makes this cable lighter in comparison with the previous type.

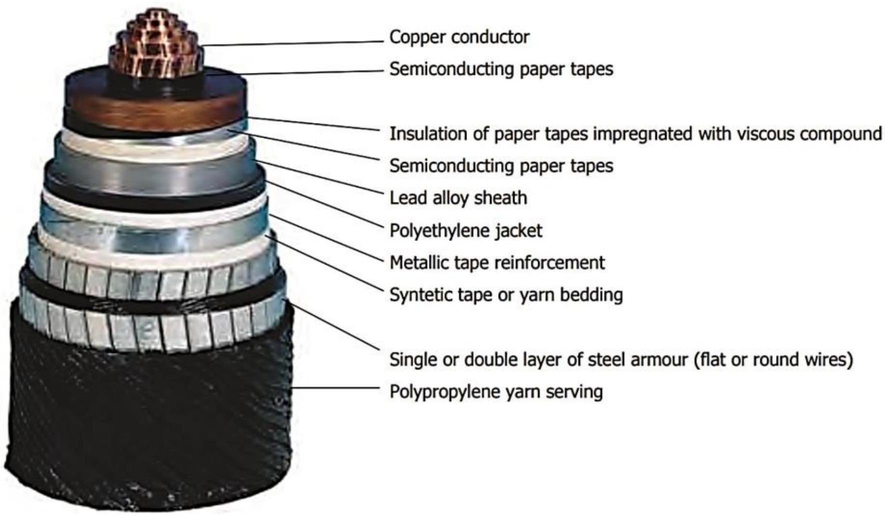


Fig. 26 – The structure of a mass-impregnated cable (Zaccone, 2009)

Extruded cables (Fig. 27) are used for voltages up to 300 kV but the technology improves quickly. They are associated with Voltage Source Converters (VSC), which permit to reverse power flow without reversing the polarity. Tests have demonstrated that for the moment the maximum transmissible power for VSC with extruded cables is up to 800 MW. The drawback is that there are issues with uneven distribution of charges inside the insulation which in the case of rapid polarity reversals can cause localized high stress which results in accelerated ageing of the insulation. Their advantages are related to their weight (20-35 kg/m) and diameter (90-120 m), which make them very competitive with the other types.

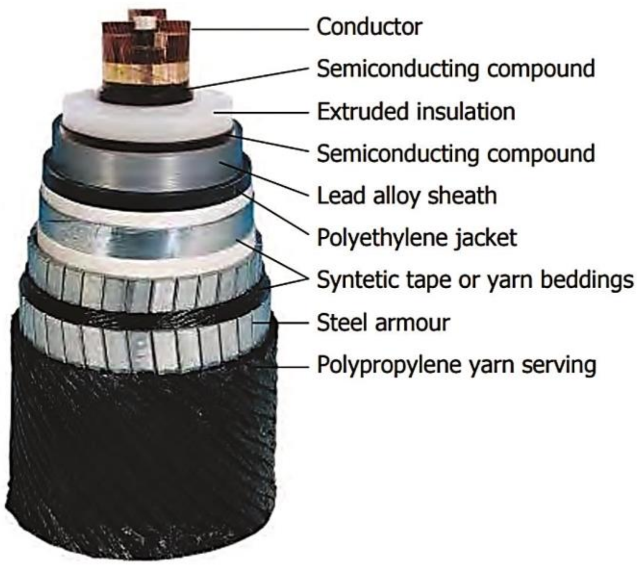


Fig. 27 – The structure of an extruded cable (Zaccone, 2009)

Mass-impregnated and extruded types have been mostly used during last years as cable insulation in space confined environments (Fig. 28).

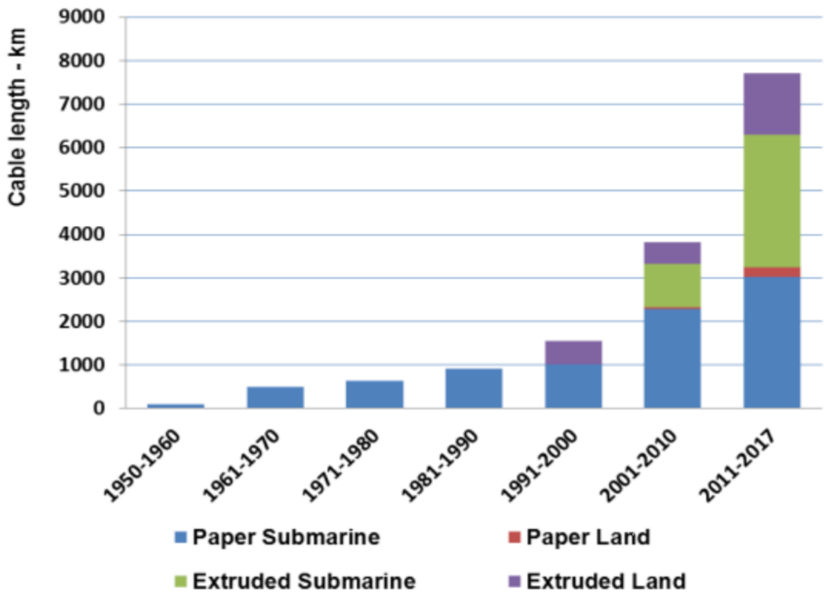


Fig. 28 – Length evolution for mass impregnated paper and extruded power cables in submarine and underground environments (Zaccone, 2014)

For various reasons optical fibres can be integrated in the submarine power cable. These range from data transmission to monitoring the parameters of the power cable like distributed measurement of temperature, measurement of cable strain or vibrations, fault detection and location (Worzyk, 2009).

In the future major technological improvements are expected for extruded cables that will extend their operational range (Zaccone, 2014). Their operating voltage would reach 550 kV with a capacity increase up to 2 GW associated with a reduction of losses. Also the maximum laying depth would be beyond 2500 m.

3.3.3 Convertors

Convertor stations are places for transforming AC to DC and/or about-face. They are part of the HVDC transmission system. There is one converter station at each end of the DC cable.

Two main types of converters are used:

- Line Commutated Converter (LCC); it uses thyristors allowing only active power control; it also has AC filters but no black start capability; it allows a higher capacity but has a large ground footprint; when the power flow is reversed, also the polarity on the HVDC cable is reversed.
- Voltage Source Converter (VSC); it allows both active and reactive power control and can be turned on and off (by using IGBT transistors) which in turn allows the commutation processes in the power converter to run independently of the grid voltage; it has black start capability but no AC filtration; while the capacity is lower it is more flexible and has a smaller footprint; no need to reverse the polarity when the power flow is reversed.

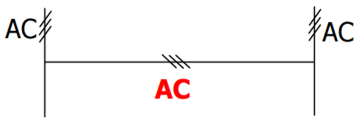
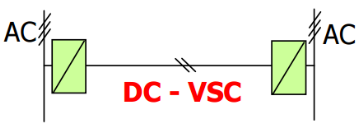
The LCC is the oldest and best established technology, used for the last 40 years in HVDC transmission. However, its performance depends on the good functioning of the AC grid. Voltage drops in the AC grid will affect the inverter by preventing the thyristors to fire and triggering a short circuit.

VSC is more complex and more expensive and it is not dependent on the good functioning of the AC grid.

Conversion from one type of current into the other comes with a cost in terms of losses. LCC has at the moment fewer losses than VSC but the technology for the latter is recuperating and the difference in losses is decreasing. Most convertors have an efficiency of over 85% and this continues to improve with the advent of new technologies. 50% of the losses are countable to the transformers and 25% to the converter valves.

A comparison between the two types of convertors and an AC solution is presented in Table 3.

Table 3 – Comparison of different transmission solutions (Zaccone, 2009)

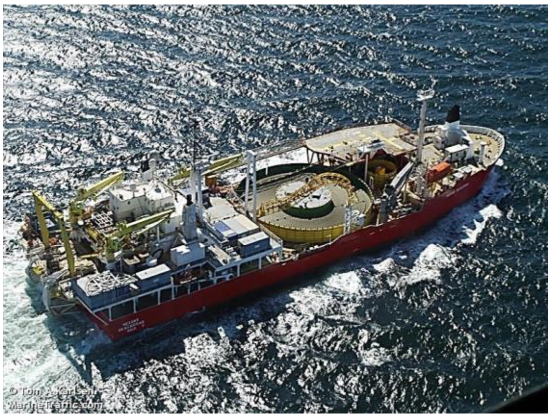
Transmission solution	Advantages	Drawbacks/Limitations
	- simple (no conversion) - no maintenance - high availability	- heavy cable - limited to 50-150 km - rigid power control - require reactive compensation
	- less no. of cables, lighter - no limits in length - low losses - good power control - very high transmission power	- needs strong AC networks - cannot feed isolated loads - polarity reversal for reverse flow - large space occupied - special equipment (trafo, filters)
	- can feed isolated loads (oil platforms, wind parks, small islands, etc.) of medium power - modularity, short delivery time - small space and environmental impact - no polarity reversal for reverse flow - standard equipment	- higher conversion losses - limited experience - limited power

3.4 Installing the cable

3.4.1 Laying the cable

Installing a submarine cable is a costly and challenging activity. The lifetime of a submarine cable might be tens of years and the technical interventions for its repairing in case of faults are also costly and difficult. Therefore the cable route must be carefully surveyed and selected in order to minimize the environmental impact and maximize the cable protection.

Laying down the cable on the seafloor is done by specialized vessels (Fig. 29). The most active vessels used for such operations are: Skagerrak (owned by Nexans), Giulio Verne (Prysmian), Team Installer (Topaz Energy and Marine) and C.S. Sovereign (Global Marine Systems Ltd). They are all equipped with a turntable for at least 4000 tons of cable and have the appropriate gear to handle it.



Skagerrak (Nexans)

Giulio Verne (Prysmian)

Team Installer a.k.a. Team Oman (Topaz Energy and Marine)

C.S. Sovereign (Global Marine Systems Ltd)

Fig. 29 – Specialized vessels for cable laying at sea; owner mentioned in brackets

Installing a submarine cable involves a series of actions:

- Selection of the provisional path;
- Obtaining permission from the relevant authorities;

- Survey of the path;
- Designing the cable system in order to meet the conditions of the selected path;
- Laying the cable, including burial in appropriate areas;
- A post-lay inspection may be necessary in some cases;
- Notification of cable position to other marine users.

The complexity of laying down the cable requires a coordinated work of many specialists in different fields. Path selection is done by power system engineers together with marine specialists. The survey is performed by geologists, geophysicists and oceanographers. Laying the cable on the seafloor is executed by special structures engineers.

The vessel represents just a part of the required gear needed for laying down the cable. It carries the cable and stands for the command centre. But once the cable is in the water other submersible equipment performs the task of settling the cable on its path. For shallow waters divers might be employed to assist the installation while for deep water Remotely Operated Vehicles (ROVs) are manipulated (Fig. 30). The work is done with the help of acoustic instruments such as echo-sounders and accurate Global Positioning System (GPS) and differential GPS.

