Undergrounding high voltage electricity transmission lines

The technical issues

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Front cover photo: National Grid works with Arup
to deliver London Power Tunnels

Introduction

The purpose of this document is to provide information about the technical merits and challenges associated with undergrounding high voltage electricity lines, compared with installing overhead lines. Overall, there are a number of issues that make the undergrounding option more technically challenging and expensive. However, despite the costs and technical challenges, there are circumstances in which underground cables are a more preferable option than overhead cables.

This document explains the cost and potential impact on the environment of cable installations. It explains the cable types available and the various installation methods, as well as the separate components that make up an underground installation.

National Grid electricity transmission – an overview

National Grid owns the high voltage electricity transmission system in England and Wales and operates the system throughout Great Britain at 275,000 and 400,000 volts (275kV and 400kV). This transmission system is made up of approximately 7,200 kilometres (4,470 miles) of overhead line, 1,400 kilometres (870 miles) of underground cable and about 330 substations.

Government planning policy relating to electricity infrastructure can be found in two National Policy Statements (NPS) – the Overarching NPS for Energy (EN-1) and, more specifically, the NPS for Electricity Networks Infrastructure (EN-5). These are the main documents that inform decision making on major infrastructure projects. Therefore, they provide National Grid with important guidance when considering whether to use overhead lines or underground cables.

National Grid has a statutory obligation under the Electricity Act 1989 to develop and maintain an efficient, coordinated and economical system of electricity transmission, and to facilitate competition in the supply and generation of that electricity. The company also has a statutory obligation to have regard to the preservation of amenity when developing electricity lines or undertaking other works in connection with electricity transmission infrastructure. In doing so National Grid has to make careful and informed judgements on the relative merits of both overhead lines and underground cables.

In terms of reliability, capability, cost, construction impacts and land use, overhead lines do have advantages when compared to underground cables. However, a significant benefit of undergrounding cables is the reduction in visual impact. In certain areas, such as protected landscapes, this benefit could be a primary consideration and outweigh disadvantages of undergrounding such as restrictions on land use and the impact on ecological and archaeological sites. National Grid considers the views and requirements of its customers and undertakes extensive stakeholder consultation before deciding which solution to take forward.

1. Insulating underground cables

Conductors that transmit electricity need to be electrically insulated. One major difference between overhead lines and underground cables is the way they are insulated.

Overhead lines are insulated by air, while underground cable conductors are wrapped in layers of insulating material. Air is the simplest and cheapest insulation and the heat produced by the electricity flowing through the bare overhead conductors is removed by the flow of air over the conductors. When conductors are buried underground, robust insulation is needed to withstand the very high voltage. The insulation method depends upon the type of cable used (see section on 'Underground cable technologies').

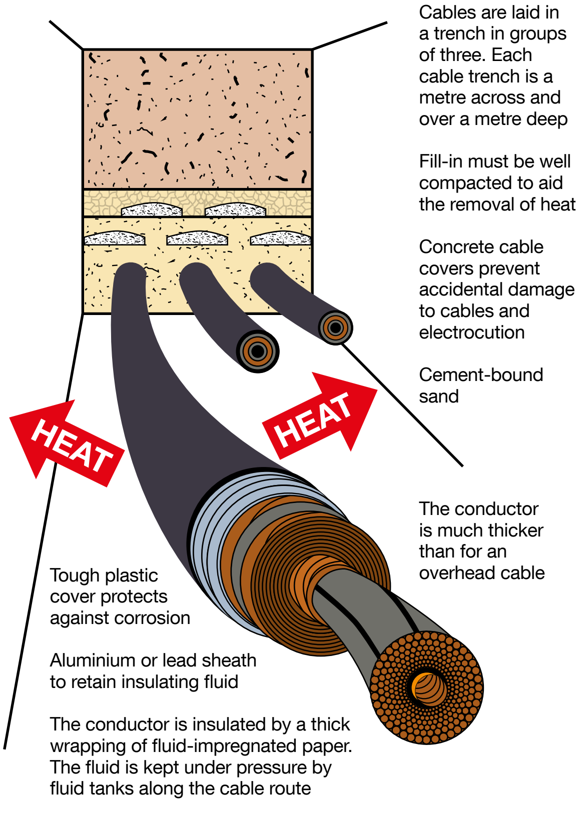
Underground cables, because of the insulation and surrounding environment, tend to retain the heat produced in the copper/aluminium conductor. This heat then has to be dissipated to the surrounding environment.

