Heimild: http://www.leonardo-energy.org/drupal/book/export/html/868

Underground High Voltage Cables: Wiring Europe for the Future

Underground High Voltage Cables: Wiring Europe for the Future

In many of Europe's largest cities and in areas where construction of overhead transmission lines creates difficulties, high and extra-high voltage underground electricity cable systems rated 220kV and above have become part of the backbone of modern day power transmission infrastructure. Although cables have been in use for over half a century, today's underground high voltage cables are leveraging state-of-the-art technology and advanced design to expand their reach and are increasingly becoming an efficient and reliable alternative to overhead lines. Underground high voltage cables are powering a changing world.

This eBook presents the main benefits of underground high voltage cables:

- Versatile and Unique
- Cost Effective Solution
- Enhanced Technology
- Increased Reliability
- Reduced Transmission Losses
- Advanced Installation Techniques
- Improved Monitoring

If you are a cable specialist and are interested in learning more details about underground high voltage cables, choose from the topics below:

- Environmental: Information about EMFs, land issues, recyclability, installation impacts, and sensitivity benefits.
- Regulation: Details on basic mechanisms, regulatory drivers, and incentives.
- Case Studies: Presentation of reliability showcases, unstopping bottlenecks, overcoming obstacles, and strategies for success.
- System Reliability: Information about overload capacity, failure issues, technical changes, and warranties and testing.
- Life Cycle: Details about transmission losses, planning delays, and replacement cycles.

Versatile and Unique

Underground cables have unique properties for transmitting power - they are out of sight, often require only a narrow band of land to install, emit no electric field and can be engineered to emit no magnetic fields, have better power loss characteristics and can absorb emergency power loads. As a result, underground cables assist the transmission of power across:

- Densely populated urban areas;
- Areas where land is unavailable or planning consent is difficult;
- Rivers and other natural obstacles;
- Land with outstanding natural or environmental heritage;
- Areas of significant or prestigious infrastructural development; and
- Land whose value must be maintained for future urban expansion and rural development.

Cost Effective Solution

In the past, the higher cost of underground cables was a significant deterrent to their use. However, with lower cost production methods, improved technologies and increased reliability, the cost differential between underground cables and overhead power lines is narrowing. This means that power project developers are more frequently turning to underground cables as an economic and technically effective alternative when physical obstructions or public opinion hinder the development of networks. Opportunity costs from lengthy planning delays are reduced and the expense and complexity of public legal cases are minimized.

Apart from the reduced visual impacts, underground cables also offer lower maintenance costs than overhead lines. They are also less susceptible to weather-related issues such as storm damage, interruptions, costs of storm damage surveys and precautionary storm shutdowns. In addition, underground cables contain high quantities of copper, the most conductive engineering metal, resulting in 30 percent lower power losses than overhead lines at high circuit loads and improved system efficiency.

Advanced Features Offer Savings and Reliability

Today's cable manufacturers are able to provide innovative and customized solutions for the modern state-of-the-art power transmission industry. Underground high and extra-high voltage cables are equipped with new design features, such as real-time monitoring, which make them an effective and reliable alternative to overhead lines.

Enhanced Technology

Cables for burial on land using extruded insulation technology are taking the place of traditional oil-filled cables because of significant advantages that include:

- Easier installation and jointing;
- Better environmental compatibility and friendliness in service;
- Reduced installation costs; and
- Reduced or practically zero maintenance.

Increased Reliability

Today's cable systems, using cross-linked polyethylene (XLPE) as the primary insulation material, have been performance tested to ensure reliability. New cables based on this technology have been running for over 20 years with an excellent reliability record.

Reduced Transmission Losses

Underground extra-high voltage cables generally have more efficient copper conductors and operate at lower temperatures than overhead lines. These properties combine to transmit energy to end users as efficiently as possible, which is especially important for remote renewable and low carbon generators. Reducing these power transmission losses makes a valuable contribution to lowering greenhouse gas emissions.

Advanced Installation Techniques

With new burial and jointing techniques, underground cable projects that once took years to complete can now take only months to install. Through the use of directional drilling and "trenchless" burial techniques, cable manufacturers are applying leading edge design know-how to dramatically reduce installation times. In some installations, where it is not possible to trench or duct the cables, underground tunnels have been built to carry the cables. In some cases, significant cost savings have been made by placing cables in existing tunnel systems.

Improved Monitoring

To reduce outage time, power system operators can monitor underground cables through built-in temperature sensors. The sensors allow the cable to safely accept enormous emergency power overloads when other parts of the network are down. This means that the overall system becomes more robust and supply is maintained. In the rare event of a cable fault, generally caused by external disturbance, advanced monitoring of temperature and integrity in real time will allow faults to be located and repairs to be carried out in a much shorter timeframe than in the past.

Powering a Changing World

Power markets across Europe are being challenged by four often conflicting drivers:

1. Requirements to carry more power generated from remote renewable and nuclear sources of energy;
2. Requirements to increase the interconnection capacity between countries;
3. Requirements to increase system security while replacing ageing transmission assets; and
4. Increased planning delays for new overhead transmission infrastructure due to heightened public interest in environmental matters.

Transmission companies and cable manufacturers are searching for new ways to manage the response to these drivers.

By targeting problem locations for overhead transmission projects at the planning stage and by proposing underground cable solutions, developers can:

- Gain support from stakeholders who would otherwise oppose transmission projects;
- Reduce or eliminate planning delays so projects are completed on reliable timescales to satisfy investors, customers and regulators;
- Leverage the improved lifecycle cost of underground cables to control costs on the overall project; and
- Demonstrate to investors that business risk from emerging environmental and corporate social responsibility drivers is being managed effectively.

1. Environmental Module

Underground cables are especially effective at helping power transmission projects to cross areas where there are environmental sensitivities. These include areas that are:

- Close to homes, schools, and other human habitation
- Of outstanding visual value, either historical or natural
- Crucial to wildlife habitation and migration
- Environments that present natural obstacles, such as waterways

Underground cables are able to address these sensitivities as they offer:

- No visual damage after installation
- The ability to engineer external fields to almost zero
- No physical obstacle to animals or birds

Choose from the options below to learn more about the environmental aspects of underground cables:

1.1. Electromagnetic Fields (EMFs)

Electromagnetic fields are generated by electric currents and voltages in conductors. There is considerable concern about the health effects of long term exposure to these fields. While the perceived risks remain difficult to quantify, it is clear that the highest exposures and concerns occur when people live or spend significant potions of time near a power conductor.

