Elia Future Grid 2030

Stevin-Avelgem and Avelgem-Center Power Corridor
Technology Review and Benchmarking Study

05 March 2019

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Contents

1 Introduction

Elia Engineering has commissioned Mott MacDonald to carry out a review of technology options for high voltage electricity power corridors to include a benchmarking exercise of relevant projects within Europe. The review will also provide a view on general trends across the world.

This report introduces the available technologies and provides a summary of similar projects, including identifying drivers behind the choice of technologies.

2 Context and Background

2.1 Introduction to Elia

Elia owns and operates the Belgian high voltage electricity transmission grid. Assets include all Belgian 150 kV, 220 kV and 380 kV electricity grid infrastructure, and almost 94% of the grid infrastructure between 30 kV and 70 kV. Elia's grid is made up of 3,000 km of overhead line, 5,500 km of underground cable and 800 substations.

Elia's main activities:

- Managing infrastructure: Maintaining and developing the grid, as well as connecting electrical installations to the grid;
- Operating the electricity system: Granting access to the grid in a straightforward, objective and transparent way, providing full services for transporting electricity, monitoring flows on the grid to ensure that electricity runs smoothly and managing the balance between electricity consumption and production 24 hours a day;
- Facilitating the market: Developing initiatives to improve how the electricity market operates and making its infrastructure available to all market players in a transparent, non-discriminatory way. Elia develops services and mechanisms allowing the market to trade on different platforms, which promotes economic competitiveness and the wellbeing.

2.2 Future Grid 2030 needs case

2.2.1 A power system in transformation

The Belgian power system is going through a transformation.

Like many power systems across the world it has traditionally been dominated by a small number of very large, centralised thermal power plants.

Today's power system must incorporate energy produced from many power generation sources and technologies and there is increased international energy exchange. Elia's grid is a key link between France, Europe's largest electricity exporter, and markets in Northern Europe.

At the same time, Elia is facing the challenge of achieving an energy system which is sustainable, affordable and reliable. This is known as the "energy trilemma".

Substantial expansion and reinforcement of the Belgian grid is required to face today's challenges, and to support an increasing amount of generation from renewable sources in line with policy targets.

2.2.2 Elia's Federal Development Plan

Elia's Federal Development Plan covers a period of 10 years and is adapted and published every 4 years. It is developed in collaboration with the Federal Public Service Economy and the Federal Planning Bureau.

The 2020-2030 Federal Development Plan identifies capacity needs for the Belgian high voltage grid (150 kV, 220 kV and 380 kV) for the period between 2020 and 2030 and describes the investment program required to achieve the plan.

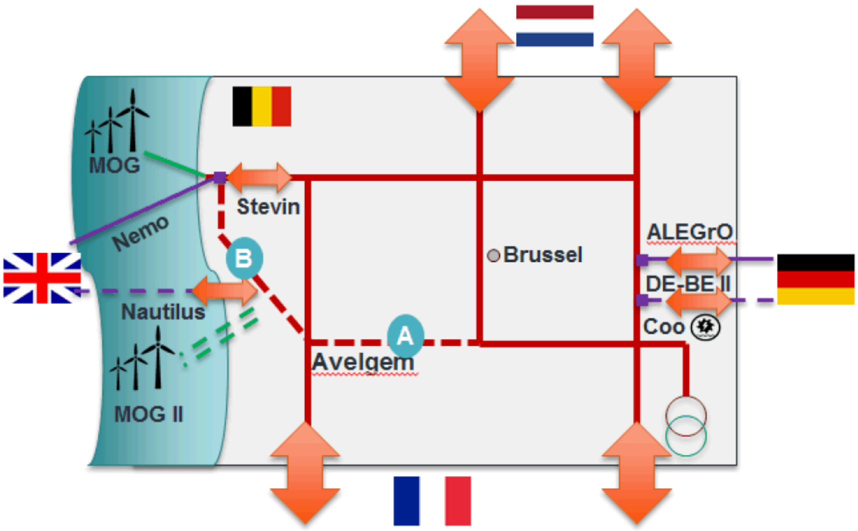
The plan includes the strengthening of the 380 kV transmission grid, the integration of additional offshore wind generation and the development of interconnections with other countries.

2.2.3 Future Grid 2030 project

The Future Grid 2030 project is included in the 2020-2030 Federal Development Plan:

- Creation of a new 6 GW (2 x 3 GW) connection between Stevin and Avelgem, the Stevin-Avelgem corridor
- Creation of a new 6 GW (2 x 3 GW) connection between Avelgem and the centre of the country, the Avelgem-Centre corridor

Figure 1: Future Grid 2030



Source: Elia

2.3 Elia's obligations

Each technology option should be considered in the context of Elia's statutory and regulatory obligations. The following obligations are considered for all new developments:

1. Safety – Compliance with all relevant safety standards
2. Reliability and availability – The extent to which the grid is available for operation, considering downtime for planned and unplanned outages.
3. Robustness and flexibility – The capability of the grid to withstand non-standard operating conditions and grid faults without loss of supply, and the provision for future grid connections and reinforcements.
4. Economic efficiency – Provision of a cost-effective solution which meets the project requirements while managing the lifetime cost of the development.

2.4 Power system basics

It is helpful to understand some basic historical and technical context about an electrical energy system, also known as an electrical power system.

2.4.1 Description of a power system

Since large amounts of energy cannot easily be stored, electricity must be produced as soon as it is needed. The grid must also be able to respond quickly to changing demand.

Electricity is produced by generators. Generators use a variety of fuel sources to produce electricity.

Traditionally, there have been a small number of large, centralised thermal power plants using coal, gas, oil and nuclear fuel sources. These plants are generally located far away from areas of high electricity demand.

In today's power system, large power plants generate electricity from renewable energy sources, and there are large international connections known as interconnectors.

There is an increasing number of smaller generators located closer to electricity demand, many of which use renewable sources such as wind and solar.

Large generators are connected to the national transmission grid, and smaller generators are connected to regional networks which operate at lower voltages, known as distribution grids.

2.4.2 Transmission and distribution grids

Transmission and distribution grids can be likened to a country's road system. Instead of vehicles, the grids carry electricity. The transmission grid is the equivalent of the national motorway system; the distribution grids are the equivalent of the regional minor road networks.

Electricity is transmitted in bulk quantity through the transmission grid and is stepped down to smaller, more manageable quantities for supply to consumers via distribution grids.

To carry large amounts of electricity efficiently over a long distance the voltage is raised, in the same way as the pressure of water is raised to carry volumes through a pipeline. Voltage can be considered a measure of the electrical pressure.

Transmission and distribution grids are made up of substations, overhead lines and underground cables. Substations control power flows and change the voltages between the transmission and distribution grids. Overhead lines and underground cables carry the power over distance between substations.

The basic electrical characteristics of a transmission circuit are typically described by its voltage in kilo-volts (kV) and its power rating in mega-Watts (MW) or giga-Watts (GW), where 1 GW is equal to 1000 MW. 1 MW is equal to 1000 kW. An electric kettle consumes about 2 kW of power.

Across the world, electrical power transmission is predominantly by high voltage alternating current (HVAC) . using overhead line technology. Underground cable technology is used in some circumstances.

High voltage direct current (HVDC) is used for specialist requirements and is increasingly playing an important part in transmission grids.

3 Power Corridor Technology Options

3.1 Technology options

This report considers the following high voltage power corridor technology options:

- Overhead lines
- Underground cables
- High voltage direct current (HVDC) as an alternative to high voltage alternating current (HVAC)

Across the world, bulk transmission of electrical power is predominantly via HVAC. HVAC makes it easy to move electricity as it responds quickly and automatically to changing electricity needs across the grid in real time.

The vast majority of HVAC is transmitted using overhead line technology.

In the transmission grid, underground cables are typically used where overhead lines are not feasible, for example, in urban regions, for long crossings over water or in areas which have high environmental sensitivity.

HVAC overhead and underground cable technologies are discussed in more detail in section 4 of the report. Gas insulated line and superconducting cable, which have been proposed as alternative underground technologies, are also discussed in section 4.

In some circumstances HVDC technology is selected in preference to HVAC. HVDC as an alternative to HVAC is discussed in more detail in section 5 of the report.

3.2 Power corridor technical requirements

The Future Grid 2030 power corridor has the following technical functionality requirements:

Table 1: Basic technical requirements

Criteria	Requirement
Power capacity	6 GW
Redundancy	50% availability after a single grid fault (i.e. the requirement is for at least two independent 3 GW circuits, or 2 x 3 GW capacity)
Length	50-100 km
Provision for future additional connections to the new lines	Required

4 Comparison of Alternating Current (AC) Options

At present Elia operates the transmission grid at 150 kV, 220 kV and 380 kV.

380 kV is considered the most appropriate alternating current (AC) operating voltage for the Future Grid 2030 power corridor to meet its required power transmission capacity. Increasing the voltage decreases the current flowing in the lines, which consequently decreases power loss.

Conductors that transmit electricity need to be electrically insulated to ensure safe and reliable operation. One major difference between overhead lines and underground cables is the way they are insulated. Conductors of overhead lines are insulated by air, except where they are attached to towers; while underground cables are enclosed in a layer of insulating material throughout their length. In this respect the design of a high voltage cable is similar in principle to that of a low voltage power lead for a domestic appliance.

Air is the cheapest and simplest insulator available. It also has the benefit that heat produced by electricity passing through the conductors is efficiently removed by the natural flow of air.

The electrical insulating materials applied to cables also act as thermal insulation. Because of this effect, and due to the burying of cables underground, the heat produced by power losses in the conductor is removed much more slowly, thus power flow must be reduced to avoid the cables overheating.

4.1 Cost Comparison of AC overhead line and AC underground cable

The cost of operation, maintenance and power losses over the lifetime of an alternating current transmission circuit is broadly the same for overhead lines and underground cables.

The construction costs vary greatly depending on many factors, including route length, power capacity, ground conditions and physical features of the landscape.

Underground cables are always more expensive when compared to equivalent overhead lines.

The major elements of this cost differential are due to the relatively higher cost of the cable itself and the cost of the civil works required to install the cables in the ground.

4.2 High voltage AC overhead line

The vast majority of the transmission grid in Europe and worldwide is made up of AC overhead line.

4.2.1 Overhead line construction

Conductors are generally of multi-stranded construction using aluminium or aluminium alloy conducting wires. Steel wires can be used for strength. In some modern conductors, steel is replaced by composite materials. The conductors are arranged in bundles and supported by insulators from towers. 380kV overhead lines have traditionally used steel lattice towers but other types of structure have been developed which include concrete, folded steel, or composite elements.

An overhead line generally carries one or two circuits, with each circuit comprising three phases;. however, in some cases a set of towers will carry additional distribution circuits. The figure below shows a lattice steel tower with one circuit carried on each side. The wires at the top of the tower are earthwires which protect the conductors from lightning strike and carry optical fibres to support communication links.

In overhead line designs, three basic structures are employed – one to go in a straight line (a suspension tower), one to go around corners (an angle tower), and one at each end of the circuit to connect the line to a substation (a terminal tower).

Figure 2: 380 kV steel lattice tower

Source: Elia

The conductor may be in a single or bundled configuration (the illustration shows an example of a twin bundle). The conductor size and configuration are selected based on the capacity requirements of the circuit, and the arrangement is designed to reduce acoustic noise and electrical losses.

The bare conductors are insulated from the towers via insulator sets made from porcelain, glass or combinations of composite and polymeric materials.

Tower height and the spacing between towers are selected so that a minimum safe conductor height above ground is maintained. The conductors expand as temperature increases, causing them to hang closer to the ground, therefore the design must consider a worst-case scenario of weather and operating conditions.

Relying on air as insulation results in a relatively large installation due to the physical distance that must be provided around the conductors. The higher the voltage, the greater the required clearance around the conductor, and hence the need for larger transmission towers.

380 kV towers are typically spaced at approximately 350-400 m intervals.

Figure 3: Two double circuit 380 kV overhead line routes

Source: Elia

The conductors are brought down to ground level at each end of the line to connect to ground mounted substation equipment or to an underground cable.

4.2.2 Overhead line reliability and availability

Transmission circuit availability is influenced by planned maintenance activity and unplanned faults. Both cases require the circuit to be switched off and therefore to become unavailable for use.

Planned maintenance activity is undertaken in a strategic and coordinated fashion to minimise the impact on grid availability.

On the other hand, unplanned faults can be highly disruptive. It is therefore important to consider their potential impact on transmission grid availability.

Overhead line faults can be categorised as temporary or sustained, depending on their impact.

When a fault occurs, the affected line is automatically switched off to prevent or minimise damage. Most overhead line faults are temporary (often caused by the effects of weather), therefore programmed switching sequences are used to re-energise the line after a short delay.

If the fault proves to be temporary, the line is immediately returned to service, often with minimal disruption to customer supply. However, when damage leads to a sustained fault, re-energisation will be unsuccessful and the line must be taken out of service. The damage can then be readily identified by visual inspection and can usually be repaired within a few days. .

4.2.3 Overhead line environmental considerations

The routing of overhead lines is a complex process and requires a balance between statutory obligations, engineering requirements, economic viability, land use and the environment.

Overhead lines are large linear developments and affect visual and other environmental aspects of the landscape they cross to varying degrees.

