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RAF021/2425 Study of the Potential for Cost Reduction in Undergrounding Transmission Lines over Long Distances

Literature Review and Cost Assessment

Department for Energy Security and Net Zero (June 2025)

Contents

Executive Summary

Ramboll has been appointed by the Department for Energy Security and Net Zero (DESNZ) to undertake a study to identify if there is potential for cost reduction in undergrounding transmission lines over long distances of 20km and 50km by using innovative methods, against a baseline of traditional burial in a trench using ‘cut-and-cover’. Cost is a key consideration when making decisions on technology solutions, however such decisions are also informed by several wider considerations including environmental impact and operability. This report documents a literature review and qualitative assessment to identify emerging undergrounding technologies and assess their benefits and disbenefits against key criteria, taking three forwards for further investigation.

New emerging undergrounding methods were identified, and a literature review was performed to qualitatively assess these methods against key criteria, including capital cost, technical feasibility, minimising environmental impact and whether it can deliver a complete solution. The literature has identified information and claims about the undergrounding methodologies and the impacts of the cable technologies on these methods. The assessment compared cut-and-cover as a baseline (being the incumbent undergrounding method) versus cable ploughing, horizontal directional drilling (HDD), microtunnelling (pipe jacking), auger boring, Direct Pipe, E-Power Pipe and Pipe Express. The assessment identified cable ploughing, HDD and microtunnelling (pipe jacking) as having the most potential to have costs approaching those of cut-and-cover, and whilst these methods are already commercially available, they have to date been limited to short distances or applications largely outside the UK.

Cable ploughing claims to reduce costs significantly compared to cut-and-cover whilst minimising the impact on landowners. It claims to being able to install 400kV cables at 1.5km per day in a reasonable range of ground conditions with methods possible to break out rock if encountered. Whilst cable ploughing may be cheaper per metre in isolation, the number of obstacles that the cable plough cannot cross needs to be factored in, as does the geology and terrain (such as forested areas), which are likely to be limiting factors for its potential use.

HDD is an established method of undergrounding for crossing obstacles but isn’t currently used over distances of more than a few kilometres, although it may see wider application as further innovations in HDD emerge. It has the advantage of using relatively simple machinery, can launch from the surface and can work in a wide range of geological conditions. Depending on the cable voltage and size required, multiple tunnels may be required for a single circuit. Some geotechnical risks were identified such as hydrofracture and difficulties dealing with variable conditions (e.g. gravel and boulders) which would need to be assessed with the specialist HDD contractors.

Microtunnelling provides a different option in which the cable is not buried but placed within a tunnel. The advantage is that the majority of geotechnical conditions can be handled, and the ground is well supported during construction. Several cable arrangements can be housed

within a single tunnel for up to 400kV cables. There are additional costs borne in setup through launch and reception shafts and intermediate shafts for drives greater than 1km, and microtunnelling becomes less viable for distances over 1-2km compared to traditional tunnel boring machines (TBMs). The microtunnelling TBM is more complex and costly than the other shortlisted methods but tunnelling may be the only option for cable installation beneath sensitive infrastructure and environments.

To allow a comparative analysis of build costs of the shortlisted methods, the gaps in information were identified and filled through interviews with cable suppliers and installers to develop a full picture of the costs of these methods. Specific scenarios have been developed to inform how cable ratings and voltages, route length, and ground conditions will impact on costs and what savings are possible over longer distances. In addition to this, non-cost benefits and disbenefits for environment, energy security and deliverability have been qualitatively assessed to provide further context to the benefits of the different methods.

The cost analysis compared the traditional cut-and-cover method to cable ploughing and HDD for underground transmission lines using scenarios that varied the circuit rating of Low and Medium capacity, voltages of 275kV alternating current (AC), 400kV AC and 400kV direct current (DC) and for route lengths of 20km and 50km. Due to the significant difference in cost by comparison with the other two shortlisted methods, microtunnelling (pipe jacking) was ultimately removed from the comparative cost assessment.

The analysis showed that cable ploughing where suitable may significantly reduce the costs of the civil works to 28% to 34% that of cut-and-cover, a reduction of 66% to 72%. However, due to the cost of cable materials being such a large proportion of the cost of an underground cable project, this means that total build costs only fall to 60% to 80% that of cut-and-cover, a reduction of up to 20% to 40%, and project-specific factors may reduce this cost advantage.

The hypothetical scenario where the whole route is constructed by HDD showed that the costs would range from 1.1 times to 1.9 times that of cut-and-cover. The deeper the HDD bore goes underground, the worse the conditions for the cable, which can increase the number of cables required and therefore the costs. Based on these findings HDD in the near term is only likely to be used as a solution for crossing obstacles, as at present.

In the case of undergrounding AC circuits, the lowest cost method is cable ploughing in flat formation, however this remains over 5 times the build cost of double circuit overhead lines (OHL) on pylons for Medium capacity circuits, and 3.5 to 4 times the cost of OHL for Low capacity circuits. For AC circuits, as the circuit rating and voltage increases, the requirement for more cables per circuit due to thermal constraints starts to make the underground methods more prohibitive in terms of costs, whereas for OHL the cost per unit of capacity falls as circuit rating rises from Low to Medium capacity. The analysis indicated that for AC, any economies of scale associated with longer undergrounding distances such as 50km versus 20km are eliminated by the cost of additional equipment needed to manage reactive power.

In the case of undergrounding DC circuits, the costs over distances of 20km and 50km will be dominated by the costs of any additional converter stations introduced by the decision to underground DC rather than AC, which are required to convert DC to AC in order to connect to the AC transmission grid. As a consequence, the cost per kilometre for undergrounding DC will normally far exceed that for undergrounding AC over such distances.

There may be some scenarios in which the decision to underground DC rather than AC does not affect the number of converter stations needed, but only their location. This might for example arise if connecting a node which is already planned to be DC (such as an offshore windfarm with a HVDC export cable) to an AC node point to point. In such a scenario, it may be appropriate to exclude the cost of converter stations when considering undergrounding options. If the costs of converter stations are excluded, the cost of undergrounding DC is significantly lower than for undergrounding AC for all methodologies, being 50% to 65% of the build cost of AC for both the cut-and-cover and cable ploughing methods. The build cost for undergrounding DC using cable ploughing falls to around 2.5 times that of OHL for Low capacity circuits and 3.5 times for Medium capacity, which whilst closer in cost to OHL than for AC, is still significantly higher.

1. Introduction

Ramboll has been appointed by DESNZ to undertake a high level study (UKSBS, 2025) to identify if there is potential for cost reduction in undergrounding transmission lines over long distances of 20km and 50km by using unconventional or innovative undergrounding methods. Cost is a key consideration when making decisions on technology solutions, however such decisions are also informed by several wider considerations including environmental impact and operability. The report is intended to fill an evidence gap in respect of the build costs of non-traditional undergrounding methods, and the reader should refer to more detailed studies for costs of traditional methods. This report documents a literature review and qualitative assessment to identify emerging undergrounding technologies and assess their benefits and disbenefits against key criteria, taking three forwards for further investigation.

1.1 Overview

The UK Government has set a mission to achieve Clean Power to 2030 and the Clean Power 2030 Action Plan sets out a pathway to a clean power system by 2030 (UK Government, 2024). Great Britain's electricity network must undergo unprecedented expansion, as the economy electrifies, to deliver decarbonisation, energy affordability and energy security, and support economic growth.

The development of new transmission infrastructure currently takes twelve to fourteen years and the Electricity Commissioner made several recommendations to accelerate this process (UK Government, 2023). Undergrounding transmission may have the potential to support acceleration as transmission operators are registered as 'statutory undertakers' which may mean that certain works such as underground cables can be undertaken without the need for planning permission and which are often more acceptable to communities. However, costs of undergrounding are typically much higher than for overhead lines and projects may require an Environmental Impact Assessment necessitating planning permission. This study was commissioned to fill an evidence gap in relation to the costs of innovative methods of undergrounding, and their potential to reduce costs of undergrounding over long distances of 20km and 50km, whilst costs for conventional undergrounding were set out in a more detailed report published by the Institution of Engineering and Technology (IET) (Mott MacDonald, 2025).

A comparative cost assessment of innovative undergrounding methods has been undertaken, against a baseline of burial using 'cut-and-cover' for undergrounding outside built-up areas. The research focused on onshore transmission lines of 275kV or 400kV AC, and onshore sections of 400kV HVDC transmission lines. However it should be noted that the onshore transmission grid is, and is likely to remain, AC, and whilst HVDC is an important technology offshore, it is difficult and costly to integrate into an AC system so its role onshore is likely to be limited to connecting offshore assets to the AC grid, or potentially operating in parallel to the AC grid for large power transfers over very long distances of several hundred kilometres.

1.2 Aims

To help inform future policy, this study aimed to answer the following key research questions:

- What are build costs of shortlisted undergrounding methods versus baseline (cut-and-cover)?
- Could costs of shortlisted methods be reduced through further innovation including that associated with scale up to longer distances?
- Do shortlisted methods have significant other benefits or disbenefits versus overhead lines or undergrounding using cut-and cover, such as in respect of environmental impact and energy security, that may be relevant to national policy?

1.3 Objectives

The objectives of this study were to:

1. Undertake a qualitative assessment of non-traditional undergrounding methods to propose a shortlist of three methods with the most potential to reduce costs.
2. Prepare a literature review of shortlisted technologies and costs.
3. Engage with specialist suppliers in these technologies to validate costs and identify innovation potential over longer distances.
4. Perform a comparative analysis of build costs of shortlisted methods versus cut-and-cover, including assessment of synergies with cable technology.
5. Assess non-cost benefits and disbenefits for environment, energy security and deliverability qualitatively.
6. Provide recommendations for further work.

1.4 Constraints and Limitations

This report has been prepared for the exclusive use of DESNZ for the cost reduction study into undergrounding transmission lines over long distances of 20km and 50km. This report should not be used in whole or in part by any third parties without the express permission of Ramboll in writing. Ramboll has endeavoured to assess all information researched during this study. The report summarises information from a number of external sources and cannot offer any guarantees or warranties for the completeness or accuracy of information relied upon.

2. Literature Review

This section presents the identification of non-traditional underground construction methods and presents the information available from literature to appraise their technical feasibility, capabilities, limitations and comparative costs.

2.1 Undergrounding Methods

Several undergrounding technologies have emerged and become more economically viable in recent years. The following underground construction methods have been identified for assessment that may have the potential to reduce costs for cable installation.

Cable Ploughing

Cable ploughing is a technique that lays the cable or duct directly into a groove cut in the ground by the plough, and closed in one pass as shown in Figure 1 (Thomas, 2024).

Figure 1: Cable ploughing (Thomas, 2024)

A supplier of cable ploughing services (ATP) provided three case studies of installing cables by plough for 132kV and 220kV, and several lower voltage cables across the UK and mainland Europe (ATP, 2024). They claim that up to 400kV is possible and have demonstrated this by installing the pipes required for 132kV and 400kV cables in flat formation, using ploughing machinery (ATP Cable Plough, 2024). Thomas, 2024 claims that open trench methods typically lay 400kV cables within 250mm diameter ducts at a depth of 1.45metres (m), so the plough machines can accommodate the sizes required as they can plough a maximum pipe size of 620mm and install to a maximum depth of 2.8m.

It is recommended that cables of 132kV or higher should be placed within a duct. It is expected that for a single AC circuit of three 400kV cables, the cables can either be laid in a trefoil formation or laid in separate trenches, separated by 400-725mm for a total width of 2.2m. DC cables can be accommodated; these typically require two cables for a circuit and could be laid in two parallel slits, or laid in the same wider slit like trefoil. The machine can also lay fibre optic cables simultaneously with electric cables if required.

The distance that the cables can be installed is limited by obstacles such as roads, rivers or geological conditions. It is claimed that as long as no utilities are present in a road, then a road can be opened up (by others) before the plough runs through to the lay the cable. However, it cannot be used in areas where other underground services such as gas or water pipes already exist and may be encountered.

Ploughing is claimed to be suitable for various soft soil conditions, including sand, gravel and moor and that rock conditions can be broken out before ploughing. It is claimed that the machines can operate in wet areas such as marshland and through ditches (reported as successful with an 8m wide, 1.5m depth ditch) and water crossings up to a depth of 1.9m. The machines have also been used on gradients up to 45 degrees.

A case study on the ‘Sea Green’ project is cited to have averaged 1.45km per day per slit including opening, installing and closing, using one cable ploughing machine. Each cable plough machine can provide one slit per run, but more than one machine can be used to speed up this process if required.

It is claimed that cable ploughing can achieve the same outcome as open cut or trench excavation, but more quickly and cheaply, and that the cost could be similar to OHL (Thomas, 2024). For commercial reasons, no specific costs are provided in published information. The method using equipment from one supplier has received special procedure approval from a European transmission system operator for laying conduits to house high voltage DC cables, and is planned to be used on a section of the SuedOstLink project in Germany.

In summary cable ploughing can be a cost-effective way of laying distances of cable in soft soils as it is significantly faster than traditional trenching methods. This can reduce labour costs, and there is less surface disturbance, reducing the need for costly and time-consuming restoration work.

Additional benefits claimed include:

- Reduced land disruption and compensation required to landowners, handovers within one day possible.
- Can reduce easement (limited to width of plough).
- Can reduce time required for planning approvals and preparatory work.

- Reduced environmental impact by eliminating or minimising spoil removal and damage to the ground.
- Reduction in diesel required to run the cable plough machinery in comparison to open cut methods. Claims of using 58 litres of diesel per km per slit, whereas open trench could use 10-15 times more.
- Increased speed of construction which reduces labour costs.
- Further scope to innovate cable ploughing technology, including design standardisation and advanced ploughing techniques to handle more challenging terrain.

Limitations

- Cable ploughing is unlikely to be a complete solution for laying cables over long distances and will have to be used in conjunction with other methods to pass obstacles.
- While cable ploughing may be cheaper, the costs of cable ploughing plus other methods required to cross obstacles and the overall cable material cost needs to be factored.
- Geology and terrain (such as forested areas) can be a limiting factor for its potential use.

Horizontal Direction Drilling (HDD)

HDD is a trenchless construction method that can be used to install cables or conduits without the need for extensive excavation. The drilling rig, as seen in Figure 2, is set up at the surface without the requirement for a shaft or pit to launch from, and a small diameter pilot hole is bored along a pre-determined path. Once complete, the reaming process is undertaken to enlarge the hole to the required diameter while a bentonite slurry maintains the holes stability. The last step undertaken is to attach a pulling head to the pipe or conduit before pulling it back through the hole. HDD has become a prevalent method for installing underground crossings for cables within the industry in the UK and globally. HDD has been used to install cables in the ground with voltages from 132kV (AMS, 2024) up to 400kV (Allen Watson, 2025).

Typical diameters range from 0.05m to 1m, larger diameters up to 2m (Herrenknecht, 2025) are possible but are not common. Drive lengths can be relatively short, typically observed up to 1km, but the technology has been innovating to allow for longer distances. HDD tunnels over 4km have been undertaken such as the 0.5m diameter Bakken Missouri River Crossing (Mott MacDonald, 2019).

The pilot bore drill and reamers can be designed to be drilled in a range of conditions including soft clays, sands and gravels to mixed grounds and rock depending on the equipment used. Mixed conditions and gravels are challenging but possible, and if required this can be managed with the use of a sleeve to support the transition into better ground conditions. However, HDD can struggle in hard rock strength greater than 150 megapascals (MPa) and when encountering boulders.

Figure 2: HDD machine (Nikitha, 2019)

It is reported that HDD can be twice as quick as traditional trenching methods (Chadalawada, 2024). Advance rates between 10 to 150m per day are possible depending on the size and soil conditions. Smaller diameters in soft soils such as clay and silty clay can be quicker, while larger diameters in mixed conditions can be slower. The larger the diameter the more reaming passes are required.

It is recommended in the DCA Technical Guidelines (Drilling Contractors Association, 2015) that 3m is the absolute minimum depth of cover to surface required for a HDD bore. However, this can be quite onerous to design, and therefore 5m is typically recommended as the minimum cover unless it can be proven otherwise.

Depending on the voltage and number of tunnels required to be drilled, HDD has been reported as being 66% of the cost of traditional trenching methods (Chadalawada, 2024) for underground fibre optic cables. However, a cost analysis of HDD versus cut-and-cover for 1km long 300mm waterlines in urban areas showed that HDD is 12.5% more expensive (Atalah & Kariuki, 2009). It should be noted for high voltage transmission lines these numbers may not be directly comparable to the above examples. Due to compromised thermal conditions for the cables in a HDD bore, the minimum of three cables required per AC circuit are typically placed in three separate bores. Whilst they can be placed in trefoil within one bore, this is more typically done in lower voltage cables.

Additional benefits:

- Surface disruption limited to launch/reception areas.
- No requirement for launch/reception shaft.

- Reduced environmental impact – quicker less intrusive construction reduces fuel consumption and carbon emissions compared to cut-and-cover.
- Depending on ground conditions it can be quicker than cut-and-cover.
- Less waste in excavation given the pipe diameter is very close to the excavated hole.
- If ground conditions allow it could potentially offer a complete solution.
- Can be steered to navigate curves and avoid obstacles.

Limitations:

- Risks associated with frac-out and borehole collapse. Frac-out is when the bentonite slurry that is used to stabilise the borehole escapes into the ground due to weak or fractured soil, or excessive slurry pressure. This can have environmental impact due to contamination and cause delays to a project.
- Geology can be a limiting factor for its potential use particularly in highly variable conditions (e.g., gravel, boulders).
- Pipes will be directly buried in the ground through different geology with varying temperatures which can affect long term performance of the cables.
- To complete a full AC circuit of 3 No. cables, it will typically require 3 separate holes, which can increase cost and time.

Microtunnelling (Pipe jacking)

Microtunnelling is a trenchless tunnelling technique that utilises a remote controlled microtunnel boring machine (MTBM) as shown in Figure 3 to install pipes underground. The MTBM is guided by a steering system to follow the desired route by using steering pistons located just behind the cutterhead. The MTBM is designed to allow curved bores both in the horizontal and vertical planes and is advanced through the ground using jacking pipes which are placed in a jacking frame within a launch shaft at one end of the route. Pistons in the jacking frame push the pipe and MTBM forward while the annulus is lubricated with a bentonite slurry to reduce the friction required to push the MTBM forward. A section of pipe is advanced with the MTBM through the ground, before the pistons of the jacking frame are withdrawn to allow the next pipe section to be added to the pipe, before continuing until the MTBM reaches the reception shaft.

Like a traditional tunnel boring machine, the shield and cutterhead can be chosen to handle a range of ground conditions to control ground movements, using a slurry or earth pressure balance machine to support the face during construction.

Diameters can range from 0.15m and can go up to 3.4m in the UK (Pipe Jacking Association, 2017), anything over 3.4m is typically done by a traditional TBM with a segmental lining, but Herrencknecht claim their AVN machines can go up to 4.8m diameter (Herrenknecht, 2025). Drive lengths can be greater than 1km with the use of several inter jacks, but this requires the use of interjacks every 100-150m. This would indicate that intermediate shafts may be required more frequently than for TBM tunnels where 3-4km is typical (Parsons Brinckerhoff, 2012). However, as the length of a MTBM drive exceeds 1-2km, the use of a traditional TBM tunnel becomes more favourable, so this scenario will be unlikely to occur. Therefore, pipejacking is typically only considered to facilitate crossings of obstacles especially when needing to limit settlements.

Figure 3: Microtunnel TBM (Ground Engineering, 2023)

Advance rates can vary from 5 to 25m per day depending on the size and soil conditions. Smaller diameters in soft soils such as clay and silty clay can be quicker, while larger diameters in mixed conditions can be slower.

Microtunnelling can be more costly in comparison to simpler construction methods like HDD. There is an initial setup cost of constructing a launch and a reception shaft, and if the distance is long it becomes more viable to go down the traditional TBM route. Unlike a TBM, a MTBM will typically not need to be purchased for a specific project, as the cost of maintenance and repair for an existing machine is accounted for by the contractor. Additionally, the set up and operation for pipe jacking is cheaper than traditional TBM tunnelling.

For a microtunnel, cables are installed within concrete pipes and the cable design will dictate what the internal spaceproofing requirements are for the tunnel, which dictates the cost of the tunnel construction. Factors that influence the spaceproofing are the number of cables, the cable voltage (higher voltages generate more heat which requires more space), and whether personnel entry is required for maintenance and safety.

Based on guidance (IEC, 2024) for thermal interaction, National Grid TS 2.10.08 for heat dispersion, (NFPA, 2024) for active ventilation requirements for fire safety, and XLPE cable specifications for cable sizing, an estimate can be made for the internal spaceproofing required for different cable formations, voltage levels and circuit numbers considered. These are presented in Table 1, and are approximate as the depth of the tunnel will also factor into the requirements.