The EU has issued standards that control the allowable exposures to EMFs, but at significantly higher levels than those found in the vicinity of power lines. The following are typical national positions on magnetic fields:

- International Commission on Non-Ionising radiation Protection, ICNIRP & EU recommendation 1999 - 100 μT
- 1996 Swedish Advisory Bodies suggest power distribution should avoid average exposures above 0.2 μT
- 1999 Swiss Government limit for new installations - 1 μT
- 2000 Three Italian Regions: Veneto, Emilia-Romagna and Toscana - limit for new installations near schools, nurseries, houses & places where people spend more than 4 hours per day - 0.2 μT
- 2002 New substation in Queensland, Australia: Energex Ltd - 0.4 μT
- 2004 The Netherlands Dept of the Environment proposal – 0.4 μT

Underground cables can help power projects to transmit power past sensitive areas of human habitation and address the concerns of stakeholders.

1.2. Land issues

Underground cables and overhead lines have significantly different footprints through the countryside when completed. While an overhead line requires a strip around 200 metres wide to be kept permanently clear for safety, maintenance, and repair, an underground cable of the same capacity requires only 10 metres or so.

With appropriate engineering works, such as magnetic shielding, a cable can even safely run under areas such as pedestrian zones with no exposure to external fields.

A recent study by the Swedish National Grid Company (Svenska Kraftnät) showed that a redesign of their grid could bring substantial benefits. By replacing 220kV lines with a mixture of 400kV overhead lines and underground cables, certain lengths of line could be completely eliminated. Benefits of the redesign included:

- Removal of 150km of lines, mostly from populated areas
- 60,000 residents will no longer live within 200 metres of a line
- 5,000 apartments could be built on abandoned rights of way
- Comparing the costs and benefits, for an up-front price of kr3.3B, land with a value of kr2.2B was released for development, potentially covering over 65% of the costs
- If electrical supply quality improvements were included, the benefits of the project covered the total investment costs

1.3. Recyclability

At the end of service life, a cable can be recovered for recycling or left in place. With older oil-filled cable technology, leaving the cable in place may have risks associated with long term oil leakage. Modern XLPE cables, however, can be left in situ with little risk of release of hazardous substances. Of course, good environmental stewardship dictates that recycling should be a preferred option for XLPE cables, if possible.

A modern cable has three recycling-related aspects to consider:

- Recovery of cables: Recovering a cable can require considerable excavation work, depending on the nature of the installation. Direct excavation is relatively costly, while physically dragging up the cable from the soil is significantly cheaper.
- Recyclability of copper: A large power cable system may have three conductors, each with a 2500 mm2 cross section of copper. Each kilometer of this cable contains around 25 tonnes of copper whose scrap value can cover the costs of recovering the cable from the ground. This copper is fully recyclable into new copper products of all types, including electrical grades and new cables. Recovering this copper saves around 70 tonnes of CO_2 emissions.
- Dealing with cross-linked polyethylene: The polyethylene in a power cable is a special grade, which has cross-linked molecules to allow it to deal with extremely high temperatures without melting or flowing under load. This also means that it cannot be remelted once it has been stripped from a cable. This makes XLPE sheathing similar to rubber vehicle tyres, which are made from a cross-linked polymer. Options for dealing with cross-linked polymers include:
    - Energy recovery in cement kilns
    - Conversion into a crumb or power for use as a filler mixed with virgin material
    - Depolymerisation, the breaking down of the molecules into feedstock gases and feeding back into petrochemical processes

It is likely that given the low quantities of cable sheathing likely to enter the market, developing a specialist recycling route and associated specifications would not be worthwhile. Therefore, energy recovery is likely to be the most attractive solution, which displaces fossil fuels and avoids use of scarce landfill space.

2. Regulation

The transmission of power over long distances is a natural monopoly market and, as such, governments regulate the market to ensure that system operators maintain standards and do not over inflate prices.

Important issues controlled by regulation are:

- Security of supply, so that power is always available;
- Quality of supply, so that the voltage and frequency are stable and that voltage spikes do not damage equipment; and
- Cost, so that a fair rate is charged for the service of transmission.

To control these issues, regulators apply a range of controls to areas such as maintenance, capital investment allowances, operating cost allowances, investment returns and asset lifetimes.

Choose from the topics below to learn more about how regulators work to ensure that consumers' interests are protected, whilst investors are able to make fair returns on their investments.

2.1. Basic mechanisms

The European power transmission network is recognised as an important factor for economic and social well-being. Within a country, system operators usually have geographical separation and, as a consequence, local monopoly status. Transmission systems are capital intensive, sized to meet demand, and fixed in nature, making it unlikely that any competition could arise to control prices.

Due to the central importance of energy and the natural monopoly status of the transmission system operator, transmission networks are regulated to maintain acceptable standards for stakeholders and prevent the disproportionate exercise of economic power by operators.

Multiple Requirements of Power Transmission

A power transmission system must reliably and cost effectively deliver power to customers while ensuring the return on investment required by the transmission system operator. Regulators attempt to achieve this balance through:

- Ensuring a safe and reliable transmission system by working with industry and consumer stakeholders to set and enforce meeting minimum reliability criteria;
- Agreeing with system operators on a set of overall cost effective investment guidelines linked to meeting the minimum reliability criteria;
- Working with broader stakeholders to balance the costs of transmission system investments with social, economic and environmental considerations;
- Ensuring that the system can respond to national imperatives to assist in the delivery of diverse and environmentally responsive primary sources of energy;
- Working with stakeholders concerned with national development to ensure that transmission solutions are used and expanded efficiently; and
- Maintaining regulatory oversight to ensure that balances are evolved to meet changing circumstances over time.

2.2. Regulatory drivers

The regulation of power networks in each European country reflects the influence of a number of drivers, some of which reflect local needs and some of which are a result of EU needs and requirements. The following topics provide an overview of the most important issues related to regulatory drivers.

EU Regulatory Environments for Power Transmission

A 2004 survey among eight leading financial analysts conducted by the EURELECTRIC Network of Experts in Finance & Economics on the regulation of the European electricity sector looked at the different regulatory environments in Europe. It gave the following results.

	Best	**Worst**
Highest clarity	UK, Italy	Germany, Greece
Consideration of all stakeholders	Italy, Finland	Austria (favours distributors) Italy, Portugal (favours generators)
Transparency	UK, Italy	Belgium, Sweden
Incentives for	Finland, Italy,	France, Spain

participants	Netherlands	
Incentives for cost reduction	UK, Italy	France
Length of price control period	UK, Italy	Belgium, Greece, Sweden

Financial Risks for Investors in Regulated Transmission Systems

The financial risks in regulatory systems include the following.

