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Underground cables or overhead lines?

Criteria for a technology-neutral, project-specific assessment

by VDE ETG, CIGRE Germany and DK-CIRED

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Recommended citation
VDE Association for Electrical, Electronic and Information Technologies e.V.: Underground cables or overhead lines? Criteria for a technology-neutral, project-specific assessment,
VDE Paper, Offenbach am Main, November 2026.

This VDE Paper is the result of work carried out by the VDE ETG Technical Committee V2 ‘Transmission and Distribution’ with the support of CIGRE Germany and DK-CIRED.

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Publisher:
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Cover image: © Herb/stock.adobe.com

Design: Stefan Mümpfer, Frankfurt

November 2026

Executive Summary

The choice between underground cables and overhead lines is not a universally applicable technological decision, but rather a project-specific assessment. A simple comparison of investment costs is just as inadequate as a blanket preference based on individual environmental, acceptance or resilience criteria. To reach a sound decision, investment and operating costs, availability and reliability, and resilience to external events must all be taken into account. To this end, the system boundaries, the voltage level, the voltage type (alternating current (AC) or direct current (DC) technology), the route conditions and their public acceptance, the expected commissioning date and the weighting of non-monetisable effects must all be considered together.

Overhead lines generally feature lower capital costs, extensive operational experience, good accessibility and comparatively direct repair routes. Underground cables offer minimal long-term visual impact, protection from direct weather conditions and, in certain project scenarios, advantages in terms of public acceptance and planning risk. These advantages are offset by more extensive land use during the construction phase, higher material and civil engineering costs, and more complex fault location and repair procedures. In the case of partial cabling and mixed systems, the additional transition assemblies, terminations and protective functions must also be taken into account as potential common points of weakness in the overall system.

The preferred option is determined by a project-specific overall assessment of the regulatory framework, technology, resilience, environmental impact and cost-effectiveness.

Regulatory framework

The choice between overhead lines and underground cables is made within a specified regulatory framework. Whilst technology-neutral assessments are generally possible for extra-high-voltage projects, statutory requirements – particularly for new 110 kV routes – may restrict the choice of technology. Technical, economic and regulatory constraints must therefore be assessed jointly.

Construction and Operation

Overhead lines and underground cable systems are technically mature transmission solutions. The differences lie primarily in system complexity, operational experience, thermal management, losses, and protection and operational management concepts. Partial cabling schemes must be assessed as a separate system variant with additional technical interfaces.

Reliability, maintenance and repair

The availability of a transmission system is largely determined by fault location, repair time and the ability to restore service. Underground cables offer advantages in terms of exposure to external influences, whilst overhead lines often offer advantages in terms of fault detection, access for repairs and recommissioning in the event of locally confined damage.

Environmental and social impacts

Environmental conflicts cannot be resolved by a general preference for overhead lines or underground cables. The environmentally preferable option depends on local conditions, the protected resources affected and the long-term impacts of the project.

Economic efficiency

Economic decisions should be based on life-cycle and system costs, and not exclusively on capital costs. Economic viability depends in particular on the voltage level, technology, losses, maintenance, service life, project progress and potential delays, and cannot be assessed in general terms in favour of one technology over another.

1. Status quo and regulatory framework

The German transmission network continues to be dominated by overhead lines. The following table shows the circuit lengths in km for the various voltage levels and technologies. For the 110 kV level, a sharp increase in the proportion of underground cables is also noted.

Level		**Overhead line**	Underground cable	Trend
Extra-high voltage	380 kV	approx. 31,000 km	approx. 400 km	Overhead lines: moderate increase; underground cables: no change
	220 kV	approx. 6,000 km	approx. 600 km	Overhead lines declining; underground cables unchanged
High voltage	110 kV	approx. 82,000 km	approx. 12,000 km	Proportion of underground cables rising sharply
Direct current	320 / 525 kV	340 km Ultranet Commissioning 12/2026	approx. 3,500 km Offshore connections	Offshore connections to date: 320 kV DC Onshore expansion primarily with 525 kV DC