Table 1: Approximate internal diameter for open tunnels with 132kV to 400kV cables

Voltage	Number of Circuits	Approximate Cable Diameter	Cable Configuration	Approximate Tunnel Diameter
132 kV	Single Circuit	100 mm	Trefoil	2.0 m
132 kV	Single Circuit	100 mm	Flat	2.2 m
132 kV	Double Circuit	100 mm	Trefoil	2.4 m
132 kV	Double Circuit	100 mm	Flat	2.5 m
220 kV	Single Circuit	140 mm	Trefoil	2.5 m
220 kV	Single Circuit	140 mm	Flat	2.7 m
220 kV	Double Circuit	140 mm	Trefoil	2.8 m
220 kV	Double Circuit	140 mm	Flat	3.0 m
400 kV	Single Circuit	180 mm	Trefoil	3.0 m
400 kV	Single Circuit	180 mm	Flat	3.2 m
400 kV	Double Circuit	180 mm	Trefoil	4.2 m
400 kV	Double Circuit	180 mm	Flat	4.5 m

This shows that 132kV and 220kV (single circuit) can be installed in 2m to 2.5m ID tunnels which are typical of diameters seen for pipe jacked tunnel projects in the UK. A single 400kV circuit would require 3m ID. It is rare to find pipe jack tunnels of this size, and when a considerable length of tunnel is required this would typically be done using a TBM, such as the

London Power Tunnels (National Grid, 2025) that runs a single 400kV circuit within a 3m internal diameter segmental lined tunnel. Therefore, a typical range that can be considered for pipe jacked cable tunnels would be 2m to 3m ID for the high voltage cables considered for this study.

Benefits:

- Minimal surface disruption.
- Comes into its own when tunnelling beneath sensitive infrastructure and environments.
- Reduced environmental impact – avoids cutting through ground surface.
- Can steer the tunnel.
- Allows a larger diameter tunnel to house a single AC circuit of three cables.
- Speed of setup and installation.
- Prevention of ground water ingress by use of pipes with sealed flexible joints.
- No personnel required in the tunnel, makes construction safer.

Limitations:

- Becomes less economical over 1-2km.
- Large launch and reception pits required, with permanent headhouses for ventilation.
- Due to steering restrictions and the need for inter jacks, the lengths of drive are limited, compared to a segmental lined TBM tunnel.
- Increased excavation and spoil removal compared to HDD.

Auger Boring

Auger boring is a trenchless tunnelling technique undertaken using a cutting head that excavates the soil while the auger housed within a steel or concrete pipe casing moves the soil back to the launch pit with no personnel access required within the pipe (Sterling, 2020). The steel pipe that houses the auger forms the support to the ground in the temporary and permanent case. A section of steel pipe is dropped in and welded to the previous piece before being pushed by jacks to turn and drive the auger. Once the tunnel is complete the cable is pulled through as required. A launch and reception pit are required to construct the tunnel, however auger boring has a simple form of machinery as shown in Figure 4 and requires little space to launch the drive. Short drives are unguided, while longer drives are guided using an initial pilot hole before boring the final tunnel.

Auger boring has some limitations in terms of the range of ground conditions it can operate in. Without any support fluid surrounding the annulus, ground settlements are harder to control so this method may not be suitable for passing under sensitive infrastructure or in certain geological conditions. Auger bores can struggle in wet ground, flowing groundwater can cause ground loss along the auger as the excavation at the face is not sealed. However, in dry conditions, loose soil such as sands and gravels can be handled. Ideal conditions are soft to firm clays, and even weak consolidated rocks can be accommodated with the use of an appropriate rock cutter head.

Figure 4: Auger boring machine (Herrenknecht, 2025)

Typical diameters range from 0.1m to 1m but can go up to 1.8m. Advance rates can be up to 30m per day, with relatively short set up times once the launch and reception pits are constructed. Drive lengths are relatively short, typically 100m or less, but longer bores have been known up to 200m. This indicates that auger boring will not be a complete solution for a project but has the opportunity to be a cost-effective option in conjunction with other methods for certain crossings. Auger boring is typically cheaper and quicker than pipe jacking, due to the simpler machinery and minimal space requirement for launch. However, the cost of the launch and reception pits needs to be factored in when comparing to HDD which has limited set up requirements to launch.

Direct Pipe

The Herrenknecht Direct Pipe claims to combine the advantages of microtunnelling and HDD (Herrenknecht, 2025), which essentially means it is a microtunnel that is launched from the surface like HDD as shown in Figure 5. It is driven and steered like a microtunnel using a slurry supported AVN machine that pumps excavated material back through a slurry circuit within the prefabricated pipeline. The method uses a pipe thruster that clamps to a section of pipe and pushes it into the ground in 5m strokes and can steer upward and downward slopes and in curves. This is a single pass method where the lining is directly installed as the tunnel is advanced, by means of pre-welded pipelines.

Herrenknecht claim that it is a quick and economic installation method for pipelines with lengths greater than 1,500 metres possible. A case study claims that a maximum of 90m per day advance was achieved for a 600mm diameter pipe (Herrenknecht, 2025). The diameters currently range from 0.8m to 1.5m. As an AVN microtunnelling machine is used to advance the tunnel, it can handle all soil and rock types based on choice of shield and cutterhead and the slurry support will limit settlements at the surface.

There is no cost information available from Herrenknecht. The manufacturer claims that it is an economic solution, although the cost of the machinery, pipeline material and construction is likely to be significantly more expensive than more simple methods of construction like HDD. However, Direct Pipe will be able to handle more difficult ground conditions.

Figure 5: Direct Pipe (Herrenknecht, 2025)

E-Power Pipe

The Herrenknecht E-Power Pipe is a trenchless microtunnelling method for installing small-diameter product pipes at shallow depths over distances up to 2 km (Herrenknecht, 2025). It combines elements of HDD and pipe jacking, allowing for precise alignment and minimal surface disruption. The process involves a two-stage method using steel jacking pipes as shown in Figure 6 and a slurry-supported microtunnelling machine to first drive the tunnel, then pull back through the required conduit or cable.

It is claimed to be able to excavate through silty soft clays to medium hard rock. Pipe diameters range from 0.5m to 0.98m, with the insertable cable pipe diameter from 0.25m to 0.914m. Advance rates claim 126m per day for pilot tunnel and 266m per day for pipe retraction. However, the costs of the machinery and use are not available within available literature.

Figure 6: E-Power Pipe (Herrenknecht, 2025)

Pipe Express

The Herrenknecht Pipe Express is a semi-trenchless method for pipeline installation designed to work at shallow depths in soft and mixed ground such as clay, silt, loam, sand, gravel, and with high groundwater levels (Herrenknecht, 2025). It is jacked from a launch pit and uses a microtunnelling machine at the front to cut soil, which is transported directly up to the surface by a trenching unit to an operated vehicle above ground while the pipeline is installed directly behind as shown in Figure 7. It can install diameters from 0.9m to 1.5m and it claims to be able

Figure 7: Pipe Express (Herrenknecht, 2025)

to install up to 2km in one drive and up to 1km in a day. The excavation is limited to a narrow corridor, and it is claimed to reduce excavation by 70% compared to cut-and-cover. This method will be limited by obstacles such as roads and water courses. The time and set up costs for the launch pit to begin tunnelling will likely be prohibitive in comparison to cable ploughing, especially for longer routes with multiple obstructions.

Baseline Comparison

To enable a cost comparison to new undergrounding technologies, cut-and-cover will be used as a baseline. To arrive at the costs the IET electricity transmission costing study (Mott MacDonald, 2025) which compares OHL to cut-and-cover and bored tunnels was used.

The report indicates that the cost per km decreases proportionally as the length of the route increases and rises with circuit capacity. It was noted that the cost of operation, maintenance and energy losses over the life of the connection is similar for undergrounding and overhead lines. However, the report concluded that the capital build costs vary significantly, with build costs up to 10 times greater for cut-and-cover than OHL.

For low capacity rating (2,494 MW) 400kV AC circuits, the study identifies that the build costs for 15km of cut-and-cover is £13.1million per km, while it is £21.8million per km for medium capacity rating (4,988 MW). The cost of cut-and-cover construction is not reported specifically, but is made up from the following categories:

- Cable installation: includes civils and cable installation
- Special construction: includes temporary works, access roads and includes a limited allowance for obstacles.
- Build contingency: calculated as 10% of the total build costs

Taking these categories into account the cost of cut-and-cover construction for the same two scenarios is £5.6m per km and £9.5m per km, which account for around 43% of the total build costs.

3. Qualitative Assessment

The qualitative assessment uses selected criteria with a weighted scoring system to evaluate the undergrounding methodologies with the most potential of reducing costs for transmission lines over long distances of 20km and 50km

To enable a cost comparison, cut-and-cover will be used as a baseline as reported in the IET Electricity Transmission Costing Study (Mott MacDonald, 2025). The criteria considered in the qualitative assessment have been chosen to focus on installation costs and technical feasibility. The costing study indicates that the cost of operation, maintenance and energy losses over the life of the connection is similar for undergrounding and overhead lines, so this has been excluded as an item from the initial sift of undergrounding methodologies. The qualitative assessment excludes non-cost benefits or disbenefits such as environment, energy security and deliverability as these will be considered in the final assessment.

The qualitative assessment is presented in Table 2. The scoring applied is between 1 and 3, with 1 representing less favourable performance against the criteria and 3 being more favourable performance. The criteria considered for the assessment and what each incorporates is described below with commentary on scoring for each technology.

Capital cost

Capital cost incorporates factors such as planning and construction, route efficiency, requirement for launch/reception pits/shafts and intermediate shafts, potential for reducing costs proportionally over long distances, and scope for further innovation to reduce costs.

Available costs within literature are limited and are mostly based on comparative claims. Cable ploughing alone is claimed to be cheaper than cut-and-cover and potentially similar to OHL. HDD has been claimed to be similar or potentially cheaper in cost to cut-and-cover and can provide a much more efficient route. Microtunnelling has larger upfront costs for launch, reception and intermediate shafts, and machinery is more costly than HDD or cut-and-cover. Auger boring is comparatively cheaper than microtunnelling but still requires a launch and reception shaft and cannot scale over longer distances due to the extremely short length of drives possible, so scaling over longer distances is impractical. Herrenknecht products Direct Pipe, E-Power Pipe and Pipe Express are innovative methods combining elements of HDD and microtunnelling, however, the costs are unknown and expected to be at least comparable to microtunnelling given an AVN machine is used to drive them.

Technical feasibility

Technical feasibility covers how proven the construction methodology is for cable installation in a range of expected geological conditions.

Microtunnelling is the most proven technology for trenchless construction especially for handling difficult ground conditions, while HDD has become more prevalent as a method for installing cables for crossings. Cable ploughing has presented three projects for high voltage cables up to 2023 and have shown it is technically feasible to install 400kV cables, but the case studies are relatively limited. Direct Pipe is technically feasible through multiple projects, with E-Power Pipe less so, but both are viable for difficult ground conditions. However, Pipe Express has a limited number of case studies available and its use case is limited.

Minimising impact

Minimising impact covers how well the method can minimise the impact on the general public and landowners during construction and operation. Trenchless solutions will ultimately prove less impactful during construction as only launch and reception shafts are required. However, open tunnels will require permanent headhouses due to ventilation requirements, which will impact during operation. Cable ploughing has a much smaller impact on the surface compared to trenching by cut-and-cover, but it still requires joint bays every 500m-1000m which require permanent access for maintenance. HDD, and to a lesser extent Direct Pipe have the best of both worlds through minimising space required at surface to launch and burying the cable underground without surface disruption but will also require joint bays at regular intervals.

Complete solution

A complete solution is one in which the route can be constructed wholly or mostly by the undergrounding method, which also factors in the length of drives that are achievable. Due to obstacles at the surface, cable ploughing, Pipe Express, and cut-and-cover will score low as they will require other methods to complete the full length of a project. Trenchless solutions such as microtunnelling, HDD, Direct Pipe and E-Power Pipe could be a complete solution, but maximum drive lengths of 1 to 4km mean that multiple tunnels would be required which may not be viable due to costs. Auger boring has a very limited range so scores low.

Shortlisted undergrounding technologies

As can be seen in Table 2, based on the criteria, cable ploughing (2.4) and HDD (2.4) score the highest, comfortably ahead of the other methodologies, mostly due to cost but also technical feasibility and minimising impact. Microtunnelling (1.8) is the next highest despite it being more costly, as it rates high in technical feasibility due to its ability to handle difficult ground conditions especially above sensitive infrastructure and environments, which makes it worthy of inclusion. These three undergrounding methods will be taken forwards to the next stage to gain more insight from cable installers and suppliers through interviews to develop accurate costings for installing cables over long distances of 20km and 50km.

Table 2: Qualitative assessment of underground methods against key criteria

Criteria	Capital cost	Technical feasibility	Minimising impact	Complete solution	Overall score
Weighting	50%	30%	10%	10%	100%
Cut & Cover (Baseline)	2	3	1	1	2.1
Cable Ploughing	3	2	2	1	2.4
HDD	2	3	3	2	2.4
Microtunnelling (Pipe Jacking)	1	3	2	2	1.8
Direct Pipe	1	2	3	2	1.6
E-Power Pipe	1	2	2	2	1.5
Auger bore	1	2	2	1	1.4
Pipe Express	1	1	2	1	1.1

Key: 1 = less favourable, 2 = average, 3 = more favourable

4. Cable Technology Implications

4.1 Summary

Cable materials make up a key segment of underground cable costs. The cost of the cable system materials is typically the highest cost, and for 400kV Low and Medium cable ratings, this is estimated as 28% to 35% of the lifetime cost of a project for cut-and-cover (Mott MacDonald, 2025) for copper cables of 2500mm2, which were also used as the basis for cost analysis in this study. Cable cost is affected by many factors that range from the choice between AC and DC transmission systems to decisions regarding cable materials, insulation types, and installation methods. It is important to balance capital expenditure (CAPEX) with operating expenditure (OPEX) and overall system performance.

4.2 AC vs DC

AC has become the method of choice for electrical power transmission due to the difficulties associated with changing voltage levels for DC systems which is not an issue for AC due to the use of transformers. However, as technology has improved HVDC has become technically feasible thanks to voltage sourced converters.

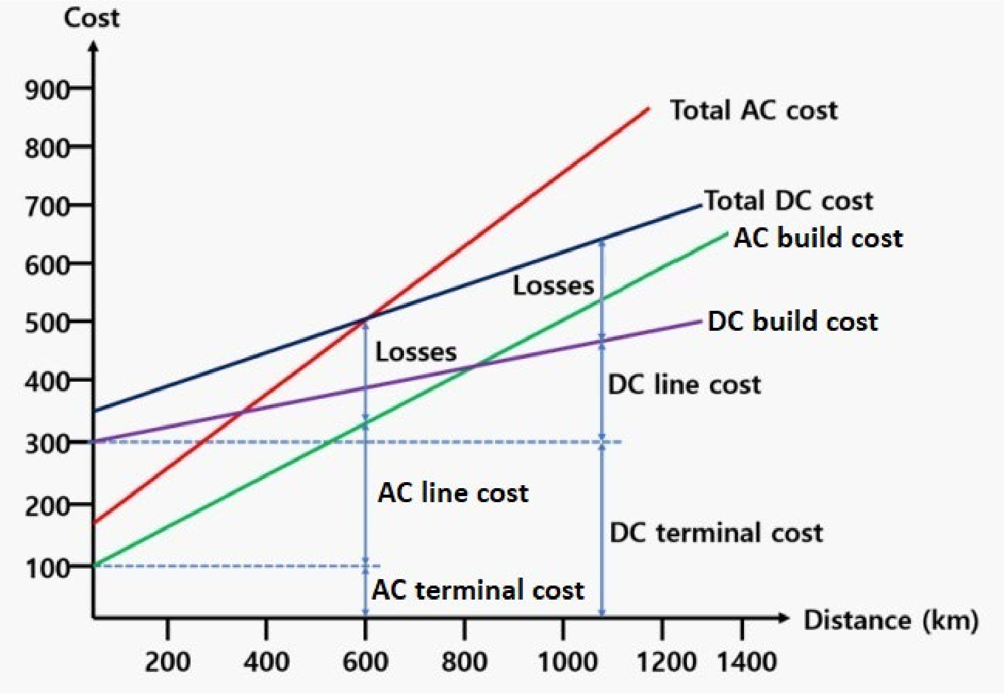
With regards to cost, the most significant factor to consider between AC and DC is the distance. The cost of a DC system is high because of the various component costs required to integrate DC into the AC system, such as the need for filters, capacitors, control systems and valves (D.M. Larruskain, 2005).

The CAPEX costs for the HVDC system converters are significantly higher than AC. However, a DC transmission cable costs less than an AC transmission cable. Cables for DC circuits are cheaper than for AC due to:

- Effects like the skin effect and higher capacitances of the cable with AC - in an AC circuits there are larger losses and higher heating effects over longer distances.
- AC circuits require more frequent reactive compensation in order to retain a high-power quality, which is achieved through shunt reactors, but DC circuits require no reactive compensation.
- DC systems are generally much simpler than AC systems, for example it can be very difficult to connect two AC systems due to stability issues.

Therefore, as the cable distance increases it becomes more economically viable to choose DC over AC, as represented in Figure 8 which shows the cost of AC vs DC against distance for overhead lines. Once the distance exceeds 600km it becomes more cost-effective to choose DC over AC, but when considering subsea cables this changes to around 50km.

Figure 8: Breakdown of Onshore AC and DC Transmission Costs: Build, Line, Terminal, and Losses (D.M. Larruskain, 2005)



The choice of AC versus DC relies entirely on the distance required. If the distance is relatively short in an area where the AC infrastructure is deeply integrated it is more cost-effective to proceed with an AC circuit, whereas if the application calls for a long-distance cable where the AC losses become prohibitive a DC circuit will be more viable.

From a review of the completed and under construction offshore wind farms in the UK, the majority are AC, with the offshore part ranging from 15km up to 120km in length, with DC projects above 120km. This appears to be the cut off as to whether AC or DC is more economically viable, however potential plans to create an offshore European DC network may influence this balance in the future.

The AC offshore windfarm projects typically are 132kV up to 220kV cables, with the underground onshore section ranging from 5km to 35km in length. However, a project in planning with 275kV AC is known to have up to 60km of onshore underground cable route. For DC offshore windfarms, the onshore underground length ranges from 5 to 50km. The DC projects place the converter station relatively close to the grid substation so the majority of the underground cable route is in DC, with a short (0.1km to 5km) section of AC to connect the converter station to the grid substation.

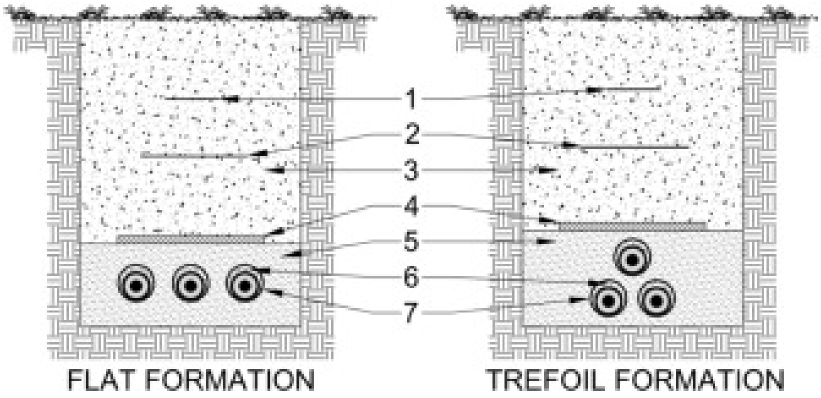
Where the windfarm transmission cable is AC, the onshore section will always be AC whether overhead or underground as this is most cost-effective. However, where the windfarm cable is DC, a large proportion of the onshore section to the substation may be undergrounded in DC.

4.3 Cable Installation

Trefoil vs Flat

There are typically two different configurations for burying cables: flat or trefoil formation (for AC only). Flat cable formation consists of laying single-core cables in a parallel plane, with equal spacing between them. In contrast, trefoil cable formation arranges three single-core cables so that they form an equilateral triangle, with each cable equidistant from the others. Effectively a flat formation spreads the cables out, while trefoil bundles them tightly together, as shown in Figure 9 (Paweł Ocłoń, 2015). This is most significant for buried cables (cable plough or HDD), but also has implications for internal spaceproofing requirements for microtunnelling.

Figure 9: Flat vs trefoil formation (Paweł Ocłoń, 2015)



Trefoil Advantages:

- The close grouping of the cables helps the magnetic field of each cable cancel each other out, reducing the magnetic field as a whole and consequently reducing cable losses.
- The symmetrical arrangement of the cables minimises eddy currents induced in the metallic sheaths/armour. This reduces the induced voltage in the metallic sheaths/armour and therefore improves the efficiency of the cable
- The trefoil formation requires a narrower trench which is easier to dig reducing installation costs.

Trefoil Disadvantages:

- As the cables are so close together this worsens the heat dissipation for AC circuits, making the soil's thermal resistivity a key factor. To achieve the required ampacity for a project, larger or additional cables could be required.
- Installation using the trefoil method is more complex leading to increased labour costs.

Flat Advantages:

- Better heat dissipation due to additional spacing of the cables.
- Quicker to install as the cable are laid next to each other.

Flat Disadvantages:

- The flat formation requires a wider trench or multiple trenches.
- The cables are further away from each other increasing electromagnetic fields.
- There will be larger induced eddy currents in the metallic cable sheaths leading to a decrease in efficiency.