Careful routeing of new overhead lines is important and needs to follow defined guidelines and rules to minimise the effect on the environment. Route option selection and consultation with stakeholders form part of the routeing process.

During construction, the overhead line corridor is cleared of trees and other high vegetation. However, low level vegetation can remain. Earth and soils are removed at tower locations to facilitate installation of foundations.

There is an ongoing requirement for vegetation to be maintained at safe distances throughout operation of the line.

Where land is used for agricultural purposes, or in open heathland and moorland habitats, there is not likely to be any significant restriction on land use once restoration is complete following installation of the cables.

Construction of buildings is not usually permitted beneath overhead lines and any construction works in the vicinity of the line must be carefully planned and controlled.

4.2.4 Summary of overhead line key features

High voltage overhead line technology provides a robust and cost-effective solution for transmission of large volumes of electricity over long distances.

An overhead line has a high level of availability and most faults can be located and repaired easily and quickly.

Overhead lines are a flexible technology that can be routed and constructed across a wide range of geophysical and topographical environments. They have a relatively low physical impact on the land.

Overhead lines may not be suitable for some urban regions or areas of high environmental sensitivity. Underground cables are often an alternative in these cases.

4.3 High voltage AC underground cable

Underground cables play an important role in transmission grids by providing an alternative solution to overhead lines for transmitting electricity where overhead line cannot be used. Underground cables are most often installed in urban or environmentally sensitive areas.

380 kV underground cables make up less than 0.5% of the 380 kV AC land transmission systems in western Europe, with approximately 99.5% using overhead lines.

4.3.1 Overview of cable systems

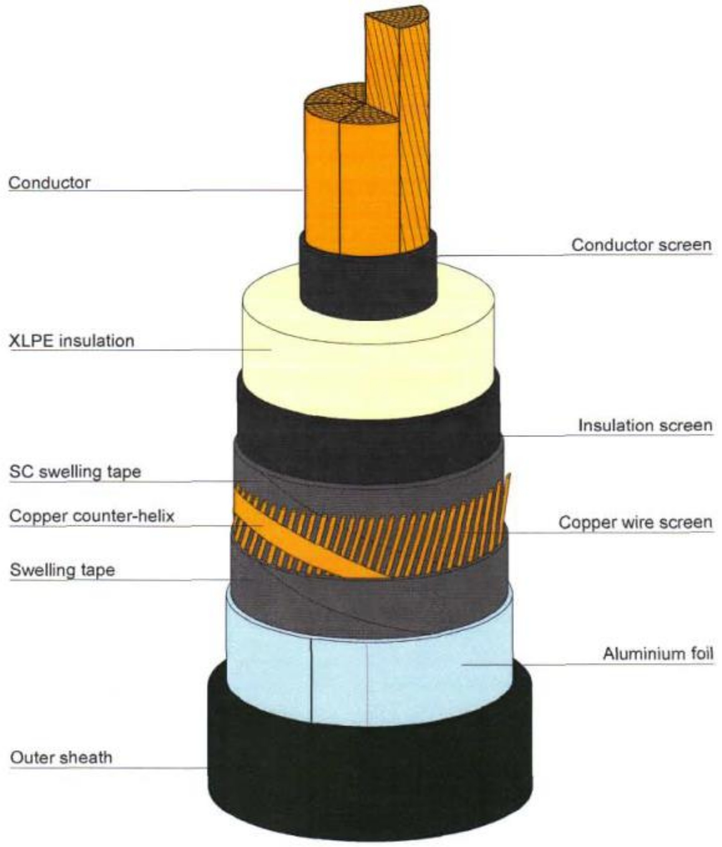
Up until the 1980's, cable insulation systems were based almost exclusively on the use of insulating paper immersed in oil. Cables of this type are known as fluid filled cables.

Fluid filled cable systems are rarely installed today due to the environmental risks associated with oil leakages from damaged cables, construction and installation complexity, decreased manufacturing capability/availability and economics.

More recently, modern underground cables use a high-performance insulating material called cross-linked polyethylene (XLPE). XLPE offers several economic and environmental benefits when compared with oil and has become the insulation of choice within the high voltage transmission industry.

Cable conductors can be manufactured from copper or aluminium, with copper generally selected for 380 kV cables due to its greater current carrying capacity. For larger conductor sizes, such as those adopted in 380 kV applications, segmental stranded conductors are used to help reduce electrical losses.

Figure 4: 380 kV underground cable



Source: Nexans

4.3.2 Underground cable construction

Cable insulation material will be permanently damaged if the temperature of the main conductor exceeds defined limits. Heat produced by electricity passing through the conductor cannot be removed by natural air flow in the same way as with an overhead line. The power capacity of a cable system is thus dependent on the ability to move heat away from the cable conductor to the environment.

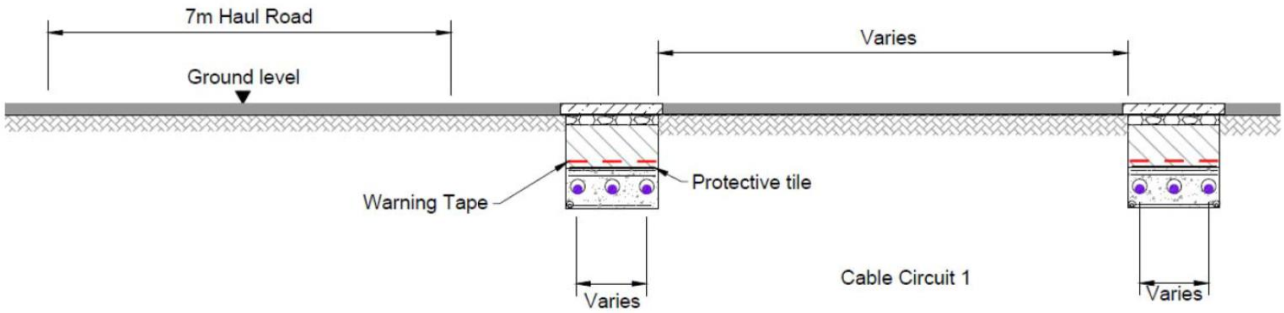
Heat gain can be limited by increasing the size of the conductor, therefore cable conductors tend to be much larger than those of an equivalent overhead line. High power cable systems often use additional conductors to increase conductor area and manage the overall heat gain. This also allows more heat to be moved away and thus helps increases the circuit capacity.

The ability to move heat away from the cable conductor is important and is influenced by the installation conditions, including:

- Burial depth
- Ground temperature
- Ground thermal resistivity

The above factors define the spacing between the cables to achieve the required heat transfers. Large spacings allow higher rates of heat transfer but can result in a significant cable route corridor width. Figure 4 shows a typical 380 kV single circuit installation with two cables per phase. The trench dimensions and distances between trenches vary dependent on the ground and installation conditions.

Figure 5: Typical 380 kV installation – a single circuit with two cables per phase, approximate rating of 2 GW)



Provision for construction activities further increases the corridor width. A dedicated road is required to carry materials to and from site and to haul the cables. Sufficient space must be provided for the operation of excavation plant and space for temporary placing of excavated material must be provided along the full length of the route.

This typically results in a construction corridor for a 380 kV installation providing two circuits roughly equal to the width of a motorway. For the period of construction activity the total width may be up to 80 m, with the completed installation width in the region of 20-30 m.

There are several different cable installation methods available, including:

- Direct burial / open cut trenches
- Ducted installation
- Surface troughs
- Tunnels
  - Deep bore
  - Cut and cover
- Horizontal directional drilling

Direct burial is normally the cheapest method for the installation of underground cables where restrictions on land use are not an issue. Cables are laid in trenches excavated in the ground and surrounded with sand (or a sand/cement mixture) to improve heat transfer. Protection covers are placed above the cables and the trench is filled with excavated material, ensuring that topsoil is reinstated in the top layer. The land can generally be returned to its previous use following completion, although there are some limitations.

Direct burial requires an entire length of cable (up to approximately 1 km) to be laid in a single operation, thus a long length of trenching must be kept open.

Figure 6: 380 kV direct buried cable circuit prior to backfilling

Source: Elia

In some situations the disruption and associated cost of direct burial excavations can be excessive. In these cases, an alternative method is to install the cables in plastic pipes, known as ducts.

Ducts can be installed in shorter sections along the cale route, reducing lengths of exposed trench and therefore reducing risk and disruption to the public. Ducts can be installed ahead of the cable delivery to save on installation time.

A more compact installation arrangement is to install the cables into a concrete surface trough. The cables are laid in sand within the troughs, which are capped with reinforced concrete covers. Heat transfer is improved as the cables are installed at a shallower depth. This technique is restricted to developed areas as the exposed concrete troughs do not allow restoration of agriculture.

Where it is not possible to lay cables close to the surface they can be installed in purpose-built tunnels or can share tunnels with other infrastructure. Tunnel installation is costly and is generally only considered where other installation methods would cause unacceptable disruption. The method of excavation and tunnel design is largely dependent on the size of the tunnel required and the ground conditions.

A tunnel requires a minimum of two head house buildings to provide access for maintenance and for installation of the cables at each end. Where the length exceeds 3 km, further access shafts may be required for safety purposes and to assist with cooling. Heat is removed from the tunnel by forced air using electric fans.

Figure 7: 380 kV cable system tunnel installation

Source: Elia

The advantage of using deep tunnels is that normal development can take place at ground level. There is also minimal disruption along the route of the tunnel during construction and maintenance.

An alternative to a deep tunnel is a ‘cut and cover’ tunnel which is constructed using pre-formed concrete sections laid in a pre-excavated deep open trench.

Many of the methods outlined above involve installing the cables relatively close to the ground level by surface excavation. However, physical constraints encountered along a route may require a change to the standard installation arrangement with potential obstacles including rivers, roads, railways and existing underground utilities.

Horizontal directional drilling can be employed for special circumstances such as obstacle crossings. A remotely controlled drill head is used to bore a hole, through which a plastic duct is pulled through and a cable is then pulled through the duct. Directional drilling is generally utilised for distances of up to 100 m, although much longer installations may be technically feasible, depending on the nature of the ground.

Where the route length exceeds approximately 1 km, installed lengths of cable need to be joined together to form a complete circuit. The joints in the cable are a vulnerable component and are prone to failure if incorrectly assembled. For direct buried or ducted installations, underground concrete chambers are constructed to provide a suitable environment for jointing of cables. Although chambers are filled with sand and the ground reinstated, the equipment at ground level will require regular maintenance and permanent access must be provided.

Where cables transition to overhead line, cable sealing end compounds are needed. The compounds contain the high voltage equipment required to facilitate the connection between the air and the XLPE insulated system.

4.3.3 Underground cable electrical characteristics

As a result of the extra insulation around a cable, AC cables hold and store some of the energy they carry. The longer the cable is, the more energy it holds. This effect is known as ‘capacitance’. Both overhead line and underground cable adds capacitance to the grid; however, due to the physical construction and installation of a cable the effect is much greater in underground cable systems.

Due to this effect, long lengths of underground cable can cause technical issues and there are restrictions to the maximum length of 380 kV cable that can be installed in a transmission network. The maximum length is dependent on the specific network and cable system parameters and will vary for each particular case.

4.3.4 Underground cable reliability and availability

In general, XLPE cable circuits are reliable and have a low rate of unplanned faults. However, there may be occasions where a circuit fails and requires repair. Cable fault repairs require the damage to be located, the faulted portion of the cable to be removed and a replacement section to be added (requiring new joints to be made). For 380 kV cable systems, repairs can be a costly and time-consuming exercise and can have a significant effect on circuit availability.

There are two main causes of cable faults:

- Failure of a component within the insulation system due to a manufacturing or installation defect
- Damage by a third party, typically a contractor carrying out excavation works in connection with another project

Cables can also be damaged by sustained electrical overloading, although cases occur infrequently.

The risk of these events occurring is not easy to control and the resilience of the transmission network can be affected.

4.3.5 Underground cable environmental considerations

The installation of transmission cables has a significantly reduced visual impact when compared to overhead lines; however, underground cables have their own environmental and landscape considerations.

During construction, large quantities of earth and soils are removed to facilitate burial of the underground cables. This is many times the removal required by construction of an equivalent overhead line, where excavations are limited to tower foundations. The process has both environmental and cost implications.

Cable installation works can cause significant short-term effects on the landscape resulting from the felling of trees, hedges, areas of woodland and other vegetation along the route. In many cases the removal of habitat is more intensive for underground cable installations than for overhead lines.

Where land is used for agricultural purposes, or in open heathland and moorland habitats, there is not likely to be any significant restriction on land use once restoration is complete following installation of the cables. Native soils can generally be replaced, allowing shallow rooted vegetation to be re-established over the route and, in many cases, for land to be fully returned to its original condition and use.

The planting of trees in the immediate vicinity of underground cables is not permitted due to the potential for deep root systems to cause cable damage.

Construction of buildings is not permitted above underground cables and any construction works in the vicinity of these cables must be carefully planned and controlled.

4.3.6 Summary of underground cable key features

Underground cables offer a reduced visual impact when compared to overhead lines and may therefore be suitable for environmentally sensitive areas. In some cases, underground cables are the only feasible solution in such areas, for example through urban areas; however, 380 kV cable installation requires a wide corridor and can lead to significant and permanent effect on the landscape.

There are significant technical challenges in connecting long lengths of cable, meaning 380 kV cable circuits rarely exceed 20 km in length.