1.1. Basic regulatory framework

The expansion of transmission lines takes place within a multi-stage regulatory framework. The first step is the determination of demand based on scenario frameworks and the grid development plan in accordance with the Energy Industry Act. The statutory determination of demand is carried out in particular via the Federal Demand Planning Act (BBPlG) or the Energy Transmission Line Expansion Act (EnLAG). Depending on the type of project, this is followed by the spatial specification and authorisation in accordance with the Act on the Acceleration of Transmission Grid Expansion (NABEG) or the relevant provisions of the Energy Industry Act (EnWG). A specific provision in the EnWG is Section 43h, which stipulates for the 110 kV level that new routes must be laid as underground cables if the cost ratio is less than or equal to 2.75 compared with overhead lines. In addition, the requirements relating to environmental assessment, nature conservation, protection against emissions, water and soil protection, heritage conservation and occupational health and safety must be observed.

1.2. Relevant regulatory frameworks

The individual regulatory frameworks fulfil different functions but are interlinked throughout the course of the project. Whilst the Energy Industry Act (EnWG), the Federal Transmission Grid Act (BBPlG), the Energy Infrastructure Act (EnLAG) and the Network Act (NABEG) primarily structure demand, planning and authorisation, the Environmental Impact Assessment
Act (UVPG), the Federal Nature Conservation Act (BNatSchG), the Federal Immission Control Act (BImSchG), the 26th Ordinance Implementing the Federal Immission Control Act (26th BImSchV), the Water Resources Act (WHG) and the Federal Soil Protection Act (BBodSchG) set out the specific requirements relating to the environment and protected resources. The following table classifies these functions and their relevance to the project.

Regulatory framework	Core function	Project context
EnWG	Grid planning, grid operation and licensing	Grid development planning s and planning approval
BBPlG / EnLAG	Statutory determination of need	Project-specific designations and special rules
NABEG	Planning and authorisation of certain extra-high-voltage power lines	Inter-state or cross-border projects
UVPG / BNatSchG	Environmental assessment, impact, species and habitat protection	Assessment and management of significant environmental impacts
BImSchG / 26th BImSchV	Emissions and electromagnetic fields	Limit values, precautionary meas-ures and evidence
WHG / BBodSchG	Water and soil protection	Particularly relevant for civil engineering, drainage and land reclamation

2. Construction and operation

For high-voltage direct current (HVDC) transmission links, both continuous overhead line and continuous cable systems are available as technically established transmission technologies. The choice is project-specific and must take into account the characteristics of the route corridor, the overarching grid and converter configuration, the political and legal framework, and the requirements for the construction, operation and further development of the system. It is not possible to conclude that either technology is universally superior from a technical standpoint. Partial cabling may represent a project-specific alternative; however, it increases system complexity at every technology interface. Therefore, the use of repeatedly alternating overhead line and cable sections should be avoided in favour of higher availability and reliability.

AC and DC systems must be considered separately: for AC cables, system design is determined by capacity utilisation, reactive power requirements, compensation and the limited operational experience with long extra-high-voltage cable sections. For HVDC, the AC-specific effects on power loading do not apply; at the same time, there is less long-term experience with 525 kV DC cable systems and their associated equipment compared to established AC systems. Partial cabling should therefore not be regarded as a technically neutral compromise, but as a distinct system variant with additional interfaces and protection requirements.

2.1. Basic technological concepts

Overhead lines in high- and extra-high-voltage networks are predominantly constructed using aluminium-steel conductors or comparable composite conductors. In cable systems, aluminium or copper conductors are used, depending on the voltage level, transmission requirements and economic optimisation. Extruded and cross-linked polyethylene (XLPE) has established itself as the state of the art for insulation in high- and extra-high-voltage cables, whilst polypropylene has also been successfully introduced to the market as an alternative material.