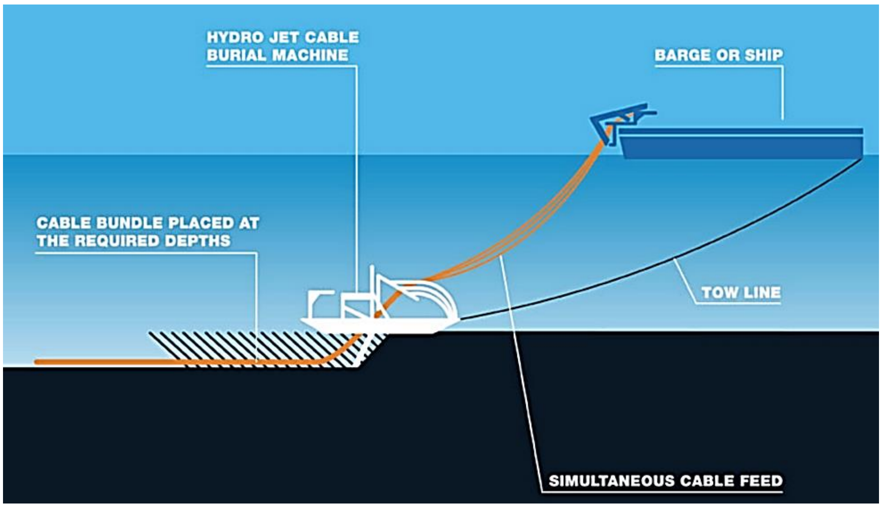
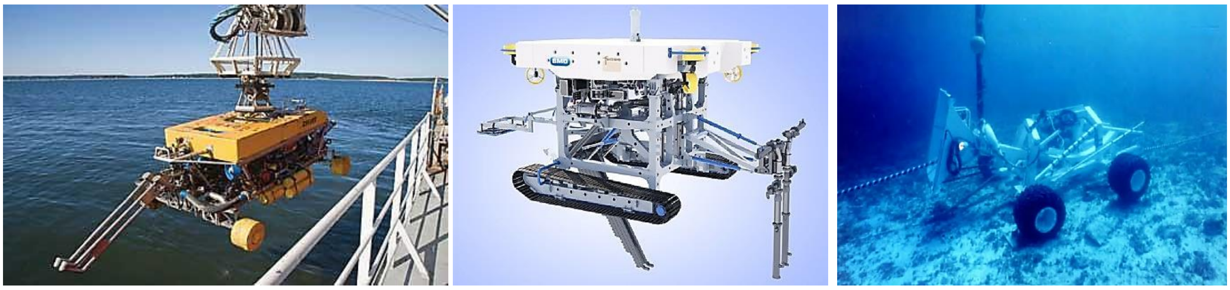


Fig. 30 – Simple sketch showing a submarine device used for installing the cable on the seabed (Source: hudsonproject.com)

The ROVs dig the trench in which the cable is laid (Fig. 31 and Fig. 32), fix the cable on the right route and cover the cable with sediment. Burying the cable in the seabed is a slowly and costly operation but it is paid back by its reliability and extended lifetime.

Fig. 31 – The trench of a submarine power cable



Nexans's CAPJET trenching system   Fugro's trenching system   Prysmian's hydroplow

Fig. 32 – Various types of ROVs

Cables are buried in the seabed in shallow waters in order to minimize the risks for damages. The trenches in which the cables are placed are dug by a submarine plough and covered by sediment or rocks. When it is not possible to use sediment as a cover other solutions are applied like using rocks or concrete mattresses (Fig. 33) as cover or using articulated pipes.

(Source: pesicc.org)   (Source: maccaferri.com)

Fig. 33 – Concrete mattresses

The rate at which the cable is laid-down depends on the type of the cable, the complexity of the cable configuration, the depth and properties of the seafloor (heterogeneous bathymetry and geology). In the case of communication cables a laying rate of 100-150 km/day, for new types even 200 km/day, is expectable. Due to the size of the cable and the volume of work, which is usually bigger, power cables are installed at a lower rate. For power cables the average burial speed is about 0.2 km/h and depends largely on the seabed conditions. The depth of the trench is usually of 1 m, only exceptionally more, up to 10 m. With increasing size of ships channels will have to be dredged or deepened. So in places the cables must be protected for such future works they have to be buried at a safe depth in the sediment. This is the case of the 30 km power cable that connects the Malaysian island of Pulau Ketam with Port Klang which was buried 14 m under the seabed.

The cables are buried in the seabed sediment up to depths of 400-600 m, below this depth they are simply laid down on the bottom of the sea. In places with strong sea currents or steep slopes they are fastened to the seabed.

In order to check the cable security periodic surveys are envisaged.

3.4.2 Protection measures

Submarine power cables must be physically protected against natural hazards or human activity. Since a fault in the good functioning of a cable might have major implications in securing the power supply serious measures are devised.

Submarine cables are the subject of several international treaties which regulate their status. These documents establish norms regarding the rights and obligations for states that wish to lay such cables as well as for states whose territorial waters are crossed by the cables. The main documents dealing with submarine cables are:

- The International Convention for the Protection of Submarine Cables (1884);
- The Geneva Conventions of the Continental Shelf and High Seas (1958);
- United Nations Convention on Law of the Sea – UNCLOS (1982).

These treaties ensure:

- The freedom to install submarine cables on the high seas beyond the continental shelf and to repair existing cables without impediment or prejudice;
- The freedom to install and maintain submarine cables on the continental shelf, subject to reasonable measures for the exploration of the continental shelf and the exploitation of its natural resources;
- The freedom to install and maintain submarine cables in the exclusive economic zone of all states;
- The ability to install submarine cables in a state's territory or territorial sea subject to conditions and exercise of national jurisdiction;
- The freedom to maintain existing submarine cables passing through the waters of an archipelagic state without making landfall.

The main threats to a submarine cable are external impacts due to predominantly anchors and fishing gears. In order to minimize the risk of a cable tear due to a vessels' anchoring, a "Cable protection zone" or CPZ is established along the cable's path. These zones are legally defined and marked on nautical charts. In these areas activities that might damage or harm the cables are strictly regulated and controlled.

They may differ in size depending on the national rules/laws and the local conditions (e.g. naval traffic). For example around HVDC Inter-Island power cable in New Zealand a seven-kilometre wide CPZ is established and enforced (Fig. 34). Vessels are not allowed to anchor or fish in this area and the protection zone is constantly monitored from sea or air. Infringement of these rules attracts a fine up to $100,000. Enforcing this rule led to no faults due to human activity.

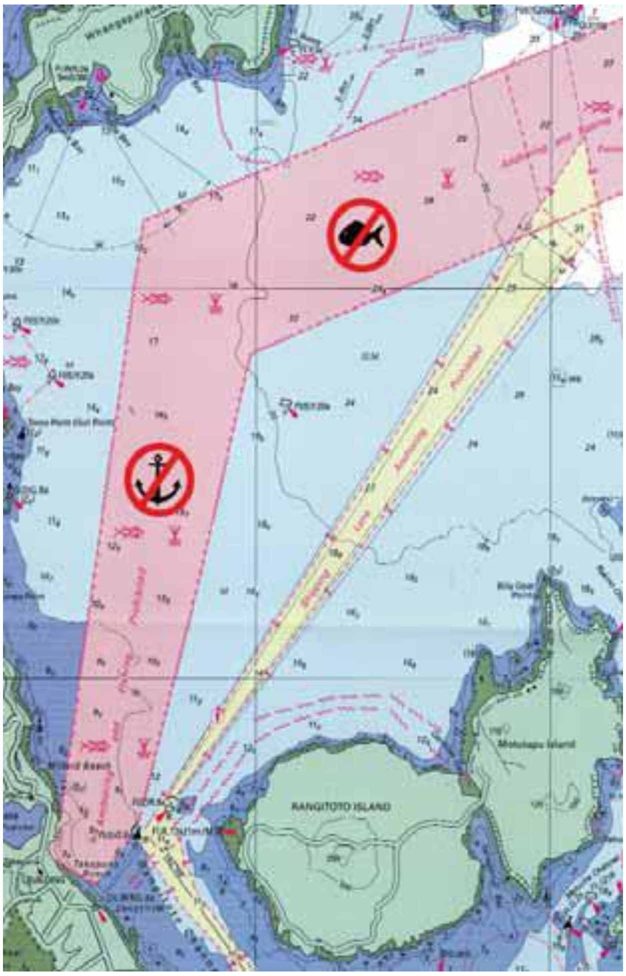


Fig. 34 – Cable Protection Zone in New Zealand (Carter et al., 2009)

An example of good practice is represented by the Kingfisher Information Service - Offshore Renewable & Cable Awareness project (KIS-ORCA), a joint initiative between Subsea Cables UK and Renewable UK, which raises awareness of submarine cable locations among operators in fishing industry for the North Sea and Western border of Europe. Its website (Fig. 35) includes online updated maps picturing sea infrastructure (pipes, power and telecom submarine cables and accompanying equipment) with contact details in case of incidents.

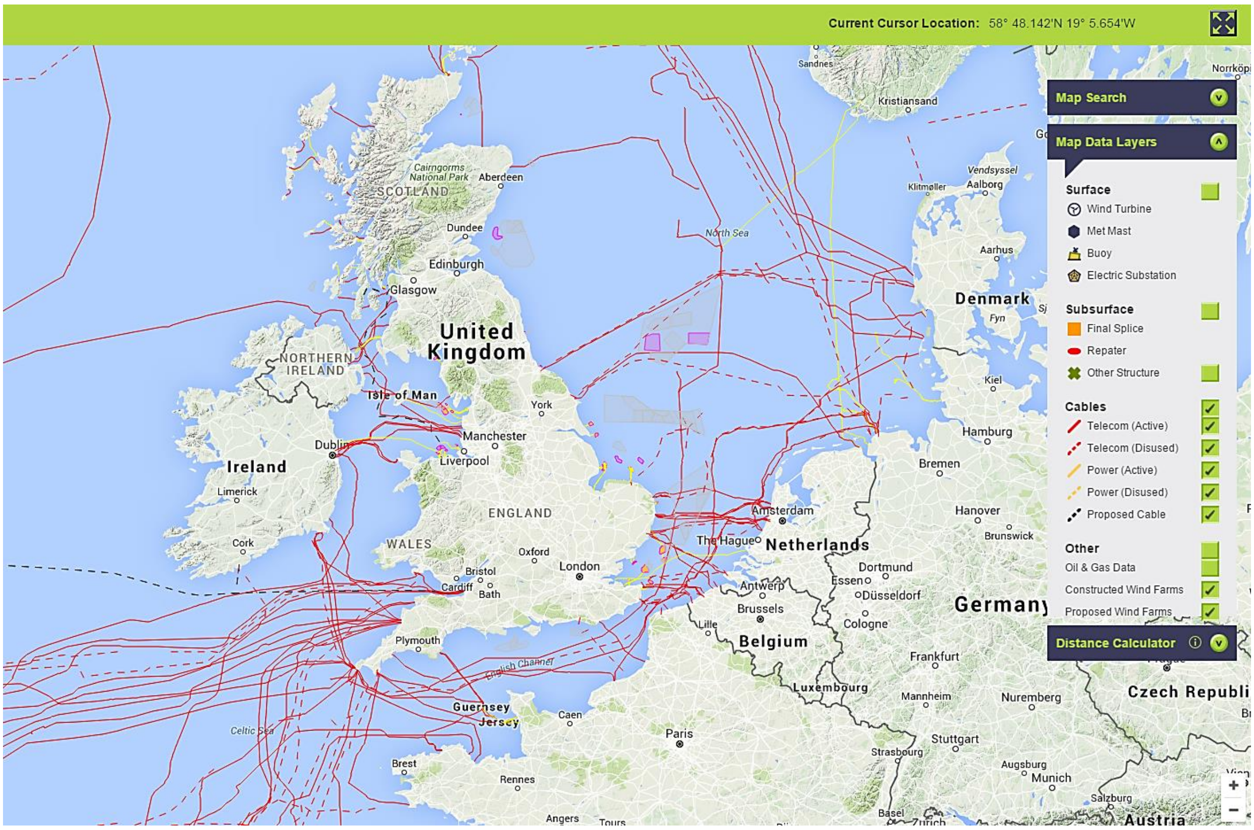


Fig. 35 – KIS-ORCA online map showing sea and submarine infrastructure (Source: kis-orca.eu)

Industry organizations such as International Cable Protection Committee (ICPC) and North American Submarine Cable Association (NASCA) have drawn a set of recommendations regarding protective measures to be implemented for a safer and longer life of submarine cables (CSRIC, 2014).