- In many countries regulatory price controls are set for five-year periods, whereas loans required to fund investment projects are taken out for much longer time frames. If the rates of return are not sufficiently adequate, the transmission system operators (TSOs) could face difficulty in raising the required funds.
- Credit ratings of stand-alone transmission companies often fare better than companies that are subsidiaries of integrated players. Stand-alone transmission companies have a clear focus on transmission, regulated rates and have visible separation from other potentially volatile segments of the industry (eg. generation and supply). They are also immune to the credit issues which can affect integrated multinationals, who may be seen to be pursuing over-aggressive expansion in other markets.
- Europe's transmission companies have a mix of ownership - some are state owned while others are private or subsidiaries of integrated companies. Public companies may be able to access equity as well as debt markets for capital, but state owned enterprises have more limited access to capital markets that can restrict investment plans.
- Underground cable projects are more expensive up front than OHL. Grid companies will have a natural concern that regulators will be reluctant to allow full recovery of the higher incremental costs from customers. Also investment projects are not "ringed fenced" from a regulatory perspective. The projects are added to the "regulated asset base". In these cases, it is important for regulators to be persuaded of the consumer benefits of certain higher cost options, such as where underground cables assist in unblocking local protests against a new transmission project
- The economics of investment into new long distance transmission infrastructure have to be weighed against the alternative of building new generation capacity. The lengthy consents process for new lines can often mean it is more attractive to build new power plants, even if this is not the optimum solution.

Overview of EU Transmission Regulation

The principles for regulatory control and financial reward for infrastructure investment were established by the European Council of Energy Regulators in a March 2003 paper, "Principles of Regulatory Control and Financial Reward for Infrastructure". The paper established eight principles:

- Governments should encourage investment in electricity transmission infrastructure to implement the internal energy market, facilitate efficient competition and safeguard security of supply. Public authorities should maintain oversight of infrastructure decisions in order to promote both security of supply and network efficiency;
- Transmission system operators (TSOs) must manage their networks in an efficient manner;
- Public authorities should establish transparent, non-discriminatory and standardised options for the development of infrastructure and aim as far as possible to minimise regulatory risks;
- Public authorities should enforce a procedure for the publication of TSO infrastructure plans;
- TSOs must be effectively unbundled to ensure that there is no conflict of interest when making investment decisions and to ensure there are sufficient incentives to provide fair third party access;
- Public authorities should establish the regulatory regime for national and cross-border investments. Merchant infrastructures should be decided on a case-by-case basis and should continue to be subject to ex-ante regulatory control;
- Public authorities should guarantee that procedures applicable to granting required licences for new investment in electricity networks are non-discriminatory and efficient;
- Swifter, more expeditious administrative authorisation procedures are required for infrastructure development, particularly those for interconnection infrastructure.

Regulatory regimes

Regulatory regimes have intrinsic biases in their effects on the firms being regulated. To overcome these effects, regulators and other stakeholders need to carefully manage the process to avoid imposing perverse incentives on the companies. There are two broad methods for regulation - "Rate of Return capping" and "Retail Price Index - X" (RPI-X).

- With Rate of Return regulation, the firms that own transmission systems are allowed a given rate of return on their investments. Without checks and balances, this could incentivise companies to invest heavily to increase absolute levels of financial returns. If checks are insufficient, firms may be tempted to gold plate projects, maximizing invested capital whilst not necessarily giving the most efficient and cost effective infrastructure. Value for money guidelines are required to manage this.

- With RPI-X, firms are regulated on their transmission service charges, which are allowed to rise with inflation minus a factor of "X". This regulatory method is very effective for controlling prices, but may incentivise firms to underinvest in order to control their costs. This means, for example, that cheaper inefficient equipment may be procured, as the cost of losses is bourne by generators and customers. Controlling this issue requires enforcement of quality standards.

Another issue for regulators is that in certain circumstances, it may be advantageous for firms to maximize their allowable annual operating expenditure within their regulatory regime, as these yearly expenditure allowances can offer a useful cashflow boost if the measures they are intended for can be delivered for less cost than originally agreed. When this underspend becomes apparent, the regulator will usually demand a transmission tariff adjustment to compensate consumers for the higher than required up-front payment. However this recovery may take place in the next control period, giving a useful cashflow advantage to the operator. There are reputational risks for operators who make a habit of over-estimating opex for this purpose, and regulators are very sensitive to requests of this type.

The Trans-European Energy Networks Programme

The Trans-European Energy Networks (TENS) programme provides about €25M per year to assist feasibility studies into cross-border power and gas transmission projects. This work is intended to create stronger cross border power trading in pursuit of internal markets, introducing competition and generating best pricing with reduced regulatory requirements. The work is an extremely important part of the European Commissions drive to ensure that European consumers have access to more reliable power at better prices.

The investments required to drive this are predicted in the table following:

