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Undergrounding high voltage electricity transmission

The technical issues

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Front cover photo; St. John's Wood – Elstree tunnel, June 2005.

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Introduction

The purpose of this document is to provide information on the technical issues associated with undergrounding high voltage electricity transmission lines. These issues make undergrounding high voltage electricity transmission more technically challenging and more expensive than installing overhead lines. This document explains the cost and potential impact on the environment of cable installations. It explains the cable types available, the various installation methods as well as the separate components that make up an underground installation.

National Grid electricity transmission – an overview

Note on use of buried facilities

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 (275 kV and 400 kV). The National Grid system is made up of approximately 22,000 pylons with an overhead line route length of 4,500 miles, 420 miles of underground cable and 337 substations.

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. National Grid also has a statutory obligation to have regard to the preservation of amenity in developing the transmission system, and in doing so has to make careful and informed judgements on the relative merits of overhead lines versus underground cables.

On the grounds of reliability, capability, cost, construction impacts and land use, overhead lines are preferable to underground cables. Whilst underground cables offer benefits in terms of reduced visual impact, their installation can significantly impact upon sensitive and protected ecological and archaeological areas, as well as restrict the use of land in the long term.

The majority of high voltage underground cables on the National Grid system are installed in urban areas and within substation sites. A number of short sections of underground cable are installed within rural areas to preserve visual amenity and for long river crossings.

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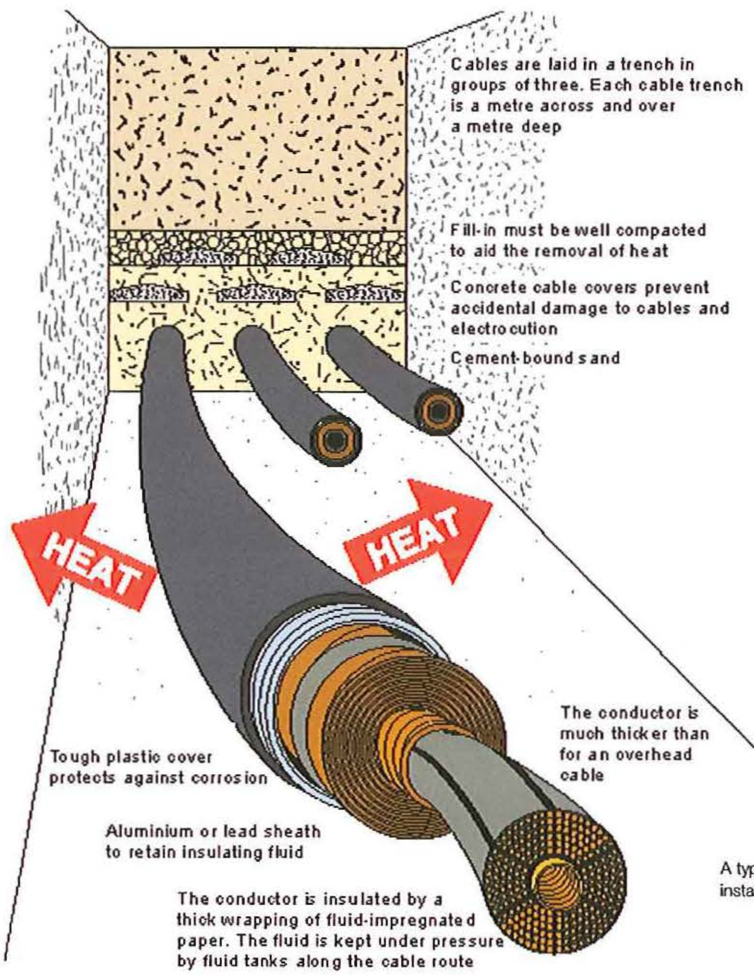
Insulating underground cables

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 whereas 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, high quality insulation is needed to withstand the very high voltage. The insulation method depends upon the cable used (see section on 'Cable technologies').

Underground cables, because of the insulation and surrounding environment, tend to retain the heat produced in the copper 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 400 kV double circuit as many as 12 separate cables in four separate trenches may be needed resulting in a cable swathe of up to 40m. 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 and (when required) water cooling.



A typical cable installation method.

