NETWORK TOPOLOGY ASSESSMENT

Network Topology Assessment Report

The Electricity System Operator

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Objective:
The provision of an independent assessment of the technical, financial, delivery and operability, environmental and community impacts associated with four high-level network topology choices:

- AC overhead line
- Onshore AC cabling
- Offshore HVDC cabling
- Offshore interconnection: Hubs & Energy Islands

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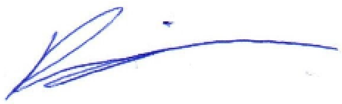

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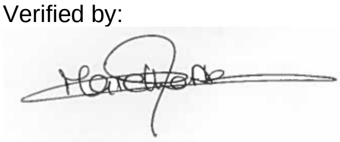

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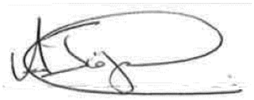

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1 INTRODUCTION

Offshore wind has been identified as a critical generating technology in achieving the UK's ambition for net zero greenhouse gas emissions by 2050, with the Committee for Climate Change (CCC) estimating as much as 125GW being needed by mid-century. The UK Government has set an interim ambition of 50GW of wind by 2030, with up to 5GW coming from floating offshore wind; however, to realise this ambition, a step-change in both the speed and scale of deployment of offshore wind is required.

One of the challenges to delivering this 50GW-by-2030 ambition is to ensure that the combined offshore and onshore transmission network connects this new generation efficiently whilst taking account of community and environmental impacts. Meanwhile, the Electricity System Operator's (ESO) licence obligations are to robustly assess network development options to ensure they achieve just that.

Internationally, transmission grids will have to change fundamentally to deliver reliable, affordable, and sustainable energy and for Great Britain in particular, the focus of change over the next decade is to bring the new bulk offshore wind power from the extremities of the grid to the demand centres.

At a high-level, the ESO's transmission network planning process follows these steps:

- Apply several possible future supply and demand scenarios to a model of the transmission network,
- Identify the emerging needs of the transmission network by studying the possible future power flows in the model,
- Appraise each reinforcement option (provided by the Transmission Owners) against its cost and its ability to satisfy the network need (including its required-in-service date).

The Government launched its Offshore Transmission Network Review (OTNR) in July 2020. The review, which concluded in May this year, considered the way Great Britain's offshore transmission network is designed and delivered in the context of its net zero offshore wind targets, and particularly how these may be achieved whilst balancing environmental, social and economic costs.

The ONTR's early opportunities workstream includes projects that have received confirmed connection agreements but not planning consent. Within that workstream, the Government launched the Offshore Coordination Support Scheme (OCSS) to provide grant payments to support offshore wind and interconnector projects that develop coordinated offshore transmission infrastructure options alongside their current network connections.

The purpose of this document is to produce a feature comparison of three different high-level transmission network archetypes that can be used for network reinforcement and connections. To keep the assessment comprehensive but at the same time general, and without making any location-specific assumptions, the document covers the following four assessment criteria: costs; deliverability and operability; environmental impact; and community impact, throughout the asset lifecycles. The three archetypes are:

- Alternating current overhead line (AC OHL)
- Alternating current underground cables (onshore) (AC UGC)
- High voltage direct current link with offshore cables (HVDC)

This assessment is based on historical examples and previous work delivered by DNV in Great Britain and worldwide. A review of the technology landscape was not in the scope of this study, therefore DNV acknowledges new technology might exist with different characteristics to the ones described in this document.

The rest of this document is structured as follows:

- Section 2 provides an executive summary;

- Section 3 provides a high-level archetype comparison;
- Section 4 provides an assessment of costing and relative costs;
- Section 5 provides an assessment of AC overhead line;
- Section 6 provides an assessment of onshore AC underground cable;
- Section 7 provides an assessment of offshore HVDC;
- Section 8 describes composite circuits.

A comprehensive glossary with technical terms and used abbreviations can be found in Appendix 1.

A detailed description of environmental and community impacts and mitigations can be found in Appendix 2.

2 EXECUTIVE SUMMARY

The report provides an independent assessment of three high-level network topology choices:

- Alternating current overhead line (AC OHL)
- Alternating current underground cables (onshore) (AC UGC)
- High voltage direct current link with offshore cables (HVDC)

The assessment focuses on the costs, deliverability and operability, environmental and community impact of each technology choice. Following a comprehensive analysis of each technology, the report also suggested a fourth option – composite circuit – to account for situations in which a combination of AC overhead lines and underground cable might provide a more feasible option.

As the purpose of this study was to provide a general comparison of different network archetypes and serve as an educational piece to inform the public of the available options, their characteristics, costs and benefits, no recommendations were made, as this would require a detailed location-specific cost benefit analysis.

In summary, the choice of a technology for the transmission of power is very situationally and locationally specific. The lowest cost and least environmentally impactful is AC overhead line, however it is the most visually intrusive once built. Composite overhead circuits with short sections of underground cable can mitigate some of the visual impact of an overhead circuit, at a marginally higher cost. Underground AC circuits are more expensive solutions, and may only be technical viable for shorter routes, typically of less than 20km. They are also more environmentally damaging during the construction phase, though once the ground has recovered the cables are invisible. HVDC is the most feasible technology for longer circuits where a cable solution is necessary, such as in marine environments, and can offer important operational benefits compared to AC equivalents, though an HVDC circuit is a significantly more expensive option (per installed km) compared to an AC overhead alternative and it is the most inflexible to adapt if the network requirements change over the lifetime of the asset.

3 ARCHETYPES COMPARISON & TABLE

In its February 2022 Holistic network Design (HND) Methodology (p.4)[1]. The ESO adopted four equally important design objectives to be considered whilst planning the electricity transmission network for Net Zero. These objectives had been developed in association with DESNZ and Ofgem as part of the DESNZ-led Offshore Transmission Network Review[2] and are set out in the HND Methodology as:

- The network design should be economic and efficient,
- The network design should be deliverable by 2030 and the resulting system should be safe, reliable and operable,
- Environmental impacts should be avoided, minimised or mitigated by the network design, and best practice in environmental management incorporated in the network design,
- Local communities' impacts are avoided, minimised or mitigated by the network design.

These characteristics, amongst others, are presented in the following comparison table.

Table 3.1: Archetypes comparison (AC overhead line, AC underground cable, HVDC link with offshore cables)

Characteristic	AC OHL	AC UGC	HVDC (VSC[3])
Archetype Description			
Maximum continuous transmission capacity (MVA)	>6000 MVA (per 400kV double circuit route)	>6000 MVA[4] (per 400kV double circuit route)	2000 MW (per +/-525kV bipole circuit route)
Maximum technically feasible route length (km):	Unrestricted - but see note[5]	~ 20 km - but see note[6]	Unrestricted
Life-span (years)	> 40 years[7]	> 40 years[8]	~ 40 years[9]
Infrastructure operational footprint	• 50-150sqm land-take per tower, 3 spans per km • Building beneath the overhead line route permanently discouraged, though many agricultural /rural land uses can resume	• Building and excavations permanently discouraged within, typically, a 25m wide cable swathe (see main text), though many rural/agricultural land uses above ground can resume	• ~45,000sqm land-take per 2,000 MVA converter station (max. 2 converter stations per circuit) • Building and excavations permanently discouraged within ~10m wide onshore cable swathe, though many

1 nationalgrideso.com/document/239466/download

2 Offshore transmission network review - GOV.UK (www.gov.uk)

3 Voltage Source Converter, see details on types of HVDC technology in Section 7

4 Comprising one or more underground cables per electrical phase

5 Intermediate compensation stations may be required for overhead lines exceeding about 200km route length

6 Beyond around 20 to 25km route length, a 400kV AC underground cable circuit would be increasingly likely to need intermediate compensation at which point, technically, interfaces with the network become increasingly complex and costly.

7 Major refurbishment(s) of overhead line conductor systems at around 40-year intervals are expected to extend overhead line lives to 80 or even 120 years.

8 XLPE cable technology track record for transmission voltages is still developing, but early indications are that these cables could possibly reach 80-year lives, or more, without major refurbishment.

9 HVDC expected to require a major refurbishment at around 20 years to achieve this design life

	• Periodic vegetation management required	• Periodic vegetation management may be required	rural/agricultural land uses can resume
Future scalability for long-term planning	✓ Uprating (at refurbishment) ✓ Route diversion ✓ Usually less cost and disruption to connect additional generation and demand in the future	✗ Uprating ✗ Route diversion ✗ Usually more cost and disruption to connect additional generation and demand in the future	✗ Uprating ✗ Route diversion ✗ Impractical to connect additional generation and demand in the future
Deliverability and operability			
Planning and consents	• An application for a Development Consent Order (DCO) is required • Process complex and time-consuming, could sometimes lead to public enquiry • Compulsory purchase authority may be used in special circumstances	• Process relatively easier for underground cables • Classed as 'permitted development' • Any sealing end compounds may require planning permission • Suitable rights over land (wayleaves and easements) are needed, often granted voluntarily	• Subject to all usual planning procedures for onshore and offshore connections • Planning consent for a converter station can vary very considerably and subject to significant delays • Complex consent process for offshore power cables due to requirements for 'no disruption' assurance to other linear services (including power, telecoms, gas, oil), other sea users, plans for the seabed and sea-life • A National Competent Authority (NCA) will provide the final approval for projects in England
Reliability, availability and maintainability	• Robust operation -auto-reclose for lightning strikes • Physical damage normally repaired within hours or days (excessive damage within weeks)	• Reliable operation • Physical damage repaired within days (excessive damage within weeks) • Maintenance; 3 days pa (average)	• Reliable operation (however limited-service experience) • Physical damage to converter repaired within hours or days

	• Maintenance; 3 days pa (average)		• Physical damage to cable repaired within months • Maintenance; 10 days pa (average)
Flexible circuit rating	• Up to 35% above rating for short period.	• Up to 30% above rating for short period.	• None
Provision of restoration Services[10] *(all of these require an intact source of energy at one end)*	• Inherent, ideal • Applies sequential switching; energising blocks of load, during which care must be taken to control the stability of the system due to risk of re-collapse • Switching is a well proven technique for system restoration	• Inherent, fair[11] • Applies sequential switching; energising blocks of load, during which care must be taken to control the stability of the system due to risk of re-collapse • Switching is a well proven technique for system restoration	• Complex and with limited track record to date, but promising emerging functionality • Provides flexibility for soft-start, smoothly ramping up the voltage on the network, eliminating risk of switching stresses to equipment • Soft-start is relatively new concept and at present, is practically more complex than switching, but has been demonstrated at a transmission level successfully
Environmental impacts[12]			
Construction	• Traffic noise and dust • Access may impact vegetation/habitats • Potential impact on biodiversity (habitat loss) • Construction activities contribute to Greenhouse Gas (GHG) emissions	• Traffic noise and dust • Excavation activities may lead to soil disturbance, vegetation removal and habitat loss • Construction activities contribute to GHG emissions	• Traffic noise and dust • Potential impact on marine species and seabed disturbance • Construction activities contribute to GHG emissions and water pollution
Operational	• Acoustic noise (poor weather crackle)	• Cable access points will require vegetation clearance	• Acoustic noise and vibration impact (permanent hum) on biodiversity

10 Ability to contribute to restart of the system following a blackout

11 See Section 6.3.4 for detail on limitations of underground cables for system restoration

12 Refer to Appendix 2 for detailed risks and Mitigations

	• Potential impact on bird species (collision risk)		• Vessel traffic
Community impacts[13]			
Construction:	• Minimal traffic disruption • Land use disruptions • Less impact in rural areas, higher impact in urban	• Traffic disruption • Potential land use disruptions due to cable trenching (depending on the route selected) • Less impact in rural areas, higher impact in urban	• Traffic disruption • Disruption to economic activities such as fishing • Low impact on both rural and urban areas, but higher impact on both with installation of new supporting infrastructure (if required)
Operational:	• Tower ground footprint occupied • Potential to depress property values • Building on route denied • Potential visual impact • Potential 50Hz EMF exposure • Noise propagation	• Building on cable route denied • Potential 50Hz magnetic field exposure	• Converter station ground footprint occupied • Building on cable route denied • Converter station visual impact • Potential DC magnetic field exposure
Cost magnitude comparison factors for a 75km 6,380 MVA / 6,000 MW transmission route (per unit)[14] [15]			
Lifetime archetype costs:	x 1	x 4.7[16]	x 8[17]
Lifetime losses costs:	x 1	x 0.8	x 1.6[18]

[13] Refer to Appendix 2 for detailed risks and Mitigations

[14] Based on cost analysis in Section 4, for all three technologies the minimum values tend to reflect the longest route length, while the maximum costs tend to associate with the shortest route length

[15] It should be noted that these cost comparisons are generalised; they are based upon many assumptions, and they are not associated with a specific application or location. For this reason they should be treated as indicative only

[16] This underground cable factor is for notional cost comparisons between the three technology archetypes, and it includes a route-length allowance for the costs of the necessary reactive compensation. In practice, it is highly unlikely that a 75km 400kV AC underground cable would be a preferred transmission solution for many reasons, including system complexity and cost - see main text

17 In practice this 6,000 MW capacity would probably be realised with 3 x 2MW HVDC links. This cost factor includes an allowance for mid-life refurbishment of the converter electronics.

[18] Mainly due to losses from converter station

Commercial & supply chain			
	• Currently, no known supply issues for overhead lines – key dependencies are supplies of aluminium and steel	• Long underground cable installations may suffer extended delivery lead times • Reactive compensation required for long cable installations may suffer extended delivery lead times	• There are presently three competitive 2000MW VSC HVDC convertor suppliers • As global demand rises (as expected in the near future), converter delivery lead times are expected to lengthen • Key issue for HVDC links is presently the lack of submarine cable manufacturing capacity. Delivery lead times already extended 2-3 years beyond normal, and likely to further increase until new production comes online around 2030.

Regarding cost ratios, it is worth noting that taking account of the estimated lifetime costs of losses can significantly alter the cost ratios between the archetypes. For example, the often-quoted procure-and-install cost ratio between the underground cables and overhead lines has been 10:1 or more. However, when including the estimated lifetime costs of losses , the lifetime cost ratio between the underground cables and overhead lines is only around 4.7:1. The reason for this significant difference in ratios is not because overhead lines cause much greater losses than underground cables (the estimated costs of losses for the two archetypes are, in fact, quite similar) but because adding the losses costs more than doubles the overall cost of overhead lines, whereas it adds less than 15% to the overall cost of underground cables.

Clearly, the three archetypes that have been described in this report can all contribute, in different ways, to achieving these objectives. Some headline characteristics of each archetype that relate to these HND objectives include the following:

Economic and efficient:

- Overhead line offers the lowest lifetime[19] financial cost transmission solution on land. Major refurbishments at 40-year intervals are expected to extend asset life by a further 40 years. Regarding system design flexibility, of all the archetypes, overhead lines are the most amenable to later uprating, mid-circuit connection alterations or route adjustments. They are also the most quickly repaired in the event of damage.
- Underground cable offers the lowest heat losses and, with that, the lowest running cost transmission solution for heavily loaded circuits, however 400kV AC underground cable circuits greater than around 20 to 25km in length

[19] The three archetypes considered here have varying levels of efficiency, depending upon the exact applications to which they are put. The IET cost study 'lifetime' cost estimates referred to here include the lifetime costs of losses as well as the original capital expenditures.

would be likely to introduce additional network operational complexities due to the need for intermediate reactive compensation stations along the route. Cable maintenance requirements are low, and major refurbishments are not anticipated to be required for at least the first 60 – 80 years of asset life – though the track record for very high voltage cross-linked polyethylene (XLPE) cable is still developing.

- For offshore connections, as transmission voltages rise and route lengths increase, HVDC offers an increasingly viable transmission solution compared to AC cables which, in practice, are limited to around a 200km route length for 275kV AC, and significantly shorter than this for 400kV; beyond these distances, only HVDC is practicable for connections that parallel the main onshore interconnected transmission system. Major refurbishment of converters at around 20 years is required to achieve 40-year asset life. Major refurbishments for the cables are not anticipated to be required, though periodic inspections of the cables (offshore and onshore) would be required to ensure, for example, that the integrity of the cable burial is maintained.