Backfilling

Cable backfill is the material used to surround and cover buried cables within a trench, tunnel or duct. Backfill can be either native soil or engineered materials like sand or cement-bound sand (CBS). Cable backfill is used for thermal dissipation, which can increase the efficiency of AC circuits, reducing cost, and for mechanical protection from damage during installation, as well as reducing cable pressures, stress and preventing damage from rocks and debris over the cable lifetime.

There are three main types of cable backfill: native soil, sand-base backfill and fluidised backfill, which are chosen based on the project requirements. Whilst using a properly designed and installed backfill typically incurs a higher upfront cost compared to native soil, it offers several significant advantages. These include a substantial improvement in the AC circuit current-carrying capacity due to the backfill’s low thermal resistivity, lower electrical losses that lead to cost savings over the cable system's lifespan, and effective protection against moisture migration or soil drying, due to its excellent thermal stability.

Research was conducted (GSES, 2021) to assess how using backfill affects the cabling cost. This research was conducted on a 1600A circuit with 4 circuits of 400V cables in parallel using thermal modelling and simulations, and the results of this research are presented in Table 3. While this study won't be perfectly reflective of the high voltage cases considered for this study, it provides useful insight into the impact of the ground conditions on cable performance.

Considering only the material costs, Option C with 200mm layer of bedding sand is the most cost-effective. Additional considerations for this option include the freight and storage of the thermal sand and the plant equipment required to move and install it.

Table 3: Backfill effects on cabling cost (GSES, 2021)

Option	Description	Approximate Extra Cost (including bedding sand, cables and conduit)
A	Install no thermal bedding sand, just add more parallel circuits: 3x additional parallel circuits are required	£297/m
B	Install a 50mm layer of thermal bedding sand, add more parallel circuits: 2x additional parallel circuits are required	£202/m
C	Install a 200mm layer of thermal bedding sand and then add more parallel circuits: 1x additional parallel circuit is required	£112/m

This has implications when comparing buried methods, including cut-and-cover, cable ploughing and HDD for AC circuits. It is claimed that cable ploughing can bury cables with a specified backfill (Thomas, 2024) in flat formation but not trefoil, but can be costly and that increasing the size of the cable can achieve the same result and avoid the need for backfilling. As the conduit which the cable sits within is pulled directly into the ground for HDD, no backfill will be possible, so the size of cable may have to be increased, or additional cables could be required to account for this compared to cut-and-cover or cable ploughing. To counter the increased thermal resistivity from the less favourable variable ground in HDD, the conduit is often filled with water or bentonite.

Cable sizing

A significant contributor to increased cable costs is cable oversizing. Oversizing involves selecting cables with capacities that exceed the minimum thermal and electrical requirements to reduce energy losses and improve safety margins. Although this design strategy can enhance long-term operational efficiency by lowering energy losses and mitigating thermal issues, it also drives up material and installation costs. While cable oversizing offers technical benefits, it underscores the critical trade-off between upfront capital expenditure, and future cost savings in the context of the operational cable system design.

Cable Materials

The main role of cable insulation is to safely separate the electrical conductor from its surroundings to prevent potential hazards, maintain efficiency and increase cable lifespan.

High voltage and high current cables require more insulation, particularly when buried underground versus in a tunnel. The following are the current insulation materials available:

- PVC – used in low voltage applications due to its low cost, flexibility and adequate insulation properties.
- XLPE – the most widely used insulator for low voltage (LV), medium voltage (MV), high voltage (HV) and extra high voltage (EHV). It has very good electrical properties with high-temperature resistance and a long lifespan.
- EPR – a rubber elastomer used for medium to high voltages it is used when high flexibility is required, however, it does not have the same standard of electrical properties as XLPE.
- PPL/MIND – There are several paper and fluid-insulated cables currently in the network however these were installed mainly in the 1970s and are no longer being installed

For extra high voltage (EHV) applications screening layers are included to manage the electric field distribution and reduce electrical stress, which consist of metallic or semi-conducting screens both inside and outside the insulation of the cable. HV and EHV cables have complex multi-layer construction consisting of a conductor, an inner semiconducting layer, the main insulating layer (XLPE/EPR), an outer semiconducting layer, a metallic screen and an outer protective jacket.

It is also important to note that underground cables need additional considerations such as moisture protection (water-blocking tapes, specialised outer jackets, or impregnation techniques to prevent moisture penetration), mechanical protection and thermal protection, when comparing to those within a concrete tunnel.

The cost of cable joints and terminations is a significant component of the overall cost of underground cable systems. Joints and terminations are required at regular intervals due to manufacturing and transportation constraints on cable lengths (typically 500–1,000 metres per drum for HV cables). In (CIGRE, 2021) the feasibility and challenges of using longer AC underground cable sections in high-voltage transmission systems (up to 500kV) are explored. The report highlights that advancements in XLPE technology (improvement in the thermal and mechanical properties of cables) now allow cable manufacturers to produce lengths of up to 2,000 metres. This would reduce the number of joints and joint bays required and the associated costs over longer distances.

Using advanced solutions such as pre-moulded cable joints can shorten installation time and enhance reliability, ultimately reducing overall costs by minimising labour costs. In larger cable systems, this approach can significantly lower the costs associated with jointing cables to establish the network. Techniques like HDD allows for longer cable pulls, reducing the number of joint bays and terminations which can decrease civil works costs and labour costs more favourably compared to direct buried methods.

4.4 Cable Requirements Summary

A summary of the cable requirements for the direct buried undergrounding methods is provided in Table 4, and covers the requirement for HVDC cables, except that DC cables (unlike AC) do not require separation.

Table 4: Cable requirements summary for direct buried underground methods

Voltage	Cable ploughing 275kV	Cable ploughing 400kV	HDD 275kV	HDD 400kV
Conduit size (diameter)	200-250 mm	250-300 mm	200-250 mm	250-300 mm
Depth below ground (minimum)	1.4-1.5m	1.5-1.6m	3m (ground stability requirement)	3m (ground stability requirement)
Separation	300mm	300mm	300mm	300mm
Backfill possible	Yes, but not trefoil	Yes, but not trefoil	No	No
Maximum cable length	0.5-1km	0.5-1km	1.5-3km	1.5-3km

5. Literature Review Assumptions and Exclusions

The following assumptions and exclusions developed for the study through the literature review are summarised below:

- The only cable insulation considered for this study is XLPE due its low maintenance properties, being a requirement for cables directly buried in the ground with limited access via joint bays.
- Pipejacking will only be considered as an option for cable crossings under sensitive infrastructure and for specific geological conditions (i.e. hard rock and boulders).
- As per Table 4 it is assumed that direct buried cables will typically be 500-1000m, but special cases can be made for longer HDD bores. For the cost assessment it is assumed that the cable length between joint bays will be 800m.
- The study is limited to 275kV AC, 400kV AC, and 400kV DC cables.
- Personnel access tunnels are excluded from this study as these are proven to be more costly than cut-and-cover.
- The length of underground cable route considered for this study is limited to 20km and 50km. Shorter routes are excluded.
- Direct buried methods such as cut-and-cover and cable ploughing will require other trenchless methods such as HDD to complete a route.
- The cost of DC undergrounding with and without converter station costs will be included in the cost comparison for the undergrounding methods.

6. Literature Review Conclusions and Gap Analysis

This section presents the conclusions from the literature review and the gap analysis that informed the evidence required through interviews with specialist cable suppliers and installers for the next stage.

6.1 Conclusions

New emerging undergrounding methods were identified, and a literature review was performed to assess these methods against key criteria, including capital cost, technical feasibility, minimising impact and whether it can deliver a complete solution. The literature has identified information and claims about the undergrounding methodologies and the impacts of the cable technologies on these methods. The assessment compared cut-and-cover as a baseline and identified Cable Ploughing, HDD and Microtunnelling as having the most potential for reducing costs over long distances.

Cable ploughing claims the potential to reduce costs significantly compared to cut-and-cover while minimising the impact on landowners. It claims to being able to install 400kV cables at 1.5km per day in a reasonable range of ground conditions with methods possible to break out rock if encountered. While cable ploughing may be cheaper per metre in isolation, the number of obstacles that the cable plough cannot cross needs to be factored in, as does the geology and terrain (such as forested areas) that could be a limiting factor for its potential use.

HDD has the potential to be a fast and cost-effective method of burying pipes directly in the ground over increasingly long distances (>4km) as further innovations in HDD emerge. It has the advantage of using relatively simple machinery, can launch from the surface and can work in a wide range of geological conditions. Depending on the cable voltage and size required, multiple tunnels may be required for a single circuit. Some geotechnical risks were identified such as hydrofracture and difficulties dealing with variable conditions (e.g. gravel, and boulders) which will need to be qualified during interviews with the specialist HDD contractors.

Microtunnelling provides a different option in which the cable is not buried but placed within a tunnel. The advantage is that the majority of geotechnical conditions can be handled, and the ground is well supported during construction. Several cable arrangements can be housed within a single tunnel for up to 400kV cables. There are additional costs borne in setup through launch and reception shafts, and intermediate shafts for drives greater than 1km, and they become less viable over 1-2km compared to traditional TBMs. The microtunnelling TBM is more complex and costly than the other shortlisted methods but offers a proven tunnelling methodology that may be the only option for cable installation beneath sensitive infrastructure and environments.

6.2 Gap Analysis

To build up a comparative analysis of build costs of the shortlisted methods, the gaps in information were identified and are presented in Appendix A1. These gaps were filled through interviews with cable suppliers and installers to build a full picture of the build costs of these methods. Specific scenarios were developed to inform how cable voltages, route length and environment impact on costs and what savings are possible over longer distances. In addition to this, the non-cost benefits and disbenefits for environment, energy security and deliverability were interrogated to provide a further context to the qualitative assessment of the undergrounding methods.

7. Specialist Engagement

Interviews with specialist cable installers and suppliers were conducted with the primary focus on the comparative cost and technical feasibility of potential undergrounding installation methods for transmission cables ranging from 275 kV up to 400 kV, including both AC and DC circuits. Industry challenges such as cost variations, regulatory compliance, and environmental concerns were also covered by the interviewed experts.

7.1 Cable Ploughing

Introduction

Cable ploughing contractors were interviewed who have installed low to high voltage cables in short and long distances. This covered the company's experience in large-scale energy transmission projects, particularly involvement in underground cable installation projects across the UK and mainland Europe.

Experience included the installation of high-voltage circuits, namely 132kV, 220kV and 400kV. While 400kV projects were rare, one project was identified which involved a 400kV circuit in a trefoil formation. It was acknowledged that asset owners tend to explore other installation methods (OHL and cut-and-cover) before considering cable ploughing for 400kV projects. It was claimed that, although clients tend to support innovative ideas that can reduce the overall cost of the project, large principal contractors tend to prefer cut-and-cover as a construction method they are familiar with, with any increase in costs passed to clients.

In the Netherlands, carbon footprints and dewatering issues led clients to instruct principal contractors to adopt cable ploughing as the installation method. Clients tend to recognise advantages in cable ploughing and consider it to be the preferred solution in subsequent projects.

Technical Insights

As part of the qualitative assessment carried out in the present study, cable ploughing was considered one of the installation solutions with the highest potential to reduce costs.

Standard advancing rates are approximately 1500 m per day, which is typically achieved within a two hour period. The remaining time is an allowance for interruptions, loading the pipes into the ploughing equipment and other setting-up operations. In large-scale projects, contractors may use three ploughs simultaneously, increasing the construction speed up to 4.5 km/day.

The installation of a trefoil formation has some inherent complexity. The three cables are inserted into the ground in separate chambers linearly arranged along the ploughing blade to prevent disturbing the top layers of the ground. The cables are arranged in a trefoil formation underground by the equipment. In a flat formation, a 1.5m separation is required between slits. In DC circuits, cable pairs can be installed in the same trench with a separation of up to 600-700mm between each circuit. Beyond that two separate slits are recommended.

132kV is typically installed in trefoil formation using 200mm diameter pipes. 275kV can be installed in a trefoil or flat formation, while 250mm diameter pipes are required for 400kV cables. For AC circuits, the designer may want to increase the cable sizing in order to avoid the need to have sand backfill (e.g. in a 132kV project, the cable size can be increased from 1600 to 1800mm2), increasing the speed and reducing the cost of the installation.

Direct cable installation (without outer ducting) is generally adopted for medium-voltage circuits, e.g. 20-66 kV. Ploughing high-voltage cables directly significantly increases the risk of cable damage, and stakeholders are typically not willing to assume liability for the potential costs. Ducting pipes are easily cut, repaired and assembled at interruptions (e.g. at a connection to a drilled section). The ducts also allow cable replacement in the event of a failure. Ploughing 275kV directly is feasible but not recommended. The cables are stiff, slowing down the installation, involving a 3-day set up operation to perform a 1-km plough within just a couple of hours. A 5-km long circuit would require 4 weeks to be installed, as opposed to 1.5 weeks in the case of using ducting.

Pipes are often pressurised during cable installation, with SDR11 (180mm) or SDR17 (250mm) pipes typically used. The client specifies whether they want PE100 (virgin material) or PE80 (recycled material). However, depending on the project lifespan, PE80 may raise durability concerns.

MDPE pipes can be pressurised to enable cables to be hydro-pushed from end to end, achieving distances of about 6 km. This is a major advantage in large projects where difficult ground poses access constraints to large cable drums. Torpedoing technique (a mixture of open cut and directional drilling) allows the installation of cable ducts at depths of about 1.2 to 3m. Cables are then pushed through the duct from where the joint bays are to be located.

By adopting adequate cable allowances, it is possible to install cable ducts with constant covers through ploughing whereas HDD requires consistent ground, which typically require a working depth from ground level of 5 to 10m depth, where heating of the circuit is of more concern. Cable ducting is required for high voltage cables which also provides mechanical protection.

Covers of 1.8m allow for the trenchless installation of drainage systems, typically running 0.6-1.2m deep. It is possible to lay additional communications ducts, such as 60 mm fibre optics, along with the transmission cables in the same ploughing operation.

Outside the urban environment, it is claimed that the average interruption occurs every 800-1200m for various reasons such as major roads, railway lines, gas pipes, electric cables, other utilities and watercourses. Some projects undertaken have had interruptions as low as one every 5km.

Pre-ripping is rarely needed. Ploughs can be attached with up to 2 winches to increase force development to 360 tonne-force, which is sufficient to go through most firm ground conditions. Under more regular conditions, this tractive force allows ploughing up to 2.5-2.8 m deep.

The ploughing method allows for quicker reinstatement, with topsoil replacement included but additional seeding and landscaping costs not accounted for by the cable ploughing contractor.

Limitations

Ground Conditions:

- Optimal in sandy, gravel, and arable land.
- More challenging in clay, shallow bedrock, and rocky terrains (possibly requiring pre-ripping).
- In extreme cases, hard rock excavation by other means may be required, adding significant costs.

Obstacles & Special Considerations:

- Crossings: Typical interruption every 1km (road, river, railway, or gas pipeline crossings) requiring trenchless or cut-and-cover methods.
- Environmental: Restrictions in nature reserves and wetlands, with increased planning requirements.
- Urban vs. Rural: Rural projects allow for more straightforward ploughing; urban environments require more frequent interruptions.
- Cover requirements are often based on cable design, but also minimum requirements based on standards such as National Grid TS 3.05.07, which specifies a minimum cover of 0.9m in good agricultural land. It was stated during the interviews that total depths of up to 1.8m can be required to allow for drainage systems above the cable in arable land.

Cost Scenarios

Costs are provided as a cost per metre for installing the polyethylene (PE) pipes, which are typically 250mm or 300mm in size. The cost for installing a circuit with three pipes in flat formation requiring three separate trenches is typically around 30% more expensive than installing three pipes in a single slit in trefoil formation.

The project length significantly impacts on cost with larger projects benefitting from economies of scale. As an example, the per-metre costs of installation of 400kV circuits in trefoil formation in distances less than 1km can be more than 2 to 2.5 times the cost of installing them over 20 to 50km.

Additional costs include the materials (cables and outer ducting) and their supply, handling and duct welding on site. Although drilling companies often have these resources in-house, plough contractors rely on third parties for these operations.

Backfilling of cables or ducts may also significantly impact on costs. Beyond the material cost, backfilling creates some operational and logistical problems. In 400kV ducted installations, the 250mm ducts occupy most of the 500mm width of the ploughed trench, hindering the pouring operation around the installed pipes. In addition, the logistics of supplying cement-bound sand (CBS) to the ploughing machine may imply the construction of haul roads.

The adoption of an increased cable size usually pays off by waiving the requirement for bedding, and its implications on costs and time of installation.

Table 5: Cable ploughing cost summary

Method	Comparative cost per slit	Speed (metres/day)	Additional Considerations
250mm pipe in flat formation (3 No. cables)	Cost for 20km route 20% more than 50km	1,500 m	Slower and more onerous than trefoil.
250mm pipe in trefoil formation	Cost for 20km route 20% more than 50km	1,500 m 4,500 m	Bedding not possible If 3 ploughs simultaneously
Pre-Ripping	50-60% additional cost per metre	-	Required in hard ground conditions
Bedding Material	50% additional cost per metre	-	Increases cost, adds logistical challenges (does not include haul roads etc.)
Hard Rock Excavation	200-300% additional cost per metre	-	If excavation is needed before ploughing
Crossing Preparation	One off cost for preparation	-	Depends on ditch or minor water crossing

Typically, interruptions do not affect advance rates, as these are already accounted for in the standard daily rates.

In rocky terrains, pre-ripping may be required. An additional passage is carried out, ploughing down to 60-70% of the final trench depth. In extreme ground conditions, excavation by other means may be required adding significant costs. As an example, if a 30-tonne excavator equipped with a ripping tooth is required, the additional cost per metre can be as much as 2-3 times.

Ploughing through wet areas (marshland and ditches) involve additional costs with preparation works. Preparation works for a ditch is cheaper, while larger shallow-sloped rivers of depth not exceeding 1.8 m are 4 times the cost. Environmental assessments may also be legally required.

Additional Cost Factors:

- Materials supply – costs with cables and ducting as well as their transport to site are not included in installation rates.
- Ploughing depth – installation of cables deeper than 2 m increases rates by approximately 15%.
- Bedding supply – depending on ground conditions, the provision of bedding to site may require the construction of haul roads, which significantly raises costs.
- Soil reinstatement – included in the standard rates (reinstatement to a reworkable status, excluding any re-seeding of agricultural fields).
- Plough mobilisation & maintenance – included within per-metre rates.
- Contingency planning – unforeseen delays and environmental restrictions require buffer budgeting.

Innovations

Recent advancements and methodologies improving efficiency in cable ploughing include:

- Ductless direct laying (for <132kV cables) – reduces material costs but increases risk of damage.
- Hydraulic pulling for long distances – used in international projects, allowing cables to be pulled over 6km at once, reducing jointing costs.
- Winch-assisted deep ploughing – enhances the ability to lay cables in difficult ground or to increase ploughing depths up to 2.8m in regular ground conditions.
- Alternative backfilling methods – eliminating need for thermal bedding by upsizing cables, as seen in UKPN’s 132kV project.

Summary

Cable ploughing presents an efficient and cost-effective method for underground transmission cable installation, particularly in rural and arable land settings. While cost reductions can be achieved for larger-scale projects, limitations in ground conditions and regulatory requirements must be carefully managed. The method offers significant benefits in reducing disruption and installation time but may not be viable in more urbanised areas and becomes less cost effective where strict sand backfill requirements exist. Continued innovation in equipment and installation techniques will further enhance its feasibility for large-scale deployment.

Pros:

- Cost-effective over long distances compared to cut-and-cover.
- Fast installation speeds with minimal surface disruption.
- Environmentally preferable in certain contexts (some clients mandate ploughing due to carbon footprint considerations).
- Can potentially reduce the need for heavy civil works and temporary access roads.
- Flexible in handling a variety of ground conditions.
- Lower per-metre cost for large-scale projects.

Cons:

- Limited effectiveness in urban areas due to frequent obstacles.
- Pre-ripping may be required in certain terrains, adding cost.
- Strict client specifications (e.g. mandatory bedding) can negate cost advantages.
- Depth requirements may necessitate additional equipment or slower speeds.
- Some projects require trenchless crossings or excavation work, increasing complexity.

7.2 Horizontal Directional Drilling

Introduction

Specialised contractors in Horizontal Directional Drilling (HDD) were interviewed who have installed cables and other underground utility pipes, including short and long distance trenchless cable laying.

Industry challenges discussed include regulatory compliance, environmental constraints, rising material costs, and the need for skilled labour. HDD can be an economically viable trenchless solution for infrastructure projects which require crossing under major infrastructure.

The interviewees had extensive experience in onshore and offshore drilling projects, including:

- Seagreen Offshore Wind Farm which included 114 wind turbines. The construction of a 19-km underground connection from the landfall site to the substation at Tealing required multiple HDD crossings (where open trench methods were unfeasible), including Sites of Special Scientific Interest (SSSI) with protected native species, crossing a double-track railway line and several roads. Three circuits (9 lines) of 220kV were installed with 3-m spacings in between HDD bore holes. Each individual cable was pulled from the entry pit through 200 mm pipes. Under the rail line, Network Rail imposed 8 metres clearance under the rail head (to limit the settlements).
- River crossings: The Paraguay River Crossings is one of the longest HDD crossings with a length of 1500 m, 30 m below the lakebed.
- Geothermal drilling: Numerous projects in Europe supporting renewable energy projects with HDD expertise.
- Oil & Gas projects: Construction of wells reaching over 9000m step-outs using Extended Reach Drilling (ERD).