Characteristic	HVDC overhead line	HVDC underground cable
Insulation system	Air insulation; temporary flashovers may be self-healing following de-ionisation	Solid-insulation XLPE or PP; faults in the cable or fittings are permanent and require repair
Thermal balance	Heat dissipation to the ambient air; high dependence on weather and conductor cable temperature	Heat dissipation via the bedding and soil; ground temperature, thermal conductivity, moisture content, laying configuration and local constrictions are decisive factors. The higher thermal time constant can be advantageous during short-term load peaks
Converters and protection	Overhead line faults and automatic reclosing (AWE) may trigger additional requirements for converters, choppers, protection and FSD	Permanent cable faults preclude AWE and require selective disconnection, location, repair and testing of the affected section
Transmission losses	In the 600-km example calculation under consideration, 1.5% line losses for 2 x 2 GW	In the 600-km example calculation under consideration, 0.9 per cent transmission losses for 2 x 2 GW
Scalability	Power reserves may be available depending on the conductor cable geometry, converters and system configuration	Subsequent expansion requires pre-planned reserves in the route, substations and cable system
Operational experience	Extensive experience with AC and DC overhead lines in high- and extra-high-voltage networks	Extensive AC experience over short and medium distances; limited long-term experience with long AC and 525 kV DC extra-high-voltage cables and fittings
Resource requirements	Material requirements mainly for conductor cables, pylons and foundations	Higher requirements for materials, civil engineering works and fittings; raw material and supply chain aspects must be taken into account in the system assessment

For AC cables, the high capacitance, the resulting active and reactive power currents, the need for compensation and the thermal current-carrying capacity are key factors in determining the maximum transmission distance that is technically and economically viable. The parallel operation of cable and overhead line sections in AC systems may require additional system studies and operational measures due to the differing electrical parameters and the resulting power distribution. In HVDC systems, the active and reactive power effects characteristic of three-phase systems do not apply. The transmission capacity of HVDC overhead lines and HVDC cable systems is therefore determined in particular by the operating voltage, conductor cross-section, permissible operating temperature, heat dissipation, system configuration, and the design and performance of the converter stations.

The line technology employed has an impact on the converter and protection configuration. Consequently, due to the fault characteristics, overhead line connections are subject to higher requirements in terms of immunity to interference and fault clearance. Depending on the grid topology, full-bridge converters and so-called fault separators may be required. In the case of purely cable-based connections, the fault characteristics are different, as insulation faults in cables and fittings must always be treated as permanent faults. To increase the availability of cable systems, a direct metallic return conductor may be used, so that in the event of a cable failure, the system can still be operated at half power; however, this increases the cost of the cable system.

Underground cables have a higher thermal inertia due to their material composition and laying configuration; however, their long-term load-bearing capacity depends on ground temperature, ground thermal conductivity, laying spacings and locally restrictive sections of the route. Bottlenecks, such as special crossings or sections with different bedding and closer cable spacings, determine the overall load-bearing capacity of the entire cable system. In the event of prolonged high loads, changes in soil moisture and the possibility of thermal drying out must also be taken into account. Condition and temperature monitoring support dynamic operational management, particularly for underground cables as well as overhead lines.

2.2. Route selection and structural design

The route selection depends on local conditions. For the example under consideration, involving 2 x 2 GW, protection and construction widths of approximately 45 to 70 m, as well as pylon heights of approximately 50 to 80 m, are specified for an HVDC overhead line. For the HVDC underground cable, a safety strip width of approximately 30 m and a construction width of approximately 45 m are cited. These values are planning parameters for the system under consideration and do not represent universally applicable minimum or maximum values. As the actual values for the 110 kV AC cables do not differ significantly from those of the HVDC cables, they are not listed separately; however, any major deviations are highlighted.

Overhead line routes require support and guying masts along their length. Cable routes are divided into supply and installation sections and connected via joint groups. For a 525-kV cable system, joint groups are provided at intervals of approximately 1 to 1.3 km, earthing points at intervals of approximately 5 to 10 km, and cable section stations at intervals of approximately 100 to 150 km. Cable section stations support commissioning tests and can be used for fault location measures during subsequent operation.