XLPE circuits are considered to provide reliable operation; however, XLPE cable system repair is a costly and time-consuming exercise, therefore availability is affected.

4.4 Partial undergrounding of HVAC overhead line

The term partial undergrounding refers to an overhead line circuit where a short section or sections are undergrounded.

Where overhead line transitions to cable, the overhead line is terminated at each end of the underground cable section. A large compound is required to accommodate the cable terminals together with other equipment required to facilitate the connection between the overhead and underground systems.

Partial undergrounding is technically feasible and could be considered in specific areas that would be significantly affected by construction of an overhead line.

There are numerous technical performance issues with long underground cable systems. A recent international study[1] considering a specific case in the Danish network concluded that the maximum length of underground cable in an overhead line circuit should not exceed 15% of the total circuit length. As stated in section 4.3.3, the maximum length for a particular case will vary.

4.5 Gas insulated line

In some cases, gas insulated line represents a viable alternative to overhead lines and underground cables. However, most applications of gas insulated line have been over short distances and are installed above ground in areas with no public access such as power plants or substations.

Gas insulated lines can be installed above ground, buried below ground or installed in trenches or tunnels.

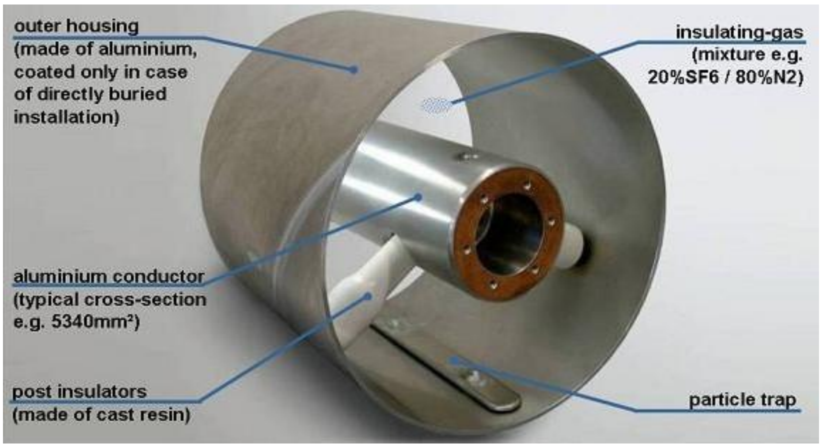
There are no gas insulated line projects with significant route lengths in service or under construction, with maximum route lengths of approximately 3.25 km.

The most extensive installation of buried gas insulated line is an installation at Frankfurt Airport in Germany which comprises two circuits, each with a route length of 900 m.

A gas insulated line conductor is supported at intervals in a rigid tubular metallic enclosure. The enclosure is filled with insulating gas, originally either sulphur hexafluoride (SF6) or a mixture of SF6 and nitrogen. New environmentally friendly insulating gases are becoming available.

A typical section of gas insulated line is shown below.

Figure 8: Typical section of gas insulated line



Source: Siemens

The gas insulated line is assembled on site and welded to form a continuous length.

Bends with radii of approximately 400 m or more can be achieved by elastic bending of straight sections. For smaller radii prefabricated bends are required. Such prefabricated bends may also be required to accommodate changes in vertical profile of the route.

[1] Technical Issues Related to New Transmission Lines in Denmark, Energinet, Doc. 18/04246-24

For free air and tunnel installation, the enclosures may require bellows sections to allow thermal expansion. Expansion bellows may also be required for direct buried gas insulated lines. They would be installed in expansion chambers at intervals along the route and may be required every 200-300 m.

In addition to the 'normal' forces outlined above, direct buried gas insulated lines are required to withstand stresses due to thermal expansion, soil pressure, surface transport loading and water table pressure.

Corrosion protection for the enclosures can be provided by use of a polyethylene coating and by cathodic protection. The coating is applied during manufacture, but additional protection must be provided where welding has been carried out on site. Protection draws on experience from buried oil and gas pipelines.

Figure 9: Example of direct buried gas insulated line prior to backfilling – Frankfurt Airport

Gas recovery plant is required for removal and storage of gas for maintenance and repair to avoid loss of SF6 to the atmosphere. While economic techniques are available for storage and direct re-use of pure SF6 there are practical difficulties in handling SF6/nitrogen mixtures.

Long lengths of gas insulated line have gas barriers at intervals to sectionalise the installation. This allows the gas pressure of individual sections to be monitored and emptied should a repair be required. It also reduces the potential gas loss in the event of a leakage. Gas section lengths vary but are approximately 200 m. Each section must be provided with access to fill and monitor the gas.

Section 4.3.3 discusses the impact of the capacitance of underground cable circuits. Gas insulated lines are also subject to this effect, but to a much lesser extent than cable.

4.5.1 Gas insulated line reliability and availability

Manufacturers have stated that gas insulated line is sealed for life. It has no preventive maintenance needs which would require internal access to the enclosures.

An insulation failure would need to be repaired by replacement of at least one factory manufactured section of gas insulated line. This would require de-gassing, removal of the section and welding/bolting into place of the replacement section. The replacement would require a skilled installation team and specialist equipment.

Fault location techniques are available but have not been demonstrated on long circuit lengths. Conventional cable fault location may not be effective due to the excellent insulating properties of SF6 which can withstand relatively low voltage tests, even after a significant fault.

4.5.2 Gas insulated line environmental considerations

The majority of gas insulated line installations use pure SF6 gas as the insulating medium.

SF6 is a greenhouse gas with a high global warming potential reported to be 24,000 times higher than carbon dioxide. The use of SF6 gas is controlled by European legislation and, while electrical uses are permitted, they are subject to strict voluntary agreements with respect to emissions.

Alternatives to pure SF6 designs use a mixture of nitrogen (80%) and SF6 (20%) as the insulating gas. This reduces the environmental impact in the event of a gas leakage.

Recent introduction of 'green' insulating gases will significantly improve the environmental performance.

4.5.3 Gas insulated line conclusion

Experience of gas insulated line over long distances is not available. As such, a 100 km route length may face previously un-encountered technical and construction challenges. The technology is therefore not considered appropriate for this power corridor.

4.6 Superconducting cable

The resistance to the flow of electricity in a conductor increases with temperature. If a conductor is cooled the resistance falls. If a copper conductor is cooled to near absolute zero (-273 ºC), the resistance of the conductor falls close to zero. In a superconducting material, if the resistance reaches zero, it means the current can flow without generating any heat and can pass through the conductor without any electrical resistive losses.

Maintaining an electrical transmission system at such a low temperature requires special cryogenic plant which is challenging to operate and maintain.

The discovery of alloys with superconducting properties at or above the temperature of liquid nitrogen has made it possible to construct some short length pilot projects demonstrating relatively high power transmission.

However, superconducting technology is still in development and, although there are a number of small-scale trials in distribution networks, is some way from implementation in an operational transmission grid. The technology is therefore not considered further in the report.

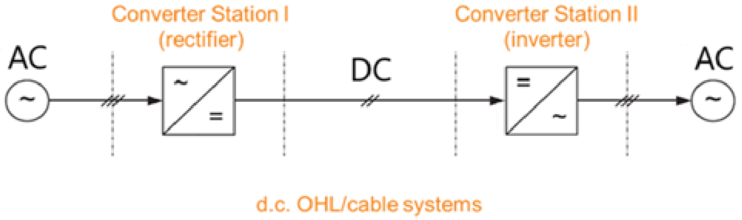
5 HVDC as an alternative to HVAC

The existing grid in Belgium is a high voltage alternating current (HVAC) system. Any new transmission project utilising HVAC would therefore be an extension of the existing technology.

High voltage direct current (HVDC) is an alternative method of transmitting electricity.

Inserting an HVDC circuit between any two points in an HVAC grid requires the AC electricity to be converted to DC at one end of the link, transmitted through the link as DC, and then converted back to AC at the other end. This tends to be an inefficient and costly method for most cases.

Figure 10: AC to DC to AC conversion



HVDC offers technical advantages when compared to HVAC for the following cases:

1. Transmission between power systems which are not synchronised
2. Very long distances high power transmission
3. To allow use of long subsea cables, or facilitate the undergrounding of an onshore transmission circuit
4. Where complete and variable control of power flow is required, i.e. for interconnection between grids

In some circumstances, HVDC is the only technically feasible solution. This is the case when electrical power is transmitted between grids which are not, and cannot be, synchronised.

HVDC may be the most cost-effective solution for power transmission over very long distances. There are many long distance high power HVDC links, for example in China, India, Canada, USA and Brazil, transporting power as far as 2500 km.

As discussed in section 4.3.3 of this report, long HVAC underground cable circuits suffer from technical performance issues. In some situations, buried or underwater cable is the only way to transport power but a practical maximum distance needs to be considered when using HVAC. HVDC can be used to facilitate the undergrounding of long circuits.

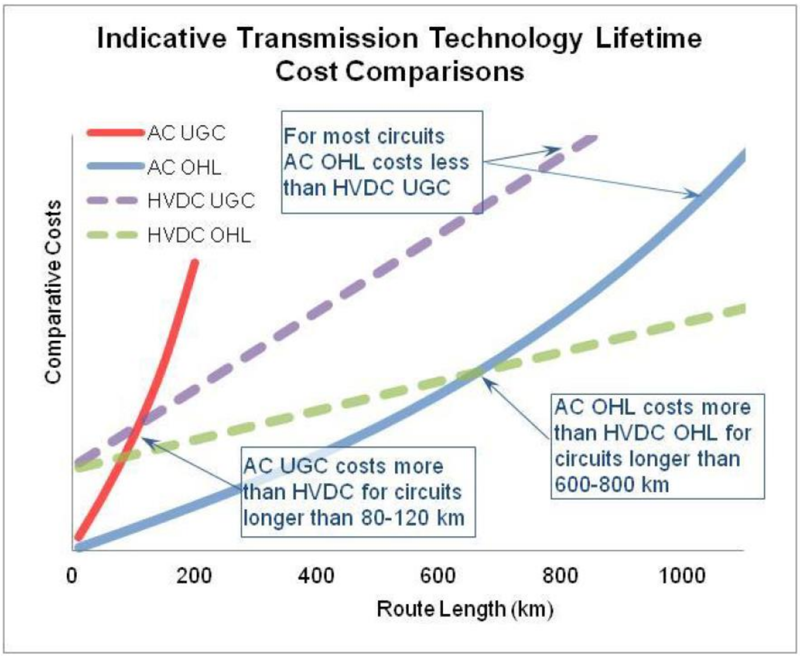
HVDC starts at a cost disadvantage to any HVAC option due to the relatively high cost of the converter stations which are required at each end of each HVDC link. The advantages offered by HVDC technology must outweigh the cost and power losses of the converter stations.

Figure 11 compares costs of HVAC and HVDC overhead line and underground cable against route length.

The graph indicates that HVAC overhead lines tend to be the lowest cost option until the route length exceeds approximately 600-700 km. Beyond this length, HVDC overhead lines may be a more cost-efficient solution.

HVDC underground cables tend to become more cost-efficient than HVAC underground cables for circuits of approximately 80-120 km or longer.

Figure 11: Transmission options - cost against route length



Source: Parsons Brinckerhoff Electricity Costing Study 2012

Power in a grid must be balanced so that the power generated is varied to match the power consumed. In an interconnected, or meshed, AC system power finds its way from generation to the consumer by the most convenient route. The system operator must ensure that the routes are able to carry the power without overloading.

HVDC interconnectors require precise control so that there is no risk of overloading. Requirements for changes in power flow must be identified and programmed into the control systems. This requires monitoring of the grid, sometimes remotely from the converter stations.

5.1 HVDC technology review

5.1.1 Converter configurations

In general, the converter used for HVDC transmission can be classified as current source or voltage source.

5.1.1.1 Current source converters

The most widely used current source converter type is the line commutated converter which is based on thyristors.

Current source converters are only suitable for operation between grids which are relatively strong in comparison with the power rating of the HVDC connection between them. Modern line commutated converter converters and overhead lines can operate up to 800 kV DC and 8 GW of power.

Line commutated converter technology is mature and is typically used for transmitting very high power over very long distances onshore, which is not normally required in Europe. Within Europe the technology has historically been utilised for subsea interconnectors, although voltage source converters are now generally adopted for new projects.

For these reasons, the report does not consider line commutated converter technology for the proposed power corridor.

5.1.1.2 Voltage source converters

A voltage source converter is based on transistors and offers significant advantage over line commutated converters. Voltage source converters can operate in weak systems and provide feed into previously dead systems (known as 'black start'). Their maximum capacity is less than line commutated converters, with the highest voltage in service being 320 kV DC (although 525 kV DC schemes are being built). Typical voltage source converter schemes are around 1-1.4 GW per circuit. For voltage source converters, capacity higher than 1.4 GW means higher risk.

Voltage source converters provide smooth control of transmitted power and the voltages at the point of connection.

The most recent regulations covering new HVDC systems in Europe demand smooth voltage control. Consequently, all new HVDC interconnectors in Europe are expected to be voltage source converter type. Only voltage source converter HVDC technology will be considered in the report.