In designing a cable system, if the electrical performance of the cables is not to be compromised, it is important that the physical environment of the cable enables:

- heat dissipation to prevent overheating and subsequent reduction in cable rating (capacity for carrying current);
- physical protection so that the cable does not become damaged or become a potential danger to third parties whilst in service; and
- proper access to the cables to ensure efficient inspection, repairs or replacement.

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Capital costs for installation of underground cables

The costs of underground cable systems can vary widely even for the same voltage, power and length, making it difficult to generalise. Costs for individual projects can and do vary significantly. Using modern cable techniques it costs approximately 12 to 17 times as much to install a typical 400 kV double circuit underground cable as it does to build an equivalent length of double circuit overhead line through normal rural / urban terrain.

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 whilst 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 that of an overhead line.

A wide range of values are quoted for apparently similar circuits due to the local ground conditions etc. 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.

Factors such as visual intrusion and threats to sensitive habitat are not generally the same along the whole route. In some cases, partial undergrounding can be considered, but the transition from overhead to underground can have a significant impact on the local environment. Numerous adjacent short sections of undergrounding are unlikely to be desirable due to the requirement for large plant / equipment compounds at each termination point.

Cable technologies

On the National Grid network there are two generic types of cable capable of operating at 275 kV and 400 kV – fluid filled cables and Cross Linked Polyethylene (XLPE).

Fluid filled cables

The majority of the cables on National Grid's network are fluid filled. In these cables insulation is provided by paper, impregnated with fluid under pressure, wrapped around the central copper conductor. Steel or copper tapes are wrapped around the insulation to reinforce the papers and retain the fluid pressure.
A sheath of lead or aluminium covers this and there is an outer covering of plastic to prevent corrosion.

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XLPE cables

Due to advances in cable technology, the use of fluid filled cable is diminishing and XLPE cables are now being introduced by National Grid. In these modern cables the central conductor is insulated by means of a cross linked polyethylene material. The absence of fluid in the cable insulation enables a simpler overall cable construction. XLPE cables require less maintenance and there is no ancillary fluid equipment to monitor and manage.

At voltages of 132 kV and below XLPE cable are buried directly in the ground. At present National Grid only installs 275 kV and 400 kV XLPE in tunnels but this is subject to ongoing review and future installations may, in some cases, be buried directly in the ground. National Grid's current concerns with burying high voltage XLPE directly in the ground relate to the risk of third party damage to the outer sheath and possible water penetration causing catastrophic failure of the cable insulation.

Gas insulated lines

An alternative to fluid filled or XLPE cable is the use of gas insulated lines (GIL). This system comprises aluminium 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 with few installed on National Grid's network.

GIL installed in tunnel.

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Planning and environmental issues for underground cables

Using underground cable can mitigate the visual impact of an overhead line but there are a number of significant environmental factors that must be considered with regard to underground cable installations.

In rural areas disturbance to flora and fauna, land use and archaeological sites must all be assessed. Overhead lines are normally less disruptive than underground cables and cause less disturbance to flora, fauna, land and archeological sites. 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. Cable burying leads to more spoil and construction activity in multiple trenches. In addition underground joint bays, which are concrete lined and wider than the trenches themselves, have to be built every 500m – 800m.

Underground cables do not require planning permission as they are permitted development. However, associated structures above ground such as sealing end compounds (at the point of transition between overhead lines and underground cables) may require planning permission from the local planning authority.

A cable swathe with a single cable trench open.

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Land use restrictions over cable routes

Buried cables occupy a significant amount of land except for cables installed in tunnels. Access to cables for maintenance and repair is also required for the duration of their life. Building over cables, earth mounding and excavating on the cable easement strip is therefore restricted for direct bury cables and cables installed in surface troughs. 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 can cause drying out of the ground around the cable causing a fall in the thermal conductivity and tree roots may also penetrate the back fill and cable construction causing electrical failure.

In urban areas the land take for direct bury 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.

Operation, maintenance, refurbishment and uprating 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. To maintain access to all parts of the cable at all times access for vehicles along the entire cable route is required.

When faults occur 400 kV underground cables are on average out of service for a period 25 times longer than 400 kV overhead lines. This is due principally to the long time taken to locate, excavate and undertake technically involved repairs. The maintenance and repair costs are also significantly greater.
The majority of faults on cables are caused by fluid leaks, faulty joints and accessories, 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 cooling. Where an increase in the rating of an overhead line is required then this can usually be achieved relatively easily by using different or larger conductors. Where there is an underground cable installed as part of a route then uprating can only be achieved at considerable expense, for example, by re-excavation and the installation of larger or more cables with additional cooling.