Technical Insights

Underground transmission installations through HDD normally use slant rigs, reaching up to 1500-2000m in length at 30m depth.

The longest known onshore drill using HDD is about 4.2km long. It was constructed in Mumbai, India, with two 500-ton rigs operating simultaneously, entering the ground from the two borehole ends and intersecting at mid distance. In the Oil & Gas (O&G) industry vertical or slightly angled drills using ERD can reach about 10km in length.

Bentonite slurry (along with some additives) is used during perforation for the borehole stability, cooling and friction reduction (such as Soltex). Most of the additives utilised at present are relatively environmentally friendly, without needing to be disposed of separately and being typically approved by local authorities for this type of construction. Due to environmental regulations oil-based muds are being replaced by water-based muds but drilling efficiency decreases. In addition, they are more reactive with clay-type formations that are often found in relatively shallow HDD environments.

Although onshore HDD rigs are smaller than those operating in Extended Reach Drilling (ERD) hence having less pushing capacity, it is possible to attach and pull a reamer through the pilot borehole to enlarge it, whilst pulling through the transmission cables or other utilities ducts in the same process.

High-voltage transmission lines are installed inside conduits, which are pulled into place during reaming. Fluids used in the perforation might be used to lubricate the conduit pulling and the cables themselves.

In the UK, smaller capacity HDD rigs allow for an advancing rate of 5-15m/hour at depths up to 8m. Larger HDD rigs, drilling at 30m depth through rock strata commonly found in the UK, allow for advancing rates of 30m/hour (except for granite formations that can slow down the process). When obstructions are encountered, the rig is pulled back and a deviated route is attempted to avoid the unchartered obstacle.

The borehole can be fluid pressurised to limit settlements to levels compared to those obtained with microtunnelling.

Limitations

Ground Conditions:

- Rock formations, clay, and sandy soils impact drilling speed and equipment wear.
- Medium-sized rigs (300-400 ton capacity) can operate in hard rock formations but the drilling speed is slower. Mudflow and other devices can be used at the drilling head to increase power and efficiency.
- Larger rigs (used in the O&G industry) have drilling heads with increased power and rotation speed.

Obstacles & Special Considerations:

- Crossings: underground utilities, water bodies, and highways require careful planning and precise bore path design.
- Environmental: projects near environmentally sensitive areas must comply with additional regulations.
- Urban vs. rural: urban projects face higher costs and regulatory hurdles, whereas rural projects often involve longer distances but fewer logistical challenges.
- Regulations: planning permissions, environmental assessments, and safety regulations vary by region, influencing project timelines and costs.
- Demand: 500 ton rigs are few in number globally, 300 to 400 ton rigs are more common but currently in high demand.
- Cables weight: Typically only flat formation installation is considered. Heavy cables (with copper cores as opposed to aluminium or carbon cores) are more difficult to be pulled back through the borehole. Weights of up to 30kg/m are common, but 40kg/m are considered heavy.

Cost Scenario

The cost of high-capacity rigs (mostly used for offshore HDD tie-backs) is highly affected by global availability and demand. The renting of a full-size rig imported from Europe to the UK would cost about £30,000/day (including drilling tools and crew). Additional associated costs (e.g. mud chemicals and mixing system, medic at rig site, site manager, security) would be another £30,000/day.

Smaller-sized rigs (up to 100-ton capacity) are typically rented with a crew of 3 people for £2500-£4000/day. They usually operate at about 6-8m depth and can achieve lengths of 150-300m. Typical crossings include motorways, railways or water ditches.

Medium-sized rigs (300–400 ton capacity) are typically rented with a crew for £8000-£10,000/day. They can operate at 30m depth and achieve lengths of 1500-2000m. Most of these rigs are operating in large onshore-to-offshore projects (in onshore-only projects they can be used to cross large rivers, to go underneath poor ground or deep assets – being required to launch from further distance).

Larger rigs have higher setup costs but lower per-metre drilling costs over long distances.

Monitoring instruments (downhole sensors, magnetic instruments, gyro instruments and gamma-ray sensors, with signals that can be emitted by Bluetooth) are permanently present close to the drilling head to assist with the steering operation. Monitoring equipment costs about £700-£1000/day (£1200-£1400/day if the operator is included) but is typically included in the standard drilling price.

Demand for drilling equipment is currently high due to geothermal drilling in Europe. Due to the war in Ukraine and environmental policy, the European governments are giving large subsidies to industry and farming cooperatives owning greenhouses to construct private geothermal wells and reduce dependence from imported gas.

Pricing can vary from meterage rates to bulk price for the entry-to-exit work including a time period from entering to the exit day on site. The latter are more common in projects up to 2km long, comprising small crossing works integrated as part of larger schemes. In large projects, there might be specified site preparation contractors responsible for the setup and reinstatement of the construction site and pits, which is then excluded from the HDD quotation. HDD companies usually offer full-package services.

Typical project prices can generally amount to £100,000 for the mobilisation and operation of a small rig over 30 days. Site preparation, fencing and security and other welfare site elements may double the price to £200,000 depending on the size of the project.

The cost of increasing the conduit diameter is not proportional to the increase in the reamer diameter. An increase in diameter may represent a 10-20% increase in the per-day cost when comparing a smaller hole size.

Nominal pilot bore sizes of 0.10-0.20m diameter can be drilled by small rigs. Bores of 0.30m are achievable with 200-300 ton rigs. The reamers can reach 0.50-0.75m diameter increasing the price of the rig by 10-20%. It is the rig capacity that governs the construction price. Back reaming large diameters increases friction and the required torque to reach the exit point. In India, 4 km-long boreholes were successfully built with 300mm diameter. Larger diameters require more back reams, impacting on construction time. However, doubling the diameter will not take twice as long as the construction time of a smaller borehole but typically only 20-30% more. Diameters up to 1.25-1.50m are achievable. Typically, a borehole of 300mm diameter would take 5 days to drill, ream, swab and pull the PE pipe through.

Table 6: HDD cost summary

Cost Component	Cost Range	Speed (metres/day)	Additional Considerations
Small rig (up to 100 ton)	£2500-4000/day	Up to 120m per day	Common up to 300m. Includes mobilisation, fluids and crew of 2-3 members
Medium rigs (300–400 ton)	£8000-10,000/day	Up to 240m per day	Common for 1.5 km drills
Large rigs (500 ton)	£30,000+/day	No data	Scarce, highly affected by global demand
Monitoring instrumentation	£700-1000/day (+£400/day for operative)	-	Usually included in drilling cost
Reaming & pullback	+10-20% of drilling cost	-	Enlargement of borehole to increase diameter
Rig Maintenance & Repair	Variable, depends on wear	-	Included in project budgeting
Mobilisation & Site Setup	£50,000-£200,000	-	Includes equipment transport and setup, groundworks, fencing, and welfare facilities

Sleeving the ends (due to non-consolidated gravel or poor ground) can reach 25-30m depth, but it has a small impact on cost and time. Usually, installation and grouting are complete within 2 days, being priced at standard rates.

Although the exact cost per metre depends on soil conditions, depth and obstacles, HDD was stated to be significantly more expensive than open-cut trenching. Nonetheless, there is potential for cost reductions through economies of scale, effective risk management, and equipment longevity strategies. Notably, if 4000-6000m lengths become achievable, savings with work site, entry and exit pits, less site preparation and rehabilitation could be possible.

Additional Cost Factors:

- Seasonal weather – aspects such as wet or dry conditions affect costs (construction work during November-January requires additional site preparation fees that are not necessary in May-July).
- Urban projects – require more site security and traffic management, adding to cost.

Innovations

Recent advancements and methodologies improving efficiency in HDD include:

- Improved drill head designs: expertise in drilling fluid optimisation and high-speed drilling motors for hard rock.
- Automated guidance systems: increased accuracy and reduced human error.
- Eco-friendly drilling fluids: minimized environmental impact.
- Remote monitoring: real-time performance tracking to optimize operations.
- Long-distance HDD: integration of O&G technologies into HDD to improve performance and cost efficiency and reach over 4km using intersection drilling techniques.
- Joint HDD projects: combination with cable ploughing reduces reliance on HDD for the entire route.

In the O&G industry, the larger rigs may potentially be used in HDD extending over distances of about 8 km. However, wider and longer drills require larger site setups and more mud usage, impacting on environment and posing planning permission concerns. Conventional sites require about 200m2, which would potentially reach 10,000m2 to accommodate larger mud pits and other needs.

Manufacturers of larger rigs are operating to deliver newly built equipment with increasing capacities (400 to 500 ton) in order to break the 4,000m limiting distance in HDD.

Summary

This section highlighted the key factors influencing HDD projects and provided insights into cost considerations, technical challenges, and industry innovations. The findings emphasize the importance of proper planning, risk assessment, and leveraging technological advancements to enhance efficiency and reduce costs.

The length and speed of HDD projects vary depending on soil conditions, pipe diameter, and project complexity. Typical drilling speeds range from 100 to 300 metres per day (up to 2000m/day with larger rigs), with longer distances requiring additional planning and contingency measures. While urban projects may face restrictions due to site constraints, traffic and existing underground utilities, rural projects often allow for faster execution.

Factors affecting cost per metre:

- Economies of scale: longer distances reduce per-metre cost.
- More HDD crossings increase mobilisation and site preparation costs.
- Complex geotechnical conditions (e.g. hard rock) increase costs.

Pros:

- Minimal surface disruption compared to open-cut methods.
- Feasible for complex and environmentally sensitive projects.
- Cost-effective for long-distance pipeline installations.
- Reduced permitting and traffic disruption particularly in more urban areas.

Cons:

- Higher upfront costs compared to conventional trenching.
- Sensitive to ground conditions, requiring detailed geotechnical studies.
- Equipment maintenance and repair costs can be significant.
- Equipment and skilled labour shortages in some regions may impact project timelines.

7.3 Microtunnelling (Pipejacking)

Introduction

Manufacturers of pipejacking machines and specialist pipejacking contractors were interviewed. The interviews covered the company experience in pipe jacking, the use cases for high voltage transmission projects, the comparative costs against other undergrounding methods, and current innovations such as the Direct Pipe and E-Power Pipe, as well as future innovations.

Industry challenges discussed included regulatory compliance, environmental constraints, rising material costs, and the need for skilled labour. It was acknowledged by the interviewees that traditional trenched methods were significantly cheaper than microtunnelling. It would likely only be considered for major crossings where a trenchless solution is required, and when HDD is not possible due to geotechnical considerations.

Technical Insights

Pipejacking is common for shorter tunnels (up to 100-200m) but has limitations due to increasing pipe weight and high jacking forces, which require the use of interjacks for lengths greater than approximately 100m. In the UK it is typical for the maximum pipe jack size to be 2.4m ID, and historically, there is some reluctance in adopting large diameters over long distances for pipejacking. Commonly, segmental lined tunnels have been used for tunnels of over 3m ID, but there is resistance in using such sizes in pipe jacking. In the Middle East, storm water tunnels have been built of 3.6m ID with 3-4m long pipes using a pipe jacking machine. The reason for this is mainly related to pipe handling and logistics in the UK. In addition, contractors usually own aged segmental lining machines in plant yards close to London that operate effectively in London Clay, and they try to make use of them on new projects. However, machine regulations have evolved, and for example there is now a need for larger walkways, so it has become difficult to maintain 3.0m-diameter lining machines of this type. Recent National Grid projects have adopted larger diameters, such as Snowdonia at 3.5m ID and Tilbury at 4.0m ID.

Ground conditions are usually what dictates the use of a pipe jacked tunnel over HDD for trenchless crossings. Typically gravelly rocky ground and the presence boulders can push the need for a microtunnel. It was stated that typical MTBMs available in the UK can bore through rock with a UCS strength up to 200MPa. Additionally, in a SSSI, HDD as a method may not be approved due to the risk of frac-out, so a traditional tunnel or microtunnel may be necessary.

Pipejacking is a proven construction methodology worldwide with case studies of its use in various sectors. It was stated that Direct Pipe has over two hundred reference projects, however it is hard for the manufacturer to follow as after the rig is sold, they may not be privy to the details of subsequent projects it is used on. It was stated that Direct Pipe is good for outfall for windfarm projects and was used recently in the Beatrice windfarm project for this purpose, as it can be launched from a shallow pit at the surface but has the benefits of the MBTM to bore through the ground and support the tunnel face to reduce settlements. However, it requires a large amount of space for storage and crane logistics and the long pipes are much more specialised, meaning they are more expensive than a typical 2.5m long concrete pipe used for pipejacking. They are also left in the ground meaning these pipes need to be purchased for each project.

E-Power Pipe is a relatively new technology that was developed for laying high-voltage cables in large-scale projects. The small-diameter conduits are constituted by HDPE pipes pulled back into the borehole, which means that the steel casing used to bore the hole initially before pulling the pipe back through can be reused. HDPE pipes are specified on the outer diameter (rather than on the ID due to installation), and thus a 400mm borehole would correspond to a 360mm ID conduit. The jet pump plays a crucial role since there is no room for several pumps installed in the equipment.

Limitations

Ground Conditions & Obstacles:

- Pipejacking is suitable for any ground conditions but comes at higher costs than HDD.

Special Considerations:

- Underground cables: installation must consider heat dissipation and protection which for high voltage cables will require the tunnel to be a larger open tunnel that needs to be permanently ventilated, so increasing costs, although heat dissipation is a challenge for all undergrounding methods.

Environmental & Regulatory Factors

- Regulations: environmental and safety regulations are becoming stricter, putting pressure on designers, contractors and equipment manufacturers, including requiring larger permanent walkways for personnel within man-entry tunnels.
- Sensitive areas: traditional tunnelling or microtunnelling may be chosen in SSSI where frac-out risks for HDD may be significant.

Cost Scenario

Cost information provided by the contractors interviewed was limited but indications of comparative cost to HDD were provided as at least double the costs of HDD, not including the need for launch and reception pits, see Table 7 below.

Table 7: Microtunnelling comparative cost summary to HDD

Cost Component	HDD	Pipejacking
Mobilisation & Site Setup	Moderate	High
Equipment Maintenance	Moderate	High
Tunnelling	Moderate	High
Launch & Reception Pit	Low	High

It was stated that 1200mm ID pipe jacking machines are very common among contractors, which means that going for a smaller size pipe jack tunnel is not cheaper. This is also because the cost of muck away and concrete is relatively cheap compared to labour and overheads costs such as document and permit delivery.

Shafts in microtunnelling represent a significant part of the costs, particularly when deeper tunnels are required. A typical minimum shaft depth is around 7 m to allow enough cover above surface to launch an MTBM.

Overheads (in particular, document and permit delivery involved) and site labour are expensive components in the construction industry. The average price for operatives is about £400/day.

Trenchless techniques like microtunnelling and HDD can reduce surface disruption compared to cut-and-cover and so be more acceptable to communities.

Innovations

Recent advancements and methodologies improving efficiency in method include:

- E-Power Pipe: a promising technology for high-voltage cables, as it avoids a permanent tunnel lining.
- Control measurement systems: reduce the need for operatives inside the tunnels (e.g., in Direct Pipe).
- AVN machines: can potentially allow construction of a 3m-plus ID microtunnel for approximately 3km length at lower costs compared to segmental construction, whilst mitigating the risks involved in high jacking forces.
- Equipment remanufacturing: Large tunnelling machines can be restored to like-new condition and resold.

Summary

In summary, with regard to selection of an appropriate technology for undergrounding cables: cut-and-cover is traditional, cable ploughing is potentially cheaper if ground conditions are favourable, and HDD remains the most cost-effective solution for crossing obstacles in favourable ground conditions. Microtunnelling can sometimes be necessary for difficult soils and environmentally sensitive areas, and whilst alternatives like Direct Pipe and E-Power Pipe can be useful to solve certain technical problems, they are significantly more costly than a pipe jack tunnel.

Pros:

- Microtunnelling: low surface impact.
- E-Power Pipe: steel casing is removed upon installation of HDPE ducts.
- Direct Pipe: moderate advancing speed. Challenging ground conditions. Low surface impact.

Cons:

- Microtunnelling: slower advancing rates, high upfront cost, equipment wear and jamming, strict requirements.
- Direct Pipe: high upfront cost, high steel permanent casing cost.

7.4 Power Infrastructure Components

Introduction

Cables, reactors, terminations, joints, and joint bays each play a critical role in power infrastructure systems, with specific technical specifications ensuring performance and reliability.

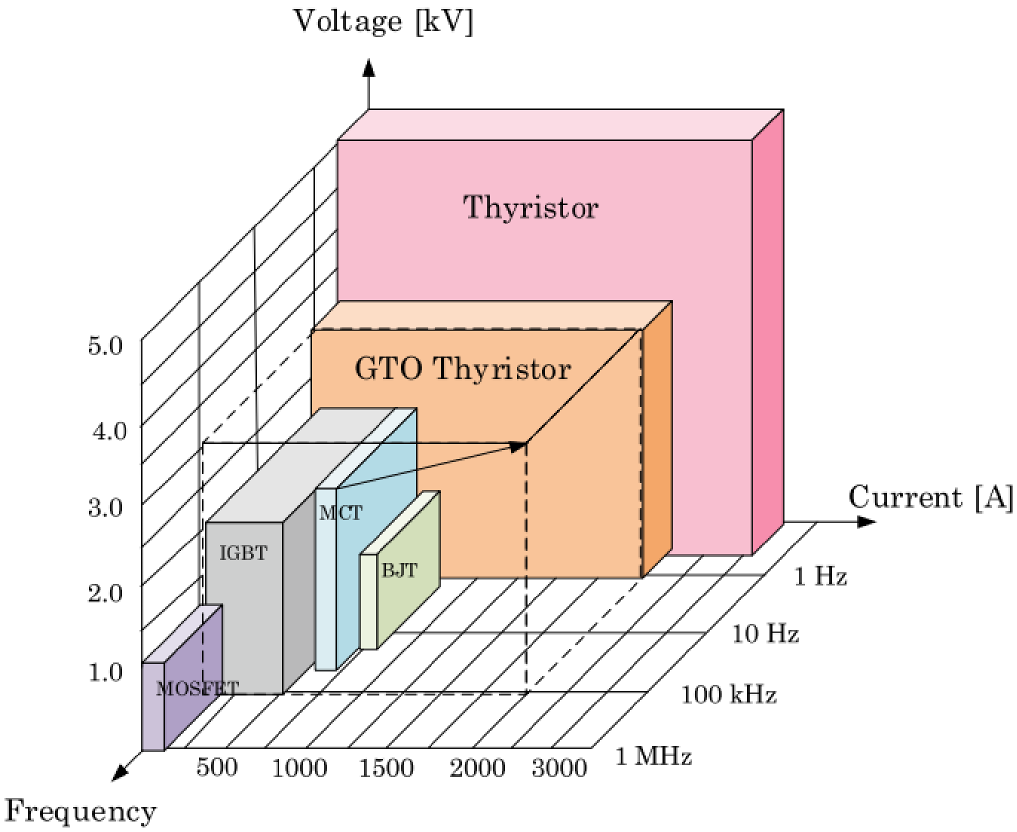
Technical Insights

AC Cables: Standard XLPE Cables, equipped with copper or aluminium conductors and XLPE insulation, offer a current-carrying capacity of up to 1500 amps and can withstand temperatures up to 90°C. These cables are highly suitable for long-distance transmission applications, ensuring minimal energy loss in standard grid configurations. For applications requiring higher capacity and operation in constrained environments with much higher temperatures, High Temperature Low Sag (HTLS) conductors are operational and capable of operating at temperatures up to 210°C to 240°C, significantly increasing transmission capacity. HTLS cables are ideal for high-demand scenarios or areas with clearance constraints, such as lines with heavy ice loads or limited corridor space. Bundling HTLS conductors can further enhance ampacity (e.g. up to 5.0kA for quad-bundle configurations), reduce corona losses, and maintain low sag, though specialized high-temperature fittings and anti-vibration measures, such as dampers and spacers are required for optimal performance.

DC Cables: Line-commutated converter (LCC) HVDC (also known as CSC-HVDC) and voltage-sourced converter (VSC) HVDC systems serve distinct roles in power transmission, with LCC-HVDC excelling in high-power, long-distance applications and VSC-HVDC offering greater flexibility for modern grid needs. LCC-HVDC, based on thyristor technology, is naturally commutated, absorbs significant reactive power, requires harmonic filtering, and cannot connect to weak AC systems, but it supports higher capacities (up to 8,000 MW) and emits losses below 1.5% for two converter stations, making it ideal for bulk power transfer over long distances. In contrast, VSC-HVDC, based on insulated gate bipolar transistors (IGBT), uses power electronic switches, operates up to 2,000 MW, can connect to weak AC systems, provides black start capability, controls active/reactive power independently, uses cheaper XLPE cables and has a smaller converter station footprint (40% less than CSC sites), but it has higher losses (around 2%), making it better suited for applications like offshore wind integration or grid interconnections with frequent power reversal needs.