To compensate for this, underground cables are generally bigger to reduce their electrical resistance and heat produced. How the heat produced is dissipated will depend upon the cable installation method.

For direct buried cables each cable needs to be well-spaced from others for good heat dissipation. To match overhead line thermal performance for a 400kV double circuit, as many as 12 separate cables in four separate trenches may be needed, resulting in a work area up to 65m wide. In addition, water cooling may be used (see section on 'Components of underground cable systems'). For cables installed in deep bore tunnels, cable cooling is provided by forced air ventilation or water cooling.

When designing a cable system, there are a number of factors to consider relating to the physical environment of the cable, which will help optimise their electrical performance. These include ensuring:

- Adequate heat dissipation to prevent overheating and subsequent reduction in its capacity for carrying current (cable rating)
- Adequate physical protection to protect the cable from damage and to ensure it is not a potential danger to people while in service
- Proper access for maintenance crews to the cable to inspect, repair or replace it.



A typical cable installation method

2. Capital costs for installation of underground cables

The costs of underground cable systems vary and have been the subject of much debate and discussion. In January 2012 the Institute of Engineering and Technology (IET) and Parsons Brinkerhoff published the findings of an independent study into the costs of new electricity transmission infrastructure. The report analysed the costs of installing and maintaining new high voltage transmission circuits under the ground, under the sea and overhead.

The report found that, **excluding build costs**, the cost of operation, maintenance and energy losses over the life of the connection was broadly the same for undergrounding and overhead lines. However, the report also concluded that the capital build costs on their own vary greatly, depending on terrain, route length and power capacity.

A copy of the report can be found on the IET website (http://www.theiet.org/factfiles/transmission-report.cfm). While the study went into a great deal of detail, the report recognised that costs and cost differentials between different technologies will vary depending on length, power, voltage and ground conditions. It concluded that underground cables are always more expensive when compared to equivalent overhead lines.

A major element of this cost differential is accounted for by the cable itself. The underground conductor has to be bigger than its overhead counterpart to reduce its electrical resistance and hence the heat produced. The requirement to properly insulate, while at the same time maintaining the cable's rating, means that special insulation is needed. Generally, tunnel installation costs more than direct burial; however, civil engineering costs for all methods of cable installation are considerable compared to those of an overhead line.

A wide range of values are quoted for apparently similar circuits due to factors such as the local ground conditions. It is the added cost of undergrounding (in both monetary terms and other factors, such as threats to sensitive habitat and damage to archaeological heritage) that is important and must be weighed against the benefits (largely visual) that it brings. The actual costs will depend on the type of cable used, method of installation, local environmental conditions and, in particular, the rating required from the circuit, as this will dictate the number of cables installed. Underground cable systems need to be tailored to meet local conditions and the same solutions may not be applicable in other locations.

Visual intrusion impacts and threats to sensitive habitats will vary along the route corridor as the landscape and species mix changes. To help reduce some of these impacts undergrounding may be considered in some cases. However, this can create further difficulties as the transition from overhead lines to underground cables requires termination points, known as sealing end compounds (see page 16). These are often large structures that require sensitive siting. For this reason numerous adjacent short sections of undergrounding are unlikely to be desirable due to the requirement for large plant/equipment compounds at each termination point.

3. Underground cable technologies

There are a limited number of cable manufacturers across the world, particularly for cables at the high voltages required by National Grid. The cable types described below include older technologies as well as emerging ones.

Cable types:

- **XLPE** cables (Cross Linked Polyethylene Extruded) 33kV to 400kV
- **FFC** (Fluid Filled Cables) 33kV to 400kV
- **PPL-FFC** (Paper Polyethylene Laminated) 275kV and 400kV
- **MIND** (Mass Impregnate Non Draining) up to 33kV
- **GIL** (Gas Insulated Lines).