3.4.3 Maintenance

For an optimal operation the cable must be periodically checked and maintained in order to prevent deterioration. This includes:

- survey of the cable in order to check for possible tears or wears;
- survey of the cable path in order to check the stability of the seabed and possible geodynamic processes that can threat the cable integrity;
- preventive replacement of cable components when signs of wear are present or when they are approaching the lifetime end;
- enforcing rules and regulations regarding the protection in the CPZ.

The operation is performed by specialized vessels with appropriate equipment. It depends heavily on the weather and sea conditions. In high latitude regions where the sea surface is covered with ice or crossed by floating icebergs these operations require additional care measures and lengthy times.

3.4.4 Cable lifespan

Submarine power cables are infrastructure elements that require high financial investment to be built and installed. Building new power generation capacities also require a high financial investment and longer pay-backs. The demand for electricity is also a long term issue. Power cables must therefore ensure on the long run the transfer of electricity between production and consumption areas. More than in the case of overhead lines, submarine power cables are designed to withstand harsh conditions and environments with limited possibilities of intervention in case of a failure. Taking into account the complexity and volume of work needed for their laying they are projected for a longer life time than their overhead counterparts. This is ensured by using the appropriate materials for conductor and insulation, good and reliable armour combined with a carefully chosen path and proper laying operations. When realised correctly submarine power cables can be reliably used for decades the only limiting issue being the increase of demand beyond the cable's capacity and the advent of newer and more performant technologies which can pose incompatibility problems. The usual guaranteed commercial lifespan for a cable is 25 years.

The main longest cables which were decommissioned had this operation done after 30-40 years of function.

4. Reliability and accident risks

For a full functionality and reliability submarine cables must be properly manufactured and installed and protected against possible accidents. The sheath of a cable is made of materials that offer a good mechanical protection and at the same time do not interact chemically with salt water.

In order to further reduce accident risks the cables are buried into the seabed for water depths down to 600 m.

Accidents or malfunctioning do however happen. They can be anything from getting hooked by an anchor or fishing trawlers to corrosion of segments or mechanical failure. A failure of a submarine cable can impact a wide area by stopping to provide electricity or disturbing the power system balance. Repairing can take from a few days to a few weeks depending on the level of damage.

Most accidents caused to submarine cables are the result of human actions. Less than 10% are due to natural hazards.

By far the most accountable activity for cable damages is commercial fishing, which causes 40% of the accidents, telecom cables included (CSRIC, 2014). They are caused by using bottom-tending fishing gear like trawl nets and dredges. Anchoring counts as the second most frequent cause of accidents.

Experience from telecom cable breaks reports that more than half of the incidents occur in shallow waters (<200 m) and are caused by shipping and fishing activities (Burnett et al., 2013). Although these accidents are much more frequent they happen closer to the surface where they are easier to detect and times for reparation are shorter. If for a transatlantic cable a repair might be necessary once every three years, for a North Sea cable once every five weeks would be normal.

At greater depths cables get damaged mostly because of internal faults. In fluid-filled insulation cables the fluid might leak out when the cable is damaged. Extruded cables have not such an issue. The same is valid for the mass impregnated cables since they contain fluid with high viscosity which cannot leak. For the older cables insulated by SCFF/SCOF or HPFF/HPOF technology faults happen because of oil leakage, which is related to imperfect installation accomplished by workers (Kent & Bucea, 1998).

Natural phenomena can affect cables directly or indirectly. A fault affecting the seabed and thus tearing the cable as well as ocean currents that erode the sediment of the seabed exposing the cable are examples of direct actions. Also deep reaching icebergs can scour the sea-bottom damaging the cables.

Examples of indirect actions include the effects of atmospheric phenomena that cause geo-dynamic processes e.g. a hurricane or an earthquake that triggers a submarine landslide, which can tear the cable. Near the coasts in shallow waters the waves' action can exert a strong abrasion leading to fatigue and stress.

The layout of the cable can influence its degree of damage. When a monopolar with metallic return or a bipolar configuration is chosen the chances of the two cables being damaged are 100% if the cables lay next to each other and 33% if they are 10 m apart (Kramer, 2000 cited by Meißner & Sordyl, 2006).

When a cable breaks or reaches its end-life it must be lifted up to the surface for repair or removal. In case of repair the complexity of the operation depends on the number of breaks, the depth of the water, the presence of covering sediment or other anchoring structures and the weather conditions.

5. Environmental issues

Submarine power cables, like any other external element intruded into the sea water or seabed, might produce disturbances to sea life or physical environment. The magnitude of disturbances relates to the way the cable interacts with the environment: positioned on the seabed, buried in the sediment or placed in a trench dug in the seabed's hard rock. Besides the presence of the cable itself other influences might be taken into account, like induced magnetism, noise, thermal radiation or chemical and physical interaction between sea water, sediment and the cable's insulation layer. The cable's path might also cross protected areas or sensitive natural environments. The procedure for obtaining the permits for installing a submarine power cable includes also an environmental impact assessment study covering the biotic elements.

Most biological activity is contained in the top 200-500 m of sea and ocean water and it is strongly correlated with the depth reached by solar radiation, mostly in the visible width band. This in turn depends heavily on the local conditions like turbidity derived from the sea bottom lithology or rivers' discharge. It is here in this depth range that the most extensive works are done for laying down and protecting the cable. Trenches are dug, sediment is displaced and consequently the sea life is also disturbed. The most damaging effects on the fauna and habitat occur during the works of cable installation. Once the works are over and the cable is secured and fastened the sea life usually recovers quickly. Most species manage to avoid the disturbances caused by the installation works by moving away from the affected area. Motionless species that use the seabed as support are thoroughly affected along the cable's pathway.

Studies addressing the topic indicate either an absent impact over the benthonic species and dynamics of sediment (Andrulewicz et al., 2003) or a 55% recovery of the submarine fauna one year after the cable installation (Fig. 36) and 85% after two years (Dunham et al., 2015). However the authors recommend avoiding to route the cable through sensitive areas populated by endangered or hard recovering species and minimizing cable movements across the surface,also during routine operation.

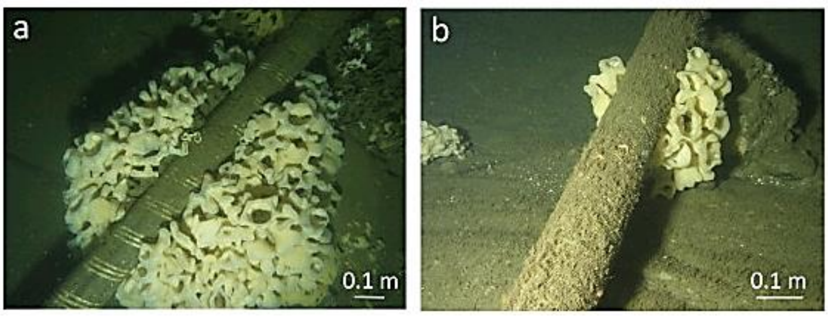


Fig. 36 – Sponge crossed by cable when installed and its recovery one year later (a); sponge covered by cable when installed and its recovery 3.5 years later (Dunham et al., 2015).

In these cases it seems that the physical damages are limited to the cable's footprint.

Where cables are exposed they can serve as mount for algae colonization (Fig. 37). Introduction of new materials can trigger the colonization with new species phenomena dubbed "reef effect" (Meißner & Sordyl, 2006).

Fig. 37 – Vegetation colonization of a submarine cable (Source: orange.com)

The diameter of submarine power cables ranges between 70 and 150 mm. Adding the sheath and protective wiry armour they can reach 300 mm. Their footprint is therefore rather small. At depths greater than 600 m they are simply laid down on the seabed where the vegetation is scarce or even absent and the impact is minimal. The regulations forbid the use of explosives for burial so the impact of this operation is drastically reduced.

The materials in the outer layer of the cable (mainly the sheath) interact weakly with the marine water. They are mechanically resistant and chemically unaffected by the sea water so there are no leakages of toxic substances that might contaminate the submarine environment. Mass-impregnated paper and cross-linked polyethylene are high-density substances that remain stable for ionic change in the salty water environments.

As the cables are specifically designed for marine environments they do not degrade in salty water nor do they pollute. They are deemed to be safe for the sea life and environment they are in.

Power cables generate electromagnetic fields (EMF) when electric current runs through them (Fig. 38). The EMF value is in close relation with the voltage. The values are highest directly above the cable and decrease with distance. At 6 m distance they are equal to the geomagnetic field of the earth. The first studies dedicated to assess the influence of EMF on marine species show no clear evidence of disturbance in their migration paths or behaviour but acknowledge that more work is needed over a longer period and over a broader array of species and environments (Meißner & Sordyl, 2006; Tricas & Gill, 2011).

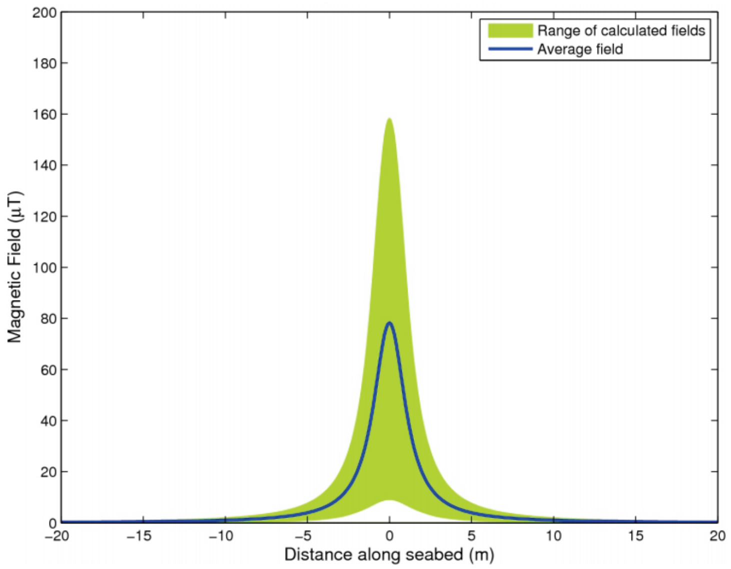


Fig. 38 – Magnetic field at seabed surface for DC cables buried under seabed surface (Tricas & Gill, 2011)

The temperature rise due to cable operation might be a cause for thermophile species relocation. Although direct on-site measurements of operating submarine power cable temperature were not performed, studies predict a rise of 2 K at 20 cm sediment depth for a cable burial depth of 1 m (Meißner & Sordyl, 2006), with higher temperature closer to the cable. According to the same authors who scrutinized the literature on this topic there is no evidence of species influenced due to water temperature rise caused by a power cable.