Deliverable, safe, reliable and operable:

- All three archetypes may be employed on land. They are all safe, reliable, and operable. They are all mature technologies that could (at the time of writing, in Summer 2023) be deliverable by 2030, subject to regulatory, planning and consenting processes.
- Only cable - AC or HVDC - may be employed in offshore environments.

Environmental (transmission losses have a carbon impact):

- Overhead line offers the lowest lifetime losses for, on average, low-to-medium loaded circuits.
- Underground cable offers the lowest lifetime losses for, on average, medium-to-highly loaded circuits.
- HVDC cables offer the lowest cable-only losses but, the HVDC converter losses overwhelm the losses of the other archetypes except for route lengths of 100s of km.

Local communities (visual impact and disruption):

- Without visual screening, overhead lines present a greater linear visual impact than underground cables because, to varying extents, they can be seen along their entire routes in perpetuity. That said, because of their fine conductor wires and, at least for lattice towers, their relatively fine structures, they are frequently not easily visible against 'busy' backgrounds, such as in a valley, when viewed from above. Construction disruption depends upon location but, following construction, most land uses may resume. Overhead lines create less strong magnetic fields than underground cables but do so over a wider area. They also create electric fields, although the strength of these is reduced by proximity to other structures and vegetation, including trees. An alternative design to lattice towers, T-pylons, are described in Section 5.1 AC Overhead Line, Archetype description.
- Except where a tunnel is utilised to house them, underground cables present the greatest visual impact during construction, requiring major road works in urban environments, and resembling a motorway construction site in rural environments. However, once construction is completed, most land uses may resume. In urban environments, therefore, cable routes will become immediately invisible where they lie beneath roads. Meanwhile, in the countryside, the cable swathe will gradually disappear as natural vegetation growth returns. Underground cables create very localised magnetic fields, and no electric fields.
- On land, and without screening, HVDC converter stations present the greatest block visual impact, because of their size and uniform colour. For the underground cable route to the coast, the same comments apply as for AC underground cables, but for the converter station site, there is no public access in perpetuity. As with AC, the HVDC cables' magnetic fields are very localised.

This section provided a comprehensive comparison of three network archetypes: onshore AC overhead line, onshore AC underground cable, and offshore HVDC. The analysis was based on a generalised application and does not consider any location-specific characteristics. More details on each archetype can be found in Sections 5-8.

4 COST ESTIMATES

Electricity transmission costs are affected by many variables, including component and raw materials prices, the cost of labour, the availability of manufacturer, supplier, and installer capacity, and financing and insurance costs. These, along with international economics, geopolitics, and the levels of global demand for transmission network development, all introduce uncertainty into future cost estimates.

At present, possibly the most significant element of uncertainty is the unprecedented demand for major expansions to national transmission networks to facilitate the global 'Net Zero' decarbonising goal, though the recent hydrocarbon fuel price variations due to the war in Ukraine and oil production volatility in the Middle East are additional confounding factors. With many nations simultaneously calling upon the same materials stocks, manufacturing capacities and project skills to develop their electricity transmission networks, prices are inevitably rising, but by amounts that depend upon many factors including contract timings and sizes, the exact equipment requirements, and any buying and production strategies adopted by transmission equipment manufacturers.

It is not the intention of this document to estimate specific transmission prices – for the reasons above, such an exercise in the absence of a specific transmission application is likely to have very limited value. However, when comparing technology archetypes, it is helpful to have a feel for the comparative costs of the solutions being considered. Accordingly, in the archetype descriptions (Sections 5 to 7) we provide some costing comments specific to each archetype whilst, here in this section, we present a brief approach to our capital cost and lifetime running cost estimates followed by an indicative cost magnitude comparison table, both for overall lifetime unit costs and, separately, for indicative costs of losses.

4.1 Approach to cost estimating

The values of transmission construction project contracts are normally kept confidential in order to protect the commercial interests of the various stakeholders. DNV's approach to providing an indicative transmission cost magnitude comparison has therefore been to turn to a well-regarded publicly available source that provides cost comparisons between HVAC and HVDC transmission, and between overhead and underground connections; the Institution of Engineering and Technology (IET)'s Electricity Transmission Costing Study[20]. This study, which was published in April 2012, covers all three of the archetypes featured in this document, making like-for-like cost comparisons relatively straightforward.

Of course, transmission prices have risen steadily since the IET costing study report was written, in line with the prices of metals and other raw materials, and with labour costs, and the pace of this rise has increased over the last two or three years, not least because of the significant rises in financing costs. There will also have been some differences, between archetypes, in the pace of price rises since publication of the costing study; however, these differences were not researched here and, for the purposes of this commentary and comparison, we have assumed that the comparative costs have not changed. We do, however, make further comment about this aspect in Sections 5.2, 6.2, and 7.2.

The IET costing study assumed a 40-year equipment life for each technology archetype and, to aid cost comparisons, derived lifetime costs for each archetype based on several pre-agreed circuit lengths and transmission route capacities. We selected the IET's 75km route length, 'Medium'[21] capacity options when preparing the cost comparison table at the end of this section.

The 'lifetime costs' or 'whole-of-life-costs' presented by the IET costing study take account not only the 'upfront' capital costs (CAPEX) such as design, procurement, shipping, installation, commissioning, and project management to place the equipment on the ground, but also the estimated ongoing revenue costs (OPEX) of maintenance, and losses, all summed over the equipment life on a present-value basis. This latter item, losses, is significant to transmission lifetime costs, so we provide further commentary on losses next.

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[20] IET Electricity Transmission Costing Study https://www.theiet.org/media/9376/electricity-transmission-costing-study.pdf

[21] 'Medium' capacity relates to the study's 6380MVA AC/6000MW DC capacity options for each archetype

One final point to note on the lifetime costs is that neither the IET costing study, nor we with this document, have attempted to estimate costs for (i) project financing, (ii) consents, wayleaves and public enquiries, or (iii) environmental assessment and mitigation. This is because these factors depend so much upon the specific application and the chosen project approach that to consider them in isolation would be misleading. They should not be disregarded during an actual transmission planning application, since they can all significantly impact the overall project budget.

4.2 Energy (heating) losses

Losses are so-called because the term refers to the loss or waste of heat energy from all transmission equipment during its operation. The levels (and therefore the costs) of losses can be seen as a measure of the operational efficiency of the transmission equipment and these inefficiencies are relevant because, over the nominal 40-year equipment lives, their costs and carbon impacts mount up significantly.

Whenever current flows through an electrical conductor it causes a rise in the conductor's temperature and therefore a heat loss into the atmosphere. The levels of heating losses in a conductor are calculated by the square of the current flowing times the conductor resistance so, to minimise this waste heat, transmission currents and conductor resistances are both minimised as much as is economically practical. The effect of the variation of losses with current is that, for a lightly loaded transmission circuit, the currents, and therefore the losses, are low whilst, when the same circuit is heavily loaded, the currents are higher and therefore the losses (proportional to the square of the current) are very much higher.

Since losses are electrical energy being released to the atmosphere as waste heat, this electrical energy has to be generated somewhere. In fact, extra electrical generators must be bought, installed and fuelled just to supply the waste heat of losses.

So, heat losses vary according to circuit load levels, but they also vary between archetypes because different factors affect the losses in each case. It turns out that, for lightly loaded AC circuits, overhead line losses are normally lower than those of underground cables whilst, for heavily loaded circuits the reverse is true. This effect is shown in Figure 4.1 where the green line depicting the overhead line losses starts low but rises much more quickly than the red underground cable line, and in fact, crosses the red line as circuit load rises.

HVDC link losses, like underground cable losses, increase very slowly with load, however, in their case, they start at a much higher level of losses because of the constant relatively high inefficiencies of the two converter stations. HVDC losses are depicted in Figure 4.1 as a blue line.

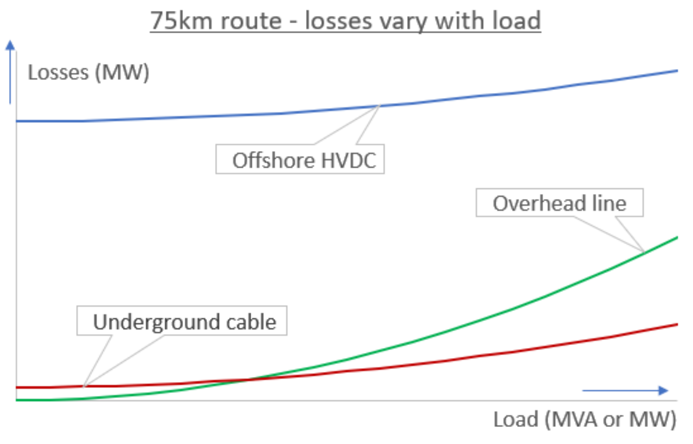

Figure 4.1: Comparative losses behaviours for the three archetypes

The three different losses behaviours illustrated in Figure 4.1 are compared there for a notional 75km transmission route. The graphic shows that the HVDC solution over this distance is the least efficient in all circumstances, whilst the loading level of the circuit determines whether an overhead or an underground cable would be the most efficient.

The IET's costing study separately identified the costs associated with transmission losses and, since these losses are highly relevant to the consumer and to the environment today, they are reflected here in our comparison of lifetime costs.

Some further notes on losses are provided under the 'Limitations' sections of each archetype description.

4.3 Cost magnitude comparison

The following Table 4.1 uses the IET costing study figures to outline cost comparisons for the two AC onshore options and the HVDC offshore alternative for a 75km, 50% loaded, double circuit 6,380 MVA AC summer, pre-fault continuous capacity transmission connection and its 6,000 MW VSC HVDC equivalent.[22] Two comparisons are presented: (i) whole-of-life costs and (ii) lifetime costs of losses only. It should be note that these comparisons are based upon many assumptions and are indicative only since they are not associated with a specific application.

Table 4.1: Lifetime cost magnitude comparisons for a 75km 6,380 MVA / 6,000 MW transmission route

	AC OHL	AC UGC	HVDC VSC Link
Lifetime cost[23]:	x 1	x 4.7	x 8
Lifetime losses costs[24]:	x 1	x 0.8	x 1.6

[22] A 6,000 MW HVDC capacity would probably be realised, in practice by 3 x 2,000 MW HVDC links.
[23] "Lifetime cost details underlying these lifetime unit cost comparisons may be found in Figure 8, page 118 of the IET costing study.
[24] Lifetime losses cost details underlying these lifetime unit cost comparisons may be found in the 'Variable Operating Costs' sections on pages p36, p56, and p112 of the IET costing study. These losses costs ratios do not include lifetime operations and maintenance costs.

5 AC OVERHEAD LINE

5.1 Archetype description

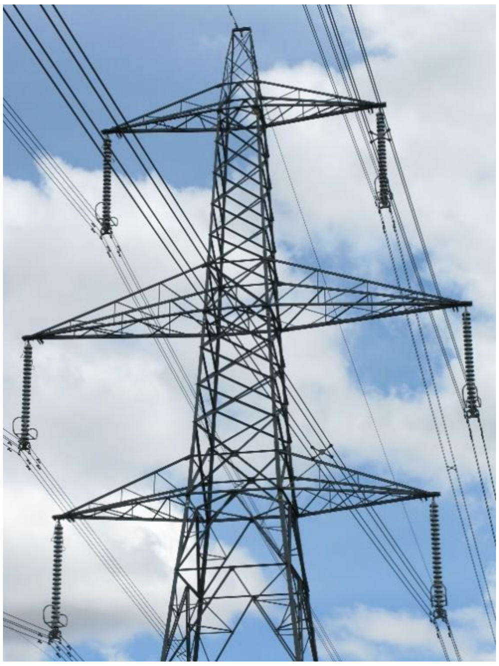

Figure 5.1: 400kV double circuit overhead line, steel lattice tower

Overhead alternating current (AC) transmission lines transport bulk supplies of electricity over long distances – sometimes hundreds of miles across country from the generators to the distribution substations and direct consumers. Most transmission networks around the world are built largely of overhead lines because, to date, this has been by far the lowest-cost method of electricity transmission – a factor that benefits every consumer's electricity bill. In general, therefore overhead lines are considered the starting presumption for electricity network development in Great Britain, although this does not apply to all types of landscape. Further details about planning presumptions are given below in Section 5.3.1

Overhead lines (OHL) normally use bare aluminium alloy conductors to transport the electricity and they operate at high voltages (400kV, or sometimes 275kV, in Great Britain) to minimise operating losses. To operate correctly and safely, therefore, the high voltage conductors must be separated from earth, and for this purpose they are suspended tens of metres above ground, normally by steel lattice towers and porcelain or glass insulator strings. Figure 5.1 shows a standard double circuit 400kV overhead line suspension tower supporting two three-phase circuits, one circuit on each side of the tower. In this case, each phase conductor comprises a bundle of four aluminium alloy wires.

More details of the modern steel lattice structures used in Great Britain are provided in the following paragraphs, however, it is worth noting that there is now an alternative design to steel lattice towers, namely the steel monopole T-Pylon. At typically 35m high compared to the lattice structure's 46.5m, T-Pylons are roughly one-third shorter than the steel lattice equivalents, although this reduction is offset by their overall width of around 31m compared to the lattice structure's narrower 18.2m. The T-Pylon monopoles have a 10 square metre ground footprint that is completely enclosed, whereas the lattice tower base covers between 50 and around 70 square metres of relatively open space.

The T-Pylon design is the result of an international competition to find a tower with a lower visual impact on the surrounding landscape. The first operational examples were commissioned in 2022 on a section of overhead line between Bridgwater and Loxton, in Somerset and all 116 of the T-Pylons on the new Hinkley Point–Seabank transmission route were installed by August 2023. Their single monopole is more visible than the lattice against some backgrounds, however, they present a 'lower outline' to the viewer than lattice structures and they can be assembled relatively quickly once they have been transported to site.

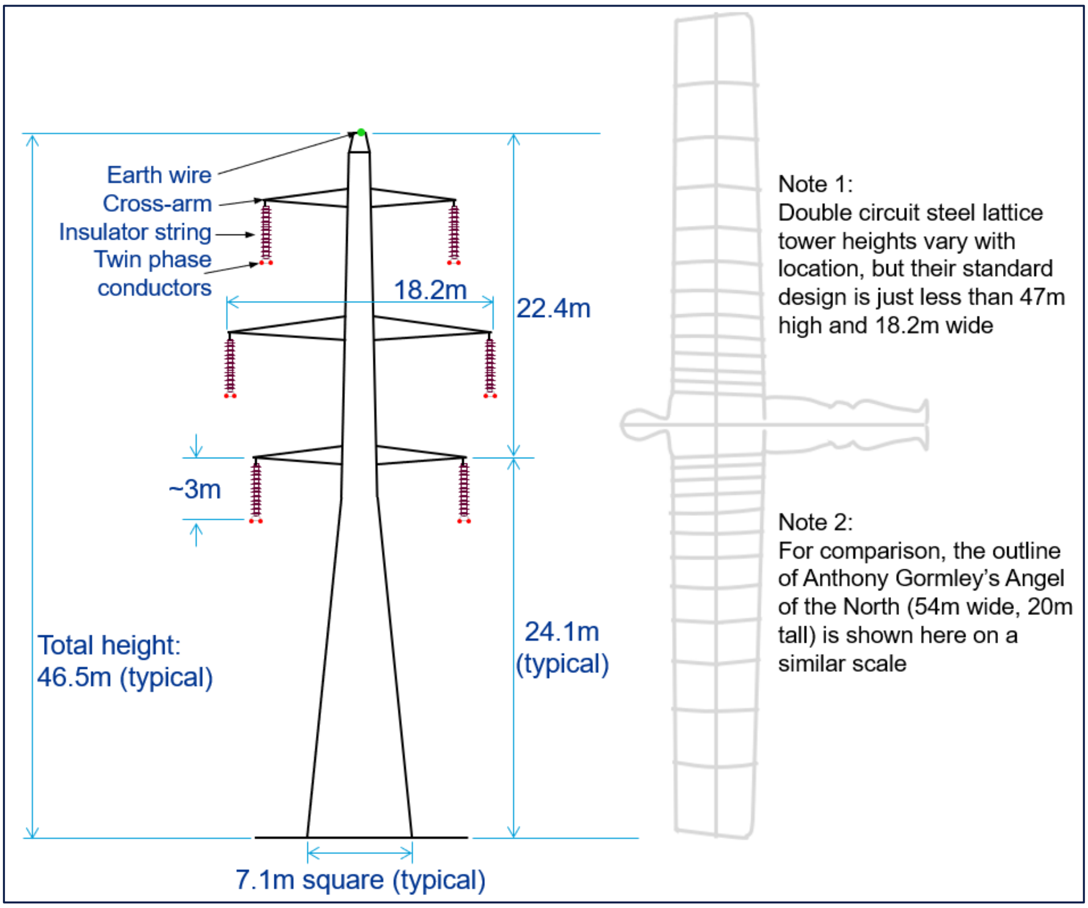

Figure 5.2: Example dimensions of a modern 400kV double circuit steel lattice tower

In Great Britain, the 400kV steel lattice towers (and the T-Pylons) support two electrical circuits, one on each side of the tower. In this way, one circuit, which comprises three separate phase conductors, can continue to supply customers even whilst the parallel circuit on the other side of the tower is out of service. This double-circuit approach to system design helps the system operator to continue to deliver secure electricity supplies even in the event of a circuit fault.