XLPE cable

Due to advances in cable technology, XLPE is now being used in preference to the use of fluid filled cable. In these modern cables the central conductor is insulated by means of a cross linked polyethylene material, which is extruded around the conductor. The absence of fluid in the cable insulation enables a more mechanically robust overall cable construction. XLPE cables require less maintenance, with no ancillary fluid equipment to monitor and maintain.

Due to the comparable simplicity of XLPE, this type of cable can be installed in most areas, such as tunnels, ducts and troughs. They may also be buried directly.

Fluid filled cable

The majority of the cables on National Grid's network are fluid filled and were installed mainly in the 1970s. These cables have paper insulation, wrapped around the central copper conductor and impregnated with fluid under pressure. Metallic tapes are wrapped around the insulation to reinforce the papers and retain the fluid pressure.

A sheath of lead or aluminium covers this. If exposed to ground water and other substances the lead or aluminium will deteriorate resulting in the ingress of water. An outer plastic sheath provides further insulation and prevents this corrosion.

A lead sheath has additional copper tapes to help support it and to prevent swelling as a result of the internal fluid pressures.

To ensure the integrity of the cable, the outer sheath is covered in a semi-conductive material, which allows any defects in the outer sheath to be detected.

Paper Polythene Laminated cable (PPL-FFC)

PPL is similar to fluid filled cables, however the insulation is wrapped with alternate layers of paper and XLPE.

Mass Impregnate Non Draining cable (MIND)

MIND cable is a paper-insulated cable and is normally used within substations on lower voltage systems for example: liquid neutral resistors (LNR). The paper is impregnated with a non-draining insulating fluid. Due to high technical stress levels this type of cable is not suitable for AC cables with voltages above 33kV and has been replaced by XLPE. MIND cable is now being used for DC cable at higher voltages.

3. Underground cable technologies continued

Gas insulated lines

An alternative to fluid filled or XLPE cable is the use of gas insulated lines (GIL). This system comprises aluminium/copper conductors that are supported by insulators contained within sealed tubes. These can be installed above ground, in trench or tunnel installations. The tubes are pressurised with a Nitrogen/Sulphur Hexafluoride (SF6) gas to provide the main insulation.

The main advantage of GIL is that a higher cable rating can be achieved and the terminations at the cable ends have a lower cost than conventional sealing end compounds (see section on 'Components of underground cable systems'). However, as SF6 gas is a greenhouse gas, it is our policy to consider using other technologies in preference unless a cost benefit can be shown. GIL is an emerging technology and currently few have been installed on National Grid's network.

Gas insulated lines installed in tunnel

4. Planning and environmental issues for underground cables

The use of underground cables has a long-term positive visual impact when compared with the use of overhead lines, and in some instances this will be the preferred choice. However, undergrounding has other impacts that should be considered, such as environmental and socio-economic factors.

In rural areas, disturbance to flora and fauna, land use and archaeological sites must be assessed. In this respect overhead lines are normally less disruptive than underground cables and cause fewer disturbances.

In both urban and rural environments land disruption is greater when laying underground cables than when erecting overhead line towers.

The volume of spoil excavated for an underground cable, where two cables per phase are installed, is some 14 times more than for an equivalent overhead line route. Vegetation has to be cleared along and to the side of trenches to allow for construction and associated access for vehicles.

The burying of high voltage cables is also more complicated than the laying of gas and water pipes. In addition underground joint bays, which are concrete lined and wider than the trenches themselves, have to be built every 500–1,000m.

A cable swathe during construction with a single cable trench open

5. Land use restrictions over cable routes

Buried cables occupy a significant amount of land and, like overhead lines, also require access for maintenance and repair for the duration of their life. Building over cables, earth mounding and excavating on the cable easement strip therefore needs to be restricted when direct buried cables and cables installed in surface troughs are used.

There are also restrictions on the planting of trees and hedges over the cables or within 3m of the cable trench to prevent encroachment by vegetation. Tree roots may penetrate the cable backfill surround which in turn may affect the cable rating or even result in physical damage to the cable.

Similarly for overhead lines, tree growth is discouraged and controlled beneath the overhead line conductors or within distances where trees could fall onto the lines. There will also be height restrictions for machinery or especially high vehicles, such as agricultural equipment, near overhead lines for safety reasons.

In urban areas the land taken for direct buried cables far exceeds that required for an equivalent rated overhead line. Cables have historically been routed under roads to avoid land sterilisation, however traffic disruption during fault investigation and repairs can be significant.