5.1.2 System configurations

HVDC systems can be configured in three ways:

- Point-to-point configuration
- Back-to-back configuration
- Multi-terminal configuration

5.1.2.1 Point-to-point configuration

Most HVDC systems are point-to-point configuration. Power is transmitted between two points in a HVAC grid. Almost all installed HVDC interconnectors have only two terminals.

5.1.2.2 Back-to-back configuration

HVDC with back-to-back configuration has two converters located at the same site in a single building and there is no overhead DC line or underground DC cable. Back-to back schemes are generally used for connection of HVAC systems operating at different frequencies or for connecting unsynchronised systems. This configuration is not suitable for the proposed power corridor and is not considered further in the report.

5.1.2.3 Multi-terminal configuration

HVDC with multi-terminal configuration has more than two terminals. In practice no scheme with more than three terminals at separate sites has ever been in operation.

There are a small number of line commutated converter schemes with three terminals and some multi-terminal voltage source converter schemes are being considered. A multi-terminal voltage source converter scheme would have fewer restrictions in operation than a multi-terminal line commutated converter scheme, but each terminal will still require a converter station, which adds to the cost.

5.2 Reliability and availability

HVDC transmission systems require a greater number of components than conventional AC circuits, including the following:

- Power electronic converters
- Complex control and protection systems
- Converter transformers
- Cooling systems
- Harmonic filters (may also be required for long AC cable circuits)
- Reactors (may also be required for long AC cable circuits)
- AC circuit breakers (also be required for long AC cable circuits)
- DC overhead lines or underground cables (similar requirement for AC circuits)

The increased components result in a more complex system when compared to an equivalent HVAC transmission system, increasing the probability of forced power unavailability due to equipment failures. All systems require maintenance from time to time. While some components can be maintained without need for an outage by use of duplication, for example within cooling systems, generally an outage is required of several days every year or two.

Redundancy is built into HVDC converter systems, for example by duplicating control systems, installing more transistors in the converters than are needed for full operation and duplication of cooling system pumps. In the event of failures, these systems can be repaired 'on-line' but replacement of failed transistors, for example, requires an outage at a convenient time. Some failures, such as transformer and cable faults, inevitably lead to tripping of the interconnector.

5.3 Technical issues associated with HVDC

5.3.1 Facilitation of future grid connections

Any future connection to a HVDC link requires its own converter station and extensive modification to the existing converter stations at the remote ends of the connection. This is likely to be expensive and will introduce increased complexity to an already complex system.

5.3.2 Power reversal

The proposed HVDC system needs to be capable of power transfer in either direction under normal conditions and be capable of reversing power transfer direction automatically under various fault scenarios. Voltage source converter HVDC changes power smoothly from full power in one direction to full power in the other, and probably at the rate required for the AC grid to remain stable.

Embedding an HVDC circuit into a meshed HVAC transmission network and requiring it to respond correctly to emergency situations within the AC system requires complex control and communications systems. Quick identification and communication of the conditions to the HVDC control system can be challenging and risk failure. Detailed studies are required to identify the control requirements. Sources of signals showing the conditions and methods to get the information to the control system need to be identified.

5.4 Key technology risks

The power corridor must provide very high availability. To maintain partial capacity during scheduled maintenance and fault recovery it would be necessary to install at least two independent links. If two circuits are provided then each would need to have a rating of 3 GW which is greater than any voltage source converter scheme that has yet been implemented. It is therefore likely that multiple links will be required to achieve the required power corridor capacity, even allowing for ongoing development of increased converter power ratings. An option would be to use three interconnectors each rated at 2 GW or four rated at 1.5 GW. This would allow more than 3 GW of capacity to be maintained with one link out of service for repair or maintenance.

5.5 Conclusion on HVDC as an alternative to HVAC

HVDC can facilitate the undergrounding of long circuits where the maximum length of AC underground cable is limited. It is technically feasible to utilise HVDC technology to underground the full length of the Future Grid 2030 power corridor.

The additional cost of HVDC would be significant and HVDC technology would not offer the operational flexibility and resilience of an HVAC solution.

A HVDC solution offers several technical risks and disadvantages when compared to a HVAC equivalent.

New connections can more easily be provided using an AC circuit. Future connections to a HVDC link are possible, but each new connection along the route would require a converter station and hence large capital cost.

Control systems for multi-terminal HVDC are complex and there are technical risks of low reliability and availability of a multi-terminal HVDC link.

Significant land area is required for converter stations at each terminal point.

A typical HVDC system requires at least four years to bring it into service. In this case, with more than one interconnector required, it would probably take a further year or more before the full scheme is operational.

6 Benchmarking Study of Similar Projects in Europe

6.1 Research methodology

The following resources have been used to identify European reference projects for this benchmarking exercise:

- The ENTSO-e website, including the 2014 and 2016 Ten Year Network Development Plan (TYNDP) documents which contain a list of transmission system projects. We filtered the lists of projects and selected those we expect will be suitable for benchmarking against Elia's Future Grid 2030 project.
- General industry knowledge
- Publicly available industry reports

The aim was to identify a range of projects covering each of the technology options relevant for the report.

6.2 Summary of shortlisted projects

The following projects have been selected:

Table 2: Overhead HVAC projects

Project	Driver behind choice of technology
Beauly Denny	Least cost technically acceptable solution
Brabo I, II and III	Least cost technically acceptable solution
North South Interconnector	Least cost technically acceptable solution
Richborough – Canterbury	Least cost technically acceptable solution

Table 3: Underground / subsea HVAC projects

Project	Driver behind choice of technology
Frankfurt Airport (gas insulated line)	Undergrounded due to proximity to airport runway. Gas insulated technology adopted due to requirement for narrow installation corridor.
Hornsea	Subsea cable. AC selected due to its relatively lower cost when compared to HVDC.
London Power Tunnels	Cable in deep tunnel due to congested urban environment
Shinkeiyo – Toyosu	Cable in deep tunnel due to congested urban environment
St John's Wood	Cable in deep tunnel due to congested urban environment

Table 4: Partially undergrounded / subsea HVAC projects

Project	Driver behind choice of technology
Hinkley Point C	Crossing of protected area led to partial undergrounding
Kasso – Tjele	Crossing of protected area led to partial undergrounding
Randstad	Crossing of obstructions and/or protected / urban areas led to partial undergrounding
Sorgente - Rizziconi	Requirement for sea crossing led to subsea cable section

Project	Driver behind choice of technology
Stevin	Crossing of obstructions and/or protected / urban areas led to partial undergrounding

Table 5: Overhead HVDC projects

Project	Driver behind choice of technology
Suedlink	Very long distances high power transmission
Ultranet	Very long distances high power transmission

Table 6: Subsea / undergrounded HVDC projects

Project	Driver behind choice of technology
Alegro	HVDC selected to facilitate undergrounding, and to enable complete and variable control of power flow
Baixas – Santa Llogaia	HVDC selected to facilitate undergrounding, and to enable complete and variable control of power flow
BritNed	HVDC selected to facilitate long submarine cable
Greenconnector	HVDC selected to facilitate submarine and undergrounding, and to enable complete and variable control of power flow
Sapei	HVDC selected to facilitate long submarine cable
SuedOst Link	HVDC selected to facilitate undergrounding, and to enable complete and variable control of power flow

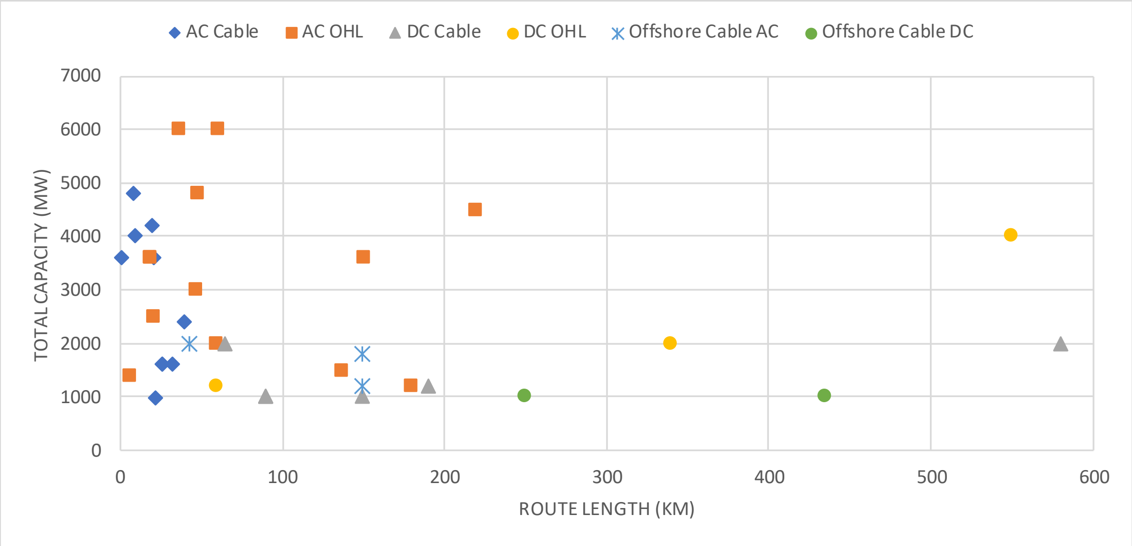
Table 7: Mixed overhead and underground HVDC projects

Project	Driver behind choice of technology
SouthWest Link	HVDC selected to facilitate undergrounding, and to enable complete and variable control of power flow

6.3 Flash cards

Please see Appendix A for a project summary sheet, or flash card, for each shortlisted project. Figure 12 shows technology type against power corridor capacity and route length for selected projects.

Figure 12: Power corridor capacity and route length for selected projects



7 Global Trends

AC overhead lines form the vast majority of the circuit length in transmission systems around the world. This situation is unlikely to change in the foreseeable future, with many new overhead line projects planned or under construction. Whilst many proposals have been made to improve the visual appearance of the 'classic' lattice steel tower, conventional designs remain cost effective and still predominate in new construction.

The use of AC cables is generally confined to the following cases:

- Where the installation of overhead lines is not technically feasible due to geographic features; primarily river or estuary crossings greater than 1 km
- Where the use of overhead lines is not practical due to the density of urban development
- Where an overhead line would have a significant impact on a valuable environment

Transmission voltage cables were developed more than 50 years ago to accommodate such situations, however the paper/oil insulation used was expensive to both install and maintain and applications were thus very limited. More recently, the introduction of cross-linked polythene (XLPE) insulation for transmission cables has reduced costs (although they are still many times the cost of an equivalent overhead line) and the use of AC cables in transmission systems has increased.

The trend to install more cable has been encouraged by increased power consumption in modern urban centres, which exceeds the capacity of existing distribution networks and requires provision of new transmission infrastructure.

At distribution grid voltage levels (generally 110 kV and below), there has been an increasing trend to replace overhead lines with cables. This has generally not extended to transmission grid voltages due to cost and practicality.

There are limitations on the maximum length of transmission voltage cables that can be added to a grid as discussed in section 4.3.3 of the report.

Gas insulated line has been commercially available for more than 40 years and has been widely used for relatively short connections (less than 500 m) within utility company power installations. Take-up for longer applications and for buried applications in publicly accessible areas has been very limited, with only one significant project providing a circuit length of 2 x 0.9 km.

Several trial installations of superconducting cables have been launched in recent years by a number of manufacturers, none at transmission voltage and none offering the power transfer capacity required for transmission applications. Commercialisation of the technology is not anticipated in the immediate future.

Since the introduction almost 40 years ago of thyristors with a high current switching capacity, HVDC has been utilised for very long distance high power transmission over land. Reduction of transmission losses has encouraged the adoption of high transmission voltages, often in excess of the capability of cable technology, thus these high-power links utilise overhead lines. Recent developments in China and India have seen the introduction of 800 kV DC 'Ultra High Voltage' transmission offering capacities in excess of 6 GW on a single line with circuit lengths of 1000-2500 km.

The ’Classic’ line commutated HVDC technology based on thyristor switches has also been widely used for submarine interconnectors. In these applications the operating voltage is reduced (to suit the capability of the cable technology) and current ratings are also reduced. Transfer capacity of these projects does not exceed 1 GW per circuit and many are designed for a lower power level than this.

More recently the introduction of high-power transistors has facilitated the development of voltage source converter technology. This is often paired with extruded XLPE cables (which are not suitable for use with line commutated converters). Voltage source converter technology was originally launched as a more economical alternative to line commutated converters for power levels less than 0.1 GW, however the inherent advantages of voltage source converters led to the technology being rapidly scaled up to achieve around 1 GW capacity; limited by the voltage capacity of the extruded cable and the current capacity of the transistors. The 1 GW designs have been quite widely adopted both in Europe and elsewhere, with interconnector circuits between transmission networks, connections to offshore islands and connection to offshore wind farms forming the main applications.

Recent technical developments have resulted in extruded cables being developed for operation up to 525 kV together with transistors offering a higher current switching capability. It is anticipated that these advances will allow a future increase in voltage source converter ratings to around 2 GW per circuit. Although projects utilising this transmission capacity are planned, there are none currently in service or under construction.