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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. The various options are considered in turn 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 below). 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).

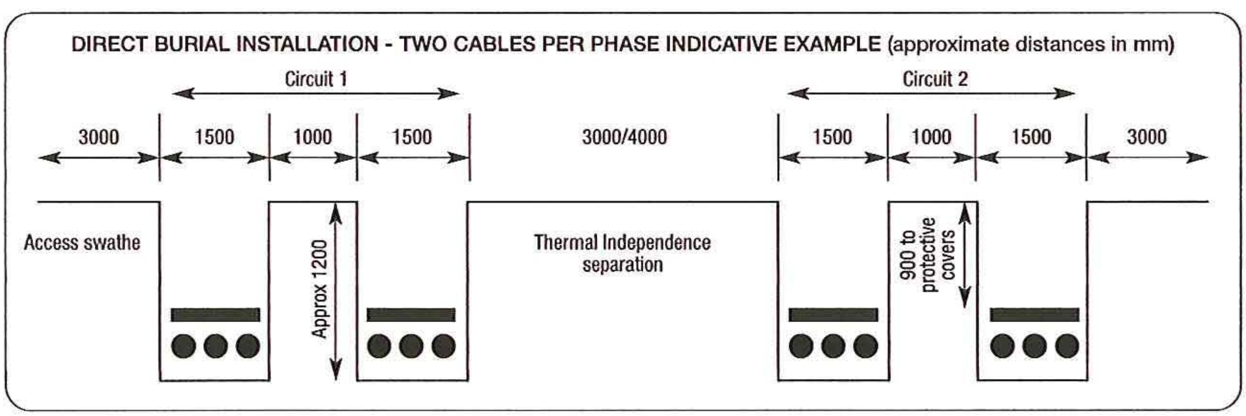
A cable easement corridor of 17m – 40m in width is required depending on the number of circuits and size of conductor to be installed. A working width of up to 55m may be required for the installation of the underground cable. Joint bays are necessary at intervals of 500m – 800m to allow jointing individual section lengths 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 sand by 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 concrete protection covers placed above the cables in the excavation. If thermally stable backfill materials such as cement bound sand are used they must be carefully compacted around the cables to ensure no air pockets exist, which would degrade the cable rating.

The major environmental issues associated with the installation of direct buried cables are the disruption to traffic, noise, vibration, visual intrusion and dust generation and deposition due to the excavation of trenches along the route. Heavy goods vehicle traffic will also be generated by the work, removing spoil and bringing in plant and materials, including backfill, to trenches.

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 go through urban areas the costs of this type of major excavation in terms of traffic management and construction can be considerable.

Direct bury cable installation in an urban and rural area.



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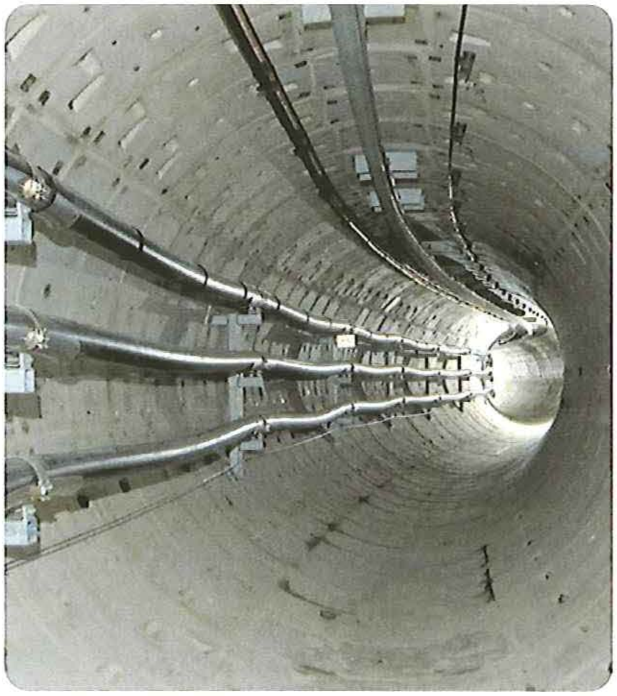
Deep bore tunnels

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 1:1000 to provide free drainage. Tunnel construction requires a significant amount of land in the order of 3000m² 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 in the order of 16m x 16m x 7m high. 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. Water cooling or chiller units can be installed, in addition to the forced air ventilation, when required.