Where cables are installed by direct burial in rural areas there are restrictions on the use of deep cultivating equipment to avoid the risk of disturbance.

6. Operation, maintenance, refurbishment and up-rating cables

Cables have an asset life of around 60 years. During their lifetime regular inspection and testing is carried out to ensure that cable insulation and joints are operating correctly.

At the time of installation, equipment is put in place that monitors the performance of the cable and its insulation. Over the lifetime of a cable significant refurbishment and repairs to ancillary equipment, such as fluid tanks, may require more significant excavations at joint bays and stop joints. Vehicular access to strategic areas of the cable route, such as joint bays, is required at all times.

If a fault occurs on a 400kV underground cable, it is on average out of service for a period 25 times longer than 400kV overhead lines. This is due principally to the long time taken to locate, excavate and undertake technically involved repairs. These maintenance and repairs also cost significantly more.

The majority of faults on cables are caused by fluid leaks, faulty joints and accessories, sheath faults, water cooling failures and, most commonly, third party damage. Under fault conditions, between two and six weeks can be required to locate the fault or fluid leak and repair the cable. During this period excavations may be required which can result in road closures and traffic management measures. In some cases, the excavations could be in the order of 4m x 30m.

Underground cables are generally matched to the rating of the overhead line route in which they are installed; this also determines the cable design and any necessary cooling. Where an increase in the rating of an overhead line is required it can usually be achieved relatively easily by using different or larger conductors. Where there is an underground cable installed as part of a route the up-rating can only be achieved at considerable expense, for example, by re-excavation and the installation of larger or more cables or with additional cooling.

7. Cable installation methods

There are a number of different cable installation methods available. The method used depends upon a range of factors including land use and each will have different environmental factors. The various options are described below.

Direct buried cables

The traditional means of cable installation for high voltage cables in urban and rural areas is by direct burial. Trenches approximately 1.5m wide and 1.2m deep are required for each single cable circuit (see indicative diagram on page 12). A thermally stable backfill of cement bound sand is used to ensure a known thermal conductivity around the cables in order to maintain the cable rating (capacity to carry current).

A large cable swathe is normally required which can be up to 65m in width depending on the number of circuits and size of conductor to be installed. Joint bays are necessary at intervals of approximately 500–1,000m to allow for the jointing of the individual sections of cable. In these areas a widening of the easement corridor may be required for the arrangement of joints.

Direct burial of cables involves excavating trenches into which the cables are installed on a bed of selected sand or cement bound sand with the use of winches or power rollers. Sheet piling or timber is used to support the sides of the trenches. Reinstatement of the excavated trench is then carried out using approved backfill material placed directly around the cables with protection covers placed above the cables in the excavation. All backfill materials such as cement bound sand/ selected sand must be carefully compacted around the cables to ensure no air pockets exist. The presence of any air pockets will degrade the cable system rating. Regular tests are carried out during this process to ensure the correct level of compaction is achieved.

There are safety and environmental issues associated with the installation of direct buried cables. These include disruption to traffic, excessive noise, vibration, visual intrusion and dust generation. The use of heavy plant and construction traffic will also be a factor. Working alongside open excavations with heavy plant and construction equipment also imposes various safety risks.

Direct burial is normally the cheapest method for the installation of underground cables where restrictions on land use are not an issue. Where there is a requirement to cross major roads or through urban areas the costs of this type of major excavation in terms of traffic management, construction and legal restrains can be considerable.