8 Glossary of technical terms and acronyms

Table 8: Technical terms and abbreviations

Term	Abbreviation	Description
Alternating current	AC	A type of electrical power where the electric charge reverses direction at regular intervals
Availability		The amount of time the circuit is available for the purpose it was designed, i.e. to transmit its rated power. This is influenced by planned maintenance activity and unplanned faults.
Capacity		The amount of electricity that can be safely and reliably transmitted on the grid or a circuit
Circuit		The overhead line or underground cable linking two substations
Conductor		The part of the overhead line or underground cable that carries the electrical power
Converter station		A station that converts direct current to alternating current or vice versa
Corridor		The strip of land of a particular width where the electricity line or cable will be routed
Current		The flow of electric charge in a circuit, analogous to the flow of water in a water system. Measured in units called Amps.
Demand		The amount of electrical power that consumers take from the grid
Direct current	DC	A type of power where the electric charge is constant in direction.
Distribution grid		A lower voltage grid which delivers power to households and businesses. The equivalent of a regional minor road networks in a country's road system
Electric and magnetic field	EMF	Invisible areas of energy which occurs naturally. When electricity flows, both electric and magnetic fields are produced.
Electrical losses		See losses
Faults		A failure of equipment requiring a circuit to be switched off and therefore to become unavailable for use
Generator		A unit that produces power in the form of electricity
Grid		A network or 'energy motorway' made up of high voltage overhead lines, underground cables and substations. The grid links energy users with energy producers. It is designed so that power can flow freely to where it is needed.
Giga-Watt	GW	A unit of power (see power). 1 GW is equal to 1000 MW.
Harmonic distortion		A phenomenon which affects the quality of supply to customers.
Insulator		A component used in electrical equipment to support and separate electrical conductors.
Interconnector		A large circuit connecting two countries
kV	kV	A unit of voltage (see voltage). 1 kV is equal to 1000 V.
MW	MW	A unit of power (see power). 1 MW is equal to 1000 W.
Phase		An AC power transmission system may be single or three phase. All AC systems described in this report are three phase hence three separate conductors, or three separate groups of conductors, are required to form a complete circuit.
Power Plant		A facility made up of generators that produce power in the form of electricity
Power system		The overall system which produces, transmits and distributes electricity as soon as it is needed
Reactive power		Energy held and stored in cable capacitance

Term	Abbreviation	Description
Reactive power compensation		Special equipment to neutralise energy held and stored in cable capacitance and balance the associated effects
Redundancy		The inclusion of additional capacity in case of failure of other circuits
Reliability		The ability of the circuit to perform consistently well
Renewable generation		The generation of electricity using renewable energy such as wind and solar
Substation		A set of electrical equipment used to control power flows and change the voltages between the transmission and distribution grids
Transmission grid		A physical network that links generators of electricity to the distribution grid. The transmission grid is the equivalent of the national motorway network in a country's road system
Voltage	V	A measure of electric potential, analogous to the pressure in a water system. Measured in units called volts.
Watt	W	This is a measure of electrical power. Measured in units called Watts. An electric kettle consumes about 2 kW

Appendices

A. Project Flash Cards

Table 9 describes the symbols on the flash card maps.

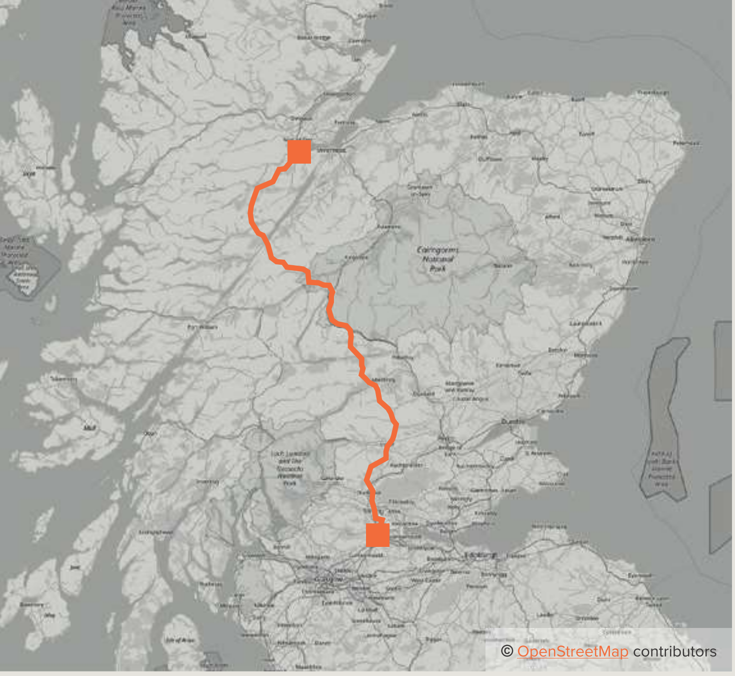
Table 9: Key to map symbols

Symbol	Description
	Terminal point (substation or converter station)
	AC overhead line
	AC underground cable
	AC submarine cable
	AC cable tunnel
	DC overhead line
	DC underground cable
	DC submarine cable

Table 10 describes each flash card criteria.

Table 10: Flash card criteria description

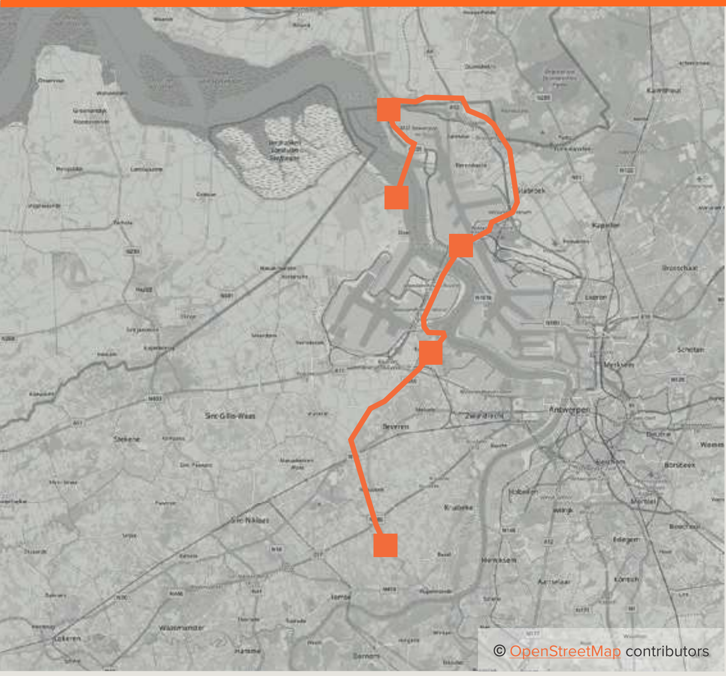
Criteria	Description
Location	-
Owner / operator	-
Project status	Planning / Consented / Under construction / In service
Actual / planned energisation date	-
Capacity	No. of circuits x circuit capacity, e.g. 2 x 1200 MW (2 circuits each of 1200 MW, giving an installed capacity of 2400 MW)
Voltage	Voltage in kV, and AC or DC
Route length	Distance between terminal points
Circuit length	Distance between terminal points x no. of circuits
AC cable system length	For AC cables only. Circuit length x no. of cables per phase
Technology	Overhead / Underground / Subsea / Partially undergrounded; HVAC / HVDC;
Route characteristics	-
Terminal point infrastructure	Substations or converter stations at each end of the circuits
Network configuration/connection type	AC connection: Meshed network / Radial connection DC connection: Point-to-point / Multi-terminal
Capital cost	Where capital cost has been reported in foreign currency a Euro equivalent has been provided based on a December 2018 exchange rate.
Construction duration	-
External drivers/issues	-



Beauly Denny

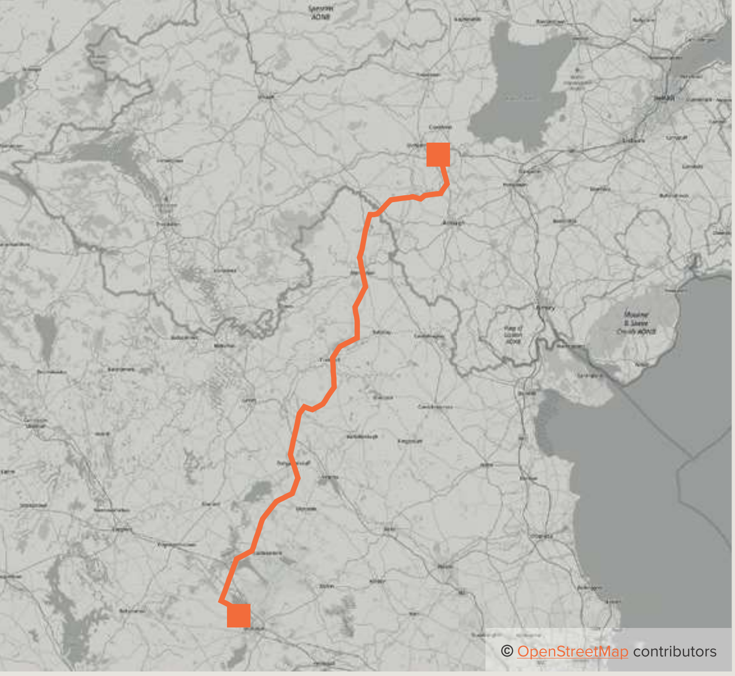
Location Scotland, UK	**Technology** Overhead line high voltage alternating current
Owner/operator SSE	**Route characteristics** Crosses remote and sparsely populated areas of Scotland including river valleys, forests and moorland
Project status In service	**Terminal point infrastructure** New Denny substation. Extension of existing Beauly substation.
Actual/planned energisation date 2015	**Network configuration/connection type** Meshed network
Capacity 1 x 2670 MW 1 x 1830 MW	**Capital cost** -
Voltage* 400 kV AC 275 kV AC	**Construction duration** 2012 - 2015
Route length 220 km	**External drivers/issues** Reinforcement of remote transmission line in Scotland to support transmission of renewable energy
Circuit length 2 x 220 km	

* The overhead line is designed for 400 kV operation but one circuit is operated at 275 kV



Brabo I, II and III

Location Flanders, Belgium	**Technology** Overhead high voltage alternating current
Owner/operator Elia	**Route characteristics** I, II and III: Existing 150 kV overhead line route
Project status I: In service, II: Under construction, III: Planning	**Terminal point infrastructure** I: Extension of existing Doel and Zandvliet substation, II: Extension of existing Lillo substations, III: Extension of existing Kallo and Mercator substations
Actual/planned energisation date I: 2016, II: 2020, III: 2025	**Network configuration/connection type** Meshed network
Capacity I: 1 x 1400 MW II: 2 x 1800 MW III: 2 x 1800 MW	**Capital cost** I: 30 million EUR II: 62 million EUR III: 62 million EUR
Voltage 380 kV AC	**Construction duration** I: 2015 - 2016 II: 2017- ongoing (estimated completion in 2020) III: Estimated 2023 - 2025
Route length I: 6 km, II: 18.5 km, III: 19 km	**External drivers/issues** Grid reinforcement
Circuit length I: 6 km, II: 37 km, III: 38 km	



North South Interconnector

Location Northern Ireland - Republic of Ireland	**Technology** Overhead high voltage alternating current
Owner/operator Eirgrid, SONI, NIE Networks	**Route characteristics** Rural land
Project status Consented	**Terminal point infrastructure** New Turleenan substation. Extension of existing Woodland Substation
Actual/planned energisation date 2021	**Network configuration/connection type** Meshed network
Capacity 1 x 1500 MW	**Capital cost** 287 million EUR
Voltage 380 kV AC	**Construction duration** -
Route length 137 km	**External drivers/issues** Further interconnection between Northern Ireland and Republic of Ireland
Circuit length 1 x 137 km	

Richborough - Canterbury

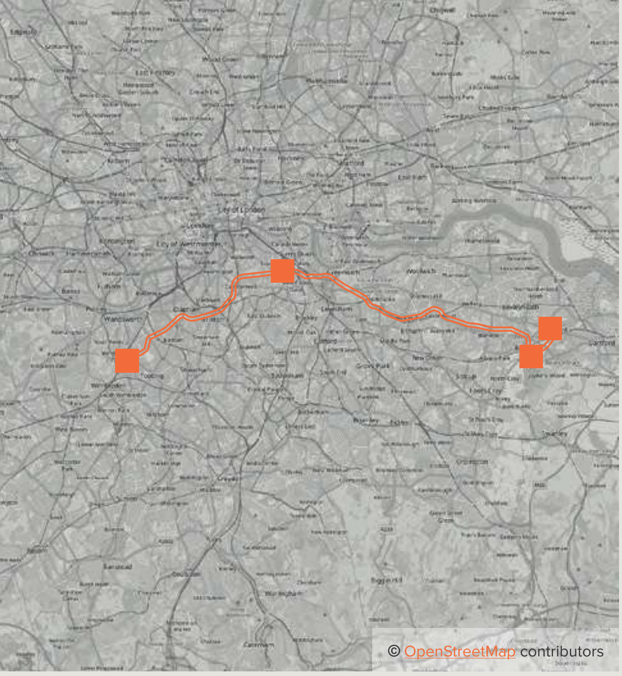
Location Southeast England, UK	**Technology** Overhead high voltage alternating current	**Capacity** 2 x 1250 MW	**Capital cost** -
Owner/operator National Grid	**Route characteristics** Rural land. The new circuit has been constructed on an existing 132 kV overhead line route	**Voltage** 380 kV AC	**Construction duration** 2017 - ongoing (estimated completion in Q4 2018)
Project status Under construction	**Terminal point infrastructure** Extension of existing 400 kV substation at Canterbury. New 400 kV substation at Richborough.	**Route length** 21 km	**External drivers/issues** Interconnection between UK and Belgium (via the NEMO HVDC link)
Actual/planned energisation date Q4 2018	**Network configuration/connection type** Meshed network	**Circuit length** 2 x 21 km	