Planning parameters of the 2 x 2 GW system under consideration	Overhead line	Underground cable
Protective strip width	approx. 45 to 70 m	approx. 30 m
Construction width	approx. 45 to 70 m	approx. 45 m
Line structures	Pole spacing every 0.3 to 0.5 km	Socket groups approximately every 1 to 1.3 km; Earthing points approximately every 5 to 10 km; Cable section stations approximately every 100 to 150 km
Agricultural use	Generally possible, apart from pylon sites and vegetation heights	Generally possible; deep-rooted plants are not permitted in the protective strip
Difficult terrain	Route should be as straight as possible; span fields and pylon locations must be adapted.	Bypasses or special structures, such as HDD boreholes or tunnels
Expected length increase factor	approx. 1.1 to 1.2	approx. 1.2 to 1.4

In difficult terrain, cable systems may require bypasses or special structures such as tunnels and horizontal boreholes. Jointing chambers, cross-bonding installations and cable transition facilities may also affect the approval and construction process. With overhead lines, on the other hand, the aim is still to keep the route as straight as possible. For long routes, cable routes tend to be longer than those for overhead lines. Intersections with other infrastructure require specific assessments for both technologies; in the case of cables, this often involves special structures as well as, where necessary, interventions affecting groundwater and drainage, whilst for overhead lines, clearance distances, pylon locations and potential inter-system faults must be taken into account.

2.3. Operational behaviour, maintenance and repair

Operational considerations	Overhead line	Underground cable
Route inspection	Annually	Annually. Special monitoring of terminations
Primary technology	Sag, thermography, monitoring, pole coating	Monitoring, partial discharges, temperature, elongation, vibration, substations and earthing.
Special structures	None in the comparison under consideration	Tunnels, crossings with other cables and lines – including those carrying other media – river crossings and other special structures require separate maintenance.

The type of insulation determines operational and fault behaviour. In an overhead line, the air gap acts as the primary insulation. Temporary faults, for example resulting from atmospheric overvoltages (lightning strikes), may result in no permanent damage to the insulation following a brief interruption in voltage and de-ionisation, and the line may be automatically re-energised. Mechanical damage, such as a broken cable or damaged fittings, on the other hand, is permanent and requires repair. In the case of cables and fittings, an insulation fault generally results in a permanent fault that must be localised and repaired, meaning that reconnection is only possible once the repair has been carried out.

An annual visual inspection of the route is necessary for both technologies. For overhead lines, the focus is on, amongst other things, profile and sag checks, infrared thermography, conductor and weather monitoring, and corrosion protection of the pylons. For cable systems, the measures relate in particular to cable transition facilities, associated structures, earthing installations and special structures such as tunnels and HDD pipe systems. The monitoring of the cable systems themselves is increasingly carried out using continuous thermal and, in particular, electrical monitoring systems, which both support operations and can detect and locate faults as they develop.

2.4. Maintenance, repair and partial renewal

Maintenance strategies vary in their technical approach. Overhead lines are monitored more on the basis of visual inspection and at fixed intervals. This includes regular inspections of pylons, conductor cables, fittings and insulators, corrosion protection, vegetation management, as well as support from drones, helicopters, sensor technology and site inspections. For cable systems, the focus is on joints, terminations, cable transitions, cross-bonding devices, route protection and condition-based thermal and electrical monitoring. Annual vegetation inspections of the routes are necessary for both technologies. Cable routes must also be kept clear of unsuitable vegetation to allow access and facilitate any necessary repair work; permissible vegetation and the required route width depend on the cable system and the repair strategy. Despite the differences in the activities involved, a similar allocation of resources and budget for maintenance and repair can be assumed.

Maintenance and renewal considerations	Overhead line	Underground cables
Route maintenance	Vegetation management and ensuring necessary clearances	Only shallow-rooted plants in the protection strip; protection of the route against external influences
Primary technology	Profiles and sag, thermography, monitoring and pylon coating	Monitoring of temperature, partial discharges, strain and vibration; inspection of substations and earthing
Special structures	None in the comparison under consideration	Tunnels and HDD pipe systems require separate maintenance measures
Partial replacement	Replacement of conductor cables and, where necessary, suspension arrangements	Sectional renewal of cables and fittings

(Source): [1,2]

Over the entire service life, partial replacements are to be expected for both technologies. For cable systems, partial replacements result from specific local ageing conditions and lead to the complete replacement of the cable and fittings on a section-by-section basis. The replacement of conductor cables and, where applicable, suspension devices on overhead lines is carried out following a condition assessment. For overhead lines, this results in greater flexibility in terms of timing and cost when implementing such work.