When electrodes are used for sea return configurations marine fauna might get harmed by high voltages and corrosive substances. Especially the anode develops chlorine which can derive in toxic by-products. In such cases the design of the basins prevents the macro-fauna from getting too close to the electrodes.

6. Long cable examples

6.1 Existing cables

6.1.1 NorNed – the longest up-to-date power submarine cable

The cable was ordered by two TSOs: Statnett in Norway and TenneT in The Netherlands. It was manufactured by ABB and Nexans Norway AS. The cable is jointly owned (50/50) by both TSOs. With 580 km length it is at the moment the longest submarine power cable in the world (Fig. 39).

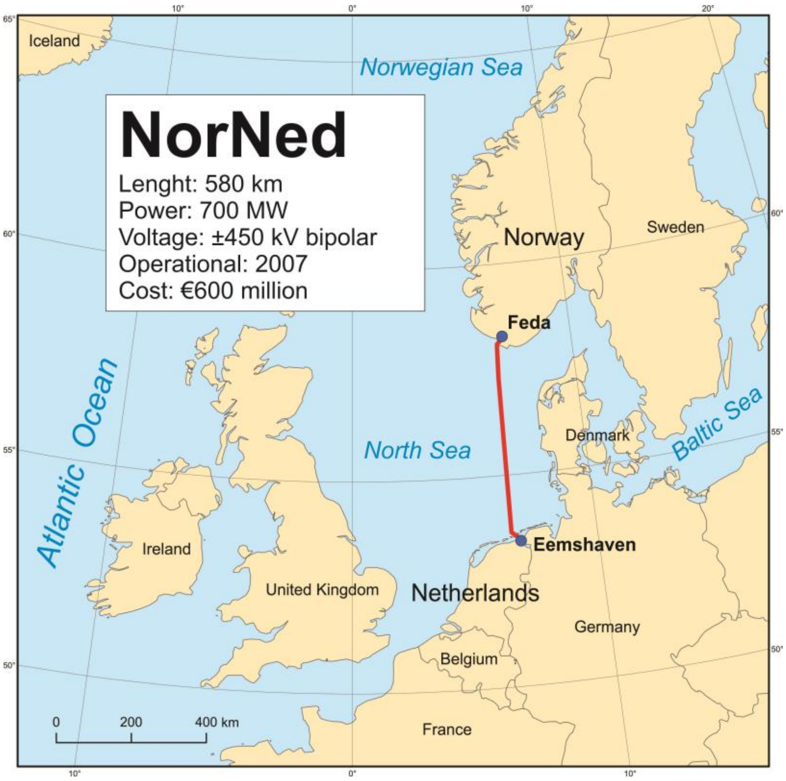


Fig. 39 – NorNed HVDC submarine power cable between Norway and The Netherlands

The goal of this HVDC cable is to connect the power grids of both countries and provide electricity transfer. The preparations for its construction began in 1994, the construction itself in 2006 and it was commissioned in May 2008.

The cable connects the Dutch grid at the converter substation in Eemshaven (380 kV) and the Norwegian grid at Feda (300 kV). The Dutch grid is integrated into the UCTE regional synchronous area while the Norwegian one is part of the Nordic regional synchronous area. The two regional AC systems are asynchronous so the only way to connect them is via a DC connection.

The cable is designed to carry 700 MW at ±450 kV DC (ABB library, 2013). It is a bipolar/symmetrical monopole link. The final cost reached 600 M€.

The weight of the cable is 47000 tons. In order to be protected from mechanical damages it is buried in the seabed or covered by rock (Stattnet SF & TenneT TSO B.V., 2008).

The cable has the capacity of transmitting power in both directions for balancing generation and consumption in both countries. In The Netherlands the consumption is higher during the day so then The Netherlands import cheap power via the cable from Norway. In Norway the power is produced by hydro power plants, which is cheaper than the power produced in the gas-fired power plants in The Netherlands. At night there is a reverse power flow since Norway consumes more electricity during the night than during the day. The Netherlands export at night gas-produced electricity via the cable allowing the Norwegian reservoirs to fill up for the day use. It is estimated that the interconnector helps to save about 1.7 million tons of CO_2 per year.

The NorNed cable is a mass-impregnated cable, of the non-draining type and paper insulated. For the shallow water part two constructive designs were used: a twin-core cable and a single-core cable. The external protective layer assures the mechanical strength and the impermeability against the water. In order to minimize the number of joints the cable was produced in lengths of 75 km for the twin-core type and 154 km for the single-core variant.

The deep water part of the cable was certified for transmission of 800 MW at 500 kV and the mechanical test was conducted for 500 m depth although the maximum depth reaches only 410 m. The cable is buried into the seabed in order to avoid or at least minimize potential external impact.

Due to its high voltage the calculated losses of the cable are very low – 3.7% at 600 MW load (Skog et al., 2006) and 5% for 700 MW (TenneT, 2004). As the demand during the day can fluctuate very rapidly, a maximum ramping speed has been set at 20 MW/min in order to meet the demand variation.

The NorNed cable is designed (like most of the mass-impregnated cables) to operate at a temperature of maximum 50-55 °C.

The expected lifetime of the cable is estimated at more than 40 years (TenneT memo, 2004).

The commercial operations started on 5 May 2008 with a capacity auction and the first commercial power transfer was operated on 6 May 2008.

The use of the cable produced revenues of 50 M€ after two month of operation. The annual revenues figure approximate 70 M€.

6.1.2 SAPEI – the deepest up-to-date power submarine cable

This is the deepest power cable up to date in the world reaching a depth of 1650 m. The interconnector entered in operation in 2012 and has a total length of 435 km, of which 420 km is submarine. The cable allows 1000 MW of electric power transfer between mainland of Italy and Sardinia (Fig. 40). It has a bipolar configuration with a voltage of ±500 kV DC. More than half of its length lies in deep waters (Fig. 41).

Fig. 40 – SA.PE.I. HVDC submarine power cable in Italy between Sardinia and the peninsula

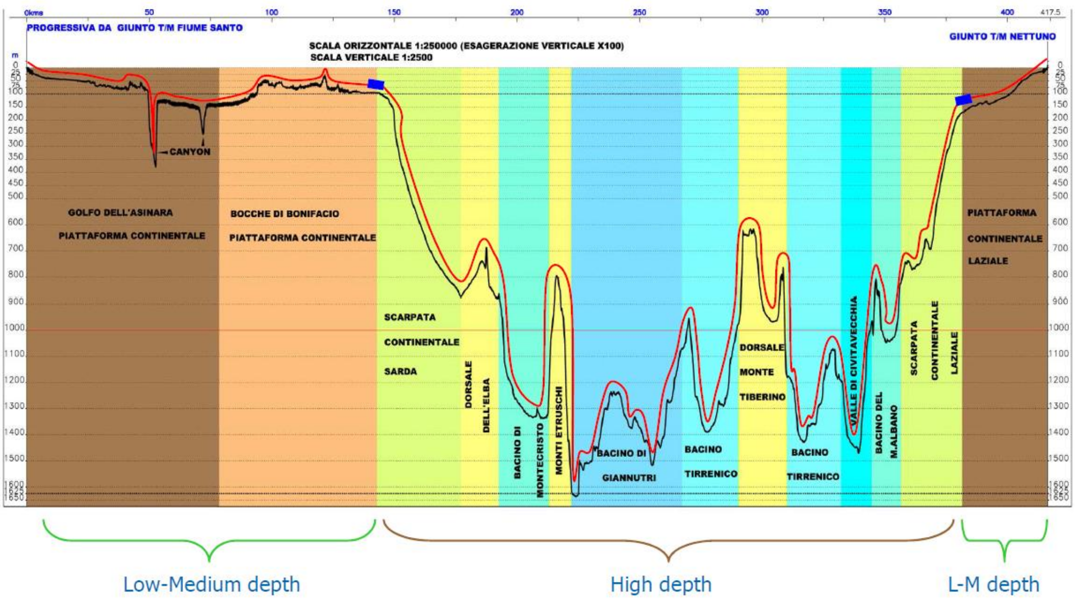
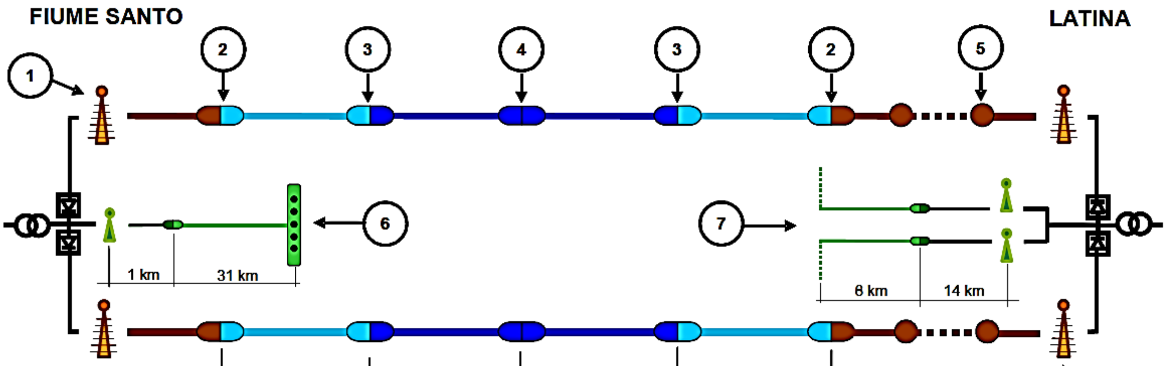


Fig. 41 – SA.PE.I. HVDC sea cable profile (CIGRÉ, 2014)

Prysmian has manufactured the cable and ABB has realised the converter stations. The total cost was 730 M€. It is operated by Terna, the Italian TSO.

The insulation of the cable is of the mass impregnated paper type. The solution found for this cable was to use a slightly different structure of the cable for the land, the shallow water and the deep water. For the deep water part the conductor is made of aluminium (Fig. 42 and 43). Using a lighter cable was the best solution for the available laying vessel and equipment and has also allowed to limit the tensile force on the cable during laying it down. It was the first time that aluminium was used as conductor for submarine HVDC cables. Copper was used for the shallower waters (<400 m).

Fig. 42 – The structure of the deep water segment of the SA.PE.I power cable (Rendina et al., 2012)



	Land Cable	Low water depth Cable	High water depth Cable		Low water depth Cable	Land Cable
Conductor	Copper	Copper	Aluminium	Aluminium	Copper	Copper
Cross section (mm²)	1400	1000	1150	1150	1000	1400
Length (km)	~ 1	~ 150	~150	~85	~40	~14
Max water depth (m)	---	400	1650	1400	200	---

1 Cable Termination; 2 Sea/Land Joint; 3 Transition Joint (max. depth 200 m); 4 Deep water Joint; 5 Land Joint; 6 Sea Electrode: Anode; 7 Sea Electrode: Cathode

Fig. 43 – The structure by segments of the SAPEI power cable (Rendina et al., 2012)

The cable was laid by the Prysmian purpose-built vessel "Giulio Verne". Down to 600 m depth the cable was buried in the sea bottom sediment. Where the rock too hard a special "trenching" machine was used in order to dig a 0.5-0.7 m deep trench, in which the cable was placed. Below this depth the cable was just laid down on the sea bottom.