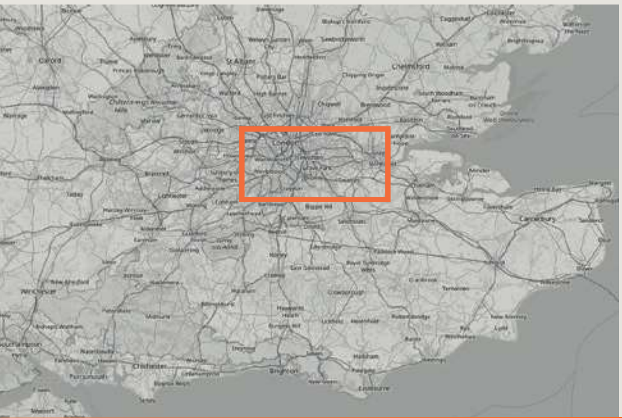
Frankfurt Airport

Location Germany	**Technology** Underground gas insulated high voltage alternating current	**Capacity** 2 x 1800 MW	**Capital cost** -
Owner/operator Ampiron	**Route characteristics** 87.5 km of overhead line precedes the underground gas insulated section near the airport	**Voltage** 380 kV AC	**Construction duration** -
Project status In service	**Terminal point infrastructure** Overhead line to GIL, GIL to new gas insulated substation	**Route length** 0.9 km	**External drivers/issues** Small section of existing overhead line required undergrounding due to vicinity to runway. Installation resulted in space saving (reduced corridor width)
Actual/planned energisation date 2011	**Network configuration/connection type** Meshed network	**Circuit length** 2 x 0.9 km	

Hornsea 1, 2 and 3

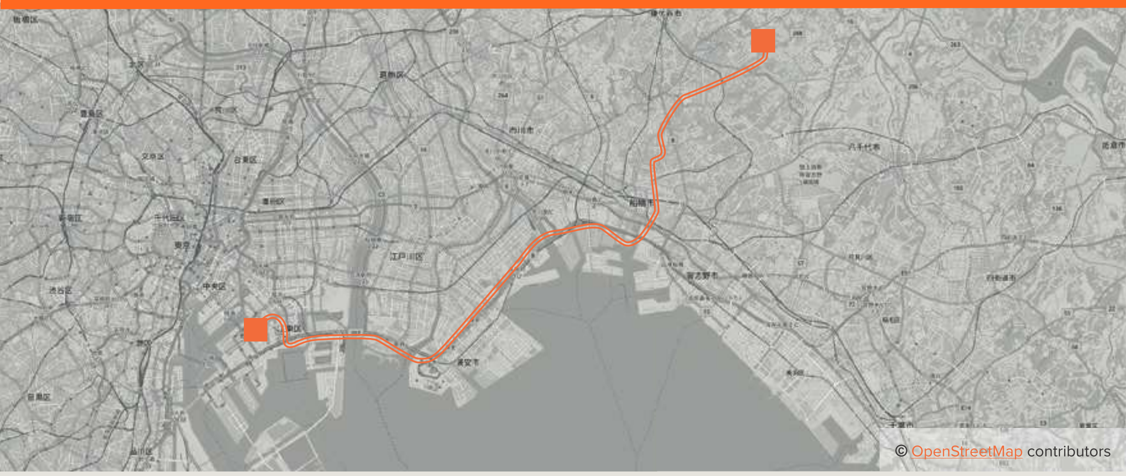
Location Eastern England, UK	**Technology** 1 and 2: High voltage alternating current subsea cable, 3: TBC	**Capacity** 1: 1 x 1200 MW 2: 1 x 1800 MW 3: 2 x 1200 MW	**Capital cost** -
Owner/operator Ørsted	**Route characteristics** 1 and 2: Subsea with onshore section. Midpoint offshore platform for reactive compensation. 1 and 2 share common route. 3: TBC	**Voltage** 1 and 2: 220 kV AC 3: TBC	**Construction duration** 1: 2016 - ongoing (estimated completion 2018 - 2020) 2: 2018 - ongoing (estimated completion 2020) 3: TBC
Project status 1 and 2: Under construction; 3: Planning	**Terminal point infrastructure** 1 and 2: Offshore platforms constructed to collect wind power and provide reactive compensation. New onshore substation at North Killingholme 3: TBC	**Route length** 1: 190 km 2: 190 km 3: 216 km	**External drivers/issues** 1, 2 and 3: Need to transmit power from Hornsea offshore wind farm projects to the mainland
Actual/planned energisation date 1: 2020 2: 2021 3: 2025	**Network configuration/connection type** 1 and 2: Radial connection to meshed network 3: TBC	**Circuit length** 1: 1 x 190 km (40km on land) 2: 1 x 190 km (40km on land) 3: TBC (53km on land)	**AC cable system length** 1: 1 x 1 x 190 km 2: 1 x 1 x 190 km 3: TBC





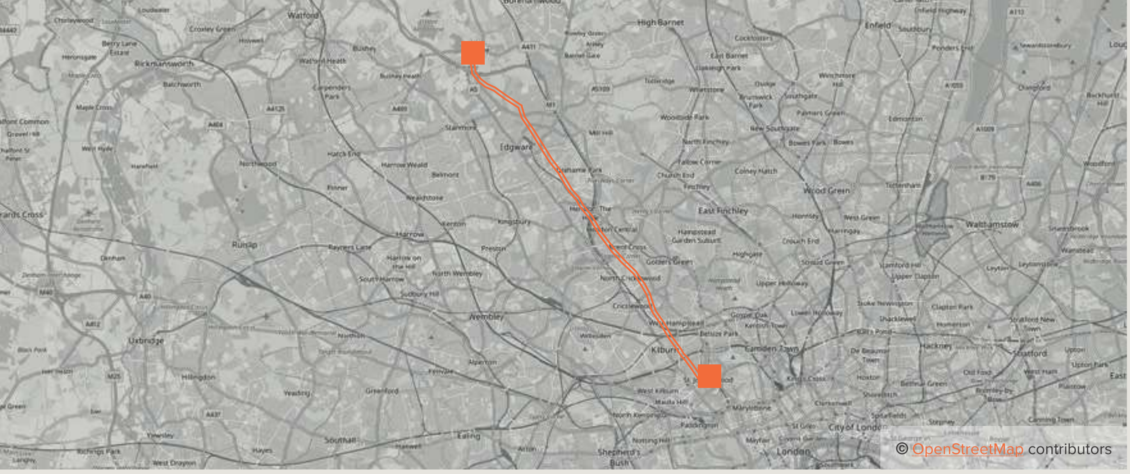
London Power Tunnels

Location London, UK	**Technology** High voltage alternating current cable tunnel
Owner/operator National Grid	**Route characteristics** Central London – cable tunnel
Project status Under construction	**Terminal point infrastructure** Upgrade of existing Wimbledon and Crayford substations
Actual/planned energisation date Wimbledon - New Cross: 2025 New Cross - Hurst: 2026 Hurst - Crayford: 2026	**Network configuration/connection type** Meshed network
Capacity 2 x 1600 MW	**Capital cost** 1.1 billion EUR
Voltage 400 kV AC	**Construction duration** Wimbledon - New Cross: July 2019 - March 2025 New Cross - Hurst: July 2019 - December 2025 Hurst - Crayford: January 2023 - December 2025
Route length 32.5 km Wimbledon - New Cross: 12 km New Cross - Hurst: 18 km Hurst - Crayford: 2.5 km	**External drivers/issues** Reinforcement of grid. Congested urban environment led to deep tunnel solution
Circuit length 2 x 32.5 km	**AC cable system length** 2 x 1 x 32.5 km (1 cable per phase)



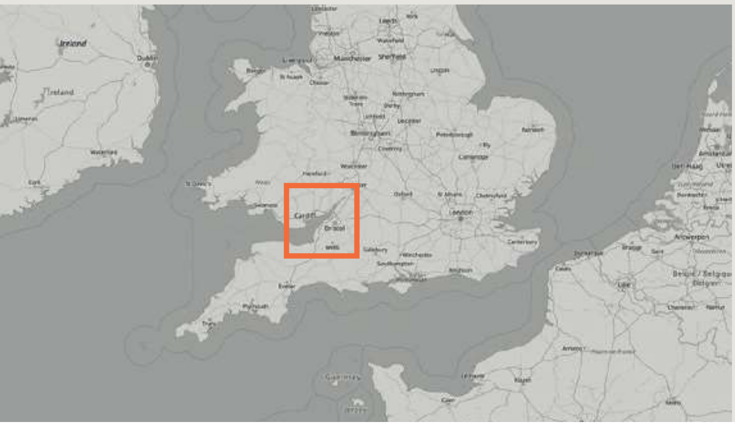
Shinkeiyo - Toyosu

Location Japan	**Technology** High voltage alternating current cable tunnel	**Capacity** 2 x 1200 MW	**Capital cost** -
Owner/operator Tokyo Electric Power Company (TEPCO)	**Route characteristics** Cable tunnel	**Voltage** 500 kV AC	**Construction duration** 1995 - 2000
Project status In service	**Terminal point infrastructure** Connects to substations at Shin-Toyosu and Shin-Keiyo	**Route length** 40 km	**External drivers/issues** Routing through urban environment led to requirement for cable tunnel. Long cable system length required 1.2 GVA of reactive compensation
Actual/planned energisation date 2000	**Network configuration/connection type** Meshed network	**Circuit length** 2 x 40 km	**AC cable system length** 2 x 1 x 40 km (1 cable per phase)



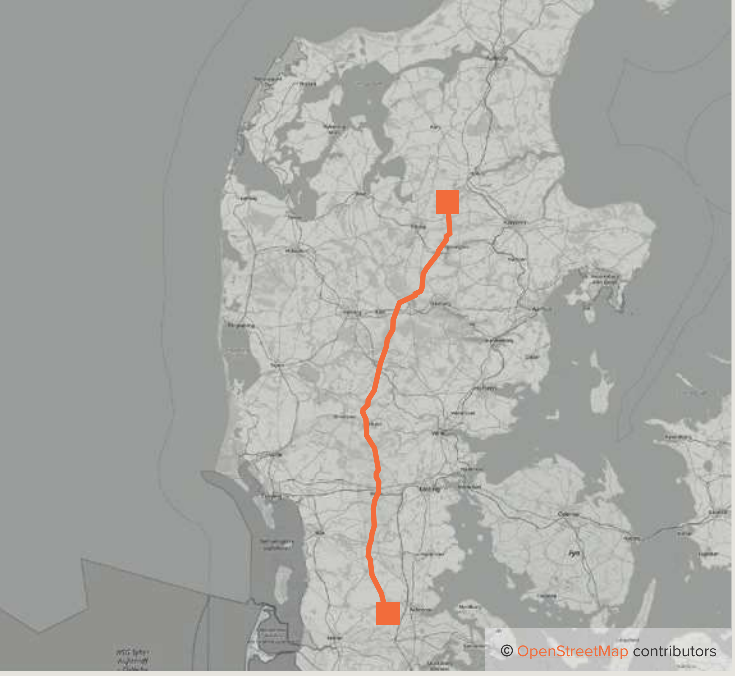
St John’s Wood

Location London, UK	**Technology** High voltage alternating current cable tunnel	**Capacity** 1 x 1600 MW	**Capital cost** -
Owner/operator National Grid	**Route characteristics** Central London – cable tunnel	**Voltage** 400 kV AC	**Construction duration** 2002 - 2005
Project status In service	**Terminal point infrastructure** Upgrade of existing Elstree and St John’s Wood substations	**Route length** 26 km	**External drivers/issues** Routing through central London led to requirement for cable tunnel
Actual/planned energisation date 2005	**Network configuration/connection type** Meshed network	**Circuit length** 1 x 26 km	**AC cable system length** 1 x 1 x 26 km (1 cable per phase)



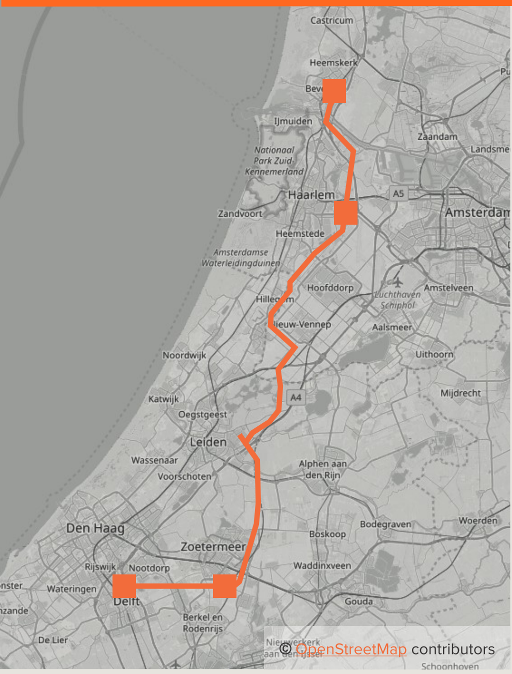
Hinkley Point C

Location Southwest England, UK	**Technology** Partially undergrounded overhead high voltage alternating current (43 km overhead and 8.5 km underground)
Owner/operator National Grid	**Route characteristics** Rural land. Crosses environmentally protected area. The new circuit will be constructed on an existing 132 kV overhead line route.
Project status Consented	**Terminal point infrastructure** Extension of existing Seabank 400 kV substation. New 400 kV substation at Hinkley Point C
Actual/planned energisation date 2026	**Network configuration/connection type** Meshed network
Capacity 2 x 2400 MW	**Capital cost** 875 million EUR
Voltage 400 kV AC	**Construction duration** 2018 - ongoing (estimated completion in 2026)
Route length 57 km	**External drivers/issues** Connection of new nuclear power station. Crossing of protected area led to partial undergrounding.
Circuit length 2 x 43 km overhead 2 x 8.5 km underground	**AC cable system length** 2 x 2 x 8.5 km (2 cables per phase)