For cable systems, optimised spare parts management concepts – such as keeping compatible spare cable lengths and fittings in stock – can support restoration work. Effectiveness depends on system design, manufacturer compatibility, qualified installation teams and available testing technology. Due to the more limited long-term experience with DC extra-high-voltage cables and their fittings, condition data, the suitability of connection technology and the spare parts strategy must be given particular consideration.

2.5. Emissions, Interference and Transmission Losses

With appropriate measures, both technologies under consideration fully comply with the requirements of the 26th Federal Immission Control Ordinance (BImSchV) and the Technical Guidelines on Protection against Noise (TA Lärm). Differences lie in the spatial characteristics of the fields as well as in high-frequency and acoustic effects. In the case of DC overhead lines, electrical fields, ion emissions, corona effects, high-frequency radiation along the route and weather-dependent acoustic emissions must be taken into account. In the case of cable systems, no electric fields occur at the surface; magnetic fields are spatially more concentrated in the immediate vicinity of the route. At converter stations, high-frequency emissions may occur with both variants. Electromagnetic interference from parallel power lines and communication systems must be investigated on a technology- and route-specific basis.

A 600 km overland route with a transmission capacity of 2 x 2 GW is taken as the reference example for this study. For such systems, line losses of 100 to 120 kW/km are calculated for the overhead line and 60 to 80 kW/km for the cable system. In the example calculation, this corresponds to a power loss of 60 MW (1.5 per cent of the total power) for the overhead line and 36 MW (0.9 per cent) for the cable system. The losses of the 2-GW half-bridge converters are assumed to be around 2.5 per cent for both variants and are specific to the manufacturer in detail. For an overhead line solution with full-bridge converters, the converter losses would need to be adjusted separately.

3. Reliability and Repair

The reliability assessment must separately account for fault frequency, fault nature, extent of damage, fault location, accessibility, repair time and network redundancy. Lower exposure to external influences does not automatically mean higher operational availability. Overhead lines are more exposed to storms, ice, lightning, vegetation and other above-ground influences. Underground cables are protected against many of these direct influences, but remain vulnerable to civil engineering incidents as well as faults at joints, terminations and transition assemblies.

Aspect	Overhead lines	Underground cable
Exposure	Storms, ice, lightning, vegetation and above-ground impacts	Largely protected from direct weather conditions; risks arising from civil engineering works, joints, terminations and transition points
Fault location	Protection system and visual inspection, using drones where necessary; Faults are typically located within hours	Protection system, electrical calibration and exposure; depending on the fault, location may take several days. Online monitoring systems also offer real-time localisation
Access	Components accessible above ground; limited site set-up	Exposure, civil engineering works and suitable installation conditions are regularly required
Repair	Selective replacement of fittings, cables or masts; temporary solutions generally possible	Replacement of the affected section of cable and installation of additional joints; specialist teams and tests required
Monitoring	Inspection, drones, sensor technology, sag, temperature and weather data	Thermal and electrical monitoring, partial discharges, strain and vibration; detecting hidden ageing remains a challenge

3.1. Fault rates and operational availability

Fault rates and downtime are known from various studies; however, due to the limited operational experience with 525 kV DC cables, the higher empirical values for 320 kV DC should be used here. For extruded cable systems above 220 kV, statistically validated fault frequencies are available primarily for AC cable systems. Applying these findings to DC cable systems presupposes that comparable dielectric and thermal ageing mechanisms are at work. For DC overhead lines, experience from AC overhead line statistics under comparable operating conditions is also drawn upon. The values derived from this are therefore not project-specific guaranteed values, but reference figures based on the documented assumptions.

The effective repair time for cables is between 20 and 30 days, and for overhead lines it is 2 days. For the assumed model analysis of a 600 km-long route, an availability of 99.1 per cent is determined for the overhead line and 94.6 per cent for the cable system. The difference of around 4.5 percentage points is primarily attributed to the greater time required for fault location and repair of the cable system. The overall availability of a specific system may differ from the reference values and depends heavily on parameters such as voltage level, system topology, route length, redundancy, number of circuits and repair strategy.