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 there is minimal disruption during construction and maintenance. However, this results in significant costs associated with planning consent, land acquisition and planning and constructing a route to avoid major surface and underground structures.



Above: Tunnel head house building.

Left: XLPE cables installed in a deep bore tunnel.

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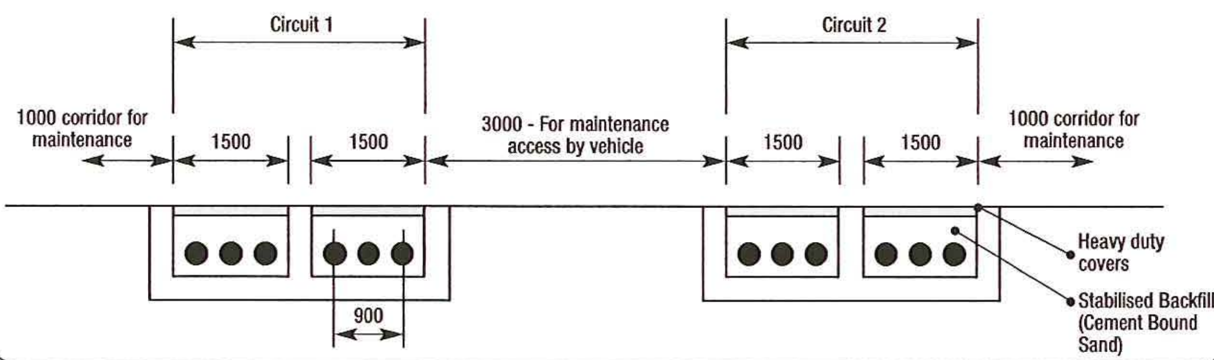
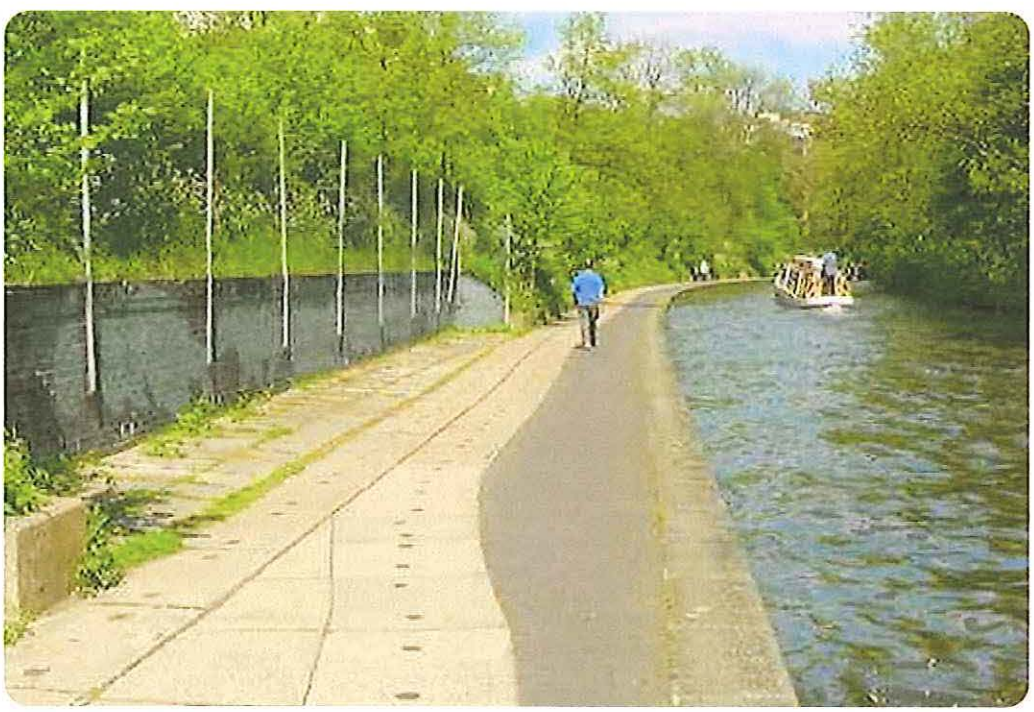
Surface troughs

For surface trough installation, a trench is excavated and concrete troughs are constructed. The cables are laid directly within the troughs which are capped with reinforced concrete covers laid flush with the ground surface. Troughs provide mechanical protection for the cables and improved thermal conductivity, however the level of rating available may be restricted.