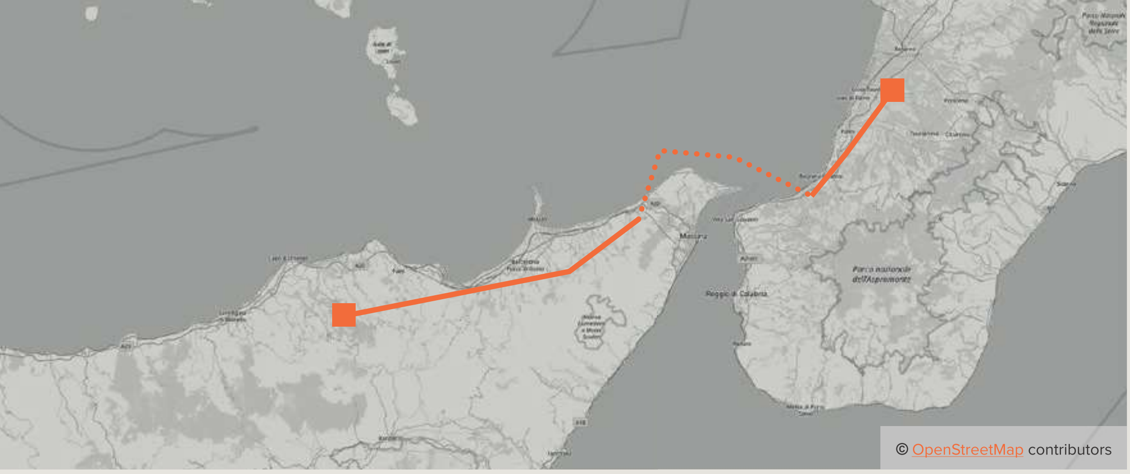
Kassø – Tjele

Location Denmark	**Technology** Partially undergrounded overhead line high voltage alternating current
Owner/operator Energinet	**Route characteristics** Existing overhead line route
Project status In service	**Terminal point infrastructure** Upgrades to existing Kassø and Tjele substations
Actual/planned energisation date 2015	**Network configuration/connection type** Meshed network
Capacity 2 x 1800 MW	**Capital cost** 390 million EUR
Voltage 400 kV AC	**Construction duration** 2010 - 2015
Route length 172 km	**External drivers/issues** Reinforcement of grid to support transmission of renewable energy. Adjustment of overhead route and section of underground cable required in environmentally sensitive areas. New overhead line tower with reduced visual impact was designed for the project
Circuit length 2 x 172 km (151 km overhead and 21 km underground)	**AC cable system length** 2 x 2 x 21 km (2 cables per phase)



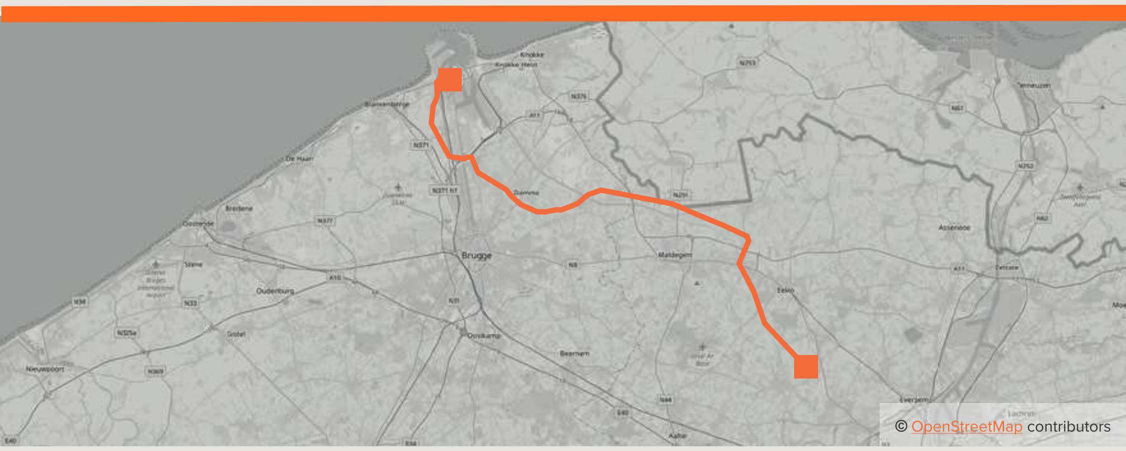
Randstad

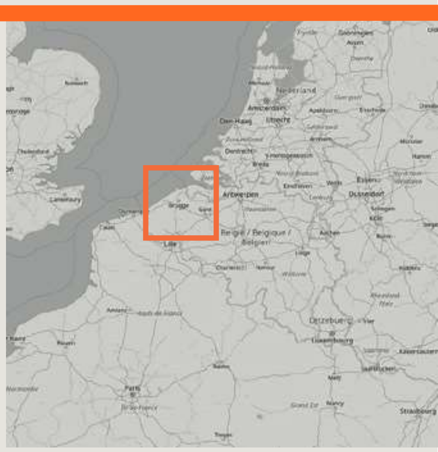
Location Netherlands	**Technology** Partially undergrounded overhead high voltage alternating current
Owner/operator Tennet	**Route characteristics** New route is combined with existing major infrastructure including existing 150 kV overhead line routes
Project status Zuidring: In service Noordring: Under construction	**Terminal point infrastructure** Zuidring: Extension of existing Wateringen and Bleiswijk substations. Noordring: Extension of existing Bleiswijk and Beverwijk substations
Actual/planned energisation date Zuidring: 2014 Noordring: Q3 2019	**Network configuration/connection type** Meshed network
Capacity 2 x 3000 MW OHL, 2 x 2100 MW UGC	**Capital cost** -
Voltage 380 kV AC	**Construction duration** Approximately 5 years
Route length Zuidring: 21 km Noordring: 60 km	**External drivers/issues** Horizontal directional drilling used to cross obstructions including railway lines, a motorway, a river and numerous watercourses
Circuit length Zuidring: 2 x 21 km (10 km overhead, 11 km underground) Noordring: 2 x 60 km (51 km overhead, 9 km underground)	**AC cable system length** Zuidring: 2 x 2 x 11 km (2 cables per phase) Noordring: 2 x 2 x 9 km (2 cables per phase)



Sorgente - Rizziconi

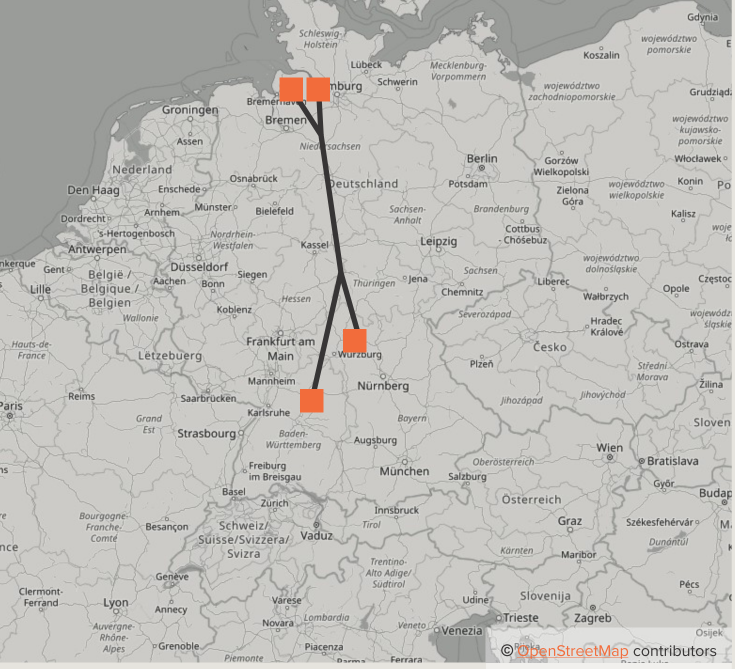
Location Mainland Italy - Sicily	**Technology** Mixed overhead and subsea high voltage alternating current	**Capacity** 2 x 1000 MW	**Capital cost** 565 million EUR
Owner/operator Terna	**Route characteristics** Onshore and offshore	**Voltage** 380 kV AC	**Construction duration** 2009 - 2014
Project status In service	**Terminal point infrastructure** Substations at Rizziconi (mainland) and Sorgente (Sicily)	**Route length** 103 km	**External drivers/issues** Increase in capacity and security of supply
Actual/planned energisation date 2015	**Network configuration/connection type** Meshed network	**Circuit length** 2 x 103 km (60 km overhead, 38 km subsea, 5 km underground)	**AC cable system length** 2 x 1 x 43 km (1 cable per phase)





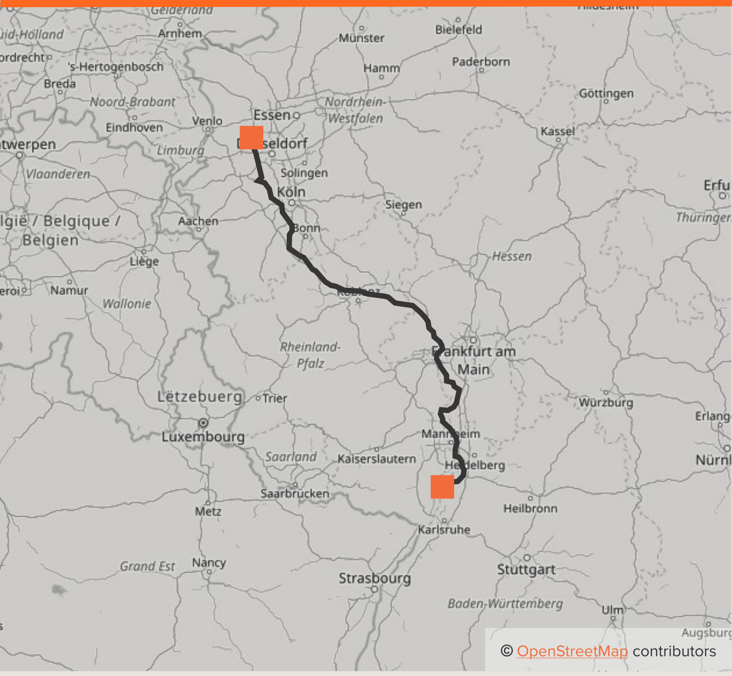
Stevin

Location Belgium, Flanders	**Technology** Partially undergrounded overhead high voltage alternating current	**Capacity** 2 x 3000 MW OHL 4 x 1000 MW UGC	**Capital cost** -
Owner/operator Elia	**Route characteristics** 12 km reuse of existing overhead line and 27 km of new overhead line. 10 km of underground cable with tunnel of 230 m under the Boudewijn canal	**Voltage** 380 kV AC	**Construction duration** 2015 - 2017
Project status In service	**Terminal point infrastructure** New substation Stevin at Zeebugge. 2 new substations Gezelle and Van Maerlant	**Route length** 47 km	**External drivers/issues** Reinforcement of grid to support interconnection with UK and transmission of renewable energy in the Northsea
Actual/planned energisation date 2017	**Network configuration/connection type** Meshed network	**Circuit length** 2 x 37 km overhead, 4 x 10 km underground	**AC cable system length** 4 x 1 x 10 km (1 cable per phase)



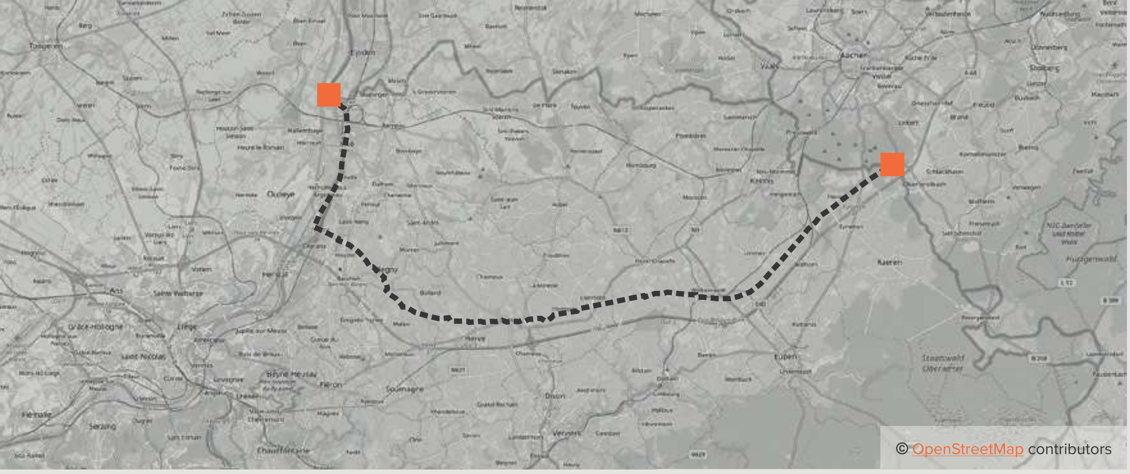
Suedlink

Location Germany	**Technology** High voltage direct current
Owner/operator ARGE Suedlink, TenneT	**Route characteristics** -
Project status Planning	**Terminal point infrastructure** New converter stations at Wilster - Grafenrheinfeld and Brunsbüttel - Großgartach
Actual/planned energisation date 2025	**Network configuration/connection type** Point-to-point
Capacity 2 x 2000 MW	**Capital cost** 5.2 billion EUR
Voltage 500 kV DC	**Construction duration** -
Route length 550 km	**External drivers/issues** Reinforcement of grid to support transmission of renewable energy. Large capacity and long distance led to HVDC technology
Circuit length 2 x 550 km	