Reference	Fault rate per year per 100 km	Average unavailability ( ) per year per 100 km
220 to 550 kV cables: CIGRE TB 379 [3]	0.15	3 to 4.5 days; 0.8% to 1.2%
Cables 315 to 499 kV: CIGRE Technical Bulletin 815 [3]	0.27	5.4 to 8.1 days; 1.5% to 2.2%
380 kV cables: VDE FNN 2004 to 2021 [4]	0.5	4.3 days; 1.2 per cent
320 kV DC cable over 2,500 km [5]	0.11	2.2 to 3.3 days; 0.6% to 0.9%
Overhead line: VDE FNN 2004 to 2021 [4]	0.25	0.5 days; 0.14%

3.2. Repairs, Temporary Measures and Return to Service

In the event of a fault, it is not only the frequency but, in particular, the time taken to restore service that is crucial. With overhead lines, the fault location can often be narrowed down using protection technology, system sections and visual inspection. Cables, insulators, fittings and individual pole components can be replaced very quickly on a case-by-case basis. In cable systems, electrical fault location is followed by exposure of the damaged section, cable preparation, connection techniques, joint installation and final tests. Civil engineering works, dewatering, traffic management, soil protection, spare parts availability and site access can further influence the duration.

In the event of major damage to overhead lines, it is generally possible to bridge out-of-service sections with temporary measures. Provided materials are available, operations can resume after approximately one to two weeks. For cable systems, a comparable temporary solution is not feasible from a cost perspective using current resources.

Restoration aspect	Overhead line	Underground cable
Diagnosis	Protection data and visual inspection; can usually be narrowed down spatially and by component	If online fault location is not in use, electrical calibration and precise route data are required; the fault location remains hidden initially
Access for repairs	Direct access via the route, pole or aerial work platform	Exposure, civil engineering works and controlled installation conditions required
Replacement strategy	Temporary poles, makeshift cable solutions or section-by-section restoration are generally possible	Temporary cable terminations and surface laying are not considered to offer a significant time saving
Inspection prior to authorisation	Inspection of components and equipment in accordance with the extent of the damage	Inspection of the repaired cable section and the newly installed fittings is required
General trend	Often quicker and more flexible in the case of locally confined damage	In the event of an actual cable fault, more dependent on specialist resources and site logistics

Examples from a joint publication by the four German transmission system operators describe the effects of specific cable faults: ‘Examples from the operation of the Berlin cable diagonal illustrate the time and financial implications: in 2006, the incorrect installation of a partial discharge sensor within a joint was identified, followed by the breakdown of a further joint due to transient equalisation processes. The repair, testing and recommissioning of the underground cable took around 25 days. The incident necessitated an investigation and refurbishment of further joints, which resulted in additional costs. Following a further cable fault on the underground cable system at the Marzahn substation in 2009, caused by a fire at the substation, the underground cable system was out of service for 10 months. The example of the 220 kV cable system in Berlin-Adlershof illustrates just how serious the consequences of such faults can be for local residents and road users. In 2008, for instance, installation errors on two systems likely led to a downtime of around 18 months. Flying debris from the cable terminations soiled parked cars and damaged buildings. “To bring the system back into operation, the underground cable system was completely overhauled and all identical cable terminations were enclosed”[6].

3.3. Resilience and recovery following unforeseeable incidents [1,2,7]

When assessing resilience, it is not solely the frequency of equipment failure that is decisive. Rather, the key factor is whether, following a sudden incident, the transmission system can maintain its essential function, temporarily replace it through network measures, or restore it within a reasonable time. When comparing underground cables and overhead lines, therefore, exposure to the incident and the ability to recover after it has occurred must be taken into account.

Underground cables have an advantage in terms of robustness against direct incidents. Should an internal cable fault nevertheless occur, or damage result from civil engineering works, ground movement, flooding, external influences or a fault in fittings, the more complex diagnostic and repair process determines the recovery phase. Overhead lines are more exposed; however, following locally limited damage, they regularly offer advantages in terms of visibility, accessibility, modular component replacement and the possibility of temporary solutions. In the event of large-scale incidents involving numerous pylons affected simultaneously or sections of line that are difficult to access, this advantage may be significantly reduced.