The interconnector allows electricity exchanges between the peninsular of Italy and Sardinia, taking advantage of the cheap renewable resources on the island. By removing the "bottlenecks" between Sardinia and the rest of the Italian electricity market approximately 70 M€ is saved every year. It is estimated that the exhaust of more than 500000 tons of CO_2 per year will be avoided (SA.PE.I webpage). With the big power potential the cable could also start the electricity system of the island in case of a blackout.

The bipolar configuration of was chosen for a higher flexibility in case of damage or maintenance (Fig. 44). The system can operate under a monopolar configuration at half power with either metallic or sea return.

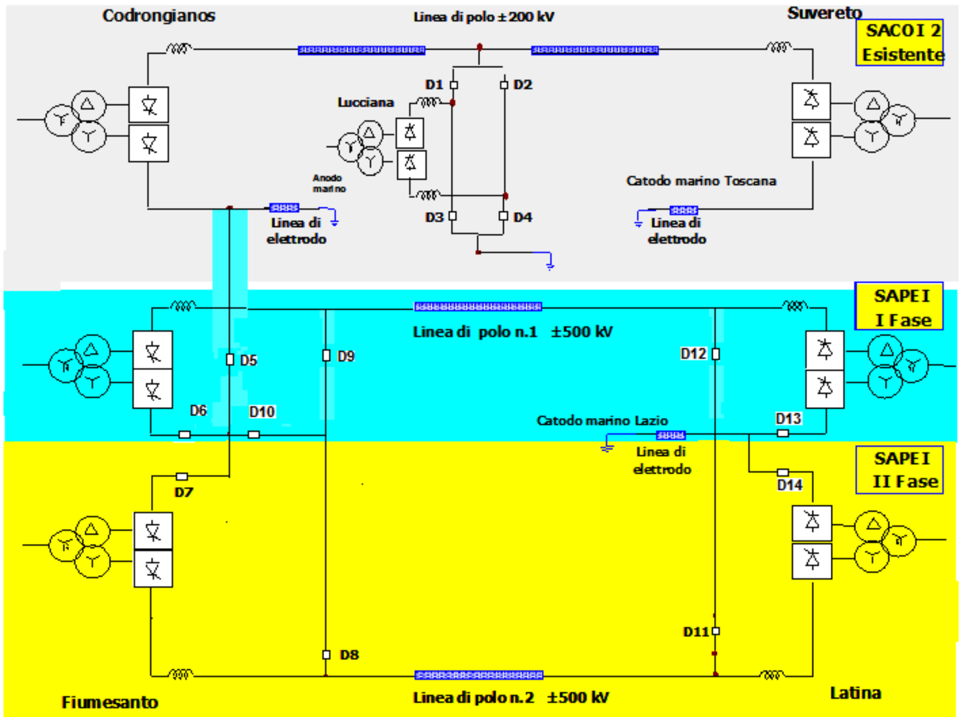


Fig. 44 – The configuration of the SAPEI HVDC interconnector (Rendina et al., 2012)

The cathode is installed off the coast of Lazio and consists of two marine bare conductors of 300 m each at 30 m depth. The anode is installed in Punta Tramontana, Sardinia which was originally used for another HVDC interconnector – SACOI. It has been reinforced in order to cope with the increased current level.

The converters were designed and built by ABB using the Line Commutated – Current Source Converters type (thyristor based), which is a mature and reliable technology.

6.1.3. Kii Channel HVDC – the most powerful submarine HVDC cable

The cable connects the Japanese islands of Honshū and Shikoku (Fig. 45). With 1400 MW it has the highest capacity in the world for a submarine HVDC power cable with a single bipolar configuration. The HVDC Cross-Channel between France and England can carry 2000 MW but has two bipoles, each of them rated at 1000 MW.

Fig. 45 – Kii Channel HVDC submarine power cable in Japan

The purpose of the interconnector is to feed the Kansai area on the Honsū Island (Kōbe-Kyōto-Ōsaka conurbation) by electricity produced by the Tachibana coal power plant on the Shikoku Island. It must also stabilize and reinforce the power system in Western Japan (Shimato et al., 2002).

At the time of its inauguration it was the first HVDC system to use Gas-Insulated Switchgear (GIS) and had the largest thyristors ever made. A bipolar configuration with metallic return was chosen in order to avoid electrolytic corrosion in the neighbouring area. The two submarine cables are oil-filled with a conductor cross-section of 3000 mm^2. The oil-filled variant was preferred against the mass-impregnated type because it could be used for a higher temperature of the conductor and also because of the relatively short distance.

An upgrade up to 2800 MW is planned.

6.2 Planned cables

6.2.1 NSN Link and NorthConnect

These are two proposed submarine power cables aimed at linking and transferring electricity between the Norwegian and UK/Scotland grids (Fig. 46). When completed in 2021 the NSN Link will be with its 730 km the longest submarine power cable in the world.

Fig. 46 – Future NSN Link and NorthConnect HVDC submarine power cable routes between Norway and United Kingdom

NSN Link cable will have a capacity of 1400 MW, powerful enough to supply nearly 1 million homes in the UK with low-carbon electricity. Its cost is estimated at around 2 G€. After a feasibility study conducted in 2009, Statnett and National Grid announced in March 2015 a decision to start with the construction phase.

The NSN Link cable will connect Norway's grid at Kvilldal and reach the UK's network at Blyth. The route of the cable was surveyed in 2012. No major bathymetric or geological obstacle was identified. The sand waves measure up to 0.75 m so no special action like pre-sweeping is required. The cable will be buried at a depth of 1-2 m in the seabed sediment.

The cable will have a copper conductor and will be of the MI (mass impregnated) paper insulated type, suitable for long submarine distances. Its diameter will be around 150 mm and it will weight approximately 60 kg/m.

The system will be a bipolar one with two cables (+550 kV and –550 kV) produced and installed by Nexans for the fjord waters and Prysmian for the off-shore. The converter stations will be built and installed by ABB. The cables will be installed separately at a distance of approximately 50 m. This will offer a degree of protection for both cables being damaged by the same incident.

With more interlinking and existing infrastructure, the North Sea becomes gradually a "crowded place" requiring careful planning in developing new structures. The challenges for building new cables will be high. The NSN Link will cross at least 14 gas pipelines, for which special solutions of protection must be designed.

The second proposed cable – NorthConnect – is expected to be operational in 2025. It will double the electricity transfer capacity between Norway and the United Kingdom. For its building, development and operation a commercial joint venture was established between the United Kingdom and Norwegian owner companies, each holding 50% of the company (NorthConnect, 2012).

The main technological problems to be solved will be the crossing of existing pipelines and laying the cable in the deep waters of the Norwegian fjords (850 m depth).

Both interconnectors would provide a better use of the energy resources in both countries. When the winds blow in the UK and produce non-carbon electricity, Norway is able to import electricity at lower prices and in the meantime store water in its reservoirs. When there is too little wind to meet the demand the hydro-produced electricity is transferred from Norway to the UK at a lower price. Besides the fact that by having such a connection there will be a better use of the renewable energy sources in both countries, the security of power supply will increase.

6.2.2 Nord.Link and NorGer

These are two power cable projects aimed at connecting Norway's and Germany's grids (Fig. 47). The developers decided to select Nord.Link as the priority route, while keeping NorGer on hold as a second route for the future.

Nord.Link is supposed to be operational in 2018 and will allow a direct transfer of electricity between Norway and Germany. It will be the first direct link between the two grids. With its 600 km length (516 km subsea) it will be among the longest in the world.

In February 2015 the three partners involved in its completion – Statnett (Norway), TenneT (The Netherlands/Germany) and KfW (Germany) have made the final investment decision. Its cost is estimated between 1.5 and 2 G€.

Fig. 47 – Future NorGer and Nord.Link HVDC submarine power cable routes between Norway and Germany

The cable will operate at 500 kV and will have a capacity of 1400 MW which is two times higher than the capacity of the longest cable to date (NorNed).

The cable will connect the Norwegian power grid at Tonsdat with the German network at Brunsbüttel.

Nexans and ABB will manufacture the cable and ABB will build the converter stations.

NorGer involves more complex technical solutions and is scheduled to go into operation 10 years after Nord.Link.

Like in previous cases these interconnectors will take advantage of the flexibility of Norway's hydropower system as storage and Germany's wind power capacity. The utilization of the German wind capacity will be increased and better used while Norway could deliver power from renewable hydro sources when wind produced electricity does not cope with demand in Germany, thus maximizing the profits.

6.2.3 IceLink HVDC power cable

This is a power cable whose execution is still under consideration. No concrete project has yet been started up although some provisional techno-economic studies have already been produced. It aims at connecting Iceland with UK (Fig. 48).

Fig. 48 – Future IceLink HVDC submarine power cable route between Iceland and United Kingdom

Iceland holds abundant energy sources due to its geographical location and geology setting. Almost its entirely 18 GWh electricity production comes from geothermal and hydro power plants. This is much more than the demand of Iceland's 317000 inhabitants (excluding industry), which makes the electricity price the cheapest in Europe. Hydroelectric power plants account for 75% of the electricity production, the rest coming from geothermal plants along with a negligible part of electricity from wind and oil. The low prices have attracted bulk electricity industrial consumers like aluminum processing factories, which now account for more than 70% of the total electricity consumption in Iceland. The potential of geothermal electricity production is only partially used but in the eventuality of an interconnector more capacity would be built, which would provide the base load for the electricity consumption. The project linking both countries could deliver 5 TWh per year to the UK at a lower cost than offshore wind electricity.

When completed IceLink will be the longest submarine power cable in the world (Fig. ???). Its 1200 MW capacity will be enough to power the equivalent of 2 million British homes. A bipolar configuration will be preferred with two single-core cables. Both poles will be independent of each other to maintain half capacity during cable or pole outages. The cables will be laid close to each other in order to eliminate the magnetic fields.

For the cable itself an already mature technology would be preferred which is more reliable and would lower the probability of an outage since there are long waits for good weather in the region in order to repair the cable in case of a damage.

Studies today (bibliography) suggest to use a voltage of 450-500 kV. A higher voltage for the length of the cable would increase the losses. A MI cable is advised to be used again because of the mature technology and because this type is currently successfully operated in other long and deep reaching interconnectors (NorNed, SA.PE.I, Cometa HVDC). In the shallow water part the conductor used will be copper while for the deeper parts aluminum could be used. The high rate advances in these technological fields might offer different solutions by the time that a solid decision to build the interconnector would be taken.

The two governments have signed a memorandum of understanding in May 2012 exploring the proposals for a cable. The date of its commissioning will be no earlier than 2022.

These three last presented projects are just a selection from many future HVDC interconnectors which aim at strengthening the power exchange links between European countries.

Conclusions

Over the last decades HVDC technology has proved to be a reliable methodology for the transmission of large quantities of electric energy over large distances with relatively low losses. It is used more and more for linking distant areas that are complementary in energy consumption and generation or for connecting grids that work at different frequencies or phases.

The development of new materials along with technological progress paved the way for integration of regions divided by water bodies by means of HVDC submarine power cables.