Direct buried cable installation in a rural area

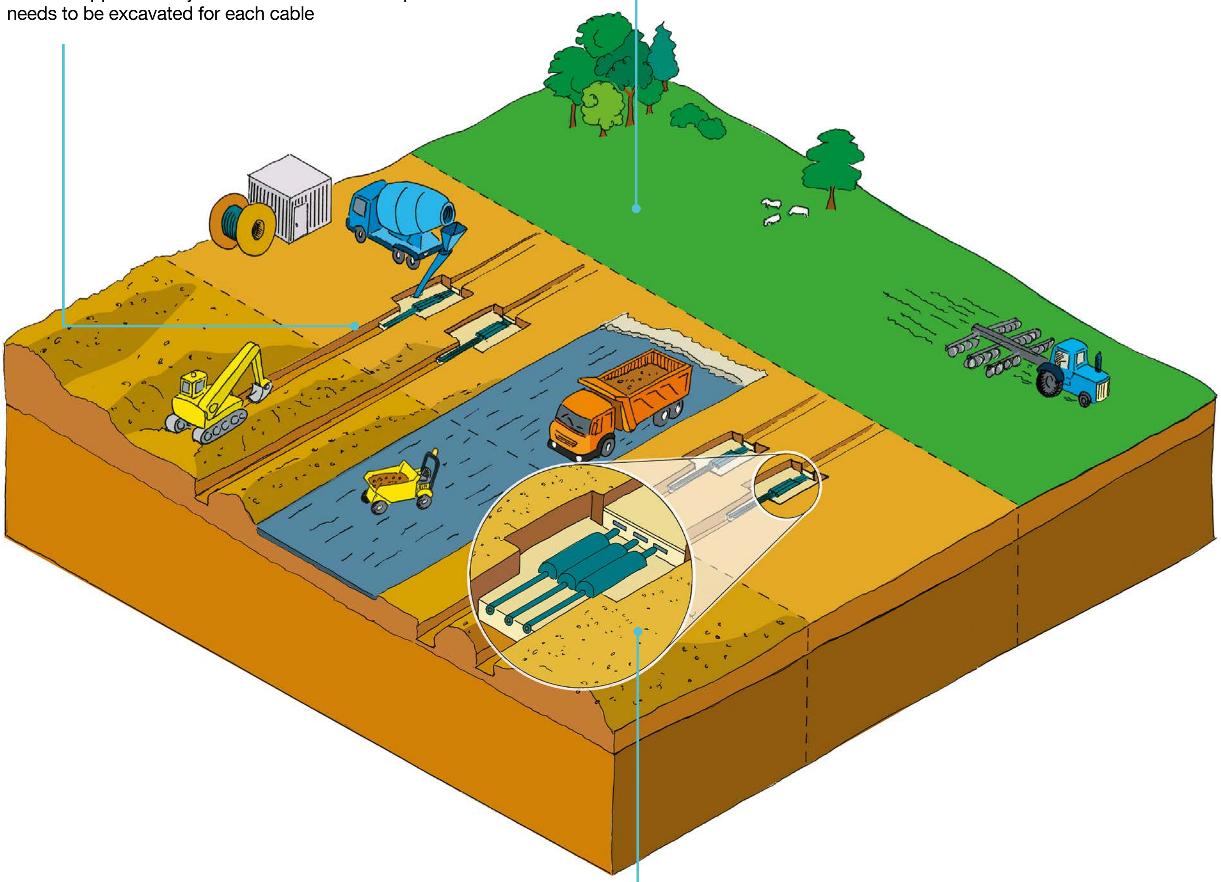
7. Cable installation methods continued

Direct Buried Cable Installation

For a 400kV double circuit connection we would need to excavate four trenches each containing three cables

A trench approximately 1.5m wide and 1.2m deep needs to be excavated for each cable

Once land is reinstated, land-use restrictions may apply to avoid risk of cables being disturbed or damaged



During construction the working width of the land needed is typically 40–65m

Joining bays are needed where one section of cable joins the next

7. Cable installation methods continued

Ducted method

An alternative, but more expensive method to direct burial is installation using ducts. The advantage of a ducted installation is that the ducts can be installed in shorter sections along the cable route leaving shorter sections of exposed trench, reducing risk and disruption to the general public. Most cable systems have specific cable designs and therefore cable can only be manufactured once the contract has been agreed. This may cause long delays. Installing ducts has the advantage of saving installation time as all the ducts can be installed before the cable delivery.

Surface troughs

For surface trough installation, a trench is excavated and a concrete base is laid in the bottom of the trench to support the troughs. The troughs are laid at a depth so that only the trough cover is visible. The cables are laid directly within the troughs, which are capped with reinforced concrete covers. Troughs provide mechanical protection for the cables and improved thermal conductivity; however, the level of rating available may be restricted.