Projected Investment in Priority Axes of TEN-Energy for Electricity

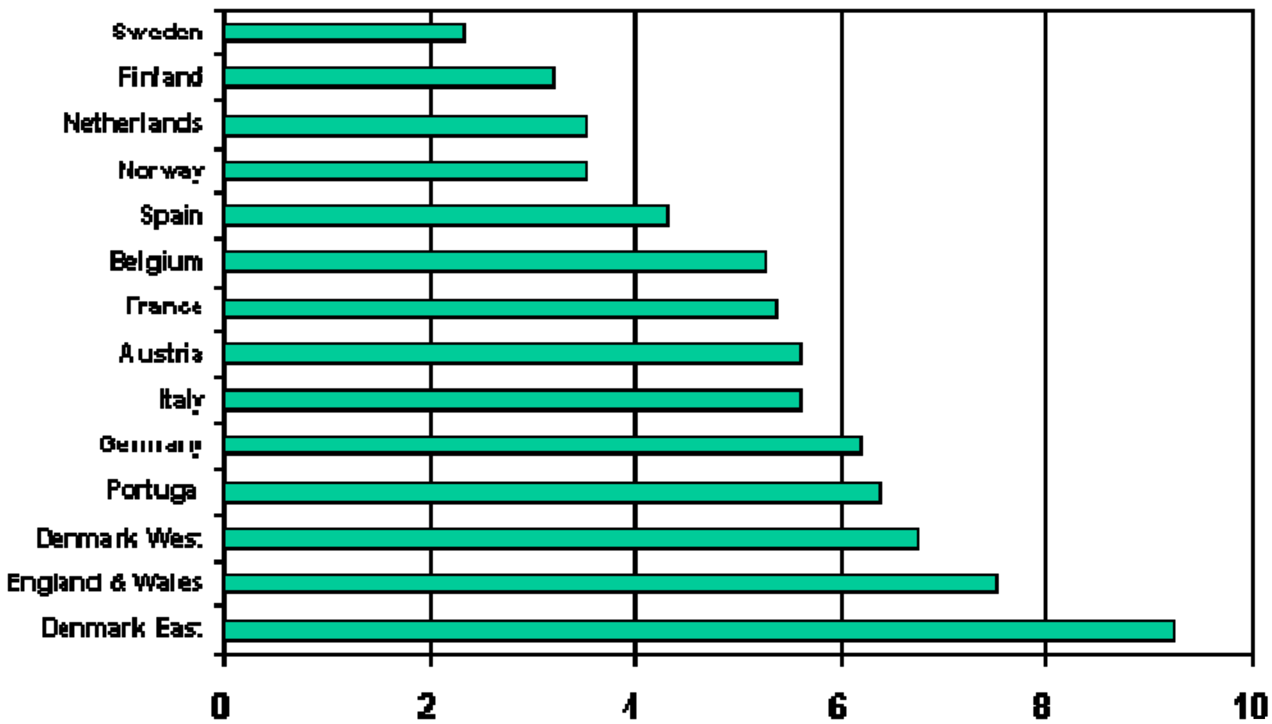
	Priority Axis	**Additional Transmission Capacity MW**	**Investment €m**

EL 1	France-Belgium-Netherlands-Germany	2500	300
EL 2	Italy Borders	4000	600
EL 3	France-Spain-Portugal	3000	400
EL 4	Greece-Balkans-UCTE	2000	100
EL 5	UK-Continental Europe	2000	1,100
EL 6	Ireland-UK	500	300
EL 7	Baltic Ring	3000	700
EL 8	Central Europe	3000	500
EL 9	Mediterranean Ring	3000	1,000
Total		23000	5,000

Transmission Costs Across Europe

Transmission costs experienced by consumers vary with the age of the infrastructure, the cost of maintenance and upgrades and the allowable financial return to the transmission system operator. Transmission costs vary widely across Europe and some examples are given below:

Transmission Costs in Euros/MWh



2.3. Investment Behaviour and the Cost of Project Delays

The environment within which a transmission system operates, evolves and grows is a result of the interaction between the regulator and the companies that own and operate the system. The regulatory framework is designed to push for changes, drive down costs and allow investment in new infrastructure or practices that allow cost reduction or reliability over the long term.

The financial structure of the transmission system operator has an effect on its investment behaviour and differs mainly according to whether the company has a high or low proportion of debt. Debt must be serviced from current cashflows, while equity borrowing has to be paid from dividends and need not be paid in certain circumstances. The company will be likely to invest in different projects according to this relative cashflow requirement. For example, more highly geared companies (i.e., those with a high proportion of debt which must be serviced) might be more likely to make higher risk-higher return investments, while operators with low debt levels are more likely to be satisfied with lower but safer returns.

One of the issues that transmission system operators face is how to balance potential financial returns from a project against the costs of delay if there are public protests against proposed routes. The costs of delay include lost revenues to system operators, due to transmission capacity not being in place, and possible regulatory penalties if delays cause transmission quality to drop, for example if the system starts to experience more faults due to overload.

Costs to industry and consumers from poor quality or supply interruption can also be significant and regulators will be interested in minimising these costs also.

In certain circumstances, operators can find that putting some sections of a project underground can help to unblock local opposition, allowing a project to proceed much sooner than if a judicial process is used to force a 100% overhead line approach. The savings from avoided delays can be significantly larger than the incremental costs of underground cables. However, transmission system operators must be able to prove these cost savings in making their case for investment to the regulator.

3. Underground Cable Case Studies

Underground cables have been employed in a range of situations to assist power project developers to overcome local problems. For example, shielded underground cables carry power through urban areas where overhead lines would be technically unfeasible or an unacceptable intrusion. In some cases, the hidden nature of cables has protected areas of outstanding natural beauty, such as the Vale of York in the UK or the Gudena Valley in Denmark. In other cases, cables have been substituted for overhead lines in order to allow new developments to work properly, such as at the new Madrid Airport.

View the following case studies for specific examples of where cables have been used effectively.

Case Study 1: Use of Cables in Areas of Outstanding Natural Beauty

The Denmark Aalborg - Aarhus line/cable is a classic example of the use of cables to protect areas of outstanding natural beauty.

To reinforce the 400kV network in the western part of Denmark, Eltra built a 140km link between Aalborg and Aarhus. The line, with a capacity of 1200MW, is mainly overhead but is buried in three sections in areas considered to be of scenic or ecological interest:

- Southwest of Aalborg, a 7km section was put underground in an urban area but also one of historical significance.
- Further south, the 150kV overhead line that crosses the Mariager Fjord was dismantled and 2.5km of 400kV and 150kV cable was laid.
- Still further south, a 4.5km section passing through the Gudena Valley was placed underground as OHL was not considered appropriate through a picturesque area of lakes and wooded hills.

The cables used were aluminium with a conductor size of 1200 m2 and were arranged in a double circuit in a trench at a depth of at least 1.2 meters.

The total cost of the project was around €140m. The underground part represents about 10% of the total length and is estimated to have cost €35m (25% of the total). The project took 11 years of political negotiations, but only one year to engineer and two years to construct.

Case Study 2: Cables Enable Development of Valuable Project at Madrid Airport

Madrid's Brajas Airport is Europe's main airport for flights to Central and South America. When AENA, the Spanish airport authority, put in place a $3.5 billion project to double capacity up to 79 million passengers a year, three new runways were an integral element of the plan.

However, an existing 400 kV overhead transmission lines crossed the line of the runway. The transmission lines, owned by REE, Spain's main Transmission System Operator, were a key element of the grid serving the city of Madrid.

The importance of maintaining a stable supply to the capital meant the reliability and capacity of any solution was of the highest importance. The only technically feasible and cost effective solution was to replace the lines with 13 km of 400 kV cables in a tunnel under the new runways, with three parallel single core XLPE cables, each with a conductor cross-section of 2,500 mm^2.