Surface troughs are used in urban situations and within substation compounds where the reduced land take provided by this option is valuable. On National Grid's network, existing installations of this type are mainly found beside canals and within our substation compounds. Surface troughs are not normally suitable for routes with vehicle traffic but suitable construction, albeit more costly, can resolve this. In rural locations direct bury cables are less visually intrusive than this option. The indicative design of an example cable installation in troughs is shown below.

SURFACE TROUGH INSTALLATION - TWO CABLES PER PHASE INDICATIVE EXAMPLE (approximate distances in mm)





275 kV cables installed in surface troughs along tow path.

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.

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 and dust generation and deposition due to the excavation of trenches along the route.

This technology has not been used on National Grid's network and is only applicable where there are few existing ground features and sufficient space for installation.

Cut and cover tunnel installation in mainland Europe. This technology is not used by National Grid.

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Components of underground cable systems

Cable sealing end compounds

A sealing end compound is needed where a section of direct buried cable or tunnel construction is terminated and the circuit continues on to an overhead line. The sealing end compound houses the sealing end joints, post insulators and earth switches, which enable the transition from cable conductor to the overhead line conductor.

The land area required for a sealing end compound is generally around 30m x 80m for a 400 kV circuit. This compound contains a terminal tower and steel work to mount and support the sealing ends and cables. As the forces acting on it are not balanced, a terminal tower needs to be heavy in design and construction and their visual impact is therefore significant.

Left: A typical sealing end compound for a directly buried cable.

Right: A sealing end compound under construction.

Joint bays

For most installations, joints are required at intervals along the route. This is because cable is supplied in fixed lengths dictated by the cable drum diameter and weight. The amount of cable on that drum is in turn dictated by the cable diameter and transport options for the cable drum.

For direct buried cables, joints will be approximately every 500m – 800m whilst for cables in tunnels, every 800m. XLPE joints are prefabricated off site and assembled on site. With fluid filled cables the majority of the joint construction / assembly is carried out on site. For both options, suitable clean conditions have to be established at the joint bay location, including provision of temporary power supplies and air conditioning. Joint bays can be 30m to 40m in length and 5m in width.

Left: Cable joint bay on a directly buried cable.

Right: Cable drum off-loading cable on site.

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.

Stop joint with adjacent fluid tanks under construction.

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. Operational problems from this type of cable can occur if the cooling system fails, resulting in a severe reduction to the cable 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.

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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 round the cable. But they still produce magnetic fields.

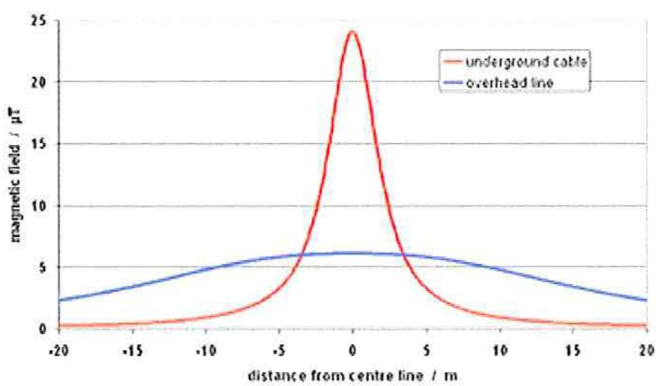
As the source of a magnetic field is approached the field gets larger. Cables are typically installed 1m below ground, compared to an overhead line where the conductors are typically more than 10m above ground, so the magnetic field directly above a cable is usually higher than that directly below the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

				Magnetic field in µT at distance from centreline			
				0 m	5 m	10 m	20 m
400kV	Trough	0.13 m spacing 0.3 m depth	Max	83	7	1.8	0.5
			Typical	21	2	0.5	0.1
	Direct buried	0.5 m spacing 0.9 m depth	Max	96	13	3.6	0.9
			Typical	24	3	0.9	0.2
	Deep bore tunnel	25 m depth	Max	3	2	1.5	0.6
			Typical	0.2	0.2	0.1	0.1

This table gives some actual field values for the same conditions.

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 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 web site www.emfs.info.



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