Typical dimensions of a modern steel lattice suspension tower design are provided in Figure 5.2. Note that, whilst the dimensions of the upper part of the tower (the top 22m) are standard, the width of the square base will increase up to around 10 - 12m where the overhead line route turns a corner or needs to clear a particularly tall obstruction. For example, towers may be higher at motorway and river crossings than when crossing flat, rural countryside. There are over 15,000 steel lattice transmission towers in Great Britain, so most people are very familiar with the sight of them; however, to provide some scale, a typical tower is about 8m shorter than Anthony Gormley's Angel of the North 54m wingspan, and about 2m narrower than the Angel's 20m height.

Overhead lines are designed as a series of straight-line sections. Tower construction starts underground where, typically, four large, pyramid-shaped holes contain the tower's steel footings encased in concrete foundations. The lattice structure is next erected on to the steel footing stubs before the six insulator strings are hung from the ends of the tower arms. Once a straight-line section of towers has been constructed, the conductors are pulled right along the section and secured to the insulators, whilst precisely adjusting the sag in each span and carefully ensuring that no damage occurs to the conductor surfaces. An exclusion swathe will be in place during the conductor stringing process. This swathe will be a few metres wider than the 18.2m tower span width, simply to avoid any risk to people, animals, vehicles, and to the conductor itself, until it is fixed at the correct height.

This steel lattice overhead line technology is mature, with a successful service track record of decades. All these overhead line designs have remained resilient even in the worst weather conditions so, although one or both circuits on an overhead line route might be taken out of service momentarily by a lightning strike, their automatic return to service following such an incident is normally accomplished within seconds. Their availability for service thus remains very high, supporting the ESO's ability to ensure excellent security of supply to the country.

5.1.1 Transmission capacity

Transmission circuit capacity is the physical capability of that circuit to transfer electrical power. This capability will depend upon several factors, particularly ambient temperature, recent loading history and, of course, the capacity (or rating) of the lowest rated component in the circuit. Transmission capacity is normally measured in megavolt-amps (MVA) for AC circuits and megawatts (MW) for DC circuits.

The transmission capacity of a 400kV overhead line depends upon the diameter (and type) of its alloy conductors, upon the number of conductors (two, three or four) that are bundled together for each of the three phases and upon the ambient temperature (the yearly seasons). With these variations, each circuit's pre-fault continuous summer rating design capacity can range from less than 1,500 MVA to over 3,000 MVA, offering double circuit ratings for the overhead line route of twice these figures. The actual design capacity of each overhead line will be carefully chosen to be compatible with the rest of the grid.

Overhead lines have a significant advantage over HVDC links in that, during emergency conditions, they have the flexibility to accommodate much higher loads than their rated capacity for short periods (Section 5.3.3. 'Flexible Circuit Rating' provides further details) whilst the system operator resolves the issue.

Overhead lines have low charging currents, typically less than 1 A/km/phase, so can successfully operate over many kilometres without needing separate reactive compensation. This same characteristic makes overhead lines ideal for reconnecting the network together during system restoration (following a blackout).

5.1.2 Lifespan

The initial expected lifespan of an overhead line is significantly more than 40 years, although a major refurbishment – for example, the replacement of the conductor systems – that is their conductors, insulators and fittings – at around this age can add another 40 years to the effective life of the asset for a cost of, perhaps, 40% that of a new build.

Apart from the conductor systems, the lives of the other components of overhead lines, namely their steel lattice towers and their concrete foundations, are proving very resilient over time and, in general, are expected to support an 80 or 120-year asset life. Regarding asset life and life extension, a particular benefit of the towers and foundations is that, even where wear and tear, ageing or direct damage have occurred, the damaged element can be repaired or replaced 'piecemeal', on demand, without needing to replace the whole overhead line. Some of the smaller maintenance tasks can even be undertaken without taking the overhead line out of service.

We note that a major refurbishment, such as that mentioned above, that includes replacement of the conductor system, can also be an opportunity to upgrade the overhead line conductor capacity, if this is an expected requirement within the network plan.

5.1.3 Limitations

The principal limitations of overhead lines relate to their space requirements, the visual intrusion on people who need to live close to them, and public concern about the electromagnetic fields (EMFs) created by towers. For these reasons, the process of routeing new overhead lines (and even of upgrading existing ones) has become increasingly complex and time-consuming in recent years. Public awareness of environment and landscape heritage has meant that new overhead line planning applications are more likely than ever to become the subject of public enquiries. Such enquiries inevitably have the effect of significantly delaying delivery of the transmission circuits and these delays might, in turn, cause alternative, quicker solutions to be favoured by the network planners even though they could be more financially costly.

Regarding energy losses, these are not normally considered to present significant limitations for overhead lines although, in practice, the losses levels depend upon several factors, some of which vary from day to day. Of these factors, two are key; (i) the overhead line design capacity, and (ii) its loading at any moment. For example, increasing conductor diameter to increase design capacity lowers electrical resistance and, therefore, losses; meanwhile, increasing transmission load and, therefore, current, at any instant raises losses at that same instant, since losses increase in proportion to the square of the electrical current flowing. There is further commentary on losses in Section 4.2.

There are situations where domestic and / or commercial buildings have been erected close to, if not beneath, existing overhead lines. Such circumstances generally represent a greater risk to security of supply due to the potential for both circuits to be faulted at the same time if, for example, a heavy vehicle was to hit a tower, or if thick smoke from a fire was to envelop all the conductors.

5.1.4 Future scalability for long-term planning

Overhead lines are a mature and versatile transmission technology, being equally applicable both to the main interconnected transmission network, which benefits many network users, and to connections used exclusively by a specific generator or large consumer.

As mentioned in Section 5.1.2 Lifespan, a specific advantage of overhead lines compared to underground cables is that, in many cases, their transmission capacity can be uprated, either by replacing their conductors with a larger cross-section or higher operating temperature (hotwiring) design or, for lower voltage circuits, by raising the overhead line operating voltage. Any of these uprating approaches may be referred to as a ‘major refurbishment’ of the overhead line.

Regarding versatility, with appropriate planning and consents, an overhead line route may be diverted to avoid a major new development project, the exact specifications of the new route being first taken through consultation with communities and statutory partners. Also, as network requirements change, it is sometimes relatively easy, compared to an underground cable circuit, to reconfigure an overhead line circuit’s terminating connection so that it lands at a more useful section of a substation, or even at a different substation altogether. Equally, if new generation or demand is to be connected to the transmission network, it is normally much easier to reconfigure overhead line for this purpose than underground cable.

5.2 AC overhead line costs

Factors affecting overhead line construction costs include ease of access to tower locations, the ground conditions for tower foundations, and the numbers and types of traffic crossings on the overhead line route. On this latter point, normally, temporary scaffolding bridges are built to protect roads and railways during conductor stringing, to keep their traffic flows running smoothly; where there are many crossings, particularly of major motorway or rail routes, these bridges can add significantly to the project budget. Other capital costs to keep in mind include those of environmental assessment and impact mitigation, public consultation and public enquiry, and consents and wayleaves. The most significant operational cost of overhead lines relates to lifetime losses.

Nevertheless, since tower foundations only need to be provided at around 330m intervals (roughly 3 per km), overhead lines frequently offer the lowest cost-per-km technology for onshore transmission of bulk electricity supplies.

5.3 Deliverability and operability

Deliverability and operability are two key aspects of the planning process for any proposed new transmission circuit. In this Section we consider first the deliverability of new overhead lines and then secondly their operability.

Overhead line technology is mature – the challenges of acquiring the technology for a new route are well understood and solved. The main unknown regarding deliverability is thus the question of whether, and when, planning consent will be granted, so this is the subject of our next subsection.

Overhead line operation is also well understood, and its technical challenges mostly solved, so the other three subsections here address some of the operating characteristics and benefits that are specific to overhead lines.

5.3.1 Planning consents

In England and Wales, a proposed new overhead transmission line build is classed as a 'Nationally Significant Infrastructure Project (NSIP)' by virtue of being an above ground electric line with a voltage of 132kV or greater (Part 3, Section 16 of the Planning Act 2008, as amended by The Overhead Lines (Exempt Installations) Order 2010). As such, an application for a Development Consent Order (DCO) must be submitted to the Planning Inspectorate who will examine the application and issue a recommendation to the Secretary of State for planning. It is the Secretary of State who makes the final decision whether to grant development consent. A DCO granted for an overhead line route would probably also cover any underground cable sections that may be required.

The preference for the use of overhead lines for electricity transmission in Great Britain would be formalised by the March 2023 draft version of the National Policy Statement for Electricity Networks Infrastructure (EN-5)[25], which confirms, at paragraph 2.9.20, the Government's position "… that overhead lines should be the strong starting presumption for electricity networks developments in general, …". That said, the same paragraph emphasises that this presumption does not apply where harm to the landscape, visual amenity and natural beauty of specific areas cannot be avoided by re-routing overhead lines. These specific areas include "… National Park, The Broads, or Areas of Outstanding Natural Beauty …", and our Section 6 AC Underground Cable provides further details.

Delivery of consented transmission circuits may be delayed by the wayleave negotiation process, although GB transmission owners do also have a little-used compulsory purchase authority.

5.3.2 Reliability, availability, maintainability

The reliability, availability and maintainability (RAM) of overhead lines are affected by several factors, but particularly by their design prior to construction, and then by the weather (especially lightning storms) during operation.

Regarding reliability and availability, the transmission overhead line designs used within GB are robust, have been thoroughly tested, and have many years of successful service history, so most overhead line unreliability (unplanned outage events) is attributable to lightning strikes. However, several overhead line circuit characteristics ensure that this unreliability does not translate into significant unavailability or loss of supply to customers. These characteristics include:

1. Due to their robust designs, neither overhead lines, nor the equipment connected to them, normally sustain permanent damage from lightning strikes;
2. Although an overhead line circuit that is struck by lightning is automatically and immediately switched out of service to isolate it from the rest of the network, almost all transmission overhead line circuits have 'automatic reclose' controls that restore the circuit to full operation within a few seconds;
3. In the rare case that an overhead line or tower is physically damaged by any cause, the defect is usually easy to locate, and its repair realised within hours, or just a few days. However, if a fundamental part of a tower or conductor system is damaged, this can take longer to repair, and both circuits may then need to be taken out of service for a week or two. Carefully planned maintenance programmes and spares holdings together minimise outage durations and maximise overhead line circuit availability. Sometimes, for a tower repair, it is even possible to erect temporary towers that allow the two circuits to return to service whilst the

[25] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1147384/NPS_EN-5.pdf

damaged tower is being repaired, a measure that supports the availability of the overhead line circuits and thus the overall security of supply of the network.

Regarding maintainability, over the course of the life of the overhead line, each element of the construction is inspected, maintained and, where necessary, replaced. Inspections will take place on foot, by helicopter or by drone, as appropriate. For example, a helicopter equipped with an infrared camera can quickly scan an entire route for hot joints, thus enabling preventative maintenance to occur before the hotspot causes an unplanned outage.

Another overhead line maintenance task is to regularly patrol the overhead line route to check that no construction work, agricultural activity, trees, or even intentional bonfires risk causing a flashover[26]. Flashovers – very high energy sparks between the high voltage conductors and ground – are to be avoided since, locally they can cause serious danger of fie or electrocution and, for the power network, they constitute an unplanned outage that may reduce security of supply. Accordingly, the overhead line inspection team will offer advice to landowners regarding activities beneath overhead lines and will also arrange brush-cutting where necessary.

Some types of overhead line inspection, such as the above-mentioned route patrols, can be carried out whilst the circuit is energised. However, from time to time, each circuit will be taken out of service for maintenance. Such outages are normally restricted to a few days or weeks over a 10-year period, yielding an estimated average overhead line circuit unavailability level of around 3 days pa, or better than 1% - that is an availability of over 99%. In fact, during the 8-year regulatory review period 2013-2021, all three of the GB TOs significantly outperformed their annual availability targets set by Ofgem by turning in an average ‘overall level of network reliability of 99.997%’.

5.3.3 Flexible circuit rating

Overhead line power capacities depend, in practice, upon many factors, but they all relate, in one way or another, to the temperature of the conductor. Solar irradiance levels and ambient temperature are two such factors, both of which are expected to be higher during the summer. Thus, whilst overhead lines need to be designed to be capable of delivering the required power levels during the more onerous summer conditions, they can offer the system operator higher power transmission capacities during the cooler winter conditions, which happens to coincide well with higher consumer energy requirements during the colder months.

During emergency conditions, for example, during the system’s recovery from an unplanned outage, overhead lines are sometimes required to carry more power than normal. However, the more power they carry, the higher their conductor temperatures rise and the more the conductors expand and sag between their supporting towers. To ensure that safety clearances beneath the overhead lines are maintained even during emergency conditions, each circuit is assigned its own specific operational temperature limit (usually within the range of 50°C to 90°C – although some special conductor types (so-called ‘hot wiring’ conductors) can exceed this temperature range without infringing safety clearances).

In conjunction with these emergency temperature limits, overhead lines have a certain amount of ‘heat capacity’, allowing them to be safely overloaded by specific amounts for given periods of time following an unplanned equipment outage. This allows the system operator enough time to re-secure the system without customers losing supply and without infringing acceptable safety clearances.

For example, following a network fault, the overhead line continuous rating would typically rise by around 20% in the summer and up to 37% (that is, to 3,820 MVA for the highest capacity conductors) during the winter months, with even higher short-term ratings available when demanded by network conditions. And of course, each double circuit overhead line route would be able to deliver twice these capacities (7,640 MVA in the above example).

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[26] A 'Flashover' is an electrical short-circuit between the high-voltage conductors and the ground, or anything connected to the ground. The short-circuit normally results in a very high-energy spark that can cause danger to property, people and animals. Should a flashover occur, the overhead line power will be automatically switched off for a few seconds, and then restored.

5.3.4 System restoration capability

To recover from the (rare) situation of a total electricity system blackout, some (relatively small) power generation is firstly required to start up the larger generating stations. Once they are operating, power can be supplied to the remaining generating stations and consumers can be reconnected. Traditionally this was achieved with diesel or gas turbine generators starting up the main gas and coal-fired power stations but, in line with Net Zero targets, and with the help of renewable generation, new energy storage technology, and a distributed approach to restoration, the ESO plans to be capable of carbon-free system restoration before the end of 2024[27].

The process of system restoration thus needs simple transmission connections that require minimum controls, absorb minimum amounts of energy, do not require supplies to be available at both ends of the connection, and are immediately available for service. Overhead lines meet all of these criteria and are therefore ideally suited to transferring restoration power across the transmission system to help network and generation operators to restart the national power supply. In this role, they are generally preferable to underground cables and HVDC links since they demand negligible real or reactive power from the weakened network whilst, at the same time, transmitting useful power.