400 kV XLPE 1x2500 mm²
Red Eléctrica de España for "Barajas" airport - Madrid

Case Study 3: How Protests Can Delay Overhead Line Projects

The overhead line (OHL) transmission project through South Burgenland to Kainachtal (Steiermarkleitung) was proposed to transmit power between surplus generation in the north of Austria and consumption in the south. In addition, the project would have assisted in the European TENS programme to create a European-wide transmission grid. The project was designed to be 100% overhead lines and provoked considerable and ongoing protest:

- 1984 - Plans for the 90km 380kV line first mooted by Verbund
- 1988 - Opposition from municipalities commenced
- 1996 - Local referendum (51% of the eligible voters participated) and 93% opposed the OHL
- 1996 - Ministry of Economic Affairs commission expert opinions from Prof Edwin (Aachen) and Dr Glavitsch (Zurich) into the need for the line and Dr Kunze (Vienna) regarding EMFs. All concluded that the line should proceed
- 1997 - Styrian Provincial government commissions four expert reports to assess the importance of the project for the province
- 1998 - Expert reports presented, overall conclusion was "not to prevent the construction of the line," however an additional expert opinion was sought looking into alternatives to the 380kV line
- 2001 - Twenty-seven local communities agree to act in solidarity against the line
- 2003 - Regulator and Economics Affairs Minister (Bartenstein) call on the missing link to be completed; Verbund signs agreements with Steweag-Steg and Bewag to act as "partners"
- 2004 - Mayors of local communities submit 1,500 objections to the line
- 2004 - Environmental Impact Assessment (EIA) including 26 sub-reports carried out
- 2004 - Hearings into the proposed line and Styrian government asks Ministry of Economy to re-study link with a 20km underground section
- 2005 - OHL proposals contained within the EIA deemed environmentally friendly by authorities in Burgenland & Styria, but prescribe 160 conditions that must be met. One-hundred-forty-nine appeals lodged against the decision. Final decision from Environmental Senate is expected at the end of 2006.

Case Study 4: Cables Enable Reinforcement of the Grid in a Built-Up Area

When the UK's National Grid Company needed to provide extra power into North-West London to meet growing demand, it was not possible to provide the transmission capacity using overhead lines as such lines would require both extremely large towers and a wide right-of-way along a route that was already heavily developed. The alterative was to install underground cable in a tunnel, which would allow the project to run with very little above ground disturbance.

The final design involved a 20 km long tunnel running from Elstree in Herfordshire to St John's Wood in North London at a depth of around 20-30 meters below ground level - although the maximum depth is around 80 meters in one stretch. The tunnel has an internal diameter of 3 meters and contains a single circuit run of 400kV XLPE (cross-linked polyethylene) cable, the cable alone weighing almost 2,500 tonnes. The cables are maintained and inspected via a monorail-mounted inspection system. To future proof the project, the tunnel was built with capacity to hold another cable circuit. The project included seven head house buildings along the cable and two new transformer substations at each end and had a budget of £200M. The project started in March 2000 and was commissioned in September 2005.

In addition to using modern tunnel boring technology to offer almost no disruption to people above the tunnel line, the project also employed advanced monitoring and planning techniques to ensure that there were no collisions between the boring equipment and existing infrastructure.

Areas where care had to be taken included Staples Corner, where road bridges on the M1 have deep foundation pilings and existing utility structures such as the Thames Water Ring Main, a major sewer system and existing electricity cables.

The project forms an important part of the London Connection Project, which is intended to reinforce power transmission into London. Much of the existing 275kV infrastructure is coming to the end of its life and is undersized for projected demand. Progressively overlaying and replacing the 275kV lines with 400kV lines and cables will significantly improve capacity whilst maintaining continuity of supply to the UK capital.

The success of this project has prompted adoption of a similar unobtrusive tunneling approach that will be used to install a second 400KV cable circuit in the UK between Rowdown and Beddington in 2010.

Case Study 5: Building a Business Case for Power Projects in Sweden

Svenska Kraftnät, the national transmission grid system operator for Sweden, in 2005 presented its plans for redeveloping the transmission network in and around Stockholm, which supplies around 20% of the Swedish population with power. These plans were prepared from the point of view of a long term and social benefit-based business case, examining issues such as quality of supply, environment, social and local development issues.

To prepare the business case properly, Svenska Kraftnät involved local government and local transmission network operators in a detailed examination of:

- Systems performance
- Effect of transmission infrastructure on land use
- Impact of power lines on social amenity
- Presence of sensitive receptors such as schools and private dwellings
- Effect of transmission lines on the natural landscape

These attributes of different system options were evaluated against three scenarios to ensure the best spatial and load match:

- Present day infrastructure and present day loads
- An evolution of the present day infrastructure supplying the predicted demand patterns for 2030
- A comprehensively redesigned network and 2030 demand patterns

The system options were designed in each case to be able to manage all (n-1) faults and some (n-2) faults.

How Transmission Systems Deal with Failures

A power transmission system must be able to supply power reliably under all conditions of demand on the network:

- Summer peak load;
- Summer off-peak load;
- Winter peak load;
- Winter off-peak load;

The N-1 criterion expresses the ability of the transmission system to lose a linkage without causing an overload failure elsewhere. The N-2 criterion is a higher level of system security, where the system can withstand any two linkages going down. Details that accompany the N-1 and N-2 criteria give further information on the robustness of the system.

An N-2 safety criterion may, for example, involve additional feed in points from lower voltage networks to provide reserve supply, so the low voltage network itself acts as a power conduit. Additional criteria may include a requirement for load shedding - knocking off certain large power consumers to maintain supplies for the rest of the network and rescheduling of generation - bringing on generation units at short notice that normally would not be used.

4. System Reliability

We tend to only notice electricity when it isn't available, such as when our central heating and water heating systems, clothes washing, or entertainment fails in our homes due to a power outage.

When power is unavailable over a wider area, much more serious impacts can occur. For example, water supplies held in treatment plants without access to standby power can be threatened. For industrial users deprived of power, research has shown that the economic value of a lost kWh of electricity may be orders of magnitude higher than its purchase price.

Grid operators work very hard to ensure continuity of supply. Choose from the topics below to learn more about system reliability:

4.1. Reliability of Cables and Lines

A power transmission system must reliably deliver power of a given quality to all parts of the network. There are high economic and social costs if this is not possible. For example, grid outages may mean that commerce must close down unpredictably, leading to missed deliveries, lost batches or damage to equipment that cannot take shutdowns - such as glass furnaces. To manage unreliability, industries may need to maintain their own standby sources of power, which are costly and reduce competitiveness.