Surface troughs are not normally suitable for routes with heavy vehicle traffic or where there is a high risk of thieves and vandals. Therefore, on National Grid's network, they are normally only used in secure areas such as substations, although historically they can also be found beside canals. In rural locations, direct bury cables are less visually intrusive than this option. Environmental impacts are relatively minimal and are likely to include noise, dust and access restrictions during the construction and subsequent maintenance phases.

275kV cables installed in surface troughs along tow path

7. Cable installation methods continued

Deep bore tunnels

Tunnel installation is generally used in urban locations where direct bury installation would cause unacceptable disruption. The method of excavation and tunnel design is largely dependent on the size of the tunnel required and the type of ground in which it is to be bored. Tunnels are lined with bolted segments and sealed using gaskets. Detailed ground condition surveys are required to determine the most appropriate design.

The depth of a tunnel is typically around 25–30m and maintains a fall (slope) of 1:1,000 to provide free drainage. Tunnel construction requires a significant amount of land – around 3,000m^2 at the primary construction site, where a 12m diameter shaft is needed. A tunnel requires a minimum of two head house buildings to provide access for maintenance and for installation of the cables at each end. Head house buildings are around 16m x 16m x 7m in height. In addition, tunnels of significant length require inspection and emergency access and exit points along the route to ensure escape from the tunnel within safe limits. A tunnel with a diameter of around 4m would be required to provide sufficient room for up to 12 cable cores and joint bays. Within the tunnel a rail mounted access vehicle may be required to provide safe emergency exit and allow inspection, maintenance and repair. Cable cooling is provided by forced air cooling from electrically driven fans. If necessary additional cooling can be provided by a water cooling system.

The advantages of using deep tunnels are that underground services such as water and sewerage are unaffected, and river or railway crossings can be made. Also, because of limited surface land take, normal development can take place at ground level and along the route of the tunnel there is minimal disruption during construction and maintenance. However, these result in significant costs associated with planning consent, land acquisition and planning and constructing a route to avoid major surface and underground structures. In addition, development at the primary construction site is likely to generate environmental impacts, such as disruption to traffic, noise, vibration and dust for the duration of the development.

Tunnel head house building

XLPE cables installed in a deep bore tunnel

7. Cable installation methods continued

Cut and cover tunnels

For cut and cover tunnels, a tunnel is constructed using pre-formed concrete sections, which are laid in a pre-excavated deep open trench. The depth at which they are laid is dependent on ground conditions and proposed future land use. The tunnel sections require a head house at each end to provide the ventilation fans for forced air cooling and entry points to the tunnels. Emergency access/exit points may also be required along a tunnel route depending upon its length. The tunnel must be of sufficient size to provide adequate space for the installation and operation of the cables, the ventilation for removal of heat and safe access for personnel during cable installation and maintenance.

Cut and cover tunnel installation in mainland Europe

The land above the tunnel can be developed, but depending on its depth, certain restrictions may apply. The environmental impacts from the installation of a cut and cover tunnel are considerable. They include noise, vibration, construction/delivery traffic, visual intrusion, dust generation and deposition due to the excavation of trenches along the route.

8. Components of underground cable systems

Cable sealing end compounds

A sealing end compound is needed where a section of cable is terminated and the circuit continues on to an overhead line. These sealing end compounds are generally around 30m x 80m for a 400kV circuit, and house the support structures for the cable terminations/sealing ends, post insulators, earth switches and a terminal tower. These enable the transition from cable conductor to the overhead line conductor.

As the forces acting on a terminal tower are not balanced they need to be heavy in design and construction. Careful siting and screening in the form of trees/earth mounds can be beneficial, but the visual impact of the terminal towers is significant.

A typical sealing end compound for a directly buried cable

A sealing end compound under construction

Joint bays

For most installations, joints are required at intervals along the route. This is because the cable is supplied in fixed lengths dictated by the cable drum diameter, the diameter of the cable itself and the maximum weight that can be transported.

For directly buried cables, joints will be approximately every 500–1,000m. In tunnels this spacing has to be consistent so it complies with National Grid safe working practices.

XLPE joints are prefabricated off site and assembled on site. With fluid filled cables, the majority of the joint is constructed/assembled on site. For both options, joint bays are required, which can be up to 40m in length and 5m in width. In these joint bays it is essential that suitable clean conditions are established and that they have the provision of temporary power supplies and de-humidification in order to achieve satisfactory jointing.