In saying that overhead lines are ideally suited in this situation, the reader should nevertheless understand that overhead lines are passive network components that do not provide any restoration energy themselves; in this role they simply facilitate the transfer of power from restoration energy sources to other, larger generators needing startup power.

5.4 Environmental impacts

As part of this section, DNV has applied the knowledge of international best practices, such as International Finance Cooperation (IFC) Performance Standards[28], IFC Environmental Health and Safety (EHS) Guidelines[29], the EHS Guidelines for Wind Energy (EHS WE Guidelines) [30]and EHS Guidelines for Electric Transmission and Distribution (EHS ETD Guidelines)[31], in performing this assessment of environmental and community impact.

The assessment in this report is based on the high-level information provided and does not constitute a full strategic environmental assessment (SEA) or environmental impact assessment (EIA) used for permitting purposes.

In the UK, the requirements for an SEA are governed by the Environmental Assessment of Plans and Programmes Regulations 2004. Certain plans and programmes are likely to be required to undertake an SEA if they are likely to have significant environmental effects, and a screening exercise is undertaken in order to determine whether it is applicable or not.

This chapter summarises the most prominent environmental impacts to be considered during the manufacturing and construction phase and operation phase for this archetype. Detailed impacts and mitigation measures can be found in the Appendix 2.

5.4.1 During manufacturing and construction

5.4.1.1 Resource efficiency and pollution prevention

The following impacts should be considered:

- **Raw Materials Consumption:** The construction of overhead line conductors, insulators and support structures requires significant amounts of materials (including steel, aluminium, concrete and porcelain or glass), which can lead

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[27] https://www.nationalgrideso.com/industry-information/balancing-services/electricity-system-restoration-standard

[28] Performance Standards (ifc.org)

[29] Environmental, Health, and Safety Guidelines (ifc.org)

[30] Environmental, Health and Safety Guidelines for Wind Energy (ifc.org)

[31] Final - Electric Power Transmission & Distribution.doc (ifc.org)

to resource depletion and environmental impacts associated with material extraction, manufacturing, and transportation.

- **Energy Consumption:** Energy-intensive activities, such as manufacturing components, transportation of materials and equipment, and installation processes contribute to energy consumption and greenhouse gas emissions, especially where these activities are supported by coal fired power plants.
- **Waste Generation:** A certain amount of waste will be generated, including some packaging materials and construction debris, leading to increased landfill waste and potential pollution. However, as with all the archetypes, component damage and replacement are normally minimised by approved methods of transport and storage, and some packing materials – notably the conductor transport drums, are frequently reused by the supplier.
- **Soil and Groundwater Contamination**: There might be some very local changes to the soil properties resulting from the soil movement for tower foundations and from other overhead line construction activities. There might also be accidental leaks of wastes or oils used by the construction machinery. Whilst measures are taken to avoid such incidents, we would expect contingency plans to be in place to minimise ground contamination and impact on nearby groundwater sources should any such incident occur.

5.4.1.2 Impacts on biodiversity

This baseline assessment will define the biodiversity net gain targets that the project should achieve, the target can be based on local biodiversity policies and government guidelines and should reflect the overall goal of enhancing biodiversity and aim to deliver a measurable increase in biodiversity compared to the baseline. The quantification of net gain can involve modelling techniques, ecological valuation methods or expert judgment.

A Habitat Regulations Assessment (HRA) is conducted to assess the potential impact of a plan or project on protected habitats and species. The HRA is required under the Conservation of Habitats and Species Regulations 2017 (known as the Habitats Regulations), based on an initial screening process which assesses the project location, proximity to any ecologically sensitive areas and if impacts cannot be mitigated/excluded, this will establish whether a specific project is required to undertake the full assessment. The responsibility of conducting the assessment lies with the public authority or the developer proposing a plan or project, or the relevant consultancies acting on behalf of these parties.

Aside from community land use, the baseline habitat within the area of the overhead line will also need to be assessed, which should include impact on birds, habitats, flora, vegetation, and wildlife (amphibians, reptiles, mammals). The following impacts should be considered:

- **Habitat Loss and Fragmentation**: Construction activities may result in the clearance of vegetation, including trees, shrubs, and other plant species, leading to the loss of habitat for various plant and animal species. The linear nature of overhead lines can also cause fragmentation of habitats, hindering the movement of wildlife.
- **Disturbance to Wildlife:** Construction activities, including noise, vibration, and increased human presence, can cause disturbance to wildlife species. This disturbance can lead to altered behaviour, displacement, or temporary abandonment of nesting or breeding sites.
- **Soil Erosion and Sedimentation:** Construction activities can lead to soil erosion, particularly during site grading and vegetation clearance, which can result in sediment runoff into nearby water bodies. Increased sedimentation can negatively affect aquatic habitats and species.
- **Watercourse and Wetland Impacts:** Construction activities may involve crossing or working near watercourses, wetlands, or other aquatic habitats, leading to potential impacts on aquatic ecosystems, water quality, and associated species.
- **Invasive Species Spread:** Construction activities and the associated disturbance can create opportunities for the spread of invasive plant species, which can outcompete native vegetation and negatively impact biodiversity.
- **Collision Risk:** Birds may be at risk of collision with overhead lines or associated infrastructure during construction, particularly if they are not properly marked or made visible.

- **Risk of Electrocution:** Overhead lines can pose a risk of electrocution to birds if appropriate measures are not in place to prevent them from perching or nesting on the equipment.
- **Nesting Site Replacement**: Construction activities may result in the direct removal or destruction of bird nests. Displacement from nesting sites can disrupt breeding patterns and affect reproductive success.

To specifically understand the impact of the transmission lines on birds a full bird observation and assessment, as part of the baseline assessment, is required for various seasons of the year. This assessment[32] would identify the following:

- Site-Specific Issues
- Species-Specific Issues
- Seasonal-Specific Issues
- Vantage Point Survey

Furthermore, the baseline study will identify if there are any high risk (categorised endangered) species and any protected areas within the radius around the overhead line.

5.4.1.3 Impacts of excess noise and dust

The following impacts should be considered:

- **Construction Equipment and Machinery:** The use of heavy machinery and construction equipment such as cranes, excavators, and pile drivers can generate significant noise levels during the installation of towers, and other infrastructure.
- **Construction Activities:** Construction activities, including excavation, foundation work, and material handling, can create noise, particularly during the assembly and erection of overhead line structures.
- **Traffic and Transportation:** Increased traffic and transportation associated with the delivery of construction materials, equipment, and personnel to the construction site can contribute to noise generation.
- **Noise Monitoring and Compliance:** Inadequate monitoring and failure to comply with noise control regulations can result in excessive noise levels that negatively impact nearby communities.
- **Airborne Emissions**: Air emissions expected during the construction of the project may include both airborne dust resulting from earthworks and exhaust emissions from construction machinery such as power generators, excavators, cranes and delivery vehicles. Dust particles in the air can cause reduced breathing air quality and can settle on vegetation, soil, and water bodies, leading to potential harm to ecosystems and nearby communities. Excess dust will also contribute to the overall emissions generated as part of the project which is highlighted as part of the climate change impact section below.

5.4.1.4 Accessibility to site

The following impacts should be considered:

- **Construction access:** During the construction phase, access routes to the transmission line sites need to be planned and constructed. This involves considering the width and condition of roads or tracks, bridges, and access points for construction vehicles and equipment.
- **Public safety and security:** Accessibility impacts also extend to considerations of public safety and security. Appropriate signage, barriers or fencing should also be installed to discourage the general public from accessing the construction site.

[32] Scottish Natural Heritage, “Guidance Note – Survey Methods for Use in Assessing the Impacts of Onshore Wind Farms on Bird Communities” (2010).
Strickland, M.D., et al. 2011. Comprehensive Guide to Studying Wind Energy/Wildlife Interactions. Prepared for the National Wind Coordinating Collaborative, Washington, DC.

5.4.1.5 Climate change impacts

The construction period of an overhead line can have various climate change impacts, primarily associated with greenhouse gas emissions, energy consumption, and changes in land use. The following impacts should be considered:

- **Construction Machinery and Vehicles:** Construction activities involve the use of heavy machinery, vehicles, and equipment that can generate direct emissions, primarily from the combustion of fossil fuels. These emissions contribute to the overall carbon footprint of the project.
- **Material Production and Transportation**: The production of construction components such as the tower steel and the aluminium conductors involve energy-intensive processes that emit greenhouse gases. Additionally, transportation of these materials to the construction site can contribute to carbon emissions.
- **Construction Operations:** The construction phase requires significant energy consumption for powering machinery, equipment, and temporary facilities on-site. The energy sources used, such as diesel generators, can impact overall energy efficiency and carbon intensity.
- **Material Production:** The production of construction materials, such as steel and concrete, requires energy-intensive processes that contribute to indirect energy consumption and associated emissions.
- **Soil Disturbance:** Construction activities can result in soil compaction, erosion, and disruption of natural soil processes, which can have negative consequences for soil health, nutrient cycling, and carbon storage.

5.4.2 During operation

5.4.2.1 Impacts on biodiversity

During the operational phase of the overhead line there are several impacts to biodiversity, namely for birds:

- **Collisions:** Birds in flight may collide with power lines, especially during low visibility conditions or when the lines are not clearly visible.
- **Nesting:** Birds may build nests on or near transmission structures, putting them in close proximity to live electrical equipment. This increases the risk of nest failure due to electrical hazards or the destruction of nests during maintenance activities.
- **Habitat fragmentation**: The construction of overhead transmission lines can lead to habitat fragmentation, and restricting the movement of wildlife, particularly arboreal species such as birds and arboreal mammals. This can disrupt breeding patterns, migration routes, and access to food and shelter. Additionally, vegetation clearance and maintenance activities around overhead line can result in the removal of trees, shrubs, and other vegetation that provide habitat and food sources for wildlife.
- **Electromagnetic fields:** There is some evidence to suggest that there some adverse impacts on birds and species from EMF, specifically around, behavioural effects, magnetic field sensitivity, health effects and species variability.

5.4.2.2 Accessibility to site

The following impacts should be considered:

- **Maintenance and inspection:** Accessibility for routine maintenance and inspection activities is crucial to ensure the ongoing reliability and safety of the transmission line.
- **Vegetation management:** Vegetation growth around the transmission line can impede access and pose safety risks such as keeping a 100m wide corridor free of trees and shrubs that can catch fire or lead to a safety violation.
- **Security and restricted access**: It is essential that security measures are in place to avoid unauthorised access.
- **Access during an emergency**: Access to the transmission line during an emergency needs to be clear and convenient for any emergency services.

5.4.2.3 Climate change impacts

Climate change can have various impacts on overhead lines, some of the key impacts of climate change on overhead transmission lines include extreme weather events, increased temperature and heatwaves, sea-level rise and coastal erosion, and changes in precipitation patters.

- **Extreme weather events**: Climate change is leading to an increase in the frequency and intensity of extreme weather events. These events can cause physical damage to overhead lines and potentially causing them to collapse.
- **Increased temperature and heatwaves**: Higher temperatures can increase the electrical resistance in overhead lines, leading to increased power losses during transmission. Please refer to Section 4.2 for further information on losses.
- **Sea-level rise and coastal erosion**: Rising sea levels due to climate change pose a threat to coastal overhead lines. Saltwater intrusion can corrode metal components, while erosion can undermine the stability of transmission towers.
- **Changes in precipitation patterns**: Changes in precipitation patterns can affect the stability of the ground on which transmission towers are built. Increased rainfall or prolonged periods of rain can saturate the soil, increasing the risk of landslides or destabilisation of the ground, which can compromise the structural integrity of the overhead lines.
- **Decommissioning and Disposal:** At end-of-life, decommissioning would normally remove all above-ground structures along with some, or all, of the foundations, unless these were to be re-purposed, and proper decommissioning practices will be applied to minimise environmental impact.
- **Life Cycle Assessment:** It is important to consider the full life cycle of the overhead line, including its manufacturing, installation, operation, maintenance, and eventual decommissioning, to assess the overall climate change impact.
- **Transfer of Renewable Energy**: One of the positive secondary impacts of the overhead line is that the network supports the transfer of renewable energy across the country, which allows the UK to increase their renewable energy mix and contribute positively to reducing the impacts of climate change.

5.5 Community impacts

This chapter summarises the most prominent community impacts to be considered during the manufacturing and construction phase and operation phase for this archetype. Detailed impacts and mitigation measures can be found in the Appendix 2.

5.5.1 During manufacturing and construction

5.5.1.1 Land use and community impacts

It is important to understand the current land use on the length of the overhead line and the presence of any residential areas or cultural heritage sites that may be affected. This should be undertaken during the environmental impact phase of the pre-construction period. If the land which will be utilised for the construction of the overhead line is currently occupied, a resettlement/reallocation of land process will need to take place, following a standard community engagement process and notice period to allow the community to make any claims. However, the likelihood of this will be relatively low (if avoidable), as the route planning exercise will consider the options with the least impact, such fields rather than densely populated urban areas. Additionally, the following impacts should be considered:

- **Visual Impact:** The construction of overhead lines involves the installation of towers and associated infrastructure, which can alter the visual landscape of an area. This change may be perceived as unsightly or intrusive by the local community.
- **Land Use Disruptions:** Construction activities may require temporary land use changes, including access roads, construction staging areas, and storage of construction materials. These changes can disrupt existing land uses and activities in the area. Dust and noise impacts may also be significant on nearby communities as well as increased traffic inflow due to transportation of materials.

- **Community Engagement and Communication:** Lack of effective communication and community engagement during the construction phase can lead to community dissatisfaction, misinformation, and potential conflicts.
- **Electromagnetic Field (EMF) Exposure:** Overhead lines emit electromagnetic fields that decrease in intensity with increasing distance from the lines. The community living or working in close proximity to the overhead lines may experience higher levels of exposure to EMFs compared to those farther away. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has established guidelines for limiting exposure to EMF. These guidelines provide reference levels for both electric and magnetic fields. The reference levels are designed to protect the general public from any known adverse health effects of EMF exposure. Compliance with these guidelines helps ensure that EMF levels near communities are within acceptable limits.
- **Disturbance of Archaeological Sites:** Construction activities associated with overhead lines, such as excavation for foundations or installation of support structures, can disturb archaeological sites of cultural significance.
- **Employment and Economy:** The construction phase can provide employment opportunities and contribute to the local economy through job creation, supply chain involvement, and ancillary services.
- **Urban vs Rural Land Occupation:** Whilst it is unlikely that the overhead line will be routed through a high-density urban population, the installation and operation of the overhead line will have a significantly larger impact on urban areas due to the need for resettlement, visual impact, reliability, and safety. Thus, it is anticipated that rural areas will hold less impact for such an installation, as the visual impact will be lower, and typically agricultural activities, forestry, and other rural land uses can usually coexist. However, this does not exclude the possibility of potential resettlement or land reallocation or visual impact.

5.5.2 During operation

5.5.2.1 Visual impact on residential areas

The placing of the overhead lines will have a permanent impact on nearby residential areas, if in proximity. This impact should be further assessed through visual impact modelling and as part of community engagement process.

- **Visual impact:** A new overhead transmission line would have a persistent visual impact on people who would see the line from their homes, and it would also be likely to affect the aesthetics of the landscape through which it passes by intruding upon the natural views of nearby communities. In doing so, it would potentially impact property values.

  National Grid Electricity Transmission would take a whole system approach when assessing the visual impacts of their electricity transmission proposals on local communities, taking into consideration infrastructure development plans from local and national authorities to minimise the likelihood of unexpected negative socio-economic impacts from the project. Part of their planning process would be to model the likely levels of visual impact from the proposed overhead line and its associated substation terminating structures and present the results of this analysis as part of a community engagement process to arrive at a final transmission proposal.

  For further insight into the typical dimensions of the overhead line and it's supporting infrastructure, please refer to Fig 5.2.