Performance standards ensure that power transmission systems are very tightly controlled. Choose from the topics below to learn more about the N-1 criterion for system reliability and how systems cope with failure.

How Transmission Systems Deal with Failures

A power transmission system must be able to supply power reliably under all conditions of demand on the network:

- Summer peak load;
- Summer off-peak load;
- Winter peak load;
- Winter off-peak load;

The N-1 criterion expresses the ability of the transmission system to lose a linkage without causing an overload failure elsewhere. The N-2 criterion is a higher level of system security, where the system can withstand any two linkages going down. Details that accompany the N-1 and N-2 criteria give further information on the robustness of the system.

An N-2 safety criterion may, for example, involve additional feed in points from lower voltage networks to provide reserve supply, so the low voltage network itself acts as a power conduit. Additional criteria may include a requirement for load shedding - knocking off certain large power consumers to maintain supplies for the rest of the network and rescheduling of generation - bringing on generation units at short notice that normally would not be used.

The N-1 criterion for power transmission

A power transmission system must be able to supply power reliably under all conditions of demand on the network:

- Summer peak load;
- Summer off-peak load;
- Winter peak load;
- Winter off-peak load;

The N-1 criterion expresses the ability of the transmission system to lose a linkage without causing an overload failure elsewhere. The N-2 criterion is a higher level of system security, where the system can withstand any two linkages going down. Details that accompany the N-1 and N-2 criteria give further information on the robustness of the system.

An N-2 safety criterion may, for example, involve additional feed in points from lower voltage networks to provide reserve supply, so the low voltage network itself acts as a power conduit. Additional criteria may include a requirement for load shedding - knocking off certain large power consumers to maintain supplies for the rest of the network and rescheduling of generation - bringing on generation units at short notice that normally would not be used.

4.2. Failure Case Studies and Correction

Overhead lines and underground cable systems have failed in the past for different reasons. While early examples of both types of systems failed due to less comprehensive understanding of the technology, both systems have solved these problems. Failures specific to each type of system include the following:

The principal failure mechanisms for overhead lines include:

- Human accidents: aircraft, vehicle and direct personal contact
- Weather-related damage: excessive wind loading and ice loading

- Tree fall: damage to lines from falling trees

The principal failure mechanism for modern underground cables include:

- Human disturbance of the ground

Underground high voltage power cables are now not prone to damage from water and defects in cable joints, while high voltage overhead lines are less prone to metal fatigue and collapse.

To learn more about cable and line failures, choose from the topics below:

Case Studies and Impacts

Over the last few years, Europe and the US have experienced a number of significant power blackouts caused by transmission failure. The reasons for these failures are summarised below.

Where	**When**	**Were Overhead Lines or Cables a factor?**
Germany	Nov 2005	**Overhead lines**. On 25 November, around 120,000 consumers in the Munster region in Germany suffered four days without electricity after around 50 pylons on the 220kV and 110kV network collapsed in the wake of a heavy snowstorm. Some local communities were without power for a week
Italy	Sept 2003	**Overhead lines**. Tree fell across 380kV line in Switzerland causing initial disruption. Italian system became isolated and overheating of conductors on 380kV line (Sils-Soazza) in Italy led to sags in the line which led to contact with a tree and trips of generation plant. Recommendations include better right-of-way maintenance practices
Copenhagen	Sept 2003	**Neither**. Valve problems at nuclear power plant in Sweden led to its shut down. Other plants increased production but busbar failure at substation led to four 400kV lines being disconnected. This led to shutdown of other nuclear plant and a shortage of power in southern Sweden and eastern Denmark
North East USA/Canada	Aug 2003	**Overhead Lines**. Started with a tree flashover on 345kV line. There were 3 other factors but inadequate vegetation management re: tree pruning and removal a key reason
London & Birmingham	Aug/Sept 2003	**Neither**. These were due to problems with recently commissioned protection equipment at sub-stations. Maintenance procedures questioned
France	Dec 1999	**Overhead Lines**. Lines damaged by falling trees. Also many pylons were not able to withstand very high wind velocities. Investigation into the incident recommended increasing pylon wind velocity resistance from 150/160 km/hour to 160/170 km/hour. Accord between EdF, RTE and the government also agreed to underground 25% of future HV lines (63kV-150kV)

Auckland	Feb 1998	**Underground Cable**. Contractor cut through a 110kV UGC and three others had failed due to aging cables (two of which were over 50 years old) and high ground temperatures. Power was out for up to 7 weeks

Failure Statistics for Overhead Lines and Underground Cables

The best way to compare underground cables with overhead lines is through the availability of the system to transmit power. The UK National Grid published statistics that show non-availability of 0.126 hours per year per kilometer of 400 kV overhead line, compared with 6.4 hours per year for its 400 kV underground cables, some of which are old oil-filled lines. The international average for 400 kV cables appears to be around 3.4 hours per year. This reflects the fact that although cables suffer interruptions much less frequently than overhead lines, they do take longer to put back into service. However, despite difficulties claimed for repairing underground cables, cables in service are still available for 99.96% of the time.

Underground power cables are up to 90 percent cheaper to operate than overhead lines as they are out of reach of many of the accidents that can befall overhead lines. However, underground cables have much higher costs when a fault does appear.

Hydro Quebec estimated that a minor fault for an underground cable takes about five days to repair, compared with one day for an overhead line, whilst a major cable repair will take 20 days compared to 7 days for an overhead line.

Storm, Weather Damage and Accidents

Two major benefits of underground cables are that they are not susceptible to storm and icing damage and are far less likely to cause death or injury due to accidental contact with the lines/cables.

Minor storm damage to overhead lines across Europe is only a frequent event for low/medium voltage lines, as lines on the taller 400kV pylons are safely out of reach and the pylons are much more sturdily constructed.

When people come into accidental contact with overhead lines, the implications are extremely severe. Information from France shows that there were 19 deaths due to contact with overhead lines in France in 2000 compared to no deaths for contact with underground cables.

4.3. Technical Improvement

As transmission system operators have sought further solutions to assist them with their transmission projects, both cable and overhead line manufacturers have developed new solutions designed to improve the flexibility of their products and to reduce costs.

For overhead lines, the principal issue has been to improve the strength of towers whilst reducing the visual impact. For underground cables, the drive has been to reduce costs and to ensure that reliability expectations are met.