The HVDC submarine power cable technology is now mature starting to pay back the high investments.

Much of the experience for laying the cable on the seafloor is inherited and adapted from the much older technology of telecommunication submarine cables.

Europe is the leading region both in terms of the number of cables and the length. The longest one, the deepest one and one of the most powerful cables are found to be here. Also, the major actors in manufacturing and laying submarine power cables are based in Europe.

For the moment mass-impregnated cables are the most frequently used type but a new generation of extruded cables are promising improved performance in the future. Most of the converters, used to couple HVDC with AC grids, apply LCC (Line Commutated Convertor) technology but with the improvement of VSC (Voltage Source Converter) technology the latter will become more prominent.

The first submarine power cables used a monopolar configuration but the newly built types are bipolar. This allows for a higher capacity and improved reliability.

The fast rate, at which technologies in power systems and material science make progress, promises to bring in the near future important improvements in conductor and insulation materials. Moreover improved manufacturing technology will allow for the production of longer and more powerful cables. Thus longer distances could be covered and greater depths reached.

References

ABB library, Submarine Cable Link The NorNed HVDC Connection, Norway – Netherlands, https://library.e.abb.com/public/e554905a1153efc2c1257c2f004b8304/NorNed_SEHVC%20M-063E.pdf, accessed on 19.05.2015

Alstom, 2010, HVDC for beginners and beyond, http://www.alstom.com/Global/Grid/Resources/Documents/Systems/HDVC%20for%20beginners%20and%20beyond%20Brochure%20GB.pdf, accessed on 14.09.2015

Andrulewicz, E., Napierska, D., Otremba, Z., 2003, The environmental effects of the installation and functioning of the submarine SwePol Link HVDC transmission line: a case study of the Polish Marine Area of the Baltic Sea, *J. Sea Res.*, 49: 337–345, DOI: 10.1016/S1385-1101(03)00020-0

Brunstad et al., 2008, A Revision of the Rogaland Group, Norwegian North Sea, *Norwegian Stratigraphic Lexicon*, accessed on 10.09.2015

Burnett, D.R., Beckman, R.C., Davenport, T.M., 2013, Submarine cables: The handbook of law and policy, Martinus Nijhof Publishers

Carter, L., Burnett, D., Drew, S., Marle, G., Hagadorn, L., Bartlett-McNeil, D., Irvine, N., 2009, Submarine Cables and the Oceans – Connecting the World, *UNEP-WCMC Biodiversity Series* No. 31, ICPC/UNEP/UNEP-WCMC

Carter, L., R. Gavey, P.J. Talling, and J.T. Liu, 2014, Insights into submarine geohazards from breaks in subsea telecommunication cables, *Oceanography* 27(2):58–67, http://dx.doi.org/10.5670/oceanog.2014.40

Carter, L., Burnett, D., Davenport, T., 2013, The relation between submarine cables and the environment in Submarine cables: The handbook of law and policy, Martinus Nijhof Publishers

CEDA, 2005, Cable lying in the Waddenzee, *CEDA presentation* 22.11.2005, Breda

CIGRÉ, 2009, Third-Party Damage to Underground and Submarine Cables, *Working Group B1.21*

CIGRÉ, 2014, SAPEI ±500 kVdc – 1000 MW interconnection Sardinia – Italian peninsula, presentation accessed 16.09.2015

CSRIC, 2014, Protection of submarine cables through spatial separation. Final report, *The Communications Security, Reliability and Interoperability Council IV*

DNV, 2012, Electrical power cables in subsea applications. Recommended practice, *DNV-RP-F401*, https://www.dnvgl.com/oilgas/subsea-facilities/world-class-codes.html, accessed on 11.09.2015

Dunham, A., Pegg, J.R., Carolsfeld, W., Davies, S., Murfitt, I., Boutillier, J., 2015, Effects of submarine power transmission cables on a glass sponge reef and associated megafaunal community, *Marine Environmental Research*, 107: 50-60, doi:10.1016/j.marenvres.2015.04.003

Econ Pöyry Report, 2011, Effects of intraday trade on NorNed, Pöyry Management Consulting (Norway) AS, Oslo

EPA, 2008, Renewable Energy Certificates, U.S. Environmental Protection Agency, http://www.epa.gov/greenpower/documents/gpp_basics-recs.pdf, accessed on 20.07.2015

Kent, H., Bucea, G., 1998, Inquiry into the Auckland Power Failure - Technical Report on Cable Failures, Integral Energy Australia

Kjørholt, Å.M.H., 2014, HVDC Transmission Using a Bipolar Configuration Composed of an LCC and MMC, Master of Energy and Environmental Engineering, Norwegian University of Science and Technology

Kramer, K., 2000, Kabelbauarten sowie Verlegemethoden und ihre Auswirkungen auf magnetische und elektrische Felder im Meer. In: Merck T, von Nordheim H (Eds) *Technische Eingriffe in Marine Lebensräume*, BfN-Skripten 29: 77 – 87

Meißner, K., Sordyl, H., 2006, *Literature Review of Offshore Wind Farms with Regard to Benthic Communities and Habitats, in Ecological Research on Offshore Wind Farms: International Exchange of Experiences. PART B: Literature Review of Ecological Impacts*, Editors: Zucco, C., Wende, W., Merck, T., Köchling, I., Köppel, J., Bundesamt für Naturschutz (BfN), Federal Agency for Nature Conservation

NorthConnect, 2012, NorthConnect, http://www.northconnect.no/files/31860-E01d_A4-version.pdf, accessed on 29.05.2015

NorthConnect, 2015, NorthConnect Interconnector Converter Station and High Voltage Alternating Current Cable Route, Vol. 1

Rendina, R., Guarniere, M.R., Niccolai, R., Pazienza, G., Gualano, A., Malagrotti, S., Danelli, A., Jansson, B., Alvarez, F., Lovison, W., Persico, A., Orini, A., Bocchi, F., Aleo, S., Curtoti, G., 2012, The realization and commissioning of the ±500 kV 1000 MW HVDC link Sardinia Island – Italian Peninsula (SAPEI), CIGRE 2012, B1-101

SAPEI webpage, SA.PE.I.'s economic, electricity and environmental advantages, accessed on 20.05.2015

Shimato, T., Hashimoto, T., Sampei, M., 2002, The Kii Channel HVDC Link in Japan, *CIGRÉ Session*, 14-106

Skog, J.-E., Koreman, K., Pääjärvi, B., Worzyk, T., Andersröd, T., 2006, The Norned HVDC Cable link. A Power Transmission Highway between Norway and the Netherlands, presentation at *ENERGEX*, Stavanger, NorwayJune 12-15, 2006

Stattnet SF & TenneT TSO B.V., 2008, NorNed. Europe's link for the future

Stølan, R., 2009, Losses and Inductive Parameters in Subsea Power Cables, Norwegian University of Science and Technology Department of Electric Power Engineering, Master Thesis

Talling, P.J., Paull, C.K., Piper, D.J.W., 2013, How are subaqueous sediment density flows triggered, what is their internal structure and how does it evolve? Direct observations from monitoring of active flows, *Earth-Science Reviews*, 125:244-287, DOI: 10.1016/j.earscirev.2013.07.005

TenneT memo, 2004, HVDC Transmission and Lifetime Expectancy, http://www.tennet.eu/nl/fileadmin/downloads/About_Tennet/Publications/Other_Publications/Application%20for%20Norned/plugin-19-B7-HVDC_Transmission_and_Lifetime_Expectancy_tcm41-12302.pdf, accessed on 19.05.2015

TenneT, 2004, NorNed kabel HVDC Project. Continuous Transmission Capacity, http://www.tennet.eu/nl/fileadmin/downloads/About_Tennet/Publications/Other_Publications/Application%20for%20Norned/plugin-17-UK-B5-Continuous_Transmission_Capacity_tcm43-12300.pdf, accessed on 23.05.2015

Tricas, T., Gill, A., 2011, Effects of EMFs from Undersea Power Cables on Elasmobranchs and Other Marine Species, U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Regulation, and Enforcement, Pacific OCS Region, Camarillo, CA. OCS Study BOEMRE 2011-09

Worzyk, T., 2009, Submarine Power Cables: Design, Installation, Repair, Environmental Aspects, Springer-Verlag Berlin Heidelberg, DOI 10.1007/978-3-642-01270-9

Zaccone, E., 2009, HVDC transmission cable systems. State of the art and future trends, presentation at Spring 2009 ICC Meeting Subcommittee C – Cable Systems, 17-20 May, 2009 Orlando, USA

Zaccone, E., 2014, High voltage underground and subsea cable technology options for future transmission in Europe, presentation at *E-Highway2050 WP3 workshop* April 15th, 2014 Brussels

Annex 1 - List of main existing submarine power cables in the World

	Cable name	Countries linked or involved	Body of water	Power (MW)	Voltage (kV)	Submarine length (km)	Commissioning year	Configuration
Europe								
1	NorNed	Norway, Netherlands	North Sea	700	450	580	2007	bipolar
2	SAPEI	Italy	Tyrrhenian Sea	1000	500	420	2012	bipolar
3	SACOI	Italy, France	Tyrrhenian Sea	300	200	121	1968	monopolar
4	HVDC Italy-Greece (Grita)	Italy, Greece	Ionian Sea	500	400	160	2001	monopolar
5	East-West Interconnector	UK, Ireland	Irish Sea	500	200	186	2012	symmetrical monopole
6	BritNed	UK, Netherlands	North Sea	1000	450	240	2011	bipolar
7	SwePol	Sweden, Poland	Baltic Sea	600	450	239	2000	monopolar
8	Baltic Link	Sweden, Germany	Baltic Sea	600	450	231	1994	monopolar
9	Skagerrak I	Denmark, Norway	Baltic Sea	250	250	127	1977	monopolar
10	Skagerrak II	Denmark, Norway	Baltic Sea	250	250	127	1977	monopolar
11	Skagerrak III	Denmark, Norway	Baltic Sea	440	350	127	1993	monopolar
12	Skagerrak IV	Denmark, Norway	Baltic Sea	700	500	137	2014	monopolar
13	Cometa HVDC	Spain	Mediterranean Sea	400	250	244	2012	bipolar
14	Fennoskan 1	Sweden, Finland	Gulf of Bothnia	500	400	200	1989	bipolar
15	Fennoskan 2	Sweden, Finland	Gulf of Bothnia	800	500	200	2011	bipolar
16	EstLink 1	Estonia, Finland	Gulf of Finland	350	150	74	2006	bipolar
17	EstLink 2	Estonia, Finland	Gulf of Finland	650	450	145	2014	monopolar
18	Kontek	Germany, Denmark	Baltic Sea	600	400	52	1995	monopolar
19	Gotland I	Sweden	Baltic Sea	30	150	98	1954	monopolar
20	Gotland II	Sweden	Baltic Sea	130	150	92	1983	monopolar
21	Gotland III	Sweden	Baltic Sea	130	150	92	1987	monopolar
22	HVDC Cross-Channel	France, UK	English Channel	2000	270	46	1986	bipolar
23	HVDC Moyle	UK	Irish Sea	500	250	55	2001	monopolar
24	Storebælt	Denmark	Baltic Sea	600	400	32	2010	monopolar
25	Kontiskan 1	Denmark, Sweden	Kattegatt Strait	250	285	21	1965	bipolar