5.5.2.2 Impacts on the neighbouring communities

Once the overhead lines are in operation, there are several impacts to consider:

- **Electromagnetic fields:** Overhead transmission lines produce electromagnetic fields due to the flow of electrical current. Concerns have been raised regarding potential health effects associated with prolonged exposure to EMFs.
- **Safety considerations:** Communities living near transmission lines need to be aware of the potential risks associated with high voltages, the infrastructure and adhere to safety guidelines. There are additional risks associated with additional installations (such as antennas) on the overhead line, which increase EMF exposure. Effective communication and engagement with the community are crucial to address concerns, build trust, and ensure that community members feel heard and involved in decision-making processes.

- **Noise Generation:** AC overhead lines can generate audible noise due to electromagnetic fields interacting with conductors and other components, as well as electrical arcing or corona discharge (which is when high-voltage transmission lines ionize the surrounding air, creating a bluish glow and a hissing noise).
- **Noise Propagation:** Noise can propagate to nearby residential areas, potentially causing disturbance to residents. The nearby communities should be made aware of such potential impacts, and relevant mitigation measures should be implemented to reduce this impact.
- **Land/Property Value:** The accumulation of the impact's discussion in the above section, including visual, noise and EMF may influence the land/property value in the nearby communities depending on people's perception of the infrastructure and the proximity of the structures to residential areas, urban centres, schools, recreational facilities, and other amenities.

5.6 Commercial & Supply chain impacts

The unprecedented penetration rate of renewable energy sources on the GB's electricity network, coupled with our increasing need for international transmission interconnection to maintain security of supply and control energy prices, are prompting previously unknown levels of electricity transmission and distribution system development. These GB network development needs are presently reflected around many of the world's electricity supply systems.

However, many of these supply systems are mature and ageing. To date they have provided little stimulation to equipment manufacturers to prepare for a fundamental gear-change in demand for their products or for the skills necessary to support that change. The US Department of Energy's February 2022 report 'Electric Grid Supply Chain Review: Large Power Transformers and High Voltage Direct Current Systems' noted, about US commitments to reduce greenhouse gas emissions, that "Meeting these targets will require a significant expansion of the power system to integrate a large amount of new renewable resources". In the same paragraph, however, the report also observes "However, many critical components supporting the power grid have limited to no domestic manufacturing capacity and face complex challenges in supporting a rapid expansion of the grid ….".

Europe's situation is slightly different, in that the EU hosts many of the global leaders in power system component manufacture including, for example, suppliers of HVDC cables, substation equipment, and transformers. Nevertheless, given the simultaneous circumstances of international growth in equipment demand, global increase in the prices of raw materials such as copper and steel, and multiple major national conflicts, the EU notes, in its 'Communication from the Commission to the European Parliament …', COM(2023) 757 final, dated November 2023 that "… grid project promoters flag long and growing lead times for procuring specific grid components, sometimes of several years even for the most urgent Projects of Common Interest, … because of tight supply of some components or increasing raw material prices."

The same EU document cites several other procurement difficulties, too. These include, firstly, the need to procure secure systems, both in terms of cybersecurity and relating to the weaponisation of supply chain dependencies, and secondly, the need to standardise products, both in order to reduce costs and also the speed of production. A third, and equally vital area attracting their concern for the power industry supply chain is "the lack of skilled workers [which] affects the increasing staffing needs of transmission and distribution system operators, HVDC cable manufacturers and other power system suppliers. This includes the need to acquire further advanced digital and technological skills, such as automation, controlling, big data and advanced analytics, to detect and control network challenges as well as develop the necessary technologies".

At present, these supply chain concerns affect some transmission equipment archetypes more than others, so we provide a brief summary table of key concerns for each archetype. In this section we focus upon overhead lines (Table 5.1), with equivalent tables in Sections 6.6 and 7.6 for underground cables and HVDC submarine links, respectively.

Table 5.1: Commercial and supply chain impacts – overhead lines

Overhead Lines	
Towers and foundations	No known concerns, though both lattice steel tower and monopole tower prices are critically dependent upon the supply of steel
Insulators and conductor systems	No known concerns, though conductor system prices are critically dependent upon the supply of aluminium
Sitework	We note the availability of the necessary skills for construction, testing and commissioning will require concerted development effort in the face of an ageing workforce at a time of expanding skills demand.

6 AC UNDERGROUND CABLE

6.1 Archetype description

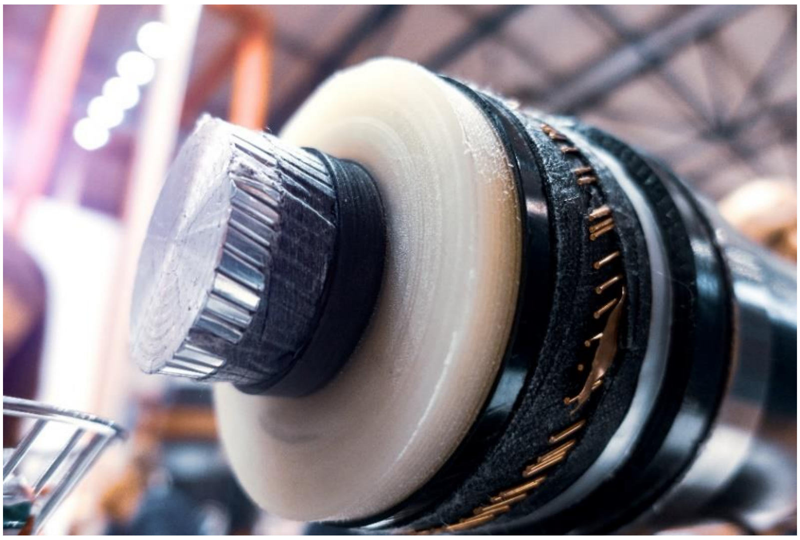


Figure6.1: Section of an underground cable

Underground cables at 275 kV and 400 kV make up approximately 5% of the existing transmission system in England and Wales[33]. This is typical of the proportion of underground to overhead equipment in transmission systems worldwide, though this proportion is increasing gradually in Europe, driven by urbanisation trends and negative land value impacts of overhead alternatives.

The National Policy Statements EN-1 and EN-5 require that Nationally Significant Infrastructure Projects (NSIPs) demonstrate that they are efficient and economical (see, for example, EN-1[34] para 3.3.75), giving overhead lines the general starting preference when planning a new transmission route. For this reason, most underground cable is installed in non-industrial urban areas, where achieving consent for an overhead route is much less feasible. However, there are further details on this starting presumption in Section 6.3.1 Planning Consents (underground cables).

However, examples of other situations where underground cables have been installed in preference to overhead lines, include passing through nationally designated landscape areas, where they preserve important views from intrusion by overhead lines. To achieve this objective, underground cables will often be used in short sections of a composite circuit that principally comprises overhead line.

Underground cables are very heavy and cannot be tightly coiled, so they are delivered to site on large drums in lengths of up to a maximum of around 1,000m, though sometimes less than this. The cable systems thus comprise two main components – the cable sections themselves, and their connectors. The connectors along the underground cable route that join lengths of cable together will be buried in joint bays, out of sight except for an above ground joint testing kiosk or man-hole cover. Meanwhile, the cable's terminating connectors in substations are necessarily above ground.

As the photograph at the start of this section shows, an underground cable consists of a central electrical conductor, which is usually copper or aluminium, surrounded by insulating material and sheaths of protective metal and plastic. The purpose of the insulating material is to ensure that, although the conductor is operating at a very high voltage, the outside of the cable remains safely earthed. These days the insulation is normally made of cross-linked polyethylene (XLPE).

High voltage underground cables may be installed in many ways, depending upon the environment they are passing through; they can be pulled into ducts, laid in surface troughs, cleated to the sides of deep bore tunnels or, more commonly, (the cheapest option) directly buried in the ground. Direct burial requires trenches approximately 1.2m deep with a width that varies between about 0.5m and 3m per circuit, depending on the burial formation and the number of cables per circuit. A thermally stable backfill of cement bound sand is used to ensure a known thermal conductivity around the cables, to avoid the cable overheating.

[33] Electricity Ten Year Statement (ETYS) 2022: Appendix B – System Technical Data

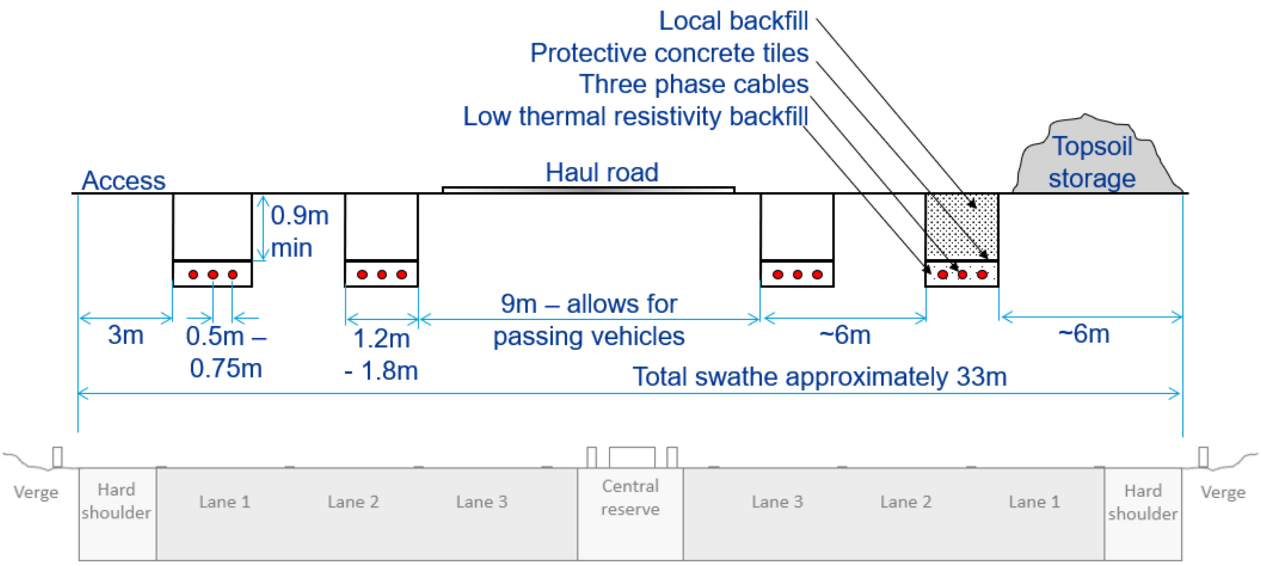
[34] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1147380/NPS_EN-1.pdf

This direct burial approach is depicted in the diagram of Figure 6.2, which shows a cable construction swathe cross-section. This layout is for a high-capacity installation (2 transmission circuits, each with 2 cables per phase). The reason for laying three phase cables fairly close to each other in a single trench is to minimise electrical imbalance for the system operators, and to minimise magnetic field strengths around the cables. However, the reason why the cables are often spaced apart from each other within the trench, and the reason why the trenches are spaced well apart from each other, is to allow heat from the cables to dissipate without their temperatures rising to damaging levels. For high-capacity cable routes – for example, 2 cables per phase (12 cables total), this need for heat dissipation results in a construction swathe width of around 33m – almost the same width as a 3-lane motorway – as shown in the construction phase swathe graphic. The good news, however, is that once the construction project has been completed, the land can be reinstated for the original above-ground rural and agricultural uses so long as the ground immediately above and around the buried cables is not disturbed. To ensure that the cables stay safe and do not pose any risk during their operational lives, activities such as building, excavation, tree-growing, and fence post insertion are permanently discouraged within the swathe contained between the outermost cables – that is, for the 2-cable-per-phase example, a swathe width of around 25m.

Lower capacity circuits may require only 1 cable per phase and a construction swathe width of around 12m narrower than that depicted in the graphic, whilst higher capacities may even require 3 or 4 cables per phase and a correspondingly greater swathe width.

A cable construction swathe would be granted to a network company in the form of an easement, permitting the company access for the specific purpose of installing the cable. The width of the easement would be a function of the number of circuits, the number of cables installed per circuit and the required work areas. Whilst the following graphic depicts a typical 2-cables-per-phase construction swathe width along most of the circuit length, the swathe width is often greater at joint bays to allow space for the jointing process to take place.

Whilst the focus of this section is to provide information on AC cable systems in onshore networks, it should be noted, for completeness, that offshore AC transmission can sometimes also be an option – however, see Section 6.1.3 for further information about limitations to cable route lengths.



Note 1: A double circuit, 2-cables-per-phase, underground transmission cable construction swathe cross section – 2 trenches per circuit, 4 trenches total. Intermediate dimensions are approximate, varying with application

Note 2: For comparison, the cross-section of 3-lane motorways in Great Britain (33m wide including hard shoulders) is shown here on a similar scale

Figure 6.2: Example dimensions of an underground cable construction swathe cross-section

6.1.1 Transmission capacity

The transmission capacity of a 400kV underground cable circuit depends on the diameter (and type) of its conductors and upon the number of cables (two, three, four) that comprise each of the three phases. Depending on the choice of conductor type and the form of burial, capacities for a single transmission circuit can range from less than 600 MVA to more than 3,000 MVA, where a circuit comprises multiple cables per phase. Generally, the rating of underground cable sections used in composite overhead line circuits would match the rating of the overhead line circuit, and for high power transfer requirements, two cables per phase may be installed to achieve the desired transmission capacity.

The limiting factor, in terms of underground cable transmission capacity, is the permissible cable temperature, for example 65°C or 90°C. The core of the conductor, which may have a cross sectional area of, for example, 1,600mm^2 or 2,500 mm^2, can transfer power up to a ‘continuous current rating (for a given season)’ that is determined by its permissible temperature. Since copper has a lower electrical resistance than aluminium, for a given conductor temperature, copper can pass a higher current than aluminium. As an approximation, a copper conductor can transmit 30% - 40% more power than the equivalent sized aluminium cable core. This allows a cable designer to choose between using two aluminium cables, each with a conductor cross sectional area 1,400mm^2 and a single copper cable with a cross sectionof 2,500mm^2; the choice is largely dependent on the market prices of the metals at the time that they need to be purchased for the cable’s manufacture.

The continuous current rating should, however, be ‘derated’ by a factor of the environment that encapsulates the cable. The derating factor considers the thermal properties of the cable core’s surroundings, such as the cable insulation, the burial backfill (or air, if in ducts) and the ambient conditions above the surface of the ground. The formation of the cables in the ground, whether bundled together in a trefoil formation, or equally spaced apart in a flat formation, can also make over 10% difference to the cable rating, because of the heating effect of each core on the adjacent cables.

6.1.2 Life-span

The expected life-span of an underground cable is well in excess of 40 years although this can depend on the operational utilisation of the cable; for instance, routinely operating a cable close to its maximum permissible rated load for long periods which can significantly shorten its expected life-span. Cable life can also be affected by external factors that the cable has been exposed to which could cause it to degrade over time, for instance UV light (particularly at cable terminations), chemicals, and excessive flexing or mechanical action.

It is not practicable to refurbish or upgrade underground cable conductors in the way that can be achieved for overhead lines. However, since underground cables are mostly tucked well away from the corrosive and mechanical stresses of the weather there is the expectation that modern cable designs have the potential to reach 60 or 80 years of satisfactory service-life without needing to be disturbed.

6.1.3 Limitations

The electrical resistances of underground cable conductors are usually lower than the conductors of equivalent overhead lines. For this reason, heavily loaded cable circuits tend to generate lower losses (that is, they generate less wasted heat) than the equivalent overhead lines with the same loads. However, , the high voltage cable capacitances still cause significant losses even at no-load, so cable circuits with light average loads can be less efficient than equivalent overhead lines. The longer the cable circuit, the greater are the no-load losses and, since losses use cable capacity that would otherwise be available for sending power to consumers, there are practical limits to cable circuit length before reactive compensators must be added to the circuit.