Advances in materials have ensured that the low cost potential of XLPE insulation materials in underground cable systems has been available in a reliable form for many years. Consequently, the key issues that transmission system operators have to consider are associated with maintenance and the detection of faults.

Choose from the topics below to learn more about how cables contribute to lower overall system maintenance and how new cable technology allows faults to be rapidly and precisely located and repaired.

Detecting faults

Modern underground power cables are sophisticated assemblies of insulators, conductors and protective materials. Within these components are temperature sensors, which enable cable operators to monitor conditions along the cable in real time.

An optical fibre is built into a protective metal wire and that metal wire is then incorporated into the normal "screening" of the cable - the outer winding of copper wires that prevents electric fields from being transmitted outside of the cable.

Optical fibres are extremely sensitive to temperature and measurable changes to the light transmitted are used to detect the temperature along the light path. Modern sensing techniques mean that the temperature along the fibre can be measured with a resolution of around a metre. Therefore, any factor that increases the cable temperature can be rapidly detected, including human disturbance, changes in the soil around the cable, damage to cable insulation, etc.

Installation

The use of new high performance materials, such as cross-linked polyethylene (XLPE), has allowed cable manufacturers to produce thinner, more flexible cables for a given electrical service. These cables can be produced, shipped and handled in longer lengths and are easier to handle during installation. This reduces manufacturing and installation time and costs because of longer production runs, reduced number of shipments, fewer cable joints and improved handling during installation.

Cables can be installed using a range of techniques, allowing costs to be controlled and installations to be engineered to suit the environments and risks that they face in service.

- Mechanised trench laying methods avoid extensive excavations and transport of material
- Trenchless methods of cable installation, such as thrust boring and directional drilling, reduce time installing cables around other infrastructure, such as motorways and railway crossings, or in sensitive rural areas where existing habitats must remain undisturbed
- Installation of cables in mini tunnels allow the use of longer cable lengths that save on joints, installation time and costs

The engineering around the cable can also be optimized to provide special levels of protection to the cable and to the surrounding environment. For example, in rural areas it my be appropriate for the cables to be direct buried in a trench, with labeling above the system only to warn farmers and constructors from inadvertent disturbance to the cable and its surrounding.

In the urban environment, where construction and utilities maintenance is a constant disturbance hazard, cables may be laid in concrete ducts with concrete lids. Lastly, the cable trench or conduit system may, in certain cases, be surrounded with metal shielding structures to ensure that minimal magnetic fields are emitted in service.

Maintenance

Transmission networks, as engineered systems, can be maintained according to regimes with different levels of sophistication and corresponding implications for effectiveness and reliability (after P Birkner, 17th CIRED International Conference on Electricity Generation, 2003).

- Low sophistication: Corrective maintenance that will only react when failures occur
- Basic: Time-based maintenance or preventive maintenance of devices within fixed time periods
- Advanced: Condition based maintenance based on the results of a self-monitoring or a diagnostic system
- Sophisticated value-led: Reliability-centred maintenance that takes into account the functional importance of the device regarding service availability as well as its condition

When examining the record of modern cable-based systems, the key innovations in cables that have improved reliability and reduced the need for costly maintenance procedures are associated with jointing the lengths of cable together. These improvements have allowed transmission systems to receive benefits from the increased current-carrying capacity of cables. When an area of an overhead line network needs repair or essential maintenance, having cables in strategic areas of the system can assist in re-routing power to ensure continuity of supply.

4.4. Testing and Development

Underground high voltage power cables are high value systems and manufacturers subject them to stringent testing regimes to ensure that components have been manufactured and joined together correctly.

Choose from the topics below to learn more about the standards and facilities applied to test cables:

Pictures of Testing Facilities

Ultra high voltage testing equipment

On-site testing of a power cable

Testing Standards

High voltage underground power cables must be tested in accordance with the standards of the International Electrotechnical Commission (IEC), which sets specifications for electrical equipment and systems. The IEC provides a framework for international discussion and collaboration, from which agreed upon standards emerge for use in national specification systems and procurement.

The standard for testing of underground cables and systems is IEC 62067:

IEC 62067 (2006-03): Power cables with extruded insulation and their accessories for rated voltages above 150 kV (Um = 170 kV) up to 500 kV (Um = 550 kV) - Test methods and requirements

The standard can be purchased from the IEC.

The standard identifies that a high voltage underground power cable is a heavily integrated system and that the components cannot be meaningfully tested in isolation from each other. This requirement means that cable manufacturers have invested considerable sums to ensure that cables and components are not only tested before dispatch, but that they are also effectively tested at each stage of installation.

5. Life Cycle Module

Underground cables cost more per kilometer than overhead lines, but are a valuable solution where overhead lines are unacceptable. Europacable has published a position paper explaining its views on where the higher costs of cable should be accepted in power projects.

However, there is a considerable confusion about exactly how much more cable costs. When thinking about a power project, you must consider the costs over the life cycle of the system installed as well as the up front costs:

- The up front cost is paid in the first instance
- The life cycle cost includes not only the up front cost, but also the costs of maintenance and cost of power losses in the system over time

Efficient systems of any kind usually cost more up front, but save money in the long term. This module seeks to explain this situation for cable projects.

Choose from the options below to learn more about the life cycle of underground cables:

5.1. Installation Costs

Cables are more expensive than overhead lines, but given that cables are a developing technology, it is intuitive that costs to install cables will reduce faster than those for long-established overhead line technologies.

Cables also require less land than overhead lines, and as land becomes more valuable, the effect of value lost in providing portage for lines will have an increasingly beneficial effect on the overall cost of cable projects.

Europacable produced a position paper describing where and how much of a role cables should play in transmission projects. Europacable advocates that life cycle costs should be considered when analysing the relative costs of cable and overhead lines.

However, even when considering just the up front costs, there is considerable disagreement in the analysis available:

- A recent report by Eurelectric indicates cost ratios between cable and lines of 10-25 to 1
- “Undergrounding of Extra High Voltage Transmission Lines

Relative Cost Figures

The table below illustrates various claimed installation cost ratios between cables and lines.