	Cable name	Countries linked or involved	Body of water	Power (MW)	Voltage (kV)	Submarine length (km)	Commissioning year	Configuration
26	Kontiskan 2	Denmark, Sweden	Kattegatt Strait	300	285	21	1988	bipolar
America								
27	Neptune Cable	US	Lower Bay	660	500	80	2007	bipolar
28	Trans Bay Cable LLC	US	San Francisco Bay	400	200	85	2010	bipolar
29	Vancouver Island Pole 1	Canada	Strait of Georgia	312	260	33	1968	bipolar
30	Vancouver Island Pole 2	Canada	Strait of Georgia	370	280	33	1977	bipolar
31	Cross Sound Cable	US	Long Island Sound	330	150	39	2005	bipolar
Asia								
23	HVDC Leyte - Luzon	Philippines	San Bernardino Strait	440	350	21	1988	monopolar
33	HVDC Hokkaidō–Honshū	Japan	Tsugaru Strait	300	250	44	1979	monopolar
34	Kii Channel HVDC system	Japan	Kii Channel	1400	250	50	2000	bipolar
Australia-Oceania								
35	HVDC Inter-Island	New Zealand	Cook Strait	1200	350	40	1965	bipolar
36	Basslink	Australia	Bass Strait	500	400	290	2006	monopolar

List of main planned submarine power cables in the World

	Cable name	Countries linked or involved	Body of water	Power (MW)	Voltage (kV)	Submarine length (km)	Commissioning year	Configuration
Europe								
1	Ice Link	Iceland, UK		1200	N/A	1170	2022	N/A
2	NorGer	Norway, Germany	North Sea	1400	450	630	N/A	bipolar
3	NSN Link	UK, Norway	North Sea	1400	N/A	711	2021	bipolar
4	NorthConnect	Scotland, Norway	North Sea	1400	500	650	2025	N/A
5	Nord.Link	Norway, Germany		1400	525	500	2020	N/A
6	NordBalt HVDC	Sweden, Lithuania	Baltic Sea	700	400	400	2015	N/A
7	UK Western Link	UK	North Channel	2200	600	385	2016	bipolar
8	Interconnexion France-Angleterre (IFA 2)	France, UK	English Channel	1000	N/A	208	2020	N/A
9	Nemo Link	Belgium, UK	English Channel	1000	400	130	2019	N/A

	Cable name	Countries linked or involved	Body of water	Power (MW)	Voltage (kV)	Submarine length (km)	Commissioning year	Configuration
10	Euro-Asia Interconnector	Israel, Cyprus, Greece	Mediterranean Sea	2000	N/A	1000	2022	N/A
America								
11	Labrador-Island Link	Canada	Strait of Belle Isle	900	315	35	N/A	N/A
12	Maritime Link Project	Canada	Gulf of St. Lawrence	500	200	170	2017	N/A
Asia								
13	HVDC Sumatra-Java	Indonesia	Malacca Strait	3000	500	35	2017	N/A
14	India-Sri Lanka Power Link	India, Sri Lanka	Palk Strait	1000	400	39	N/A	N/A

Annex 2 - Glossary

Abrasion	Mechanical scraping of a rock surface by friction between rocks and moving particles during their transport by wind, glacier, waves, gravity, running water or erosion. After friction, the moving particles dislodge loose and weak debris from the side of the rock.
AC	See Alternating current
Active power	It is the product of voltage and current. Its measure unit is the watt (W). Synonym: real power, true power
Alternating current (AC)	An electric current in which the flow of electric charge periodically reverses direction.
Anode	A positively charged electrode.
Armouring	A protective covering of a submarine power cable made out of metal wires wound around the cable in order to provide both tension stability and mechanical protection.
Asynchronous	A state in which two alternating current systems function at different phases.
Availability	For HVDC schemes, the term represents “energy availability”. Energy availability is the ability of a HVDC scheme to transmit, at any time, power up to the rated power. Hence, a converter scheme which can transmit 1.0 pu power for 100% of the time would have an energy availability of 100%. Any outage of the HVDC scheme or, for example, the outage of one pole in a bipole, will impact the energy availability, reducing the figure to less than 100%.
Back-to-back (B2B)	A high-voltage direct-current (HVDC) system with both ends (converters) in the same switchyard. This is used to couple asynchronously operated power grids or for connecting power grids of different frequencies where no DC transmission line is necessary.
Bathymetry	The measurement of the depths of oceans, seas, or other large bodies of water. It is the underwater equivalent to hypsometry or topography.
Bedrock	Solid rock exposed at the surface of the Earth or covered by unconsolidated material, weathered rock, or soil.
Bipolar	A layout in HVDC transmission when a pair of conductors is used, each at a high potential with respect to ground, in opposite polarity.
Black start	The process of restoring an electric power station or a part of an electric grid to operation without relying on the external transmission network.
Blackout	A short- or long-term loss of the electric power to an area. Synonym: power cut, power blackout, power failure, power outage
Bus	Thick conductor acting as a node in an electrical substation. It may or may not correspond to the physical bus in substation.
Cable laying	The operation of placing a submarine power (or communication) cable on the seafloor.
Cable route, cable path	The selected corridor on the seafloor used by a submarine cable between the two anchor points on the continent.
Cable strain	Any force or pressure tending to alter shape or cause a fracture to a power cable.
Capacitance	The property of being able to collect or store a charge of electricity.
Capacity	The amount of power that is stored in an electric system (battery) or that can be transferred via a conductor.
Casing	The framework and material for a covering.
Cathode	A negatively charged electrode.
Conductivity	A measure of a material's ability to conduct an electric current. Its measurement unit is siemens per metre (S/m).
Conductor	An object, substance or material allowing the flow of an electric charge.
Consumption (electricity)	The actual energy demand made on existing electricity supply.

Continental rise	The gently sloping transition between the continental slope and the deep ocean floor, usually characterized by coalescence of submarine alluvial fans. Together, the continental shelf, continental slope, and continental rise are called continental margin.
Continental shelf	An underwater landmass which extends from a continent, resulting in an area of relatively shallow water. Together, the continental shelf, continental slope, and continental rise are called continental margin.
Continental slope	The sloping region between a continental shelf and a continental rise. Together, the continental shelf, continental slope, and continental rise are called continental margin.
Conversion (current)	The act of converting electric energy from one form to another, converting between alternating current and direct current, or just changing the voltage or frequency, or some combination of these.
Converter station	A specialized type of substation which forms the terminal equipment for a high-voltage direct current (HVDC) transmission line and where the conversion from alternating current to direct current or the other way round takes place.
Corrosion	A natural process, which converts a refined metal to a more stable form, such as its oxide or hydroxide. It is the gradual destruction of materials (usually metals) by chemical reaction with their environment. A process of erosion whereby rocks and soil are removed or worn away by natural chemical processes, especially by the solvent action of running water, but also by other reactions such as hydrolysis, hydration, carbonation, and oxidation. Synonym: chemical erosion
Cross-linked polyethylene insulation (XPLE insulation)	Material consisting of polymer chains of polyethylene linked to one another by covalent bonds. Insulation of a power cable made of this material.
DC	See Direct current
DGPS	See Differential global positioning system
Differential global positioning system (DGPS)	An enhancement to Global Positioning System (GPS) that provides improved location accuracy. DGPS uses a network of fixed, ground-based reference stations to broadcast the difference between the positions indicated by the GPS (satellite) systems and the known fixed positions.
Direct current (DC)	A unidirectional flow of electric charge.
Distribution (electricity)	The final stage in the delivery of electric power; it carries electricity from the transmission system to individual consumers.
Distribution System Operator (DSO)	A natural or legal person responsible for operating, ensuring the maintenance of and, if necessary, developing the distribution system in a given area and, where applicable, its interconnections with other systems and for ensuring the long term ability of the system to meet reasonable demands for the distribution of electricity.
DSO	See Distribution System Operator
Earthquake	A series of perceptible vibrations induced in the earth's crust by the abrupt rupture and rebound of rocks in which elastic strain has been slowly accumulating.
Echo-sounding	A technique used to determine the depth of water by transmitting sound pulses into water. The time interval between emission and return of a pulse is recorded, which is used to determine the depth of water along with the speed of sound in water at the time.
Efficiency	The ratio of the energy developed by a device (machine, engine) to the energy supplied to it, usually expressed as a percentage.
Electric current	A flow of electric charge. Its measure unit is the ampere (A).
Electric grid	An interconnected network for delivering electricity from suppliers to consumers. It consists of generating stations that produce electrical power, high-voltage transmission lines that carry power from distant sources to demand centres, and distribution lines that connect individual customers. Synonym: electricity network, power network
Electricity network	An interconnected network for delivering electricity from suppliers to consumers. It consists of generating stations that produce electrical power, high-voltage transmission

	lines that carry power from distant sources to demand centres, and distribution lines that connect individual customers. Synonym: electric grid
Electrode	An electrical conductor used to make contact with a nonmetallic part of a circuit.
Electromagnetic field	The field of force associated with electric charge in motion, having both electric and magnetic components and containing a definite amount of electromagnetic energy.
Erosion	The process by which the surface of the earth is worn away by the action of water, glaciers, winds, waves, etc.
Failure	A short- or long-term loss of the electric power to an area. Synonym: power cut, power blackout, power outage
Faraday cage	An enclosure formed by grounded conductive material used to block electric fields.
Fault (geology)	A break in the continuity of a body of rock, with displacement along the plane of the fracture (fault plane).
Feasibility (study)	A study designed to determine the practicability of a system or plan.
Feeder	A circuit conductor between the power supply source and a final branch circuit over current device. A voltage power line transferring power from a distribution substation to the distribution transformers.
Fluid-filled insulation	Self-contained pressure cable in which the pressurizing fluid is the insulating fluid and which is designed to maintain free movement of the fluid within the cable.
Frequency	The number of complete cycles per second in alternating current direction. Its measure unit is the hertz (Hz). In Europe the electric grid operates at 50 Hz.
Functional parameters	The range of values that characterizes the proper functioning of a process, phenomenon, system, or device.
Gas-Insulated Switchgear (GIS)	A type of switchgear that uses a tight metallic enclosure filled with gas acting as insulation between live parts of the equipment and earthed metal enclosure.
Generation (electricity)	The process of generating electrical power from other sources of primary energy.
Geomorphology	The study of the characteristics, origin, and development of landforms.
GIS	See Gas-Insulated Switchgear
Glacier	A persistent body of dense ice that is constantly moving under its own weight. It forms where the accumulation of snow exceeds its melting over a long period.
Global Positioning System (GPS)	A system of earth-orbiting satellites, transmitting signals continuously towards the earth, that enables the position of a receiving device on or near the earth's surface to be accurately estimated from the difference in arrival times of the signals GPS. It was devised and is maintained by the US Department of Defense but other countries or entities have also devised and placed on orbit similar systems or intend to (Russia, China, EU).
GPS	See Global Positioning System
Harmonic filter	A filter that is tuned to suppress an undesired harmonic in a circuit. It is intended to improve the quality of the power that is delivered to electrical load equipment. Synonym: power conditioner, voltage regulator
Hazard	The absence or lack of predictability. A situation that poses a level of threat to life, health, property, or environment.
High-voltage alternating current (HVAC)	High-voltage alternating current. By extension, in power transmission engineering it is considered any voltage over approximately 35.000 volts.
High-voltage direct current (HVDC)	High-voltage direct current. By extension, in power transmission engineering it is considered any voltage over approximately 35.000 volts.
Hydrostatic pressure	The pressure exerted by a fluid at equilibrium at a given point within the fluid, due to the force of gravity. Hydrostatic pressure increases in proportion to depth measured from the surface because of the increasing weight of fluid exerting downward force from above.