Reactive compensators for underground cables themselves cause additional energy losses, introduce further protection and control complexities and, of course, raise the circuit lifetime cost[35] . So, as proposed cable circuit lengths increase, their additional complexity and lifetime costs make it increasingly attractive to consider alternative transmission solutions. The practical result of these underground cable limitations is that, to date, GB's longest 400kV underground cable circuit is only about 22km long, although greater cable circuit lengths become more practical at lower transmission voltages - for example, 200kV or 275kV. As typified by ESO's Pathway to 2030 Holistic Network Design July 2022 report[36], greater cable circuit lengths are also practical for radial circuits (whether offshore or onshore) since radial circuits don't unbalance the current flows in the main onshore interconnected transmission system

Another limitation of underground cables (that is shared to a lesser extent by overhead lines) is that their currents set up magnetic fields that can induce voltages in nearby insulated metallic structures such as pipelines, especially where these lie in parallel with the cables over significant distances. Magnetic fields diminish rapidly with distance from the power cables; nevertheless, close, parallel metallic structures can suffer safety and corrosion issues, in which case cable designers have recourse to various technical solutions that can reduce the effects of the magnetic fields.

6.1.4 Future scalability for long-term planning

Underground cable systems are a mature and versatile transmission technology, being equally applicable to both the main interconnected transmission network and to specific network user connection applications. Once installed, underground cable circuits have limited potential for future development, as their capacities are controlled by their conductor cross-sectional areas, and their geographical routes are dependent upon successful negotiations with landowners.

However, underground cable circuits can accommodate the evolving demands of the system by supporting power overloads for short periods of time, and by allowing instantaneous changes in power flow levels and direction. In this way

[35] Lifetime costs are the costs to install equipment plus the lifetime running costs of maintenance and losses.

[36] https://www.nationalgrideso.com/document/262681/download

they can at least start to accommodate regional long-term variations in supply and demand, within their capacity limits, offering some potential support for future system development.

6.2 AC underground cable costs

Compared with the bare wire conductors of overhead lines, underground transmission cable manufacture processes are far more complex and use far more materials. They are also heavier, and less flexible than overhead line conductors, so their transport to site is more complex, too, even though they are delivered in much shorter lengths than overhead line conductors. Once the cables are delivered to site, there is far more groundwork to be performed, and over a wider working swathe, and there are many more conductor joints to be made than for overhead lines. For all these reasons, underground cable costs tend to be higher than for an overhead line option.

Another possible reason for higher costs of long underground cables can be the need for reactive compensators, to reduce the effects of the cable capacitances on the rest of the network. These compensators look and sound like grid transformers and they would normally be placed at either end of the cable route. The length of cable circuit that would require these separate reactive compensators depends upon the capability of the nearby network to provide reactive compensation to the circuit but, beyond a few km of circuit length, specific compensation would most likely be required. The same would apply to offshore AC cable circuits except that, for lower transmission voltages (for example, 275kV) significantly longer circuits can be installed before compensators are required.

Other capital costs to keep in mind include those of environmental assessment and impact mitigation, public consultation and public enquiry, and consents and wayleaves. Meanwhile, the most significant operational cost of underground cables relates to lifetime losses.

6.3 Deliverability and operability

As with overhead lines, the deliverability and operability of any proposed new underground cable are key aspects for its ability to satisfy its required in-service date. In this Section we consider first the deliverability of new underground cables, and then secondly their operability.

Underground cable technology is mature, although new cable developments – especially improvements in electrical insulation technology – are introduced incrementally from time to time. Apart from the current manufacturing capacity pressures that we anticipate will reduce as new UK cable producers come on-line, the challenges of acquiring the technology for a new route are well understood and solved. As with overhead lines, therefore, the main unknown regarding deliverability is thus the question of whether, and when, planning consent would be granted, so this is the subject of our next subsection.

Underground cable operation is also well understood, and its technical challenges mostly solved, so the other three subsections here address some of the operating characteristics and benefits that are specific to underground cables.

6.3.1 Planning consents

Unlike overhead lines, underground cables are classed as 'permitted development' under the Town and Country Planning (General Permitted Development) (Scotland) Order 1992 (as amended), (England) Order 2015, (Wales) Order 2014. Such developments may automatically be granted planning permission, by statutory order, and do not require submission of a planning application to the local planning authority.

However, (EN-1) Mar-2023[37] indicates that, where "*[an underground cable proposal]* … is considered to be nationally significant, there is a power under section 35 of the Planning Act 2008 ... for the Secretary of State, on request, to give a direction that a development should be treated as a nationally significant infrastructure project for which development

[37] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1147380/NPS_EN-1.pdf

consent is required.” So, if either of these situations were to occur for a proposed underground cable, then as for overhead lines, the planning process would after all require the proposed cable installation project to apply for a Development Consent Order (DCO) to the Planning Inspectorate, with a final decision taken by the Secretary of State.

The July 2011 version of the National Planning Statement EN-5[38] starts with the presumption that new transmission will comprise overhead line but, at paragraph 1.7.3 (b) it specifically adopts “a presumption that electricity lines should be put underground (generally, or in particular locations, such as Areas of Outstanding Natural Beauty (AONBs))”. The March draft version of EN-5 strengths this presumption at its paragraphs 2.9.20 - 21, where it specifically identifies “nationally designated landscape (i.e. National Park, The Broads, or Area of Outstanding Natural Beauty” as being places where “the strong starting presumption will be that the applicant should underground the relevant section of the line”.

The consenting process for underground cables does not have to address the long-term visual impacts issue normally associated with overhead lines, however the cable installation process itself would still comprise a very significant visual impact for the duration of the construction work. In rural environments, the construction process also has the ability to disrupt local wildlife habitats, and these factors, and the time taken to agree ways to mitigate or avoid these effects may jeopardise achievement of a transmission network required in-service date. Page 8 of National Grid Electricity Transmission’s paper ‘Undergrounding high voltage electricity transmission lines – The technical issues’[39] shows an example underground cable construction swathe.

As a separate exercise, to permit the construction, operation and maintenance of underground cables, suitable rights over land (wayleaves and easements) are needed from every owner or other party holding a relevant interest in the land crossed by a proposed major electrical infrastructure project. Often these will be granted to the utility voluntarily following negotiation, but if this cannot be achieved, the utility can apply to the appropriate body (Government Office) for any necessary authority.

6.3.2 Reliability, availability, maintainability

Reliability: Underground transmission cables are buried about a metre underground, normally within specially stabilised backfill and beneath sets of concrete tiles and warning tape, so it is very unusual for third party physical disturbance or damage to cause unplanned outages and reduce their reliability. Ground subsidence could damage an underground cable, as could an unattenuated lightning strike or switching surge at the end of a cable, however these latter risks are normally avoided by installing lightning protection equipment at the cable ends. Once commissioned, therefore, underground cables have a good track record for highly reliable operation.

Availability: High reliability tends to deliver high availability, too, however the significant difference between underground cables and overhead lines is that, because the cables are buried, if a cable fault should occur (a rare event), it can take much longer to locate the fault, and it can take much longer to repair the fault, once located. Although fault locators are becoming increasingly sophisticated, because cables are buried and not easily accessible, the entire fault-finding and repair process can easily take between 2-4 weeks, during which time the cable circuit would be unavailable for operational service.

Maintainability: Being buried, underground cables are protected from the forces of the weather and from most third-party interference, so the cables themselves are largely maintenance free. However, it is important that the cable circuit’s environment is maintained and, in particular, that the cable joint earthing systems operate effectively throughout its operational life so two key maintenance tasks are, firstly, the periodic patrol of the cable swathe to ensure that the cable circuit is not in danger of being disturbed, and secondly, tests of each of the cable joint sheath earthing arrangements along the route to ensure that they remain healthy and are not degraded by corrosion. Whilst the patrols can be undertaken during cable circuit operation, the sheath tests require the circuit to be taken out of service which, depending

[38] https://www.gov.uk/government/publications/national-policy-statements-for-energy-infrastructure

[39] https://www.nationalgrid.com/sites/default/files/documents/39111-Undergrounding_high_voltage_electricity_transmission_lines_The_technical_issues_INT.pdf

upon circuit length and the number of test teams, might take 1 to 3 days per year on average, still amounting to an availability of over 99%.

6.3.3 Flexible circuit rating

As with overhead lines, a useful property of underground cable systems is their ability to withstand overloads for short periods of time before they reach their safe temperature limits. This is a valuable characteristic because, during emergency conditions such as during an unplanned outage, it allows the system operator time to reconfigure the network and return power flows to normal levels without damaging the equipment or disconnecting customers. Allowable overload periods can vary from 30 minutes to tens of hours, depending upon the circumstances, before the cable reaches its safe temperature limit and the load must be reduced again.

In fact, by applying these cable circuit dynamic ratings carefully, it is possible to effectively gain significant additional transmission capacity on a routine basis – up to 30% in some cases, depending on factors such as the cable type, the cable laying configuration, its immediately previous load levels and the weather. To facilitate this approach, most modern high-voltage cables include optical fibres for monitoring their temperatures and this allows the system operator a greater degree of certainty that the cable is not reaching damaging temperatures during such operation.

This cable overloading facility is particularly useful where the operator knows the cable overloading cyclic, for example, when it covers a 2- to 4-hour winter evening peak demand period. In this case the operator knows that demand, and therefore the circuit loading, will reduce again later in the evening. Fully exploiting this cable cyclic loading flexibility allows system design engineers to optimise network capability whilst being efficient with materials and costs.

6.3.4 System restoration capability

As explained in Section 5.3.4, the process of system restoration needs simple transmission connections that require minimum controls, absorb minimum amounts of energy, do not require supplies to be available at both ends of the connection, and are immediately available for service. Underground cables meet most of these criteria and thus are fairly well suited to transferring restoration power across the transmission system to help network and generation operators to restart the national power supply.

A downside to using underground cables for system restoration is that the significant charging currents required by long underground cables before any useful power is transmitted (over 20 times more than that required by an equivalent capacity overhead line) makes system restoration with them more complex than with overhead lines.

In saying that underground cables are well suited in this situation, the reader should nevertheless understand that, like overhead lines, underground cables are passive network components that do not provide any restoration energy themselves; in this role they simply facilitate the transfer of power from restoration energy sources to other, larger generators needing startup power.

6.4 Environmental impacts

This chapter summarises the most prominent environmental impacts to be considered during the manufacturing and construction phase and the operation phase for this archetype. Detailed impacts and mitigation measures can be found in the Appendix 2.

6.4.1 During manufacturing and construction

6.4.1.1 Resource efficiency and pollution prevention

The following impacts should be considered for resource efficiency and pollution prevention:

- **Material Usage:** underground cable installations require various materials, including cables, conduits, and backfill materials, which can sometimes result in excess waste.

- **Energy Efficiency**: Construction activities, such as trenching, drilling, and installation, should aim to maximise energy efficiency by using modern, well-maintained equipment and employing energy-saving practices during construction operations.

6.4.1.2 Impacts on biodiversity

The following biodiversity impacts should be considered during the construction phase:

- **Excavation Activities:** The trenching required for installing underground cables can result in the loss and fragmentation of habitats, especially if the project traverses areas with existing vegetation or natural habitats. However, the use of directional drilling may cause minimal disturbance due to the limited area of interference.
- **Soil Disturbance:** Construction activities can disturb the soil, potentially affecting the viability of plant species and disrupting soil-dwelling organisms.
- **Vegetation Removal:** Clearing vegetation along the cable route (typically only a few metres wide, directly above the cables) can result in the direct loss of plant species, including trees, and understory vegetation. This can impact the food sources, shelter, and nesting habitats of various wildlife species.
- **Disturbance of Ecological Processes**: Construction activities may disrupt natural ecological processes, such as seed dispersal, pollination, and nutrient cycling, which are important for the maintenance of local biodiversity.
- **Disruption of Wildlife Movement**: Construction activities and the presence of underground cables can disrupt the movement patterns of wildlife, including terrestrial and arboreal species. This can lead to isolation of populations and limit their access to essential resources or breeding grounds.
- **Barrier Effect:** Underground cable installations may act as barriers for small mammals, reptiles, or amphibians that cannot easily move through or beneath the infrastructure, depending on the depth of the installation. This can impact population dynamics.

6.4.1.3 Impacts of excess noise and dust

The following impacts should be considered for excess noise and dust in the construction phase:

- **Air Quality:** Dust generation from excavation or construction machinery can contribute to air pollution. Effective dust control measures, such as water suppression or dust screens, should be implemented to minimise airborne dust emissions.
- **Noise Pollution:** Construction activities can generate significant noise levels, potentially impacting nearby communities. Proper planning, use of noise-reducing equipment, and adherence to noise regulations can help mitigate noise pollution.

6.4.1.4 Accessibility to site

The following impacts should be considered for site access in the construction phase:

- **Construction Area - Road Closures/ Traffic Disruptions:** The construction activities associated with underground cable installations may result in restricted access to certain areas close to the site. For example, depending on the location and extent of the construction activities, temporary road closures, lane restrictions, or traffic diversions may be required. This can impact local transportation routes and accessibility for nearby communities.
- **Construction Site Infrastructure:** The construction phase may involve the establishment of temporary infrastructure, such as site offices, storage areas, or construction laydown yards. These temporary facilities will occupy space and potentially affect access to surrounding areas. A work-road in parallel with the underground cables is also required to accommodate vehicles for site deliveries, ground works and installation activities.
- **Material Transportation:** Transporting construction materials, equipment, and machinery to the site can temporarily impact access routes, especially if the project requires large deliveries or specialised vehicles.

6.4.1.5 Climate change impacts

The following climate change impacts should be considered in the construction phase:

- **Construction Machinery and Vehicles:** The use of construction machinery, vehicles, and equipment during the installation of underground cables can locally generate greenhouse gas emissions, primarily carbon dioxide (CO2) and other pollutants, which contribute to climate change, when combustion engines are used.
- **Material Production and Transportation**: The production of construction materials, such as cables, conduits, and insulators, can involve energy-intensive processes that emit greenhouse gases. Additionally, transportation of these materials to the construction site can contributes to carbon emissions.
- **Energy Consumption from Construction Activities:** Construction activities, such as excavation, trenching, and drilling, require energy for equipment operation and lighting. The energy consumed during these activities may contribute to increased greenhouse gas emissions if it comes from fossil fuel-based sources.
- **Deforestation and Vegetation Loss:** The construction phase of underground cable installations may (but not necessarily so) require the permanent removal of vegetation along the cable route. Deforestation and vegetation loss contribute to reduced carbon sequestration capacity and the release of stored carbon dioxide into the atmosphere.

6.4.2 During operation

6.4.2.1 Impacts on biodiversity

During the operation phase, the following impacts should be considered:

- **Cable Access Points:** Vegetation clearance around these access points may be required to ensure proper access and maintenance, which can affect local vegetation and small-scale wildlife habitat.
- **Indirect Impacts:** The operation of underground cable systems is connected to energy generation sources, which may have indirect impacts on biodiversity through associated infrastructure, such as power plants or renewable energy installations.

6.4.2.2 Accessibility to site

During the operation phase, the following impacts should be considered:

- **Cable Access Points:** Access points, such as manholes or cable pits, may be present along the cable route, but not necessarily so. These access points may require covers or markers to indicate their presence, which can be located within public spaces or private properties.
- **Maintenance and Repair:** Access may be required to perform maintenance, inspections, or repairs on the underground cable system. This may involve temporary disruptions or limited access to certain areas while work is being carried out.

6.4.2.3 Climate change impacts

During the operation phase, the following impacts should be considered:

- **Energy Losses:** underground cables can experience some energy losses due to resistance, resulting in heat dissipation during transmission. While these losses are generally low, they contribute to increased energy consumption and associated greenhouse gas emissions from the power generation sources. Please refer to Section 4.2 for further information on losses.
- **Decommissioning and Disposal:** At end-of-life, decommissioning would normally remove all above-ground structures along with some, or all, of the foundations, unless these were to be re-purposed, and proper decommissioning practices will be applied to minimise environmental impact.
- **Life Cycle Assessment:** It is important to consider the full life cycle of the underground cable, including its manufacturing, installation, operation, maintenance, and eventual decommissioning, to assess the overall climate change impact.
- **Transfer of Renewable Energy**: One of the positive secondary impacts of the underground cables is that the network supports the transfer of renewable energy across the country, which allows the UK to increase their renewable energy mix and contribute positively to reducing the impacts of climate change.

6.5 Community Impacts

This chapter summarises the most prominent community impacts to be considered during the manufacturing and construction phase and operation phase for this archetype. Detailed impacts and mitigation measures can be found in the Appendix 2.