The choice between LCC-HVDC and VSC-HVDC technologies depends on the outcomes of technical and economic studies that consider various factors. LCC-HVDC networks primarily utilise thyristors, whereas VSC-HVDC networks rely on IGBTs. As illustrated in Figure 10 below, thyristors inherently offer better performance in terms of withstanding higher voltage and current. Additionally, LCC-HVDC is generally preferable in situations that require higher capacity, a simpler transmission network (without multi-terminal configurations), no need for ancillary services, and lower losses.

Figure 10: Maximum characteristics (voltage, current, frequency) of some power semiconductor switches (Gonzalez-Longatt & Rueda Torres, 2021)



Reactors: Shunt reactors, rated at 200 Mvar (megavolt-ampere reactive), are utilised for voltage stability management. These come as air-core reactors and oil filled reactors. For oil-filled reactors, the temperature rise of the top oil during continuous operation at maximum operating voltage should not exceed 60°C, and the windings' temperature rise should not exceed 65°C. In the event of over fluxing, the reactors must remain within allowable temperature limits during continuous operation at 110% of rated volts/Hz, one-minute operation at 125% of rated volts/Hz, and ten-second operation at 140% of rated volts/Hz.

Terminations: Cable terminations, available in both dry-type and oil-filled versions, are designed for voltages up to 400kV and conductor cross-sections up to 2500 mm². They are engineered to function reliably within a temperature range of -40°C to 65°C. These terminations incorporate composite insulators to provide weather resistance and sufficient creepage distance, preventing flashovers in polluted environments. Designed to ensure safe connections of cables to overhead lines or equipment, the terminations feature stress cones for effective electric field management, and comply with IEC 60840, IEC 60815, and IEEE Std 48-2020 standards. Where a cable is terminated and the circuit transitions to an overhead line, a sealing end compound is required. These sealing end compounds typically measure around 30m x 80m for a 400kV circuit and accommodate the necessary support structures for the cable terminations/sealing ends, post insulators, earth switches, and terminal towers.

Joints: Cable joints, including heat-shrinkable, one-piece, three-piece, and pre-moulded types, are engineered for conductor cross-sections up to 2500mm² and operating voltages up to 400kV. These joints are constructed using silicone rubber or ethylene propylene rubber (EPR) to achieve high dielectric strength (≥35 kV/mm) and are equipped with metallic shielding to effectively manage electrical stress. They resist moisture ingress with IP68-rated sealing, ensuring reliable underground connections. The joints comply with IEC 60840 and IEEE Std 404-2021 standards, supporting transitions between cables of differing sizes (e.g., 1200mm² to 2500mm²) and insulation types (e.g. XLPE to paper-insulated).

Joint Bays: These are concrete enclosures, normally located within or adjacent to the public road designed to house cable joints. An excavation is undertaken, approximately 7m x 3m and 2m deep. A reinforced concrete joint bay is then constructed within the excavation. For most installations, joints are required at intervals along the route. This is because the cable is supplied in fixed lengths dictated by the cable drum diameter, the diameter of the cable itself and the maximum weight that can be transported. Cable weight ranges from 7kg/m to 50kg/m, depending on the required cable size, with the combined weight on the drum reaching up to 20,000kg. A typical cable length on one drum ranges from 600 metres to 750 metres, although other references indicate lengths varying from 500 metres to 1000 metres. In these joint bays it is essential that suitable clean conditions are established and that they have the provision of temporary power supplies and de-humidification to achieve satisfactory jointing.

Limitations

This study aims to technically compare the different undergrounding methods to illustrate their impact on the capacity of underground cable networks and analyse how the choice of method influences the project costs. For the purposes of this evaluation, HDD and cable ploughing have been selected. Table 4 provides the technical requirement for these methods.

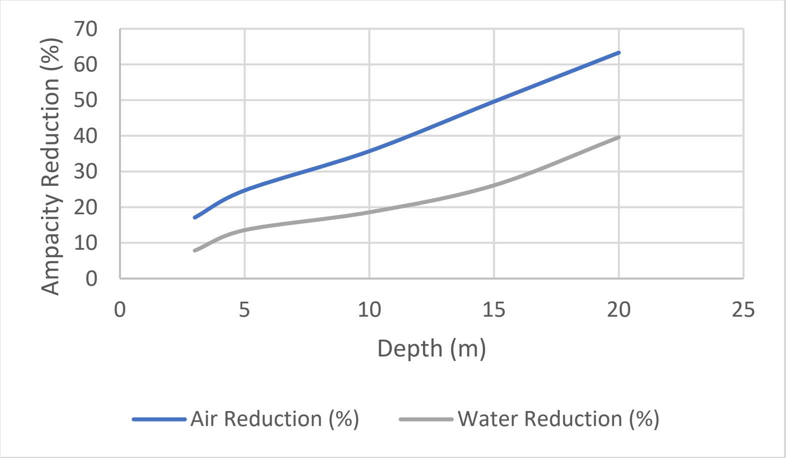
The main differences between these methods are the burial depth, the cable length, and the type of backfilling material. Regarding depth, cable ploughing depth ranges from 1.4m to 1.6m for voltages of 275kV and above. In contrast, HDD depths can vary from 5m up to 50m, highlighting a significant difference between the two methods. As specified in IEC 60287-2-1, understanding thermal resistance of the surrounding medium (soil, backfill, or air in some cases), which is also known as external thermal resistance, is crucial for determining the impact of burial depth on underground cable capacity. For cable ploughing at a depth of 1.5m, and assuming the thermal resistivity of the soil is 1.2°C·m/W, the external thermal resistance is 0.718°C·pm/W. In HDD the cables are placed inside a pipe installed in a bore created by the HDD method. In HDD, the space between the pipe and the bore can be filled with air, water or bentonite. In Table 8, the external thermal resistances for different depths of HDD are given.

Table 8: HDD thermal resistivity at different depths and fill

Depth (m)	Air (°C·pm/W)	Water (°C·pm/W)
3	2.094	0.943
5	2.191	0.994
10	2.324	1.136
15	2.401	1.214
20	2.456	1.279

The value of external thermal resistance directly influences the maximum current permitted to pass through the single-core cable. As external thermal resistance increases when the buried depth of the cable in soil increases, the maximum current decreases. This occurs because the depth directly impacts the cable's heat dissipation capability, making it more challenging to maintain the cable temperature below the allowable limit for AC circuits. Consequently, the current must be reduced to prevent exceeding the permissible temperature and ensure the safe operation of the cable. Figure 11 presents additional details on the capacity reduction for different conditions between the pipe and the bore relative to depth.

Figure 11: Ampacity reduction versus depth



Similarly, the construction method can affect three-phase systems where cables are installed in flat or trefoil formations. The reduction in network ampacity for flat formation when using HDD with various materials between the pipe and the bore at different depths, can be compared to cut-and-cover/cable ploughing, where cables are directly buried in sand backfill or the ground. This can be used to inform the number of cables required per circuit for each method and ground condition.

An underground network can be comprised of sections constructed using HDD and trenches formed by cut-and-cover or cable ploughing. In such configurations, the capacity of the network may decrease depending on the depth of the bore created by HDD. This decrease in capacity can lead to increased capital costs, as the capacity of the network sections at greater depths must be enhanced to maintain performance.

To address this challenge, two parallel circuits can be implemented, the entire system's cable size can be designed based on the requirements of the cable used in the HDD bore, or a larger, higher-capacity cable can be employed specifically for the HDD bore. Implementing the first option results in a significant increase in capital cost, with an estimated minimum of 100%. The third option would be preferable if minimal trenchless crossings are required.

Costs

Cables

The overall lifetime cost of an underground cable transmission network comprises various expenses including the cost of the installed cable length, the equivalent cost at the installation date for maintenance and losses over the economic life of the cable, the cable installation cost, and the backfill cost. Additionally, it is important to consider the costs for cable accessories along with the cost of the cable itself. The final cable price per length includes material costs, production costs, and the manufacturer's margin (including the distributor's margin).

The material costs of a cable should be broken down into individual structural layers. The volume (in m^3) of each layer should be determined, which will then allow the cost of the cable to be calculated. Typically, a power cable consists of eight distinct types of layers:

1. Conductor (Cu, Al)
2. Conductor Shield (semiconducting polymer)
3. Insulation (XLPE, PE, PVC, etc.)
4. Insulation Shield (semiconducting polymer)
5. Metallic Shield or Screen (Cu, Al, Lead Sheath)
6. Inner Sheath or Bending (PVC, PE)
7. Armouring (steel wire, aluminium wire, or steel tape)
8. Outer Sheath or Jacketing (HDPE, PVC, PE)

To accurately calculate costs considering different layers, detailed information about cable construction and material costs is required, which is often unavailable. Survey data regarding different cables prices used at various voltage levels has been gained from multiple cable manufacturers.

Beyond cable costs, a project encompasses additional expenses that contribute to the overall capital cost. The capital costs of underground cables per kilometre, segmented by voltage level and capacity, are detailed in Table 9 as reported in the National Grid Strategic Options Technical Appendix 2020/2021 Price Base (National Grid, 2022).

Table 9: Installation costs for different technologies (National Grid, 2022)

Capacity	Circuit Ratings by Voltage	Circuit Ratings by Voltage	Capital Costs
Capacity	275kV AC Technologies Total rating for two Circuits (2 x rating of each circuit)	400kV AC Technologies Total rating for two Circuits (2 x rating of each circuit)	AC Underground Cable (AC Cable) Cost for a two circuit AC cable route (Cost per circuit, of a two circuit AC cable route)
3190MVA (Lo)	[2000MVA 2 x 1000MVA for AC Cable only]	3190MVA (2 x 1595MVA)	£14.64m/km (£7.32m/km)
6380MVA (Med)	[3190MVA 2 x 1595MVA for AC Cable only]	6380MVA (2 x 3190MVA)	£26.96m/km (£13.48m/km)
6930MVA (Hi)	-	6930MVA (2 x 3465MVA)	£32.46m/km (16.23m/km)

For Table 9, several assumptions have been made as follows:

1 Capital costs for all technologies are based on installations in rural/arable land with no major obstacles (e.g., roads, rivers, railways). The values would increase if areas with more barriers are considered.
2 Costs for all underground AC cables are based on direct burial installations only. AC cable tunnel installations, or using HDD, would have higher capital installation costs than direct buried rural installations.
3 It is assumed that old tunnels will not be repaired; hence, the values in this table do not benefit from (are not reduced by) reusing old tunnel infrastructure.
4 AC cable installation costs exclude the cost of reactors and mid-point switching stations, which are described later in this report.

In addition to the capital costs (i.e., the costs of the cables, installation, and backfill), the Net Present Value (NPV) is calculated to estimate the costs expected during the lifetime of an asset. This includes considering both operation and maintenance costs as well as electrical losses. For underground cable networks, the annual maintenance cost per circuit is £2,822.22/km. Thus, the maintenance cost is not dependant on the capacity and is always constant for different voltages and capacities.

Regarding the costs of losses, the energy losses of the network must be calculated according to the resistance of the cables used in the underground network, the utilization factor (which is normally 34% in the United Kingdom), and the voltage level. National Grid charges £60 per MWh for energy.

For both maintenance and energy losses costs, NPV calculations are carried out using annual cost estimates and a generic percentage discount rate over the design life period associated with the technology option being considered. For underground technologies, the discount rate used by National Grid is 3.5%.

Shunt Reactors

One important factor that requires attention is the reactive power gain (capacitive) of underground cables. As a result, the voltage at one end of the cable system can change dramatically, potentially causing damage to transmission system equipment. The amount of reactive power gained by using underground cables as a function of the cable length, line capacity, and voltage level, is provided in Table 10. As shown, the reactive power gain can vary from 5 Mvar/km to 30 Mvar/km, depending on the network specifications.

Table 10: Reactive power gain within AC underground cables (National Grid, 2022)

Capacity	Voltage	Design	Reactive Power per Circuit
3190MVA (Lo)	275kV	One 2500 mm2 cable per phase	5 Mvar/km
6380MVA (Med)	275kV	Two 2500 mm2 cables per phase	10 Mvar/km
3190MVA (Lo)	400kV	One 2500 mm2 cable per phase	10 Mvar/km
6380MVA (Med)	400kV	Two 2500 mm2 cables per phase	20 Mvar/km
6930MVA (Hi)	400kV	Three 2500 mm2 cables per phase	30 Mvar/km

According to the NETS SQSS, the total amount of reactive power gain in an underground transmission network (in one circuit) must not exceed 225 Mvar. This necessitates the installation of reactors throughout the network to ensure that the voltage level remains acceptable and the reactive power gain does not surpass 225 Mvar. For example, in the case of a 400kV Medium capacity transmission line with a length of 50 km, the reactive power gain can reach 1000 Mvar. To address this issue, new reactors must be installed. The standard reactor used by National Grid has a capacity of 200 Mvar. Therefore, four reactors are needed to provide 800 Mvar (inductive).

Mid-point switching stations are typically utilized to house reactors. The distance at which these stations should be constructed to accommodate the reactors, according to the capacity of the underground transmission circuit, is detailed in Table 11.

Table 11: Mid-point switching substation requirements (National Grid, 2022)

Capacity	Switching Station Requirement
Lo	Reactive Switching Station every 60km between substations
Med	Reactive Switching Station every 30km between substations
Hi	Reactive Switching Station every 20km between substations

The cost details for the reactors and mid-point switching stations are provided in Table 12. For instance, for a network with a voltage level of 400kV and Med capacity, having a length of 40km and two reactors, the capital cost for the reactors and associated mid-point switching stations, as indicated in Table 18, is approximately £26.9 million.

Table 12: Costs of reactors and mid-point switching stations (National Grid, 2022)

Category	Cost per mid-point switching station	Cost per reactor (200 Mvar)
Lo	£14.3m	£4.7m
Med	£17.5m	£4.7m
Hi	£17.5m	£4.7m

In addition to the capital costs, the NPV is calculated to estimate the costs expected during the lifetime of an asset. This includes considering both operation and maintenance costs as well as electrical losses. For underground cable networks, the annual maintenance cost per reactor is £6,719.58, while the maintenance cost for the corresponding mid-point switching station is approximately £41,661.

The process for calculating the annual loss cost for underground cables is the same. The only difference for reactors is that a standard 200Mvar reactor has power losses of 0.4MW. This value should be used to calculate the annual loss costs for reactors installed in mid-point stations.

Cable Joints

The cost of cable joints is £776 each, irrespective of the voltage level. This fixed pricing simplifies cost estimation for projects requiring cable joints across various voltage applications.

Innovations

A number of power infrastructure component innovations are being developed by industry suppliers which are at varying degrees of maturity, but may see wider application over time, with some examples below.

Recent advancements in power system infrastructure components, particularly cables, reactors and power electronics, have the potential to improve efficiency, sustainability, and ease of deployment.

Cables with Graphene-Enhanced Conductors: Researchers have developed cables with graphene-coated copper conductors, increasing electrical conductivity by up to 10% while reducing weight by 15%. This makes transportation and installation easier, especially for long-distance transmission projects.

Eco-Friendly Insulation for Cables: New bio-based insulation materials, such as those derived from soybean oil replace traditional XLPE, reducing the carbon footprint of cable production by 20%. These insulations maintain high dielectric strength while being fully recyclable.

Self-Healing Cables: Innovations in polymer technology have led to self-healing cable insulation that can repair minor damages autonomously, extending cable lifespan and reducing maintenance costs in harsh environments like offshore wind farms.

Compact Superconducting Reactors: Advances in high-temperature superconducting (HTS) materials have enabled the development of reactors that are smaller and lighter than traditional models, while maintaining the rating. This reduces installation space and costs, ideal for urban substations.

Internal Self-Supported Gas-Free Dry-Type Design: A novel dry-type outdoor termination design is introduced that is completely gas-free and internally self-supported, optimised for high and extra high voltage systems. This innovation ensures easy installation, environmental sustainability, and robust performance, featuring stretchy silicone rubber integrated with field control elements and shield modules.

Power electronics are the building blocks of inverters in converter stations, and advances in semiconductors such as high bandwidth semiconductors could significantly impact HVDC by enhancing efficiency, increasing power and improving switching speed, ultimately leading to more compact converter stations and more robust and reliable HVDC systems. This might reduce HVDC costs in the longer term.

Summary

Power infrastructure components are essential for reliable high-voltage networks, incorporating technologies and sustainability features. However, their implementation entails challenges related to cost, complexity, and environmental impact, necessitating careful planning for optimal deployment.

8. Comparative Cost Analysis

This section covers the comparative cost assessment of undergrounding transmission lines using different technologies, including cable ploughing and HDD compared to traditional cut-and-cover methods, using scenarios expected in rural UK conditions.

8.1 Scope and Methodology

The cost estimates in this study relate to the underground installation of high voltage cables, with the ratings currently in use in the England, Wales and Scotland transmission network, assuming copper cables 2500mm2. For the analysis, a double circuit is considered, given this is usually the minimum that would be installed on a project in the UK for underground or overhead transmission lines. The cable rating for two circuits at 400kV has been aligned with the IET study (Parsons Brinckerhoff, 2012) as 'Low' (3,190 MVA) and 'Medium' (6,380 MVA). The scenario rating for AC has been aligned with the IET Study (Mott MacDonald, 2025) as 'Low' (2,494 MW) and 'Medium' (4,988 MW), whilst for DC it has been aligned with standard converter station capacity. The High rating (6,930 MVA) has been excluded from this study as it is not currently a realistic scenario for underground cable projects. The assumed megawatt (MW) ratings for Low and Medium capacity scenarios are indicated in the table below.

Type of Power	Low Capacity (MW)	Medium Capacity (MW)
275kV AC	1,563	2,494
400kV AC	2,494	4,988
400kV DC	2,000	4,000

Scenarios have been built up to assess the comparative costs of cable ploughing and HDD in rural conditions against a baseline of traditional cut-and-cover. Microtunnelling has been ruled out due to the sizeable cost difference, given the study's aim is to investigate the potential for cost reduction compared to cut-and-cover.

Two options are considered for route length (20km and 50km) to investigate if costs reductions can occur for longer distances. Current underground cable routes have been assessed to indicate the proportion of a route that can be completed by trenched methods, and what requires trenchless crossings.

Two AC voltages are considered, namely 275kV and 400kV, as well as 400kV DC. Additionally, the cable rating is also taken into account, as this can affect the number and size of cables required per circuit. Current onshore underground transmission lines particularly from offshore windfarms are mainly Low capacity with most windfarms generating 300MW to 1,500 MW, whilst most of the 400kV overhead lines in the UK are up to 4,000 MW, so categorised as Medium capacity. There are some Hi (6-7,000 MW) capacity 400kV OHLs in the UK, but these are only possible with series capacitors.

8.2 Scenarios

An underground cable route analysis was performed which assessed the number of major and minor crossings typically required in rural areas in the UK. Major crossings requiring a trenchless solution have been assumed as:

- Major road (A road, motorway)
- Major water course (river, canal, lake)
- Railways
- Underground HV power lines
- Underground O&G lines
- Water grid installations
- Archaeological remains
- Sites of Special Scientific Interest

Minor crossings that can be completed by trenched methods have been assumed as:

- Paved minor road
- B-road
- Small water course/ditches

The analysis identified that on average a major crossing occurs every 5km, and the costs of such crossings were included in the estimated costs for affected methods (cable ploughing and cut-and-cover). The average length of the major crossings was approximately 100m in length which is costed as per HDD construction.

A minor road crossing occurred every 1.5km, while a small water course or ditch occurred every 3km, these were separated out for the purposes of the cost build up. Minor road crossings were costed as per cut-and-cover construction for 10m length each, including a 2 lane road with verges on either side, while the minor water crossings were costed as per the additional setup costs for cable ploughing.

The analysis assumed that for cable ploughing, other than crossings, over 95% of the route would be suitable for ploughing. In practice, there may be sections that are unsuitable for ploughing and require cut-and-cover to be used instead, and this will have the effect of increasing the cost of the cable ploughing option to closer to that of cut-and-cover.

In terms of the cable voltages and rating, the permutations considered and the typical number of cables required for 2 circuits is presented in Table 13 as per the guidance in the Strategic Options Technical Appendix Price Base (National Grid, 2022).

Table 13: Cable circuit rating per voltage and no. cables required (2 circuits)

Circuit Rating	275kV AC	400kV AC	400kV DC
Low	2000 MVA (6 cables)	3190 MVA (6 cables)	3190 MVA (4 cables)
Med	3190 MVA (12 cables)	6380 MVA (12 cables)	6380 MVA (4 cables)

For AC circuits, the ground conditions and the depth at which the cables are laid can have a significant effect on the thermal resistivity of the cable and therefore the size and number of cables required to achieve the ampacity for each voltage and rating described in Table 13. Additionally, cables buried directly in native soil will not perform as well as those with a sand backfill surrounding the cables. Cables laid in a flat formation will have a lower thermal resistivity than cables laid in trefoil formation, even though trefoil will reduce the extent of the excavation required. The increase in the size and/or number of cables can increase the cost of construction, cable installation and cable price. The combination of scenarios considered for the cost analysis of depth, native soil versus sand backfill and flat versus trefoil for the analysis considered are as shown in Table 14.