HVAC	See High-voltage alternating current
HVDC	See High-voltage direct current
Iceberg	A large floating mass of ice detached from a glacier and carried out to sea.
Iceberg drift	The movement induced to an iceberg by sea currents or winds.
Impermeability	The property of a material or rock not to permit the passage of a fluid through the pores.
Impregnated	A material whose interstices are filled with an allogenic substance in order to improve its physical, chemical or mechanical properties.
Impregnation	The action of filling the interstices of a material with a substance in order to improve the properties of the host material.
Insulator	A material whose internal electric charges do not flow freely, and therefore make it nearly impossible to conduct an electric current under the influence of an electric field. It is used to cover the conductor in a cable both for the protection of the cable and operators or people who might come in contact with it.
Interconnection	A structure which enables electricity to flow between networks operating at different physical parameters (voltage, frequency, phase). A link between power systems enabling them to draw on one another's reserves in time of need and to take advantage of energy cost differentials resulting from such factors as load diversity, seasonal conditions, time-zone differences, and shared investment in larger generating units.
Inverter	An electronic device or circuitry that changes direct current to alternating current.
Isolation	An electric grid which operates with no connection with outside world. It is usually characteristics for remote islands.
Joint (cable)	A location where two cable segments come into contact. A special technique is used in order to ensure an efficient passage of electricity from one segment to another and special attention is paid in order to guarantee the tightness and mechanical resistance.
Lava flow	A moving outpouring of lava, which is created during a non-explosive volcanic eruption. The landforms resulted after the lava stopped moving and solidified may bear the same name.
LCC	See Line commutated converter
Line commutated converter (LCC)	A current sourced converter based on thyristor technology. The conversion process depends on the line voltage of the alternating current system to which the converter is connected in order to perform the commutation from one switching device to its neighbour. The direct current does not change direction.
Lithology	The study of rocks based on their macroscopic physical characteristics. Synonym: petrography
Losses	A measure of the power lost in an electrical system expressed as the ratio of or difference between the input power and the output power.
Low-carbon electricity	Processes or technologies that produce power with substantially lower amounts of carbon dioxide emissions than is emitted from conventional fossil fuel power generation.
Magnetic shielding	The practice of reducing the electromagnetic field in a space by blocking the field with barriers made of conductive or magnetic materials. It is applied to isolate the wire in a power cable from the environment through which the cable runs.
Maintenance	The upkeep of power facilities and equipment.
Mass-impregnated paper	Impregnated paper insulation in which the paper tapes are impregnated after lapping.
Maturity (technology)	A stage in the advance of a technology that has been in use for long enough that most of its initial faults and inherent problems have been removed or reduced by further development.
Mechanical stress	An external force applied to an object and causing deformation.
Metallic mattress	An array of metallic pieces held together by a net used to cover or exert pressure on

	submarine power cables.
Metallic return	A low voltage cable used in HVDC monopolar transmission.
Mid-ocean ridge	An underwater mountain system formed by plate tectonics. They are usually found in the middle of ocean running for thousands of kilometres and represent the locus of seafloor spreading.
Monopolar	A layout of HVDC transmission where usually only one line is used and one of the terminals of the rectifier is connected to earth ground.
Off-shore	Any construction (fixed on seabed or floating) or activity that takes place in a marine environment. It can be related to electricity production and transmission by using wind turbines, hydrocarbons extraction or drilling.
Outage	A short- or long-term loss of the electric power to an area. Synonym: power cut, power blackout, power failure
Outcrop	Part of a rock formation or mineral vein that appears at the surface of the earth.
Overhead line	A structure used in electric power transmission and distribution to transmit electrical energy along large distances. It consists of one or more conductors suspended by towers or poles. The insulation is provided by air.
Phase (electricity)	Any conductor of a polyphase system, which is intended to be energized under normal use.
Polarity	Nominal property of an electrode, having values negative or positive according to the sign of the electrode potential, or neutral when the electrode potential is zero.
Pole	Designation of a conductor, terminal or any other element of a DC system which is likely to be energized under normal conditions; e.g. positive pole, negative pole.
Polyethylene	The most common form of plastic. Thermoplastic material produced by the polymerization of ethylene molecules.
Power cable	A metal wire that is used to transport electricity from the generation facility to the consumption place. It can be one or more electrical conductors, usually held together with an overall sheath.
Power network	An interconnected network for delivering electricity from suppliers to consumers. It consists of generating stations that produce electrical power, high-voltage transmission lines that carry power from distant sources to demand centres, and distribution lines that connect individual customers. Synonym: electricity network, power grid
Power plant	An industrial facility for the generation of electric power.
Prosumer	A person or entity that consumes and produces electricity.
Photovoltaic panel (PV panel)	An integrated assembly of interconnected photovoltaic cells designed to absorb the sun's rays as a source of energy for generating electricity or heating.
PV panel	See Photovoltaic panel
Quaternary	The most recent geologic period starting approximately 2.5 million years ago and which continues to present. It is characterized by soft, loose consolidated rocks found generally on top of the crust.
Reactive power	The power that continuously bounce back and forth between source and load. Its measure unit is volt-ampere reactive (var).
Rectifier	Component of an electric circuit used to change alternating current to direct current.
Reliability	Reliability is a measure of the capability of the HVDC link to transmit power above some minimum defined value at any point in time under normal operating conditions. Reliability is normally expressed as the number of times in one year the scheme is incapable of transmitting power above a minimum defined value. This inability to transmit above a defined power level is termed Forced Outage Rate (F.O.R.).
Remotely Operated Vehicle (ROV)	A crewless submersible vehicle that is tethered to a vessel on the surface by a cable used to perform various operations needed to lay down a power cable on the seafloor and perform its maintenance.

Resistance	Property of an electric conductor by which it opposes a flow of electricity and dissipates electrical energy away from the circuit, usually as heat. Its measurement unit is the ohm (Ω).
Resistivity	An intrinsic property that quantifies how strongly a given material opposes the flow of electric current. Inverse of the conductivity. Its measurement unit is the ohm meter (Ω·m).
Reverse power flow	Transmission of electric energy through a circuit in a direction opposite to the usual direction.
ROV	See Remotely Operated Vehicle
Safety	A set of methods and techniques designed or set in place in order to avoid accidents.
Salinity	The total amount of dissolved salts contained in a body of water. The salts can be compounds like magnesium sulphate, potassium nitrate, sodium bicarbonate but the term refers generally to sodium chloride. Expressed as grams per kilogram of water or parts per thousand.
SCOF	See Self-contained oil-filled cable
Sea current	Continuous movement of seawater involving large swaths of waterbodies generated and affected by wind, Coriolis effect, temperature and salinity differences.
Sea wave	A disturbance on the surface of a liquid body, as the sea or a lake, in the form of a moving ridge or swell.
Seabed	The bottom of the ocean. Also known as the seafloor, sea floor, or ocean floor.
Seafloor	The bottom of the ocean. Also known as the seabed or ocean floor.
Sediment	A collection of transported fragments or precipitated materials that accumulate, typically in loose layers as of sand or mud. The transport agent can be wind, water, ice or gravity.
Sediment flow	A movement of sediment on a submarine slope under the action of gravity.
Seismography	The scientific measuring and recording of the shock and vibrations of earthquakes.
Self-contained oil-filled cable (SCOF)	Cable having insulation impregnated with an oil which is fluid at all operating temperatures and provided with facilities such as longitudinal ducts or channels and with reservoirs.
Sheath	A uniform and continuous tubular covering of metallic or non-metallic material, generally extruded.
Single core	An electrical cable that has only one conductor usually made of copper wire protected by a sheath.
Six-pulse converter unit	An electric circuit that converts alternating current into direct current using six valves that fire at specific moments.
Skin effect	The phenomenon in which the current density for an alternating current carrying conductor is greater near the surface than in the interior of the conductor.
Slope	The inclination of profile gradeline from the horizontal, expressed as a percentage. Synonym: gradient
Submarine canyon	A steep-sided valley cut into the sea floor of the continental slope, sometimes extending well onto the continental shelf. They can continue the river valleys from the continent but most of them begin on the continental slope.
Submarine fan	Underwater geological structures associated with large-scale sediment deposition and formed by turbidity currents.
Submarine power cable	A major transmission cable for carrying electric power below the surface of the water.
Suitability	The quality of having the properties that are right for a specific purpose.
Switchgear	The combination of electrical disconnect switches, fuses or circuit breakers used to control, protect and isolate electrical equipment.
Switchyard	A part of the substation where the switchgears are located.

Synchronous	Occurring or existing at the same time. A state in which two alternating current systems function at the same phase.
Telecom cable	A cable designed to transmit data signals.
Tensile force/strength	The maximum stress that a material can withstand while being stretched or pulled before failing or breaking.
Thermal radiation	The electromagnetic radiation generated by the thermal motion of charged particles in matter.
Thyristor	Bi-stable semiconductor device comprising three or more junctions which can be switched from the off-state to the on-state or vice versa.
Topography	Precise description of the surface features of a place or region on a map, indicating their relative positions and elevations.
Transducer	An electrical device that converts one form of energy into another with the aim to facilitate the measurement of its parameters. A device designed to provide a direct current signal which is proportional to a sensed direct current.
Transformer	An electrical device that transfers electrical energy between two or more circuits through electromagnetic induction. They are used to increase or decrease the voltages of alternating current in electric power applications.
Transmission	The bulk transfer of electrical energy, from generating power plants to electrical substations located near demand centres.
Transmission System Operator (TSO)	An entity entrusted with transporting electrical power on a national or regional level, using fixed infrastructure.
Trench	Long narrow topographic depressions of the sea floor formed where to tectonic plates collide and one plunges under the other.
TSO	See Transmission System Operator
Turbidity currents	A type of sediment movement where grains are suspended by fluid turbulence within the flow.
Turntable	A circular horizontal rotating platform on a vessel used to store and gradually release a power cable in a laying operation.
Twelve-pulse converter unit	An electric circuit that converts alternating current into direct current using twelve valves that fire at specific moments.
Twin core	An electrical cable that has two conductors usually made of copper wire isolated one against the other but protected by the same sheath.
Valve	An indivisible electric device for electric power conversion or electronic power switching, comprising a single non-controllable or bistably controlled unidirectionally conducting current path.
Viscosity	The property of a fluid that resists the force tending to cause the fluid to flow. Its measurement unit is newton seconds per metre squared (n).
Voltage	A measure of the difference in electric potential between two points in space, a material, or an electric circuit, expressed in volts.
Voltage Sourced Converter (VSC)	A self-commutated voltage-sourced converter based on thyristor technology. The conversion process is attained by turning-on and off the bipolar transistors.
VSC	See Voltage Sourced Converter
XPLE	See Cross-linked polyethylene insulation

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As the Commission's in-house science service, the Joint Research Centre's mission is to provide EU policies with independent, evidence-based scientific and technical support throughout the whole policy cycle.

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