6.5.1 During manufacturing and construction

6.5.1.1 Land use and community impacts

It is important to understand the current land use on the length of the underground cable and the presence of any natural habitats or cultural heritage sites. This should be undertaken during the environmental impact phase of the pre-construction period. The main impacts to be considered:

- **Excavation and Trenching:** Underground cables require extensive trenching or, alternatively, directional drilling to lay the cables. This process can disrupt land use and temporarily impact areas where the cables are being installed and can potentially disturb archaeological sites, including buried artifacts, features, or structures.
- **Right-of-Way Requirements:** Underground cables may require a dedicated right-of-way, which can involve land acquisition or easement agreements with landowners.
- **Substation Infrastructure:** Underground cables may necessitate the construction of substations or distribution hubs, which can have additional land use implications.
- **Construction Disruptions:** The installation of underground cables involves construction activities that can disrupt local communities, including noise, dust, traffic congestion, and restricted access to certain areas during the construction phase. Engaging with local communities throughout the planning and construction phases can help address concerns, provide information, and involve community members in decision-making processes.
- **Soil Disturbance:** Construction activities can cause soil disturbance, which may result in the disruption or destruction of archaeological layers and deposits.
- **Chance Finds:** During construction, unexpected archaeological discoveries may occur. These chance finds need to be appropriately managed and reported to preserve and document any cultural heritage that may be encountered.
- **Employment and Economy:** The construction phase can provide employment opportunities and contribute to the local economy through job creation, supply chain involvement, and ancillary services.
- **Urban vs Rural Land Occupation:** The installation and operation of the underground cable in urban areas will have a higher impact due to the presence of other utility infrastructure, dense population and limited available space. The installation will also likely cause temporary road and traffic disruptions during the construction phase. In rural areas, the impact is anticipated lower, as the underground cables can be installed more easily due to the availability of space and fewer infrastructure conflicts.

6.5.2 During operation

6.5.2.1 Visual impact on residential areas

During the operation phase, the visual impact of underground cables are minimal in comparison to overhead lines. However, the following impacts should be considered:

- **Cable Terminations:** Cable terminations are always placed within securely fenced-off areas to ensure safety of the public. Within the context of a substation, therefore, although the cable terminating structures can be several metres high, visual impact is normally minimal.
- **Cable Joint Access Points:** Access points for underground cable joints, such as manholes or cable pits, may be present along the cable route, but not necessarily so. These access points may require covers or markers to indicate their presence, which can be visible at ground level. Alternatively, cable access points may be approximately 1m high and 1m wide in occupancy and will be present every 800 - 900m throughout the length of the cable route.

- **Composite Route Transition Points:** For a composite route comprising sections of overhead lines interspersed with one or more sections of underground cable, above-ground transition points bring the overhead line connections down to the cables at the start of each underground cable section. A second transition point at the far end of the cable brings the connections back out of the ground and up to the overhead line. Such transition points ('sealing end compounds') safely and securely fence–off the high voltage cable ends and overhead line connections and vary in area between around 0.2 and 0.4 ha (0.5 to 1 acres). Their local visual impact, unmitigated, can thus be similar to that of a small substation, however, transmission owners work hard with local communities to effectively place and screen these installations from public view.

  For further insight into the typical dimensions of the underground cable and it's supporting infrastructure, please refer to Fig 6.2.

- **Swathe Management:** Depending on the location, there may be periodic vegetation management activities, such sapling removal and clearing around access points, to ensure the integrity and accessibility of the underground cables. These activities may have temporary visual impacts.

6.5.2.2 Impacts on neighbouring communities

During the operation phase, the following impacts should be considered:

- **Information Dissemination:** Effective communication with the local community is essential to ensure awareness of the underground cable system, its operation, and any potential impacts.
- **Public Engagement:** Engagement with the community, stakeholders, and local authorities to address any concerns, provide updates on maintenance activities, and ensure transparency throughout the operation phase.
- **EMF Impact:** The community should be informed of the potential EMF impact from the underground cable, which should be considered during the design phase and may impact both humans and biodiversity, however with strategic planning may have no impact at all. The EMFs decrease rapidly with distance, so the immediate vicinity of the cables experiences higher levels of EMF compared to areas further away. The exact levels depend on factors such as the type of cable, current flow and laying formation of the cables.

6.6 Commercial & Supply chain impacts

We refer the reader to Section 5.6 for a short, general discussion of some aspects of the supply chain to the electricity supply industry. In this section we provide a summary table of key supply chain concerns for underground cables (Table 6.1), with equivalent tables in Sections 5.6 and 7.6 for overhead lines and HVDC submarine links, respectively.

Table 6.1: Commercial and supply chain impacts – AC underground cables

AC underground cables	
Cable systems	Raw materials for the conductors, insulators and the cable external protection are all managed by the OEMs. The metals, in particular, will be bought ahead of manufacturing requirements, to attempt to minimise costs as the commodity prices vary. With a number of suppliers, including Prysmian, Nexans, NKT, Sumitomo, Hellenic, LS Cable and Taihan, competition should be healthy, Current indications are that lead times are driven by manufacturing capacity and not availability of materials. This manufacturing capacity is a global constraint, with manufacturers presently expanding production capacity. Current orders are expected to deliver in 2031 - 2032, depending on specific length and technical requirements of the cables.
Reactive compensation	Reactive compensation, most frequently provided by shunt reactors, is required for any significant length of HVAC underground cable installed on a transmission

	network, Shunt reactors are heavily dependent upon copper and, depending upon their design, upon grain orientated steel. Historically, there has been only a limited number of suppliers, worldwide, which may become an increasing issue if the proportion of transmission built is installed underground rather than overhead.
Sitework	We note the availability of the necessary skills for construction, testing and commissioning will require concerted development effort in the face of an ageing workforce at a time of expanding skills demand.

7 HVDC LINK WITH OFFSHORE CABLE

7.1 Archetype description

An offshore High Voltage Direct Current (HVDC) transmission link comprises two on-shore AC-DC converter stations connected to separate nodes on the transmission network, along with two (or three) HVDC offshore cables connecting the two converters. Such a link can transport bulk supplies of electricity over long distances, either between two nodes of the same transmission network (for example, the 422km 2,250MW offshore HVDC link between Scotland and North Wales), or between separate transmission networks - when it is known as an 'interconnector'.

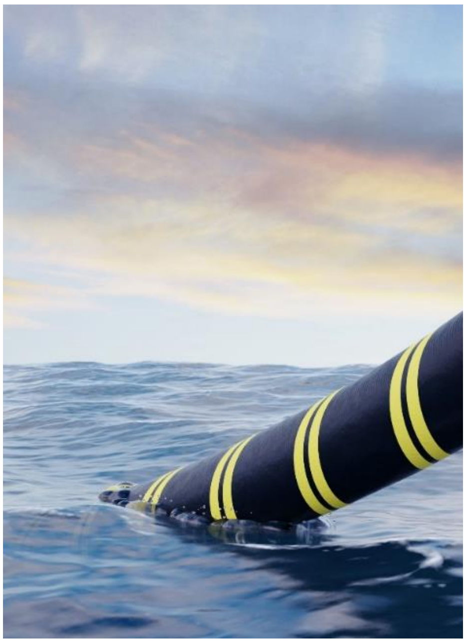


Figure 7.1: Offshore cable being installed

In this latter case, that of the international interconnector, another benefit of HVDC comes into play; not only can international HVDC links transmit large volumes of electrical energy over great distances, but they also act as effective interfaces between AC transmission systems with different frequencies. Examples of HVDC delivering this benefit for GB include the short 51km, 1,000MW Eleclink route through the channel tunnel between France and England and the 720km 1,400MW NSL subsea route between Norway and England.

HVDC links come in many voltage, technology, and connection configurations, each with its own degrees of system flexibility. In this document we concentrate upon a modern, flexible configuration that is expected to offer[40] transmission capacities of the same order of magnitude as the overhead line and underground cable archetypes already described in this document. With this configuration, the converter stations are based upon 'voltage-source converter' (VSC) technology which is now usually configured in a modular multi-level converter (MMC) format. The MMC 'bipole with dedicated metallic return' (DMR) arrangement, with shore-based converters and offshore cable route summarised in the following diagram, Figure 7.2, is the HVDC configuration that is considered in the rest of this document.

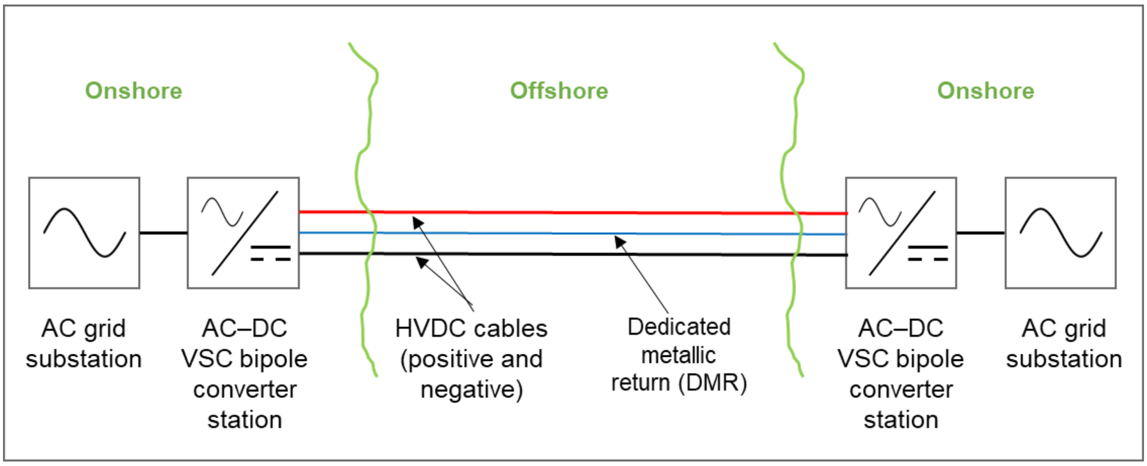


Figure 7.2: HVDC link configuration considered in this report

The two HVDC converter stations (one needed at each end of the link) represent a significant part of the overall construction project cost (see further discussion in Section 4 'Cost Estimates') so the economics of HVDC transmission

[40] We say 'expected to offer' because, although the technology has been proven at lower transmission capacities, the first 2.000 MW VSC converter stations, which have been ordered by the Netherlands, have yet to be delivered and successfully commissioned.

normally only work in specific circumstances. One of these circumstances, the application considered here, is where the transmission route is long and uninterrupted, but where overhead lines are not practicable, for example, crossing long stretches of water.

Unlike AC overhead lines and underground cables, which both connect straight into their terminating substations, HVDC connections are very space hungry. Each connection of an HVDC link to the transmission network requires a converter station which, as shown in Figure 7.3 for a 2,000 MW VSC HVDC converter, is expected to occupy between 4ha and 5ha. For comparison, the area of a football pitch, which we show on a similar scale in the diagram, is around two-thirds of a hectare. That said, the ground space needed for a VSC converter is expected to be significantly less (around 40% reduction) in the ground space that would be required by a similar capacity ‘classic’ line commutated converter (LCC) station that have been used in many HVDC links to date.

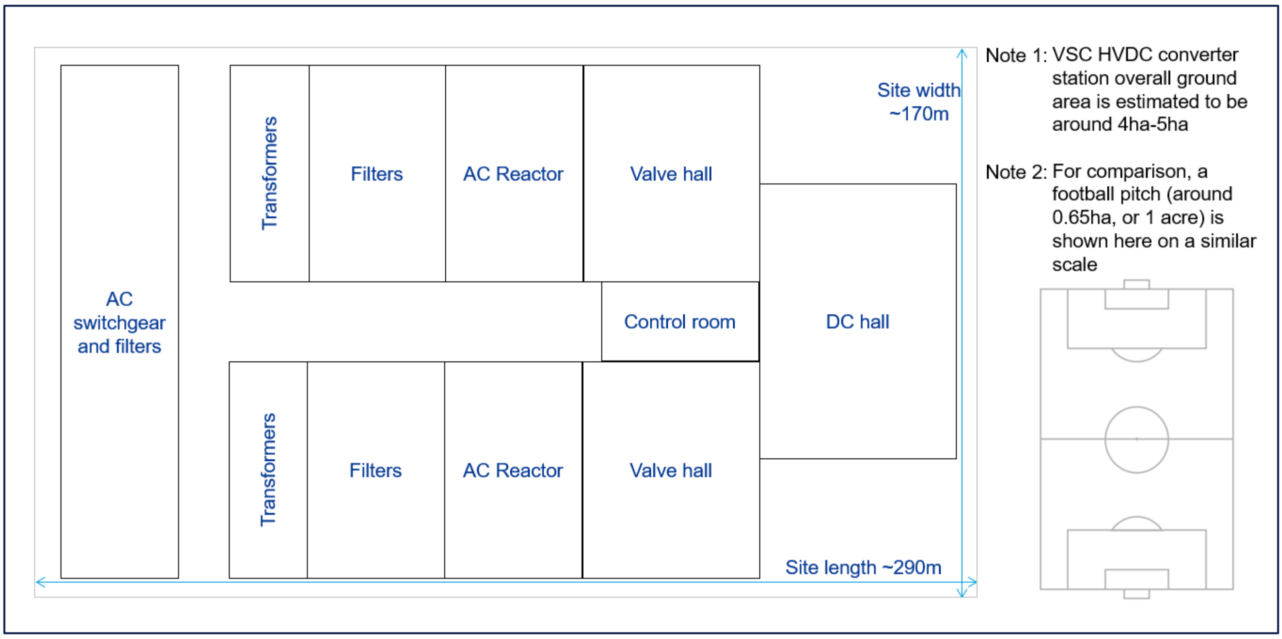


Figure 7.3: Expected ground area of a 2000MW VSC HVDC converter station

Looking at the heights of the converter station buildings, Figure 7.4 provides an outline elevation of the installation. The HVDC sections – the grey-shaded blocks – reach 25m above ground, whilst the remaining housings are somewhat lower than this. To provide an idea of size, this diagram includes a sketch of the front face of Buckingham Palace on the same scale as the converter buildings.

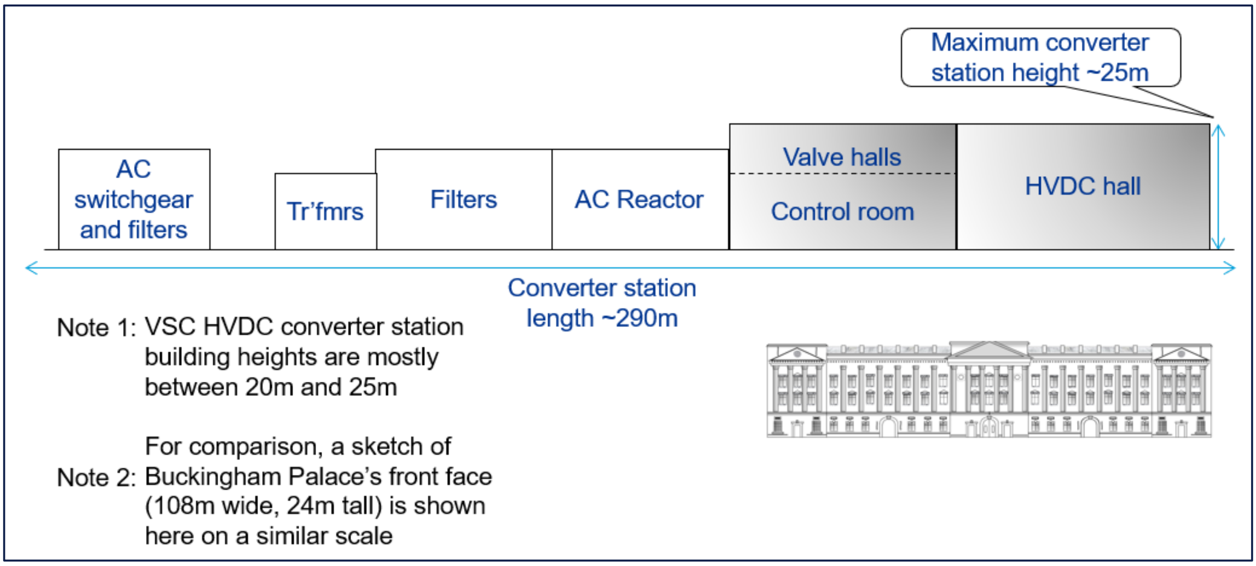


Figure 7.4: Expected block elevation of a 2000MW VSC HVDC converter station

However, when considering the land-take of the HVDC offshore cables, the opposite is the case. Here the HVDC solution has the advantage in that, whilst both the AC options occupy (or, at least, share with other users) an onshore swathe of the landscape tens of metres wide along the length of the circuits, most of the HVDC route is taken offshore; out of sight, and avoiding the need to share land usage, whilst that part of the HVDC underground cable route that passes over land would probably need only a single trench with an operational width of between 1m and 1.5m.