Cable ploughing cannot currently backfill with sand in trefoil formation but it can when single cables are laid in flat formation. It is assumed that cut-and-cover will always use sand backfill based on the precedent from projects, whilst only soil in flat formation is considered for DC.

It was assumed that cable ploughing would not require cables to be de-rated relative to cut-and-cover for sand backfill and the same cable layout. Whilst valid for DC circuits for which heat dissipation is not limiting, for AC circuits the validity of this assumption will depend on project specific construction elements such as whether and how cables are housed in a conduit. This assumption was felt to be a reasonable simplification, although any project specific de-rating required would have the effect of increasing cable ploughing cost to closer to that of cut-and-cover.

The 100m trenchless crossings are considered to be constructed by HDD at 5m depth, given the smaller rig and shorter length of drive. It is assumed that these only require one launch site.

Table 14: Costing scenarios for depth, native soil vs sand backfill and flat vs trefoil

No.	Description	Ground conditions	Sand Backfill?	Flat/Trefoil
1	Cut & Cover + HDD for crossings	1.5m depth HDD 5m depth	Yes	Flat
2	Cut & Cover + HDD for crossings	1.5m depth HDD 5m depth	Yes	Trefoil
3	Cable Ploughing + HDD for crossings	1.5m depth HDD 5m depth	Yes	Flat
4	Cable Ploughing + HDD for crossings	1.5m depth HDD 5m depth	No	Flat
5	Cable Ploughing + HDD for crossings	1.5m depth HDD 5m depth	No	Trefoil
6	HDD whole route	10m depth	No	Flat

For HDD, a hypothetical scenario where the whole route is constructed by a succession of 1km long HDD drives at 10m depth has also been included. It is assumed for this scenario that two rigs would work from launch sites at either end to intersect, this has been taken as a conservative approach in case sleeving is required at either side. This length has been assumed considering the upper limit of cable lengths typically available in the UK. It should be noted that the contractors interviewed did not expect this to currently be an economically viable option. Longer HDD drives are possible, however the larger rigs required to drill over 2km are not typically used for onshore projects in the UK and therefore not readily available.

The number of cables and the cable size required for each circuit rating and voltage for two circuits was calculated to inform the cost for each scenario and is presented in Table 15. This informs the size of the trench or number of slits/bores required which affects the civils costs.

Table 15: No. cables required per circuit rating, voltage and ground conditions (2 circuits)

Circuit Rating	Depth	Sand Backfill	Formation	275kV	400kV	400kV DC
Lo	1.5m	Yes	Flat	6	12	4
Lo	1.5m	No	Flat	6	12	4
Lo	1.5m	Yes	Trefoil	12	18	-
Lo	1.5m	No	Trefoil	12	18	-
Lo	5m	No	Flat	12	12	4
Lo	10m	No	Flat	12	12	8
Med	1.5m	Yes	Flat	12	18	8
Med	1.5m	No	Flat	12	24	8
Med	1.5m	Yes	Trefoil	18	24	-
Med	1.5m	No	Trefoil	18	30	-
Med	5m	No	Flat	12	24	8
Med	10m	No	Flat	12	24	8

Costs to account for reactive power gain within AC underground circuits were built up for each of the options presented in Table 13 for the 20km and 50km route options. The basis for the costs were taken as per guidance in the Strategic Options Technical Appendix Price Base (National Grid, 2022) for the number of reactors and mid point switching stations required, and are presented in Table 16 below. As can be seen the longer the distance and the larger the circuit rating and voltage, the higher the costs will be. These costs are significant as each reactor is reported to cost £4.7m and each mid-point switching station £14.3m to £17.5m depending on the circuit rating.

For the purposes of this study a cost for DC without converter station costs will be presented so as to have a direct comparison of cost per unit length underground, and may be relevant for some projects.

Table 16: Number of reactors and mid-point switching stations required for each cable circuit rating per voltage for two circuits in the route lengths considered

Circuit Rating	Route Length	275kV	400kV
Lo	20km	Reactors: 0 Switching Station: 0	Reactors: 1 Switching Station: 0
Lo	50km	Reactors: 2 Switching Station: 0	Reactors: 4 Switching Station: 0
Med	20km	Reactors: 1 Switching Station: 0	Reactors: 3 Switching Station: 0
Med	50km	Reactors: 4 Switching Station: 1	Reactors: 9 Switching Station: 1

8.3 Limitations

The costs presented for each scenario are not actual costs, but indicative costs based on idealised factors and best available information at the time of writing. These costs are intended to be used to inform the comparative costs between underground construction methods. Costs for actual projects are likely to vary greatly depending on the specific conditions. The costs for this study have been derived from interviews with contractors and suppliers and from benchmarking against other projects and previous studies. Due to the limited scope and time for this study the sample size of responses from suppliers was relatively small.

8.4 Cost Comparison

This section presents the costs build up and comparison for the scenarios presented in Table 14 with permutations for circuit rating of Low and Medium, for voltages of 275kV AC, 400kV AC and 400kV DC and for route lengths of 20km and 50km. The build costs for the assessment have been categorised as presented in Table 17, including the basis for how the costs were developed.

Table 17: Build cost categories

Category	Description	Cost basis
Civils	Includes trenched (cut-and-cover or cable ploughing) construction and reinstatement, temporary works and access roads, cable pulling and joint bays For the whole route by HDD, the HDD cost is incorporated into the civils cost	Contractor data and benchmarking against IET Reports where data was limited (Parsons Brinckerhoff, 2012), (Mott MacDonald, 2025)
Crossings	Trenched minor crossings and trenchless major crossings by HDD method	Contractor data
Cables	Includes the cost of cables, joints and delivery for each specific scenario	Contractor data
Reactive compensation	Includes the reactor cost & mid-point switching stations required for each scenario, calculated specifically for each case, not as an average per/km	Calculated as per guidance in the Strategic Options Technical Appendix Price Base (National Grid, 2022)
Cable terminal compound, termination and testing	Fixed build costs	As per IET Report (Parsons Brinckerhoff, 2012).
Build contingency	Calculated as 15% of the build cost	Aligned with the approach in the IET Report (Parsons Brinckerhoff, 2012).
Project management	Calculated as 20% of the build cost	Aligned with the approach in the IET Report (Parsons Brinckerhoff, 2012).

The total cost build up for each scenario with each costing category is presented in Appendix A2 in Figure 14 to Figure 25. A comparative bar chart reporting the total build cost per km for each scenario is presented in Figure 12 for a 20km route and Figure 13 for a 50km route. The cost per MW per km is reported in Table 18 to allow direct comparison between all scenarios.

Table 18: Total build cost in £/MWkm for each scenario

Description	20/ 50km	Sand /Soil	Flat/ trefoil	Low 275kV AC £/MWkm	Low 400kV AC £/MWkm	Low 400kV DC £/MWkm*	Med 275kV AC £/MWkm	Med 400kV AC £/MWkm	Med 400kV DC £/MWkm*
Cut & Cover	20	Sand	Flat	£6,667	£4,865	£3,106	£7,108	£4,127	£2,211
Cut & Cover	50	Sand	Flat	£6,617	£4,827	£2,948	£7,208	£4,171	£2,120
Cut & Cover	20	Sand	Trefoil	£8,141	£6,691	-	£7,197	£4,347	-
Cut & Cover	50	Sand	Trefoil	£8,077	£6,637	-	£7,318	£4,389	-
Cable Ploughing	20	Sand	Flat	£3,915	£3,139	£2,057	£4,288	£2,717	£1,754
Cable Ploughing	50	Sand	Flat	£3,889	£3,117	£1,908	£4,415	£2,775	£1,667
Cable Ploughing	20	Soil	Flat	£3,922	£3,044	£2,003	£4,574	£3,281	£1,671
Cable Ploughing	50	Soil	Flat	£3,888	£3,020	£1,855	£4,683	£3,330	£1,649
Cable Ploughing	20	Soil	Trefoil	£5,262	£4,303	-	£5,591	£3,694	-
Cable Ploughing	50	Soil	Trefoil	£5,205	£4,249	-	£5,687	£3,724	-
HDD	20	Soil	Flat	£11,258	£7,461	£5,596	£8,029	£7,458	£3,983
HDD	50	Soil	Flat	£11,248	£7,452	£5,461	£8,168	£7,523	£3,907

*Costs shown for DC cases exclude converter stations. This may be relevant where the number of converter stations isn't impacted by whether the cable is AC or DC (e.g. connecting a DC node to an AC node point-to-point). For most projects which connect two AC nodes, the DC option will require additional converter stations which dominate costs, and would add £14,000/MWkm and £35,000/MWkm to 50km and 20km routes respectively for 2GW converter stations based on converter station costs from Mott MacDonald, 2025.

Figure 12: 20km route build cost per km for each scenario

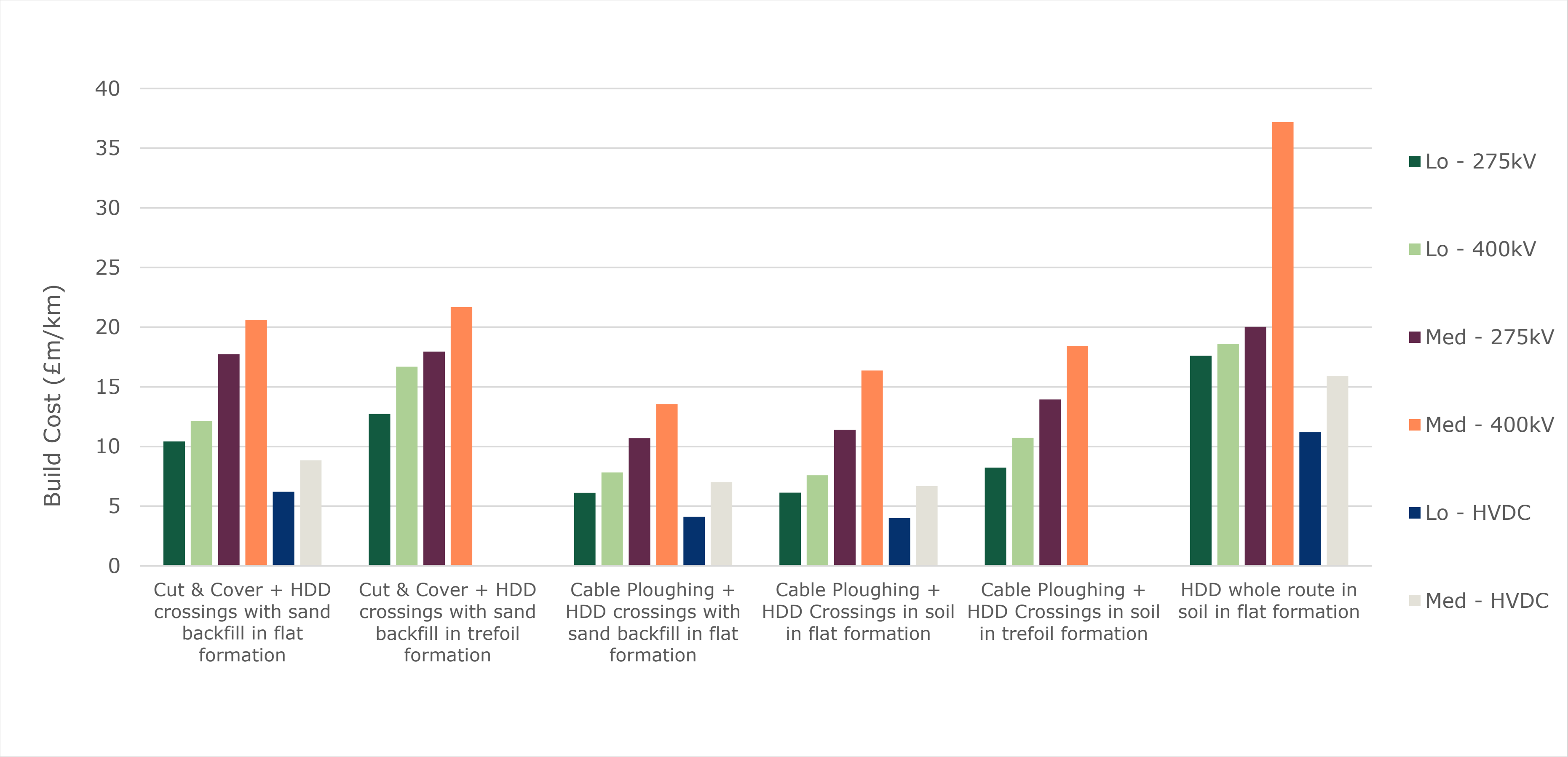
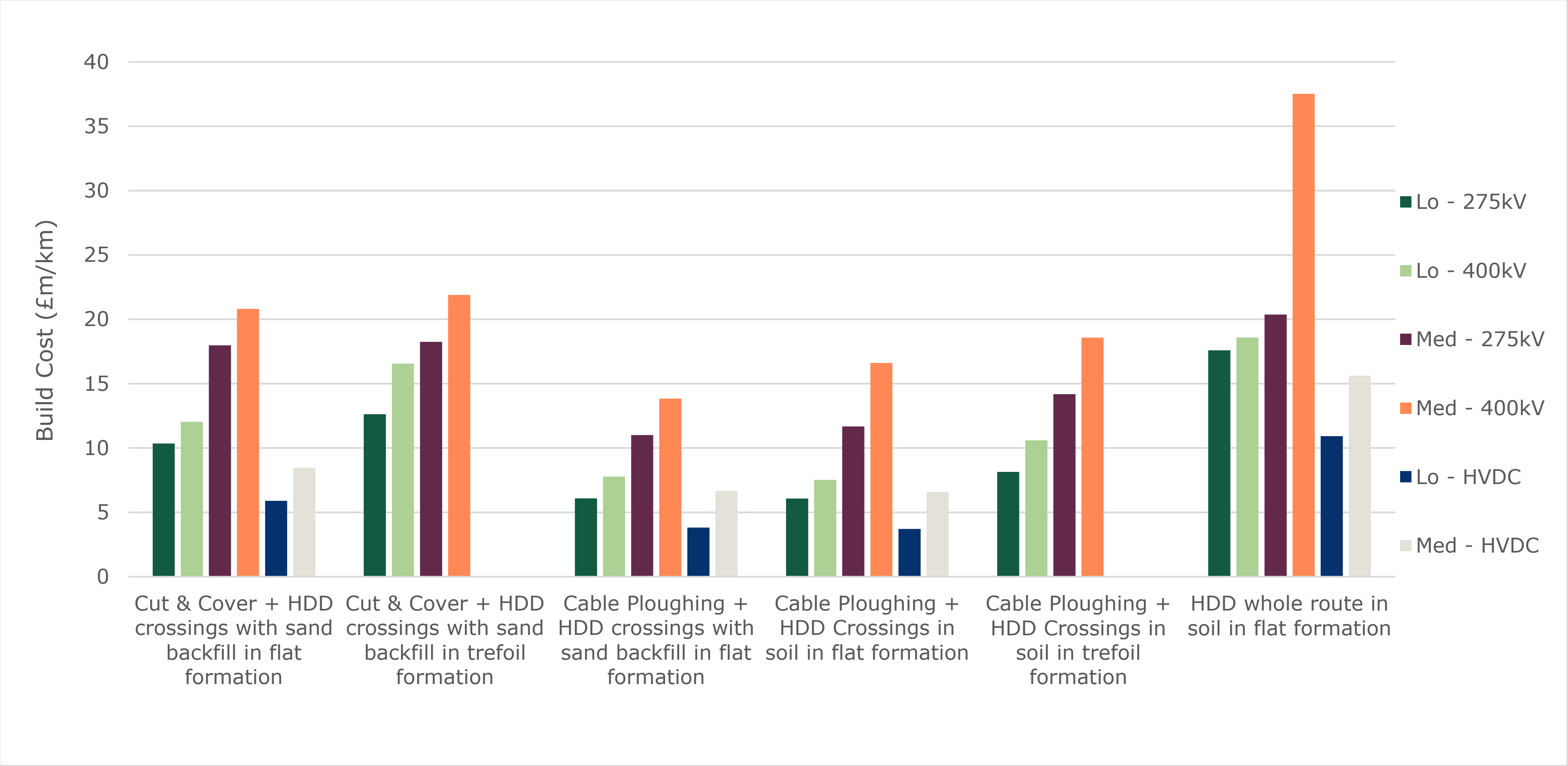


Figure 13: 50km route build cost per km for each scenario



8.5 Cost Analysis

From Figure 12 and Figure 13 which show overall build costs for the scenarios considered, it can be seen that cable ploughing is 60% to 80% of the build cost of traditional cut-and-cover method, a reduction of up to 20% to 40%. This is mostly borne out of a reduction in the civils cost for cable ploughing, which is significantly cheaper at 28% to 34% of the civils cost of cut-and-cover, a reduction of 66% to 72%. However, due to the significant proportion of project costs coming from the cables, which increases in proportion as the cable rating increases, the overall build cost reduction is not as large as the civils cost reduction. For cut-and-cover, installation costs, as well as covering civils work, includes special constructions and build contingency, and vary from 40% to 45% of the total build cost, whilst cables cost 27% to 38% of the total build cost. Whereas for cable ploughing, installation costs are only 19% to 23% of the total build cost, but cables costs rise to 44% to 72% of the total build cost.

The analysis for cable ploughing assumed almost all of the route (other than crossings) would be suitable for cable ploughing and that for AC circuits, cables wouldn’t require de-rating for the sand backfill cases relative to the cut-and-cover method. If project-specific factors mean these assumptions aren’t valid, this will increase the cost of cable ploughing to being closer to that of cut-and-cover, and a point will be reached of cost parity where there would be no cost benefit to cable ploughing, although there may be other (non-cost) benefits.

The hypothetical scenario where HDD is used for the entire route shows that the costs range from 1.1 to 1.9 times more expensive than cut-and-cover. The main reason is that as the circuit rating and voltage increases the number of cables required rises, which increases not only the civils costs but also the cable materials costs.

The lowest build cost per MWkm for AC is cable ploughing in sand flat formation Med Capacity 400kV over 20km at £2,717/MWkm. However, this is over 5 times the reported build cost of OHL of £499/MWkm from the IET Study (Mott MacDonald, 2025) for a similar distance. Due to costs of OHL per unit of capacity falling significantly as the rating is increased from Low to Medium capacity, the lowest build cost as a proportion of OHL cost is for Low Capacity, where cable ploughing is 3.5 to 4 times the build cost of OHL.

The AC scenarios showed no significant economies of scale for a longer route when comparing 20km to 50km route lengths. Whilst the civils cost of cable ploughing alone is cheaper for longer distances, the significance against the whole build costs is minor. The requirement for reactive compensation over longer distances and for higher ratings and voltages limits the reduction in cost to less than 1% for Low capacity, whilst costs were actually slightly higher for Medium capacity rating over 50km by 1 to 2%.

The cost for undergrounding DC (where connecting two AC nodes) is typically dominated by the cost of any additional converter stations introduced by the decision to underground DC rather than AC, which are required to convert DC to AC in order to connect to the AC transmission grid. If 2GW converter stations are assumed to be added (two for Low capacity, and four for Medium capacity), this adds £14,000/MWkm for a 50km route and £35,000/MWkm for 20km, based on converter station costs from the IET Study (Mott MacDonald, 2025). This results in total undergrounding build costs in the range £15,000/MWkm to £37,000/MWkm, which far exceeds the costs of AC undergrounding over such distances.

There may be some scenarios where the number of converter stations is not changed by the decision whether to underground AC or DC, for example when making a point-to-point connection where one node is already DC (such as an offshore windfarm with a HVDC export cable). In such cases, it may be appropriate to exclude the costs of converter stations in comparing undergrounding options. If excluded, it can be seen from Table 18 that the build cost for undergrounding DC is significantly less than for undergrounding AC for all methodologies and for example the cost of 400kV DC is 50% to 65% of the cost of 400kV AC for both the cut-and-cover and cable ploughing methods, which stems from a reduction in the civils and cable costs due to needing fewer cables and less spacing between cables for DC. When comparing 20km to 50km route lengths, DC costs are 2-7% less for 50km than 20km, so there are also some economies of scale as distance increases in the case of DC, unlike for AC.

The lowest build cost per MWkm for DC is cable ploughing in soil flat formation Medium capacity 400kV over 50km at £1,649/MWkm. However, this is still over 3.5 times the reported build cost of OHL of £443/MWkm from the IET Study (Mott MacDonald, 2025) for a similar distance. The lowest build cost for DC as a proportion of OHL is again for Low Capacity, where cable ploughing is approximately 2.5 times the build cost of OHL which, whilst closer in cost to OHL than for AC, is still significantly higher.

9. Assessment of Non-Cost Benefits and Disbenefits

This section of the study covers the assessment of the non-cost elements of underground transmission line projects and to compare the traditional cut-and-cover method to the shortlisted methods of cable ploughing and HDD.

9.1 Environment

In terms of carbon impact, this is directly proportional to the cost of the civil works and cable material quantity. Compared to cut-and-cover, cable ploughing allows for a significant reduction in civils related carbon impact as the amount of backfill material and disposal of spoil is eliminated or minimised, which also reduces the number of lorry loads. In addition to this the diesel required to run the cable plough machinery in comparison to cut-and-cover could be up to 10-15 times less. Depending on the specific project this may be offset slightly by the potential need to have larger or more cables to achieve the same circuit rating. HDD also minimises the spoil required (to just the conduit size) but there are risks associated with frac out and bentonite loss in the ground that need to be managed.