For projects involving partial cabling, it must be borne in mind that transition structures for the transition from cable to overhead line have a similar level of vulnerability to substations for AC systems and converter stations for DC systems.

4. Environmental and social impacts [8,9]

The environmental impacts of underground cables and overhead lines differ primarily in terms of the protected resources affected and the temporal distribution of the interventions. During the construction phase, underground cables cause widespread interventions in the soil, vegetation and water balance. Overhead lines concentrate the immediate soil interventions more heavily on pylon sites and access routes, but permanently alter the landscape and can pose risks to birdlife. During normal operation, both systems have comparatively minor but different impacts.

Key factor	Overhead line	Underground cable
Ground	Predominantly localised interventions on foundations and access routes	Continuous trenching, relocation, compaction and possible alteration of the soil structure
Water	Generally local construction activities involving minor ground disturbance	Temporary risks due to drainage and watercourse crossings
Vegetation	Management of vegetation height in the buffer strip; isolated construction areas	Widespread impact of construction; no deep-rooted trees or shrubs across the route
Birdlife	Permanent risk of collision; depending on the type of construction, risk of electrocution	Primarily construction-related impacts
Landscape	Permanent visual impact and technical dominance	Minimal visual impact after completion
Agricultural structure	Permanent but spatially limited areas for livestock rearing and difficulties in farming	Large temporary areas, soil disturbance as well as risks to drainage and soil fertility
Operation	Corona noise under certain weather conditions; electric and magnetic fields	Ground heating in the immediate vicinity of the route; magnetic fields

4.1. Impact on climate and resources

In the case of overhead lines, concrete for foundations and steel for the supporting structures in particular characterise the resource impact associated with the infrastructure. For underground cables, higher material, transport and civil engineering costs must be assumed during construction, which are generally offset by lower operational energy losses. A reliable CO_2 balance cannot therefore be derived from general trends, but requires project-specific material quantities, service lives, loss assumptions, construction methods and replacement cycles.

4.2. Social impacts and acceptance

Underground cables can offer advantages in terms of the landscape and general public acceptance due to their minimal long-term visual impact. During the construction phase, however, they cause disruption to property owners, farmers and residents along an extensive construction site. Property owners and land users directly affected may therefore prefer overhead lines, as the long-term land use associated with these is largely limited to the locations of the pylons. Overhead lines cause more localised impacts during the construction phase, but remain permanently visible and may therefore affect a wider group of people throughout their entire operational life. Acceptance should therefore not be assessed as a fixed technological parameter, but must be evaluated on a case-by-case basis, taking into account the general public, those directly affected, the route corridor, the project phase and the available legal remedies.

5. Cost-effectiveness

5.1. From investment costs to network costs and life-cycle impacts

A robust economic analysis must take into account investment and financing costs, as well as ongoing operating costs, the costs of electrical losses, maintenance expenditure, replacement investments and any project-specific costs arising from different commissioning dates. For projects already at an advanced stage of planning, it is also necessary to assess which planning documents can be reused and what costs and delays a change in technology would entail.

Costs	Content	Assessment note
Investment	Planning, materials, construction, installation, commissioning and compensation	CAPEX comparison only applies where the transmission task is identical
Financing	Capital commitment and weighted average cost of capital	Higher initial investments have an impact via the regulatory asset base
Operation	Inspection, maintenance, repairs and energy losses	Underground cables may offer advantages in terms of energy losses; overhead lines provide access for repairs
Delay	Congestion management and redis-patch until commissioning	Only include delays that are specifically attributable to the project and for which evidence is available
Replacement	Component or system replacement over the period under consideration	Distinguish between technical, imputed and ex-pected useful life

5.2. General comparison

The economic analysis carried out indicates that, depending on the source and project context, underground cables incur additional investment costs ranging from a factor of two to ten compared with overhead lines. As illustrative planning estimates, figures of EUR 1.5 million/km for a DC overhead line up to 4 GW, EUR 4.0 million/km for a 2-GW DC underground cable and EUR 8.0 million/km for two 2-GW cable systems are given. These figures represent average assumptions and are not project-specific quotations.