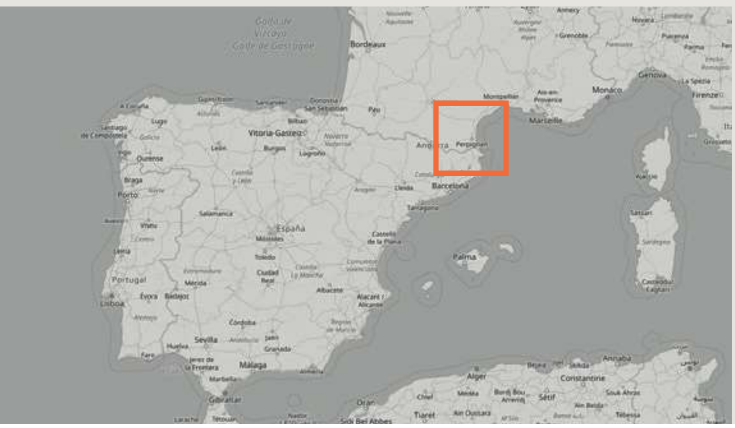
Ultranet

Location Germany	**Technology** Overhead high voltage direct current
Owner/operator TransetBW, Amprion	**Route characteristics** Utilisation of existing overhead line
Project status Planning	**Terminal point infrastructure** New converter Stations in Osterath and Phillippsburg
Actual/planned energisation date -	**Network configuration/connection type** Multi-terminal link (connecting to the A North HVDC link)
Capacity 1 x 2000 MW	**Capital cost** 910 million EUR
Voltage 380 kV DC	**Construction duration** -
Route length 340 km	**External drivers/issues** Need to transmit wind power from the north of Germany to the south where existing nuclear power plants are being decommissioned by 2022
Circuit length 1 x 340 km	



Alegro

Location Belgium - Germany	**Technology** Underground high voltage direct current	**Capacity** 1 x 1000 MW	**Capital cost** -
Owner/operator Elia, Amprion	**Route characteristics** 49 km in Belgium, 41 km in Germany. In parallel with E40 European motorway between Belgium and Germany. 700 m long microtunnel beneath the Meuse and the Albert Canal	**Voltage** 380 kV DC	**Construction duration** 2018 - ongoing (estimated completion in 2020)
Project status Under construction	**Terminal point infrastructure** New converter stations at Lixhe and Oberzier	**Route length** 90 km	**External drivers/issues** Interconnection between Germany and Belgium
Actual/planned energisation date 2020	**Network configuration/connection type** Point-to-point	**Circuit length** 1 x 90 km	

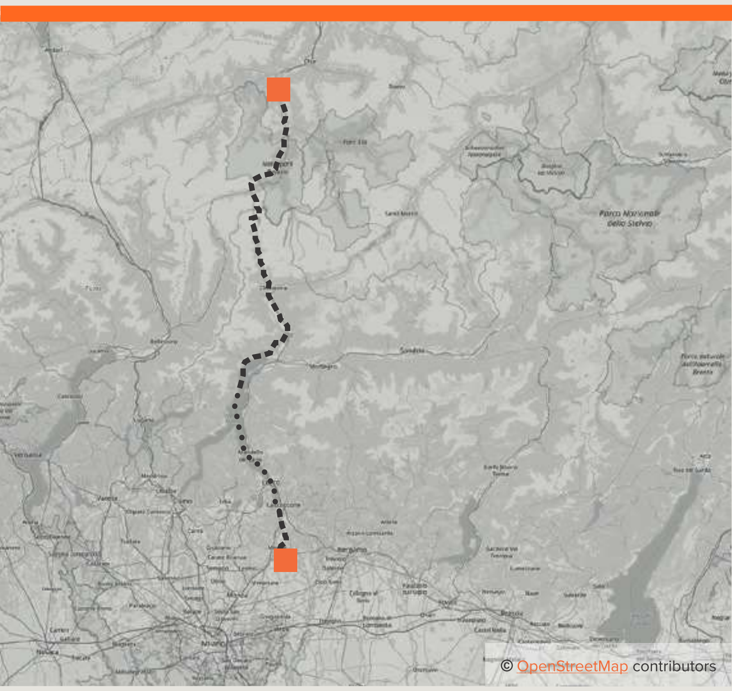


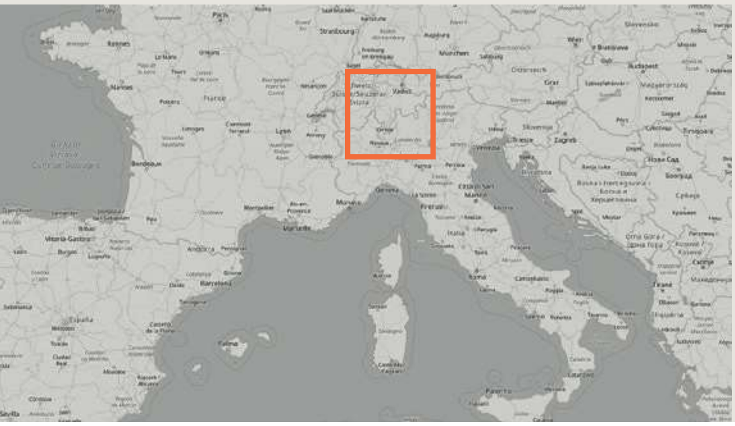
Baixas-Santa Llogaia

Location France - Spain	**Technology** Underground high voltage direct current
Owner/operator INELFE	**Route characteristics** The central part of the line crosses the Pyrenees at the Albera massif. An 8.5 km tunnel was built for this section.
Project status In service	**Terminal point infrastructure** New converter stations at Baixas (France) and Santa Llogaia (Spain)
Actual/planned energisation date 2015	**Network configuration/connection type** Point-to-point
Capacity 2 x 1000 MW	**Capital cost** 700 million EUR
Voltage 320 kV DC	**Construction duration** -
Route length 64.5 km	**External drivers/issues** Interconnection between France and Spain
Circuit length 2 x 64.5 km	

BritNed

Location UK - Netherlands	**Technology** High voltage direct current subsea cable	**Capacity** 1 x 1000 MW	**Capital cost** 600 million EUR
Owner/operator BritNed Development Limited	**Route characteristics** Subsea	**Voltage** 450 kV DC	**Construction duration** Q3 2009 - Q2 2011
Project status In service	**Terminal point infrastructure** New converter stations at Maaskvlakte and Grain	**Route length** 260 km	**External drivers/issues** Interconnection between UK and Netherlands. Length of route and requirement for subsea cable led to HVDC technology
Actual/planned energisation date 2011	**Network configuration/connection type** Point-to-point	**Circuit length** 1 x 250 km subsea, 1 x 10 km underground	



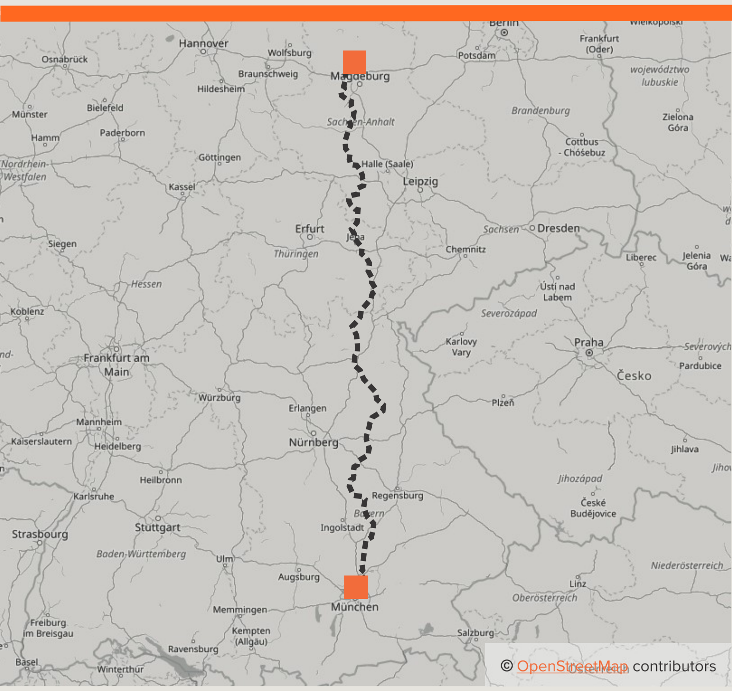


Greenconnector

Location Italy - Switzerland	**Technology** Underground and submarine high voltage direct current
Owner/operator Worldenergy SA	**Route characteristics** Part of the circuit will utilise an existing oil pipeline that is no longer in use. 47 km submarine cables (Como Lake)
Project status Consented	**Terminal point infrastructure** New converter stations at Sils and Verderio Inferiore
Actual/planned energisation date 2021	**Network configuration/connection type** Point-to-point
Capacity 1 x 1000 MW	**Capital cost** 660 million EUR
Voltage 400 kV DC	**Construction duration** Estimated completion in 2021
Route length 150 km	**External drivers/issues** Reinforcement of grid to support transmission of renewable energy through the Alps. Minimisation of environmental impact was a priority, resulting in only underground/submarine cables being considered
Circuit length 1 x 150 km	

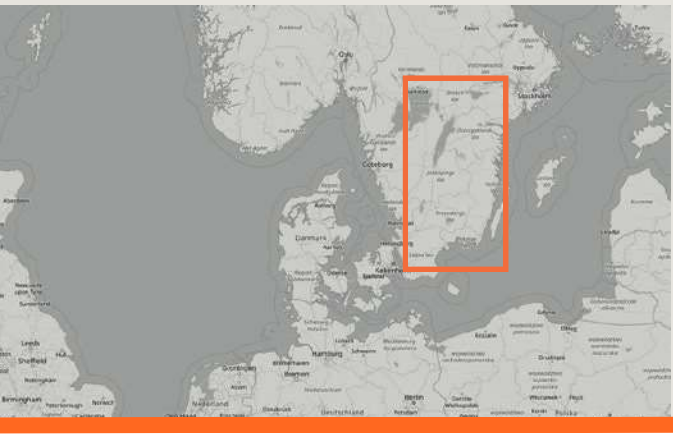
Sapei

Location Mainland Italy - Sardinia	**Technology** High voltage direct current subsea cable	**Capacity** 1 x 1000 MW	**Capital cost** -
Owner/operator Terna	**Route characteristics** Subsea	**Voltage** 500 kV DC	**Construction duration** -
Project status In service	**Terminal point infrastructure** New converter stations at Fiume Santo and Latina	**Route length** 435 km	**External drivers/issues** Additional connection between mainland Italy and Sardinia. Length of route and requirement of subsea cable led to HVDC technology
Actual/planned energisation date 2010	**Network configuration/connection type** Point-to-point	**Circuit length** 1 x 435 km	



SuedOstLink

Location Germany	**Technology** Underground high voltage direct current
Owner/operator 50Hertz, TenneT	**Route characteristics** -
Project status Consented	**Terminal point infrastructure** New converter stations at Wolmirstedt and Isar
Actual/planned energisation date 2022	**Network configuration/connection type** Point-to-point
Capacity 1 x 2000 MW	**Capital cost** -
Voltage TBC	**Construction duration** -
Route length 580 km	**External drivers/issues** Reinforcement of grid to support transmission of renewable energy
Circuit length 1 x 580 km	



SouthWest Link

Location Sweden	**Technology** Overhead high voltage alternating current. Mixed overhead and underground high voltage direct current
Owner/operator Svenska Kraftnat	**Route characteristics** -
Project status Under construction	**Terminal point infrastructure** AC substations at Hallsberg and Barkeryd with new converter stations at Barkeryd and Hurva
Actual/planned energisation date Q2 2019	**Network configuration/connection type** Point-to-point for DC Meshed network for AC
Capacity 2 x 600 MW	**Capital cost** -
Voltage 400 kV AC 300 kV DC	**Construction duration** 2013 - 2019
Route length 430 km	**External drivers/issues** Reinforcement of grid to support transmission of renewable energy. Additional western branch to Norway was planned but not built due to a revised analysis showing insufficient benefit
Circuit length 2 x 180km AC overhead 2 x 60km DC overhead 2 x 190km DC underground	

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