The damage to the ground and the reinstatement required for cable ploughing is much less than cut-and-cover. However, trenchless methods like HDD can minimise that even further with very little surface disruption in both the temporary and permanent cases. For trenched methods a corridor must be maintained above the buried cables to ensure no trees or traffic can impact the cables. Due to the greater depth of the HDD bores this gives it an advantage over the trenched methods.

For AC circuits, the higher the circuit rating and voltage, the more cables are required. This puts a limitation on methods such as HDD especially at deeper depths where the thermal resistivity is more compromised, leading to a large number of cables and land take required to launch multiple bores with appropriate spacing.

9.2 Energy security

For all of the technologies considered, the fact that the cables are buried underground means that they are more protected against extreme weather such as storms, high winds, trees falling, fire and lightning than overhead lines. However, the route above the buried cables must be surveyed periodically to ensure that it is protected from external factors such as infrastructure development, ground movement and the risk of vandalism.

For the high voltages being considered for this study, all of the methods would typically place the cable into a conduit, which would protect it from any ground aggressivity whether they are buried within sand backfill or directly in the ground. Joint bays allow access to test and maintain the cables, and potentially replace them if faulty, but even so sometimes civil works can be required and repairs are much more challenging than for overhead transmission lines. Cables within ducts installed by HDD will be more difficult to pull out and repair or replace than for trenched sections.

A combined analysis from "Reliability of Transmission Links Consisting of Overhead Lines and Underground Cables" (Tuinema, et al., 2015) and "Overhead or Underground Transmission? That is (Still) the Question" (Olsen & Leman, 2022) highlights the comparison between overhead and underground lines. The 2015 study indicated that underground cable connections, particularly extra-high-voltage (EHV) systems, faced reliability challenges due to extended repair durations (5-9 days for XLPE cables) compared to overhead lines (less than a day), using actual failure statistics to assess individual components. Conversely, the 2022 article cites an Australian study showing overhead lines (over 110 kV) having a total outage rate of about 1 per 100 km per year, whilst underground XLPE cables have a lower failure rate of approximately 1 out of 1,600 km per year. Advancements in materials and design have improved the reliability of underground cables, making them competitive with or even superior to overhead lines in terms of fault occurrence, though repair times remain a consideration.

In summary major and minor faults will occur much less in undergrounding cables compared to overhead lines, but it takes more time to locate and repair underground faults if significant civils works and reinstatement are required. However, some newer technologies such as fibre-optic acoustic sensing are leading to more efficient detection of faults on underground cables.

9.3 Deliverability

Cable ploughing is a relatively new technology in terms of its use in the UK for high voltage cables. However, it has seen considerable application outside the UK in rural locations for undergrounding high voltage distribution cables up to 100kV, as well as some transmission voltage applications up to 400kV. Cable ploughing can reduce the easement required (limited to the width of the plough) especially when no sand backfill is used, hence reducing land disruption.

In environmentally sensitive areas such as SSSIs, the surface disruption caused by trenched methods may present challenges, and whilst HDD could reduce surface disruption, the risk of frac out may need to be considered. HDD is very sensitive to ground conditions, which requires detailed geotechnical studies and could increase the length of the planning and approval process.

9.4 Qualitative Assessment

To analyse how the technologies considered in this study compare in terms of environment, energy security and deliverability, a qualitative assessment was performed. The results of the qualitative assessment are presented in Table 19, in which the scoring applied to each category is between 1 and 5, with 1 representing poor performance against the criteria and 5 being good performance. It should be noted that the assignment of scores is based on general expectations for each technology described above.

As can be seen cable ploughing comes out ahead with 3.7 compared to 3 for HDD and 2.7 for cut-and-cover. However, it should be noted that these scores could change significantly based on individual project circumstances. For example, HDD is highly sensitive to the circuit rating and cable voltage capacity due to the additional cables required at higher ratings. As such a low capacity and lower voltage cable will require less additional cables, and the environmental and carbon impact would be consequently lower.

Table 19: Qualitative assessment of undergrounding technologies against environment, energy security and deliverability criteria

Criteria	Environment	Energy Security	Deliverability	Overall score
Cut-and-cover	1	3	4	2.7
Cable ploughing	3	4	4	3.7
HDD	3	4	2	3

Key: 1 = poor, 3 = moderate, 5 = good

10. Conclusions and Recommendations for Further Study

10.1 Conclusions

The cost analysis compares the traditional cut-and-cover method to cable ploughing and HDD for underground transmission lines using scenarios that vary circuit rating of Low and Medium power capacity, voltages of 275kV AC, 400kV AC and 400kV DC, and for route lengths of 20km and 50km.

The analysis showed that cable ploughing can significantly reduce the costs of the civil works to 28% to 34% that of cut-and-cover, a reduction of 66% to 72%. However, due to the cost of cable materials being such a large proportion of the cost of an underground cable project, this means that it can only reduce the total build costs to 60% to 80% that of cut-and-cover, a reduction of up to 20% to 40%, and project-specific factors may reduce this cost advantage.

The hypothetical scenario where the whole route is constructed by HDD shows that the costs would range from 1.1 times to 1.9 times that of cut-and-cover. The deeper the HDD bore goes underground the worse the conditions for the cable which increases the number of cables required and therefore the costs. Based on these findings HDD is currently only likely to be used as a solution for crossing obstacles.

In the case of undergrounding AC circuits, the lowest cost method is cable ploughing in flat formation, however this remains over 5 times the build cost of OHL for Medium capacity circuits, and 3.5 to 4 times the cost of OHL for Low capacity circuits. For AC circuits, as the circuit rating and voltage increases, the requirement for more cables per circuit due to thermal constraints starts to make the underground methods more prohibitive in terms of costs, whereas for OHL the cost per unit of capacity falls as the circuit rating rises from Low to Medium capacity. The analysis indicates that for AC, any economies of scale associated with longer distances such as 50km versus 20km are eliminated by the cost of additional equipment needed to manage reactive power.

In the case of undergrounding DC circuits, the costs over distances of 20km and 50km will be dominated by the costs of any additional converter stations required to convert DC to AC in order to connect to the AC transmission grid. As a consequence, the cost per kilometre for undergrounding DC will normally far exceed that for undergrounding AC over such distances.

There may be some scenarios in which the decision to underground DC rather than AC does not affect the number of converter stations needed, but only their location. This might for example arise if connecting a node which is already planned to be DC (such as an offshore windfarm with a HVDC export cable) to an AC node point to point. In such a scenario, it may be appropriate to exclude the cost of converter stations when considering undergrounding options. If the costs of converter stations are excluded, the cost for undergrounding DC is significantly cheaper than for undergrounding AC for all methodologies, ranging from 50% to 65% of the build cost of underground AC for both cut-and-cover and cable ploughing methods. The build cost for undergrounding DC using cable ploughing falls to around 2.5 times that of OHL for Low capacity circuits and 3.5 times for Medium capacity, which whilst closer in cost to OHL than for AC, is still significantly higher.

10.2 Recommendations for further study

The recommendations for further work are as follows:

- Gather additional data from a wider range of main and specialist contractors on the civils cost of cable ploughing and HDD installation methods to inform a more robust range of cost outcomes.
- Gather additional data from cable suppliers to inform a more robust range of cable material and transport costs.
- Investigate the potential for innovation to reduce the high cost of Converter Stations.
- Further research cable technologies such as Graphene-Enhanced Conductors, that can increase electrical conductivity (improving operation temperature) and reduce cable weight. Such advancements could make undergrounding more viable as it could reduce the number and size of cables required and thus the cost. This could potentially make longer HDD bores more feasible as it will also increase the bore lengths possible between joint bays. A parallel investigation into the potential for cost reduction in larger sized HDD rigs such as efficiencies gleaned from technological advancements in the oil and gas industry could be valuable.

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Appendices

Appendix A1

Gap Analysis

To build up a comparative analysis of build costs of the shortlisted methods, the gaps in information have been identified and presented below, these gaps will be filled through interviews with cable suppliers and installers. Specific scenarios will be developed to inform how cable voltages, route length and environment will impact on costs and what savings are possible over longer distances. In addition to this non-cost benefits and disbenefits for environment, energy security and deliverability will be interrogated to provide a further context to the qualitative assessment of the undergrounding methods.

Baseline

- Cost breakdown per metre for cut-and-cover for 275kV, 400kV.
- How much can cost be reduced proportionally from 20km up to 50km.

Cable Ploughing

- Cost breakdown per metre for cable ploughing from case studies.
- What scope items cannot be covered by ploughing.
- How much can the cost be reduced proportionally from 20km up to 50km.
- Cost and implications of laying AC in trefoil versus flat formation.
- Cost of bedding and surrounding a cable.
- Cost of interruptions where the plough has to restart.
- Additional cost of breaking out the ground before ploughing for e.g. hard rock.
- Cost implication for burying a cable at 1.5m depth vs 2.8m depth.
- Additional costs for water or ditch crossings.
- Potential for innovations in cable ploughing.

HDD

- Cost breakdown per metre for HDD from case studies for shorter and longer drives.
- How much can the cost be reduced proportionally from 20km up to 50km from multiple HDD tunnels.
- What are the drive lengths possible.
- Pipe or conduit sizes and costs required for 275kV, 400kV.

- Is it possible to lay cables in trefoil formation within one pipe, or are three separate drills required. What separation is required for different voltage cables.
- What size conduits are typically required for 275kV, 400kV.
- What geotechnical conditions are not feasible for HDD and how much more expensive is it when special measures are required.
- Potential for innovations in HDD.

Microtunnelling

- Cost breakdown per metre for tunnelling from case studies for shorter and longer drives and different sized tunnels.
- Cost breakdown for launch, reception and intermediate shafts at different depths and geotechnical conditions.
- Lengths of drive achievable using inter jacks and impact on time and cost.
- Cost of headhouses and ventilation in operation.
- The range of size and length of cable tunnels possible.
- Geotechnical conditions that are not possible.
- Scope for innovations in microtunnelling.

Cables

- Up to date cost ranges of cables per metre, including transportation, jointing, joint bays, and termination and testing for 275kV to 400kV and HVDC. To inform the build costs of the different undergrounding methods when factoring thermal losses.
- Up to date costs for cable terminal compounds, cable build contingency required for damages (buried vs in tunnel) and shunt reactors.
- Cost of operation and maintenance and power/energy losses for different backfills and open tunnels.
- Cost impact of buried depth and ground conditions on cost, including backfill, ventilation and cable size considerations.
- Cost and practical implications for trefoil vs flat in buried and open conditions.
- What is the scope for reducing cable costs (e.g. buying in bulk from China).
- Any new innovations in cable materials, design and manufacture, such as increasing lengths before jointing is required.