Cost factors must be differentiated according to voltage level and application. Statements regarding HVDC ultra-high-voltage projects must not be automatically applied to 110 kV AC projects. For 110 kV AC applications, capital costs, operating costs, losses, depreciation periods, standardisation, monitoring and the qualification of joint installation must be assessed on the basis of specific data. For a transmission capacity of 419 MVA, the construction costs for an overhead line range between €1.8 and 2.5 million per kilometre, whilst for an underground cable without special structures they range between €5.5 and 8.0 million per kilometre. Power losses amount to 25 to 40 kW/km for an underground cable and 80 to 100 kW/km for an overhead line. This results in a ratio of investment costs between underground cables and overhead lines of 2.5 to 3.5, and a ratio of total costs of 2.0 to 2.5. At lower transmission capacities, the ratio of investment costs falls to approximately 2.0 to 2.3. In the case of very short line lengths and complex crossings – for example, where microtunnelling is used – the ratio may be higher.

The general studies examined indicate that overhead lines are, on the whole, the more cost-effective alternative. Lower cable losses and certain advantages in operation and maintenance narrow the gap in the life-cycle comparison, but do not fundamentally eliminate the structural disadvantage in terms of investment costs. At the same time, it should be borne in mind that the technical, calculated and actually achievable service life must not be equated.

6. Recommendations

6.1. Standardised evaluation process with project-specific weighting

The recommendation does not involve a general preference for one technology over another, but rather a reproducible decision-making process within the applicable legal framework. Quantitative and qualitative results must first be determined separately and then combined in a transparent manner. Transmission capacity, voltage, AC or DC technology, system number, redundancy, converters, interconnections and the period under consideration must be defined as common system boundaries. Where statutory requirements, particularly for new 110 kV routes, prescribe a specific design type or cost threshold, these limit the technology-neutral selection process as they must take precedence over the technical assessment.

In the next step, overhead lines, underground cables and, where applicable, partial cabling must be described in technical terms. In an early comparison of alternatives, technical feasibility, spatial and environmental compatibility, the impacts on the grid infrastructure and economic viability – taking into account life-cycle costs based on generally available assumptions – must be compared and evaluated in order to decide which alternative to proceed with in the detailed planning phase.

During the detailed planning phase, the quantitative cost components must be calculated on an identical price basis and using documented assumptions. In parallel, environmental impact, safety, resilience, public acceptance and planning risk must be assessed in relation to the assets to be protected and the respective project phases. Sensitivity analyses must demonstrate how the route, ground conditions, prices, project delays, energy losses, the standard service life of the respective technology and repair assumptions influence the outcome. Finally, the weighting, conflicting objectives and the robustness of the conclusions must be disclosed before a project decision—including mitigation, monitoring and replacement strategies—is justified.

6.2. Decision-making rules

The decision-making approach depends on the specific project situation. For greenfield projects with high cost sensitivity, the overhead line option should be assessed as a priority from an economic perspective, without disregarding public acceptance, landscape, birdlife and planning permission risks. Where there are significant visual or settlement-related conflicts, an in-depth assessment of underground cabling or partial cabling may be warranted, taking into account the impact on soil, water, agriculture and construction time, as well as technical risks associated with installation and repair. In the case of an underground cable project at an advanced stage of planning, a change of technology should be assessed solely on the basis of a comprehensive analysis of time and system costs. For projects involving partial underground cabling, particular emphasis should be placed on resilience, and both vulnerability arising from additional transitional structures and the impact on the restoration of operations should be assessed.

Situation	Trend	Audit qualification
Greenfield project with high cost sensitivity	Assess overhead lines as a priority from an economic perspective	Assess public acceptance, landscape impact, birdlife and planning permission risk
Significant visual and settlement conflicts	Examine underground cabling or partial cabling in greater depth	Take into account soil, water, agriculture, construction time and joint risks
Focus on resilience	Weigh exposure and restoration separately	Model project-specific scenarios for sabotage, weather, access and repairs
Partial cabling	Local conflict resolution possible	Systematically assess the additional costs and impact on resilience of the transitions, safety technology and operational management

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