Cable joint bay on a directly buried cable

Cable drum offloading cable on site

8. Components of underground cable systems


Stop joint with adjacent fluid tanks under construction

Stop joints
Stop joints are only required for fluid filled cables where the length of cable and/or gradient necessitates joints to retain fluid pressure. The fluid is provided in a closed system via pressure tanks at the stop joint positions. Above ground kiosks with fluid pressure monitoring equipment are situated next to the stop joints/fluid tanks. The fluid tanks significantly increase the required land take of the cable route at the stop joint locations. Depending on where they are located, these tanks can either be buried or above ground. Generally, a stop joint bay is significantly longer than a standard straight joint bay.

Water cooling
In some cases plastic/aluminium pipes filled with water are laid alongside underground cables so that the heat generated by the cables can be transferred to the water flowing through the pipes. The water is then cooled in heat exchangers every 3km or so. Buildings to house the water pumping equipment and heat exchangers are required above ground and these must be carefully sited to minimise the impact of fan and pump noise on the locality.

Where space is limited and a reduced land take is necessary, this type of cooling enables closely spaced cables to achieve a higher rating.

Reactive compensation
Reactive compensation to compensate for the changing current drawn by long lengths of high voltage cable may be required for lengths of cable greater than 5km. Reactive compensation equipment would be installed within a substation.

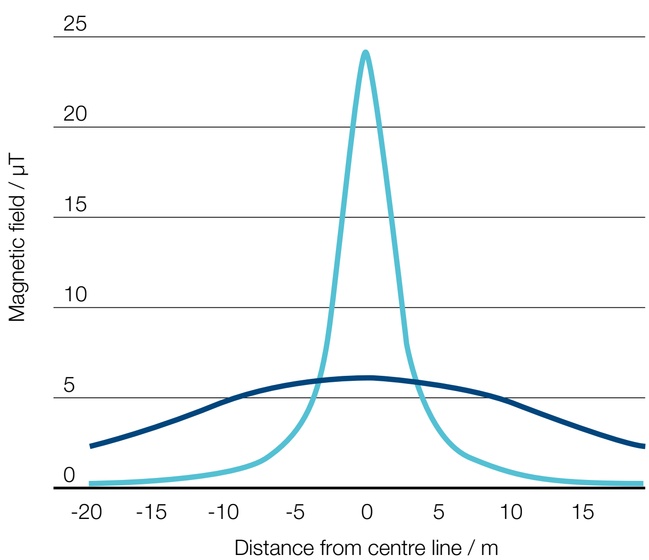
9. Electric and Magnetic Fields (EMFs) from underground cables

Overhead lines are a source of two fields: the electric field (produced by the voltage) and the magnetic field (produced by the current). Underground cables eliminate the electric field altogether as it is screened out by the sheath around the cable, but they still produce magnetic fields.

As the source of a magnetic field is approached the field gets higher. Cables are typically installed 1m below ground, whereas the conductors of an overhead line are typically more than 10m above ground, so the magnetic field directly above such a cable is usually higher than that directly below the equivalent overhead line.

However, as the individual cables are installed much closer together than the conductors of an overhead line, this results in the magnetic field from cables falling more quickly with distance than the magnetic field from overhead lines. Overall, then, directly above the cable and for a small distance to the sides, the cable produces the larger field; but at larger distances to the sides, the cable produces a lower field than the overhead line, as shown in the table below.

				Magnetic field in µT at distance from centreline			
				0m	5m	10m	20m
400kV	Trough	0.13m spacing 0.3m depth	Max	83	7	1.8	0.5
			Typical	21	2	0.5	0.1
	Direct buried	0.5m spacing 0.9m depth	Max	96	13	3.6	0.9
			Typical	24	3	0.9	0.2
	Deep bore tunnel	25m depth	Max	0.11	0.10	0.09	0.05
			Typical	0.03	0.03	0.02	0.01



The electric and magnetic fields from all National Grid overhead lines and underground cables comply with the relevant exposure limits, adopted by Government on the advice of the then Health Protection Agency. For more information on these limits and on the debate about other possible effects of these fields please see National Grid's website www.emfs.info.

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