Appendix A2

BUILD COST ASSESSMENT

Figure 14: Build costs for Low Capacity (1,563 MW) - 275kV AC - 20km

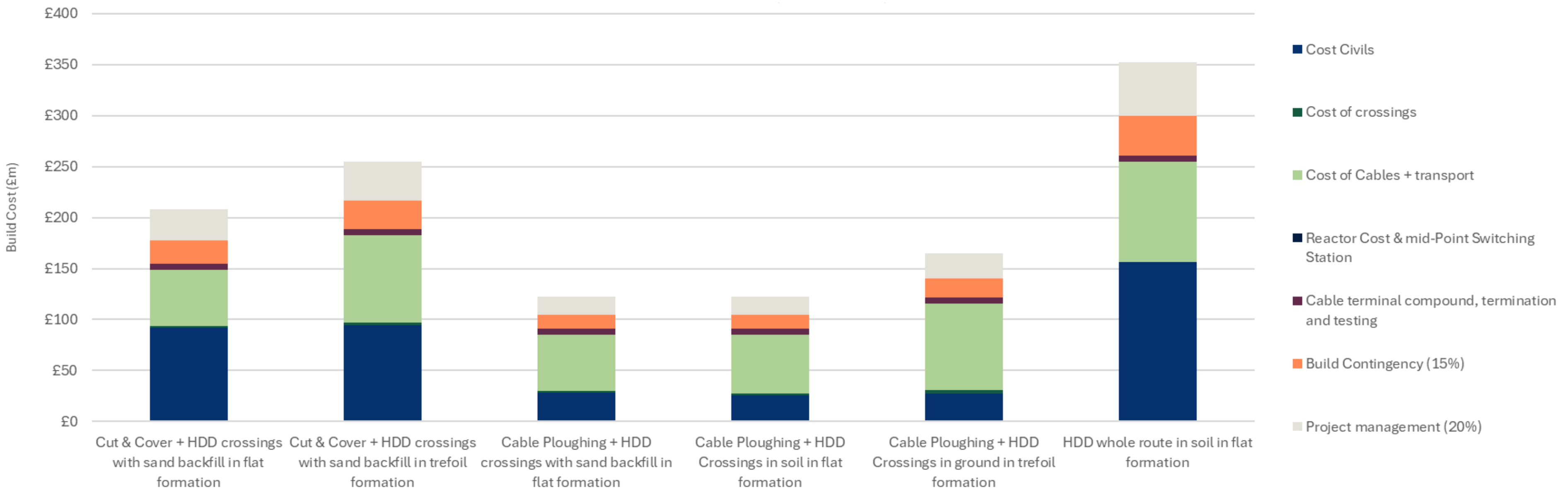


Figure 15: Build costs for Low Capacity (1,563 MW) - 275kV AC - 50km

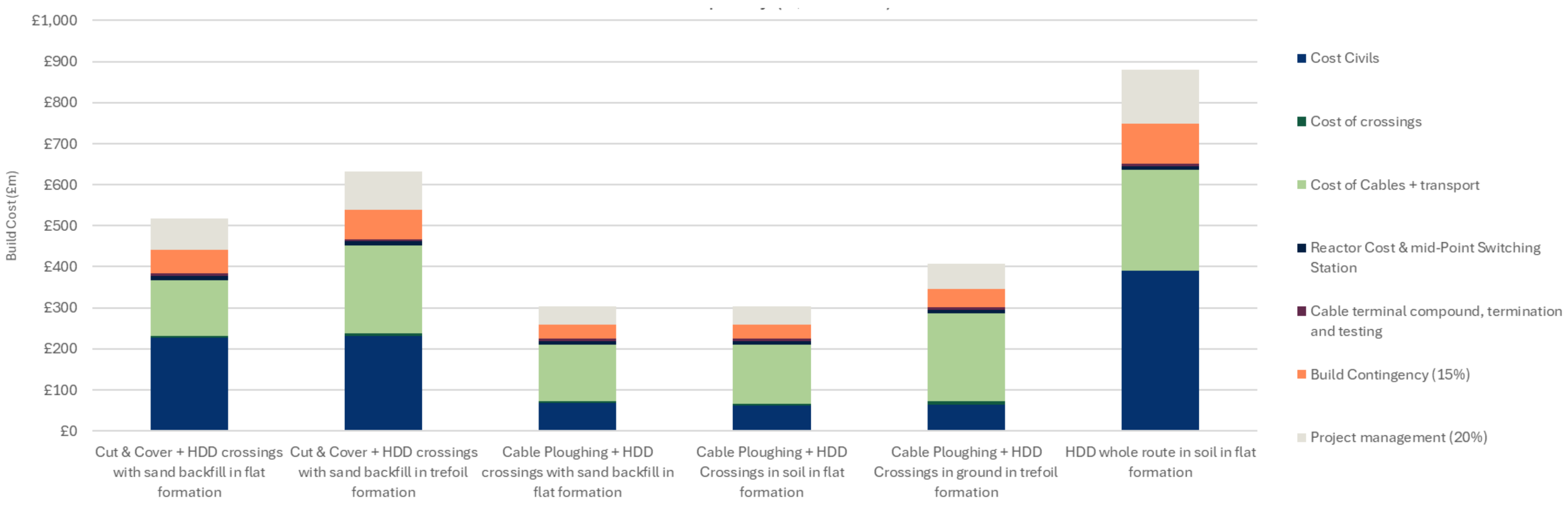


Figure 16: **Build costs for Low Capacity (2,494 MW) - 400kV AC - 20km**

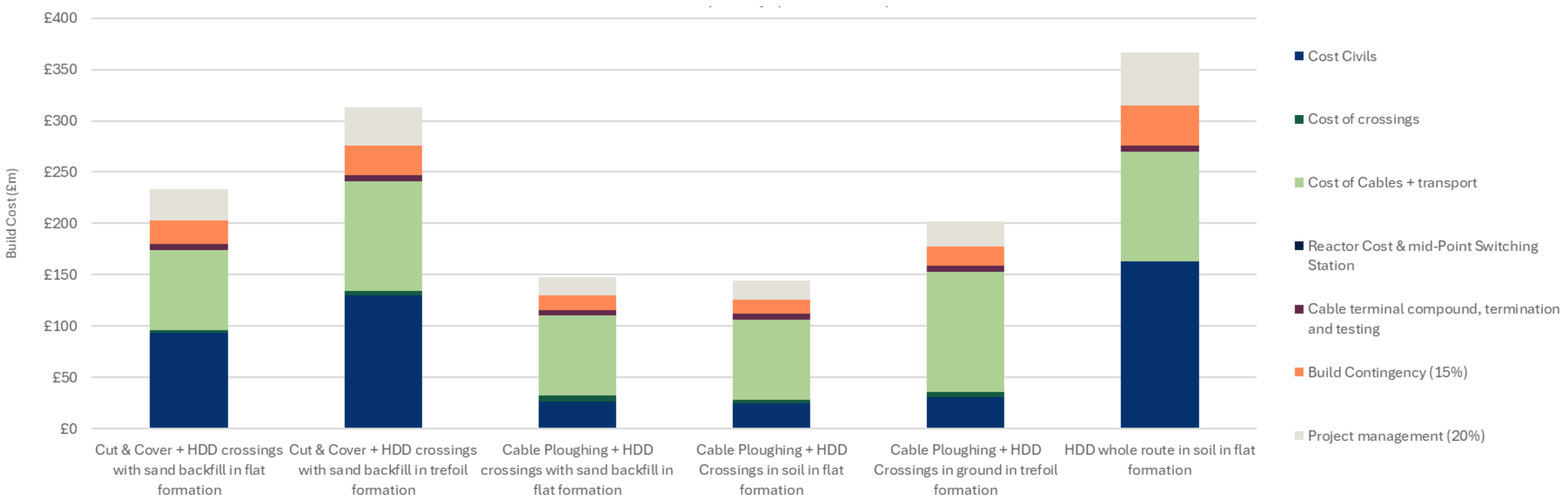


Figure 17: Build costs for Low Capacity (2,494 MW) - 400kV AC - 50km

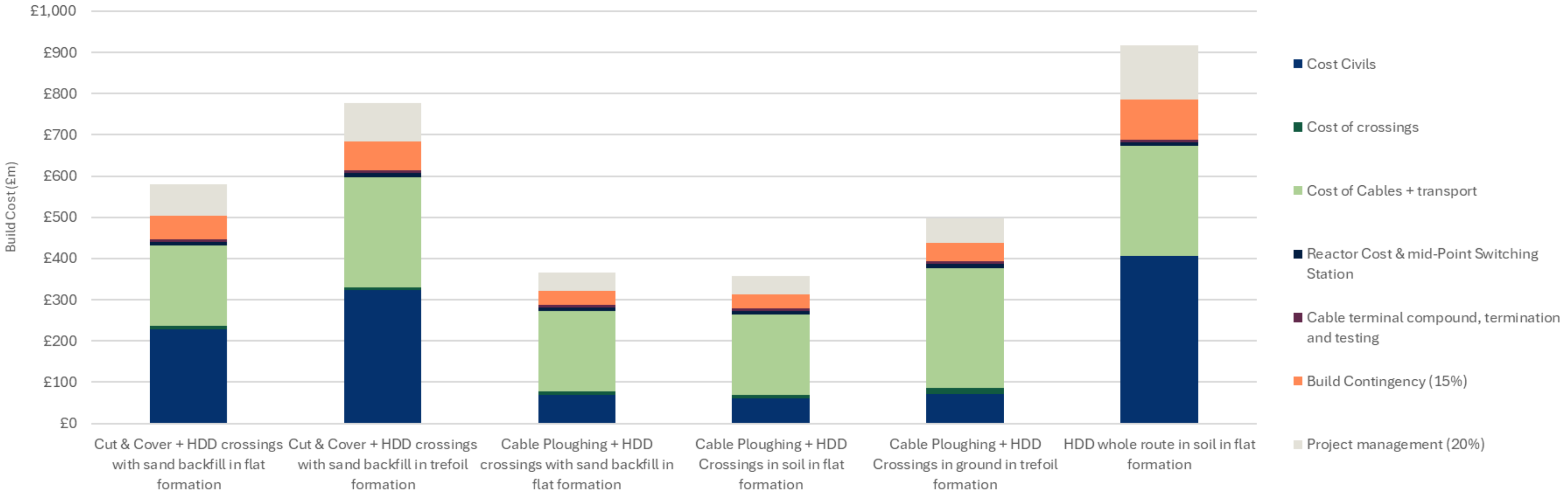


Figure 18: Build costs for Medium Capacity (2,494 MW) - 275kV AC - 20km

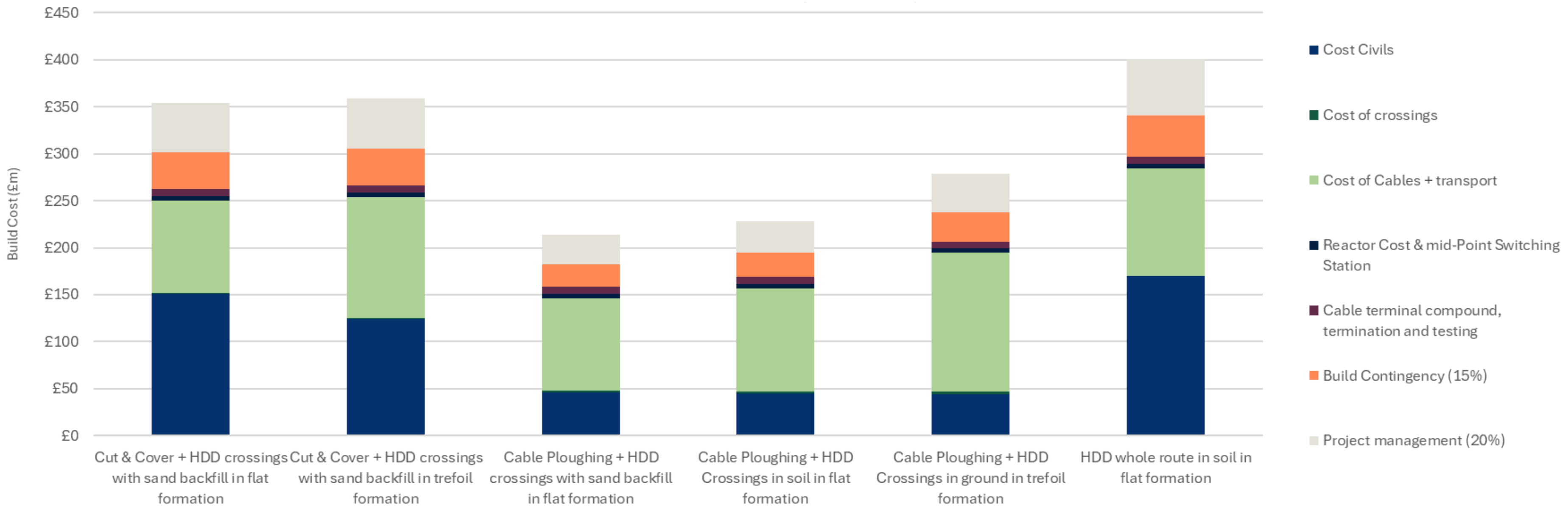


Figure 19: Build costs for Medium Capacity (2,494 MW) - 275kV AC - 50km

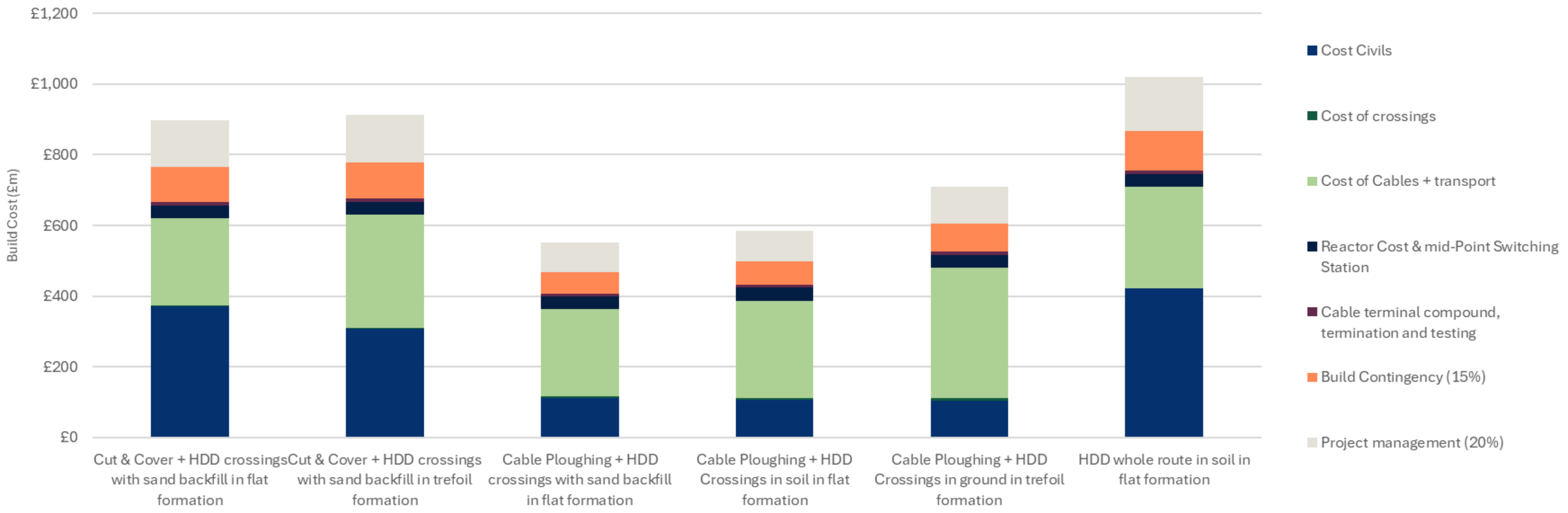


Figure 20: Build costs for Medium Capacity (4,988 MW) - 400kV AC - 20km

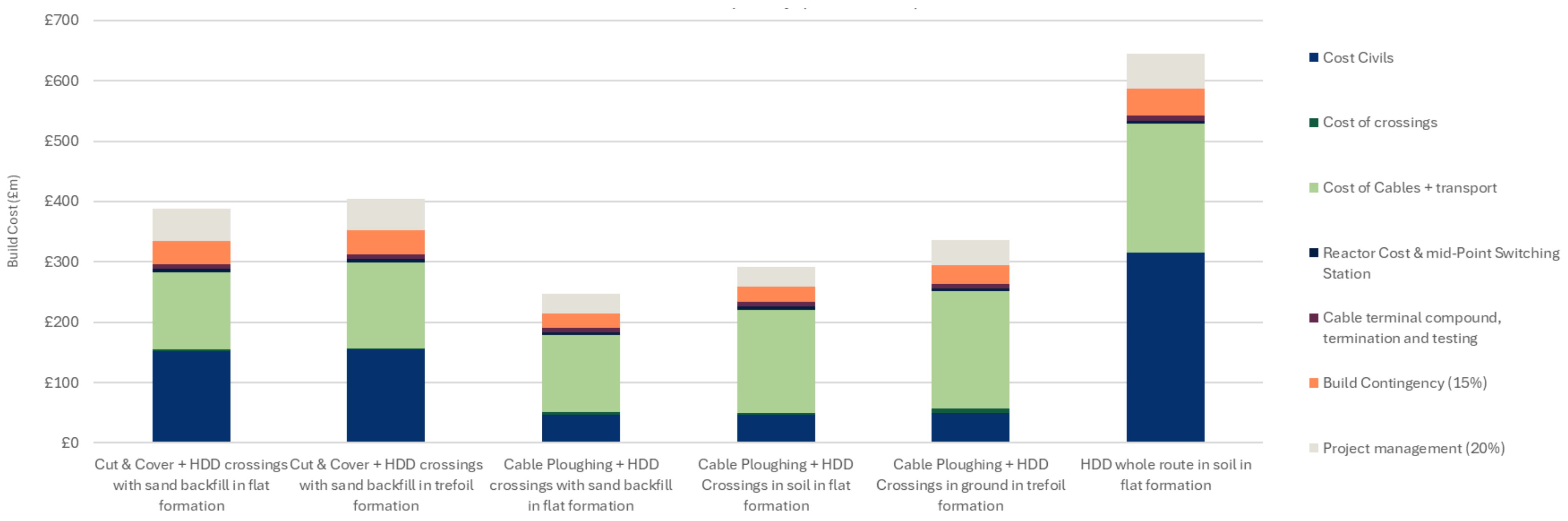


Figure 21: Build costs for Medium Capacity (4,988 MW) - 400kV AC - 50km

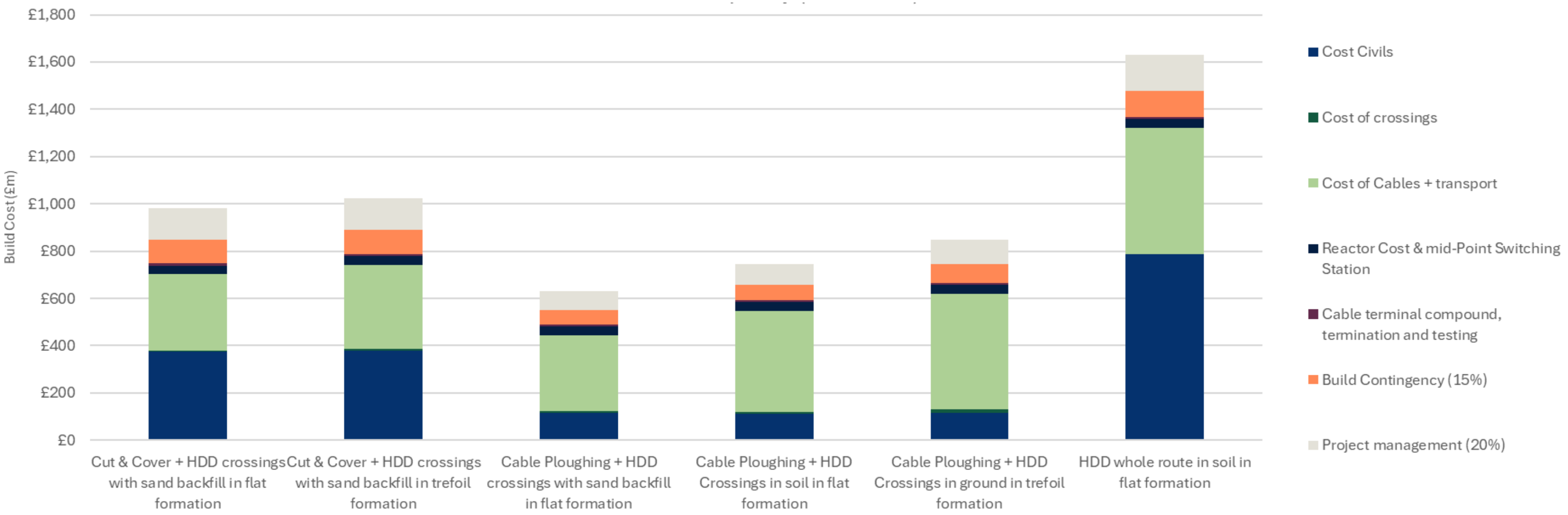


Figure 22: Build costs for Low Capacity (2,000 MW) - 400kV DC - 20km

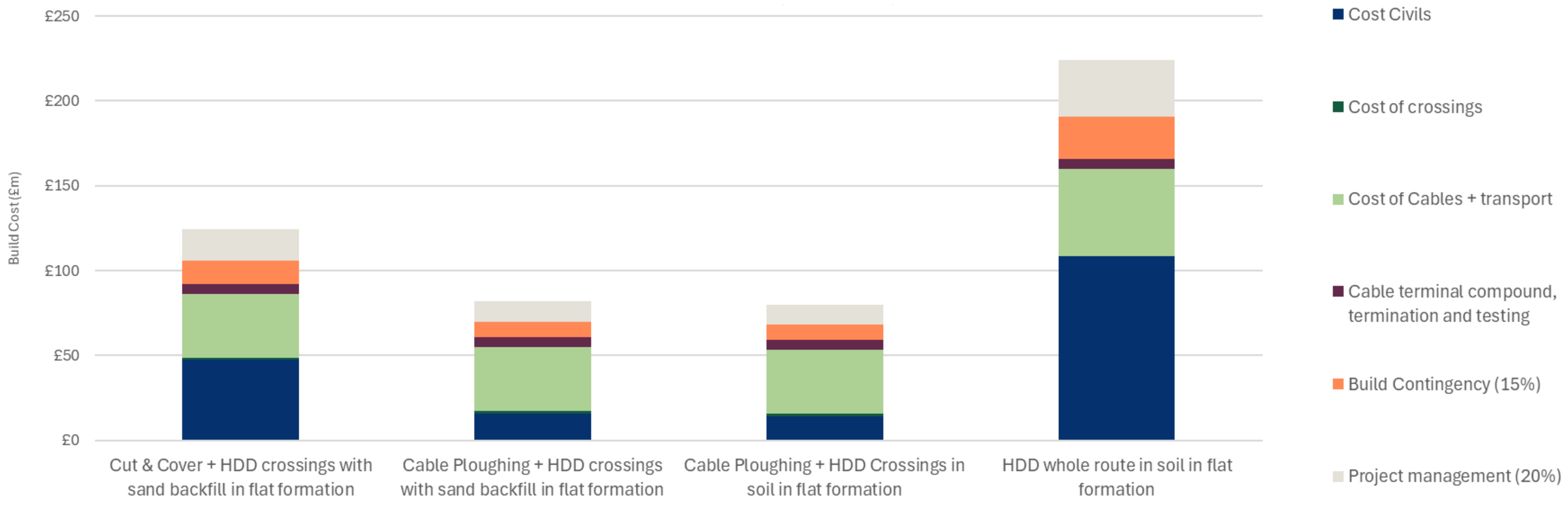


Figure 23: Build costs for Low Capacity (2,000 MW) - 400kV DC - 50km

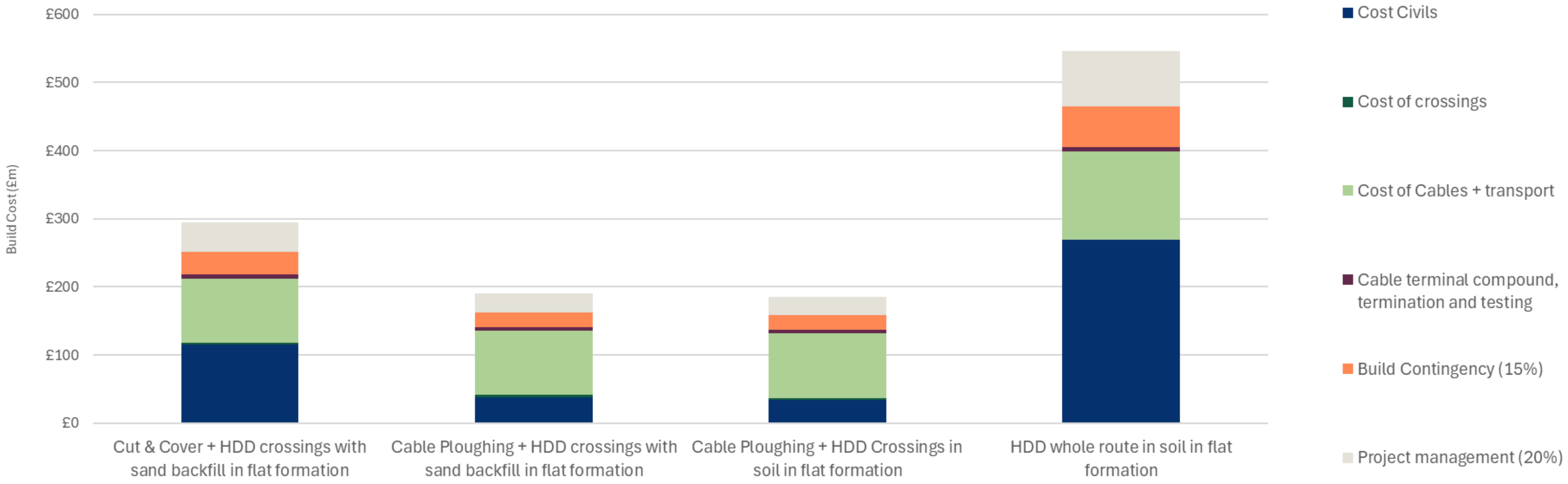


Figure 24: Build costs for Medium Capacity (4,000 MW) - 400kV DC - 20km

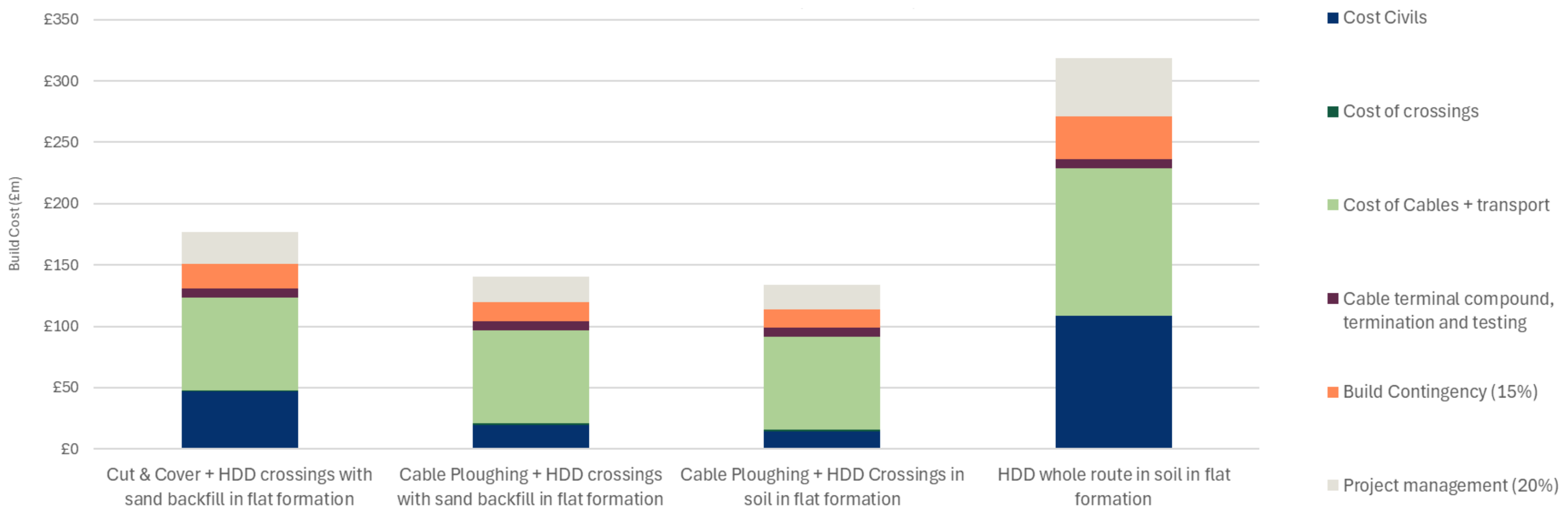
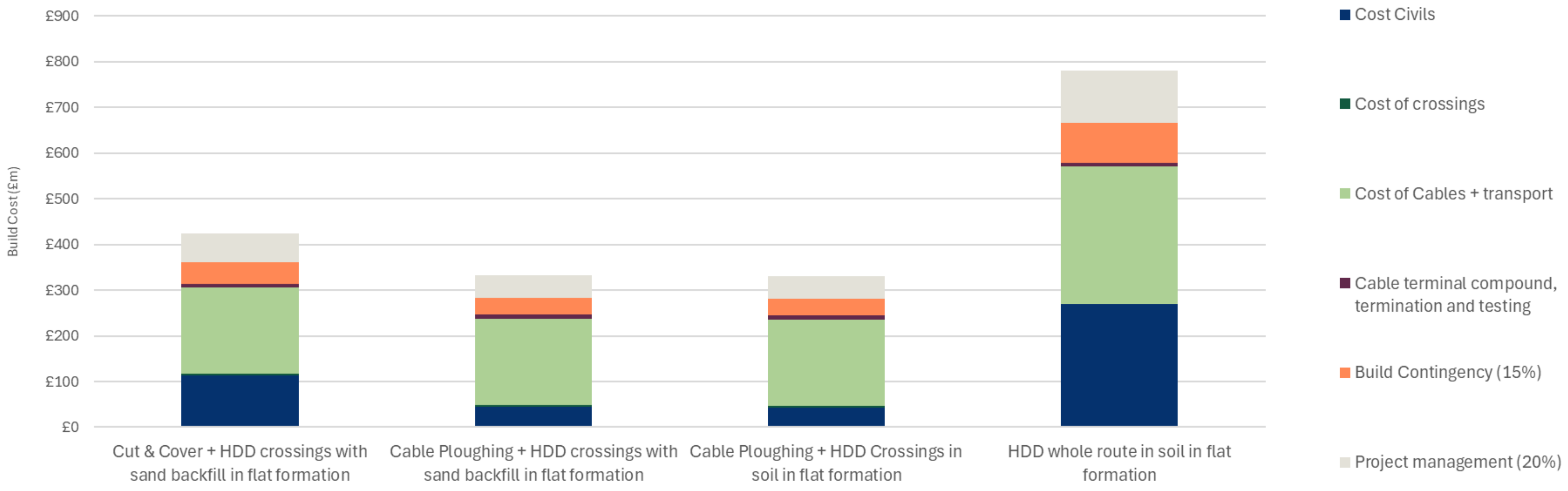


Figure 25: Build costs for Medium Capacity (4,000 MW) - 400kV DC - 50km



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