Country	220kV Cable vs. Overhead Line	380kV Cable vs. Overhead Line	Source of Data
Austria – Verbund APG	-	8	Hearings into proposed Styria line
Denmark – Eltra	4.0	4-5	Aarhus/Aalborg line/cable
France – RTE	2.2-3	10	RTE website
Germany	-	10-20	Eurelectric report on public acceptance of new OHLs
Ireland – ESBNG	6-10	-	EIA into proposed new line
Italy - Terna	5.5	5.9	Regulator
Netherlands – Tennet	-	6	Paper comparing costs for ICF
Norway – Statnett	4.5	6.5	Stattnett website
Spain	-	25	REE website
UK – National Grid	-	15-25	National Grid website & brochure
ETSO	-	10-12	Paper on undergrounding

Relative Costs When Life Cycle Issues are Included

Comparing basic up front costs between cables and OHLs:

Cabled section length (km)	5	10
Capex/km XLPE cable €k[1]	9,678	8,845
Capex/km OHL €k	1,522	1,522
Cost ratio – cable cost ÷ OHL cost	6.4	5.8

When different life cycle factors are included in the 5km example:

Life cycle costs for 5km sections	XLPE ÷ OHL
Discounted present cost at 3% discount rate (DPC)	6.4
DPC including maintenance & decommissioning	6.1

DPC including maintenance, decommissioning & losses	4.0

5.2. Transmission Losses

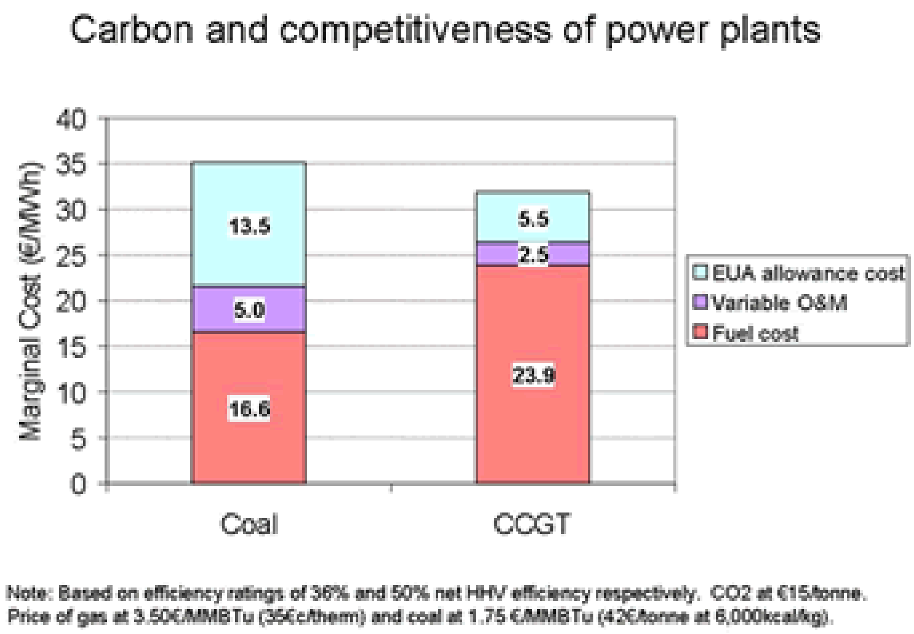
Transmission losses are the power losses in an electrical system and are typically around 5-7% of the total power put into the system. Transmission losses represent a loss in value and an increase in fuel burn and environmental impact, as every MWh of power that is generated but cannot be sold costs money.

Transmission losses are caused by:

- The electrical resistance of the conductor lines (accounts for 5% losses or 147 million MWh)
- Converting the power between high voltages used for long distance transmission and safe low voltages used in most industry and the home (accounts for 2% losses or 55 million MWh)

In Europe, the resistive loss in transmission lines alone represents the waste of around 20 million tonnes of coal, 3.1 million tonnes of gas and 1.7 million tonnes of oil. The annual loss in value is around €12 billion. The annual increase in greenhouse gas emissions is around 60 million tonnes of CO_2 per year.

In some countries, older transformer infrastructure and lines can yield losses as high as 21%. To learn more about these older systems, visit the website of the UNEP Risoe Centre on Energy, Climate and Sustainable Development (URC), which has a useful paper explaining issues associated with Indian power infrastructure.



The cost breakdown of a delivered MWh of CCGT power

5.3. Planning Delays

Transmission companies can assist in delivering against national environmental and economic targets by solving delays to power projects through application of underground cables in problem areas.

Linking in remote wind power can depend on a single high capacity transmission project. If renewable power is not available, fossil fuel stations must be run to satisfy demand.

The International Energy Agency estimates that by 2020, 137GW of new power generation capacity will be needed in Europe, including 51GW of wind power. These wind projects offer a considerable quantity of emissions-free energy.

Delaying Wind Power in the UK

In the UK, high quality wind resources lie off the western coast, remote from consumers. The UK has an ambitious wind installation programme with about AAAMW of capacity being installed every year on average.

Wind power installation depends on transmission capacity being available to take the power. The economics of wind energy are supported by a green certificate scheme called the renewable obligation.

Every MWh of wind energy is given a certificate, which is worth around €65. A year's delay in starting delivery of 1GW of wind capacity means that:

- Renewables generators miss out on certificate revenues as high as €150M and power revenues as high as €130M.
- UK fossil fuel generators will have to emit as much as 1 million tonnes of extra CO_2 at a cost of €15-€25 million in purchased emissions allowances.

The UK power sector has a target to reduce 5.5 MT of CO_2 in phase I of the EU ETS and a similar, but possibly larger amount in Phase II. A 1MT shortfall represents around 20% of the target and a major gap to bridge with other measures.

5.4. Replacement Cycles

An overhead line is exposed to the elements and depends on the air to remove heat from resistive losses. It is subject to damage from:

- Natural exposure and corrosion
- Fatigue from frequent cycles in temperature as current loads and air temperatures change during the day
- External influences such as excessive wind or ice loads, trees falling or hitting lines, or from accidental human interference

There is nothing that can be done about the problems suffered by overhead lines and the problems are built into a maintenance programme for a line over time. Typically an overhead line cable will be replaced every 15 years, while the towers will have a lifetime of around 40-50 years.

Underground cables are buried within engineered trenches or ducts. They experience no weather exposure and very stable operating temperatures. They are less prone to degradation. However, they are vulnerable to being disturbed by:

- Humans during excavations for buildings or drainage systems
- Ingress of tree roots
- Changes in soil moisture levels leading to overheating

The problems faced by cables can be dealt with through well-developed precautionary measures to minimise the chance of their occurrence. An underground cable is designed to last 40 years, but will probably last significantly longer, making a considerable difference to the life cycle economics of the cable compared with overhead line solutions.