Although HVDC cable insulation design is different to its AC equivalents, visually an HVDC cable is broadly similar to an AC onshore underground cable except that it includes additional outer physical protection such as helically wound steel-wire armouring. This external protection strengthens the cable both for the cable laying and burying process and to counter potential physical damage that could occur in a submarine environment during its operational life.

It is beyond the scope of this present document to detail alternative HVDC applications, however we note here for completeness' sake that HVDC may be used not just offshore with subsea connections but also onshore, with underground cables or overhead lines.

7.1.1 Transmission capacity

Transmission capacity, measured in kilowatts or megawatts (MW) increases as the transmission circuit rated voltage and current rise. The maximum allowable HVDC operating voltage (in a VSC system) is dependent on the number of electronic switches – known as insulated-gate bipolar transistors (IGBTs) – in the valve stacks, and recent advances in IGBT design have allowed operating voltages of up to +/-525kV DC to come into service. Accordingly, the latest VSC HVDC links (for example the Norway–UK North Sea Link) use these voltages to offer more than 1,400 MW of power transfer capability, whilst 2,000 MW +/-525kV links (such as the France-UK FAB Link) are due to enter operation by 2027.

The maximum transmission capacity of an HVDC link is achieved by arranging two converters, each generating 525kV, but with opposite polarities – one positive (+), the other negative(-) – to operate together, as a 'bipole'. Many HVDC links adopt this arrangement since a single cable for each pole will complete the return circuit for the other pole, saving on the need for separate return path cables. However, providing a single common return path for the HVDC bipole link has the benefit of allowing 50% of the link capacity to remain in service through one pole even whilst the other pole is being maintained or repaired. This return path could be provided through the earth and the sea via carefully placed electrodes, however, a dedicated metallic return (DMR) in the form of a third cable would stop the link from causing corrosion to other metallic conductors near its route. If a DMR cable is provided, it must be capable of carrying the full current of the individual pole (up to around 2,000A in the case of the above-mentioned 2,000 MW link), but its insulation levels can be much lower than those of the pole cable since it operates at close to the same voltage as the seabed and earth in which it is buried.

7.1.2 Life-span

Overall, HVDC systems have a nominal life expectancy of 40 years. However, large parts of the converter stations incorporate power and control electronics and these components, amongst others, are expected to need replacing through a major refurbishment at around 20 years.

7.1.3 Limitations

Many of the limitations of the LCC HVDC technology, such as slow-ramping changes to the power flow, the requirement for robust AC systems at both ends of the link, and the complexity and challenges of multi-terminal HVDC links, are disappearing with developments based upon VSC HVDC technology.

However, one limitation that has carried over from the older converter technology to the new, is the inability to offer significant operational overload capacity. Whilst overhead lines and underground cables can substantially exceed their rated power flows for long enough to allow the AC network to recover from a plant failure, the HVDC IGBTs heat up so quickly that even a brief overload beyond their design rating can seriously risk damaging them.

A perennial downside with all offshore power cables is the risk that they are damaged during their operational life, necessitating costly, time-consuming repairs. Modern cable installation techniques protect offshore cables from anchor dragging and water current scour by burying the cable as much as possible, so repairs are not needed frequently. However, when they are required, such repairs are highly complex, both to arrange and to execute. They demand specialist and scarce resources, complex procedures and a sustained period of fair weather to carry out the repair. Of course, emergency plans exist to cater for such events; nevertheless, the operation usually takes several months to complete (6 months is often estimated) and is very expensive – even aside from the cost of lost transmission.

An emerging risk, common to all subsea infrastructure, is the vulnerability of the asset to easy attack by hostile parties, resulting in less secure service and the potential for long, costly reinstatement outages.

The cables of the HVDC link form a very efficient path for transmitting electrical power - indeed, depending upon their design, they can be more efficient –that is, they can cause less heating losses than any of the AC solutions. However, the same is not true of the VSC converter stations at the ends of the cables. The two converters are relatively inefficient, each losing about 1% of their maximum capacity as they operate. For this reason, HVDC links can be less efficient than AC solutions unless the circuit lengths are 100s of km long.

7.1.4 Future scalability for long-term planning

Unlike AC overhead lines, offshore HVDC links are not easily uprated so, when choosing offshore HVDC technology, the designer needs to specify the full expected transfer capacity required over the lifetime of the link.

Whilst this report focusses on point-to-point HVDC links that connect two points on the main interconnected transmission network, we note that, in future, multi-terminal[41] HVDC links are also likely to become a commercially mature option in certain circumstances. They promise integrated coordination between the existing onshore transmission network and a future offshore transmission system. The HVDC Caithness-Moray link in the north of Scotland is the first multi-terminal design project in Europe; it presently exists as a 2-station (point-to-point HVDC) 800/1,200 MW 320kV link, but SSEN is contracted to connect the Viking Energy Wind Farm on the Shetland isles by 2024[42].

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[41] Multi-terminal HVDC links are HVDC transmission connections with more than two connection points. A multi-terminal link could, for example, connect several separate offshore windfarms to the onshore network with only one or two coastal connection sites being required.

[42] See paragraph 1.9 of Ofgem's consultation https://www.ofgem.gov.uk/sites/default/files/2021-09/Shetland%20HVDC%20Link%20Project%20Assessment_0.pdf

7.2 Offshore HVDC link costs

The costs of HVDC offshore links are dominated by two components: firstly, the two converter stations (one at each end of the link), and secondly the cables connecting them together. For the 75km 6,000 MW VSC HVDC link considered by the IET costing study, the cost of the two converters was estimated at 2.5 x the cost of the associated offshore cables. For this reason, HVDC link costs vary quite differently to AC connection alternatives; whilst AC underground cable (and overhead line) costs are broadly proportional to their route lengths, HVDC has a high 'starting' cost, due to the two converters, and then a much lower cost per km even than onshore underground cable. Cost comparisons of HVDC solutions with AC alternatives are thus very sensitive to the intended route length.

We note that, since the IET transmission costing study was published, developments in VSC technology have allowed standard VSC HVDC transmission voltages to rise from +/- 320kV to +/- 525kV. The hope for these developments is that they will improve HVDC link value-for-money; to date, however, there is insufficient track record with the higher voltage to declare this improvement achieved, so we remain guided by the IET costing study estimates in this document.

For cables (onshore and offshore) the uncertainties presently injected into contract prices due to the international push to attain net zero targets are exacerbated by the current scarcity of cable manufacturing capacity within Europe, so it is important to realise that all these cost estimates need to be interpreted in the light of the size, timing and location of any equipment order being considered. We understand that, presently, there are at least two new transmission cable manufacturing facilities being planned and built in Great Britain; however, for current cable requirements, transmission owners may need to 'order ahead' by significant margins of time to keep their build programmes on schedule.

Other capital costs to keep in mind include those of environmental assessment and impact mitigation, public consultation and public enquiry, and consents and wayleaves. Meanwhile, as for the AC alternatives, the most significant operational cost of HVDC links relates to lifetime losses – although constraint costs during maintenance outages may also be significant if there is no operation 'quiet season'.

7.3 Deliverability and operability

HVDC technology, whilst perhaps novel compared to AC technology, is well established in transmission systems around the world. However, HVDC VSC technology is still relatively new, with the first commercial links becoming operational around 20 years ago. Since then, VSC technology has been scaled quickly, to support higher voltages and larger power flows. It could therefore be considered that VSC remains a maturing technology, with research and development still contributing to the development of increasingly higher power links. Nevertheless, the technology is well established with over 30 links commissioned in Europe alone (and many more in planning); new links offer routine deliverability with fewer risks of the technical problems that tended to contribute to the delayed delivery of some early projects.

A long-term deliverability consideration that is highly relevant to offshore HVDC links is the supply of HV cables. In 2019, Europacable published a paper that claimed that European cable manufacturers did have, between them, the capacity to supply the needs of the European Union to 2030, as forecasted by ENTSO-E's 2018 Ten Year Network Development Plan. However, recently the demand for offshore cables has been increasing for several reasons, including (i) to evacuate power from new offshore wind farms to meet Net Zero targets and (ii) to improve interconnections between national power networks. Such interconnections improve security of supply (particularly relevant in today's political situation with Ukraine) as well as enhancing the capability for the economic transfer of power, so manufacturing capacity to meet demand requirements is presently thought to be tight.

On 14 July this year, North Ayrshire Council Planning Committee granted full planning permission for a new HVDC subsea cable manufacturing plant, the UK's first HVDC cable manufacturing facility[43] - this is welcome news for network

[43] https://www.pbctoday.co.uk/news/energy-news/uks-first-hvdc-cable-factory-secures-planning-permission/129863/#:~:text=North%20Ayrshire%20Council%20Planning%20Committee%20has%20granted%20full%20planning%20permission,for%20renewable%20energy%20grows%20internationally.

infrastructure in GB. However, as work will not begin on the construction until 2024, and since Europacable estimate a lead time for new production facilities to be in the order of 4 years, cable projects over the next few years are still likely to be at risk of cable delivery lead-time delays.

Another deliverability consideration is that the converter stations at either end of the HVDC link require detailed planning consent, as would any other building in GB and this can be a factor of uncertainty in the deliverability of a new HVDC link, this is discussed further in the next subsection.

There are some unique benefits that make HVDC VSC technology an attractive proposition and provide the system operator with tools to enhance the operability of the wider electricity system if deployed effectively, these benefits are discussed in the other subsections of this Section.

7.3.1 Planning consents

An onshore converter station installation will be subject to all the normal local town and country planning procedures and approvals, especially those associated with visual amenity, air quality, and environmental impact; however it will normally also be subject to planning approval being granted for the associated onshore and offshore connections (considered further next) and for the converter station at the far end of the link.

Consents to lay offshore power cables are complex to acquire for many reasons, including the following:

- There may be many linear services (including power, telecoms, gas, oil) already installed across the proposed new cable route, all of whose operators will require complete assurance that their existing services will not be disturbed by two or three new power cables laid over the top and then buried in the seabed either side of them.
- There are many users of the sea (including navies, merchant shipping, ferries, trawlers and pleasure craft) who, likewise will be seeking assurance that magnetic fields from the new power cables will not interfere with their navigation systems, and that the cables will not snag their anchors or their fishing nets. To minimise their magnetic fields (both for shipping and for sea animal natural navigation), offshore HVDC link cables are normally laid in a tight bundle if they are not already contained in the same overall cable ‘wrapper’, at least in shallow waters.
- Seabed authorities (for example, the UK’s Crown Estate) will be keen to ensure that the proposed new power cables do not compromise their own, or their stakeholders’ plans for the seabed (including leasing areas for new wind farms).
- Environmental organisations and authorities will be keen to ensure that the proposed subsea cables do not significantly disrupt sea-life (including plant and mollusc growing areas as well as swimming sea-life movements and migration routes) or cause new areas of seabed scouring or shoreline de-stabilisation. These aspects are further discussed at Section 7.4 Environmental Impact.
- The developers themselves will be keen to demonstrate that their proposed route avoids disturbing known or suspected wrecks, especially where there might be caches of unexploded ordnance.

A National Competent Authority (NCA), for example the Marine Management Organisation or the Secretary of State for planning, will provide the final approval for new offshore transmission projects in England[44] and, apart from the above considerations, they will need to ensure that the applicant for a new offshore connection has taken into account the provisions of the National Policy Statements, including the Electricity Networks Statement EN-5. The March 2023 draft version of that statement[45] says, at paragraph 2.14.1, that applicants should “... consider and address routing and

[44] ORE Catapult: https://ore.catapult.org.uk/wp-content/uploads/2018/02/Overview-of-the-offshore-transmission-cable-installation-process-in-the-UK.pdf

[45] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1147384/NPS_EN-5.pdf

avoidance/minimisation of environmental impacts both onshore and offshore ...". Given all these factors, the time taken to obtain planning consent for a converter station can vary very considerably.

7.3.2 Reliability, availability, maintainability

In terms of day-to-day operability, HVDC links are active network components that require instructions from the electricity national control centre to set, and then adjust, their modes of operation. Though they can generally be set to operate in automated modes, this human decision-making element can add an additional layer of system management complexity to day-to-day control room operations, which is not normally desirable.

The reliability and availability track record for +/-525kV VSC HVDC point-to-point links is only just starting to be established, so reliability figures are rather tentative to date. However, the Council on Large Electric Systems (CIGRE), a well-respected collaborative, global power systems industry body that periodically undertakes reliability surveys of electrical power systems throughout the world, has published the results of its 2019-20 survey of HVDC links' 'energy availability'; that is, the percentage time that a HVDC link is available to transfer energy and is not under a scheduled or forced outage. The overall energy availability for the six most recently built VSC technology HVDC links for the two years of the survey period was in the range of 96-99%[46], amounting to an unavailability of between 3 and 14 days, or an average of around 10 days per year.

As with double circuit overhead lines and underground cables, bipole HVDC installations can operate on one DC pole, at 50% of the link capacity, whilst the other pole is taken out of service for maintenance or repair.

Regarding maintainability, as with overhead lines and underground cables, all the main HVDC link components are either at, or are exposed to, very high voltages during operation so, whilst the two poles of a bipole HVDC installation can be separated, with one half isolated and made safe for maintenance, there is no maintenance access to any part of the primary equipment of an HVDC converter pole that is energised and in service.

The HVDC converter's electronically controlled switches, insulated-gate bipolar transistors (IGBTs), are stacked in such a way that they work together to control the whole converter voltage. However, since they work together, if an individual IGBT fails whilst in service, it puts additional stress on all the remaining IGBTs in the stack. A few such failures can be tolerated whilst the converter remains in operation but, periodically, a pole must briefly be taken out of service to replace the failed IGBTs.

7.3.3 Operational benefits

VSC HVDC offers several transmission network control features that are not available from overhead lines or underground cables without additional equipment. Through advanced controls, VSC converter stations can deliver ancillary services such as precise network power flow control, AC system voltage control, and precise reactive power control, all of which can help to alleviate issues on the AC power system. These ancillary services, which can be provided even in weak or blacked-out areas of the AC network, comprise a versatile tool for the system operator (although, as already explained in Section 7.3.2 Reliability, Availability, Maintainability, these benefits need to be balanced against the additional system management complexity that they can add to the control centre environment).

The VSC technology normally delivers these ancillary services at the expense of a small proportion of the link's power transfer capability. However, even when the HVDC link cable itself has been taken out-of-service (e.g. for repair), responsive ancillary services such as voltage control are usually still available independently at each converter station. This flexibility enables grid operators to retain partial functionality of the HVDC equipment even when power transfer via the link is unavailable.

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[46] These figures exclude a pro-longed outage of more than 100 days affecting the Cobra interconnector, however if considered over a ten-year period, this prolonged outage would result in a 2-3% reduction in annual availability

As mentioned in Section 7.1.1 Transmission Capacity, a particular advantage of the ‘bipole HVDC with common return configuration is that half of the link (one pole) can be out of service (for maintenance or for repair) whilst the other pole can continue to maintain 50% of the full HVDC link transmission capacity. Providing the common return through electrodes in the ground or sea can significantly (around 30%) reduce the overall costs of the cables, although this electrode approach can have adverse effects on vessel navigation compasses, on sea animal navigation, and on conducting metallic structures over a wide area between the electrodes. Conversely, using a dedicated metallic return (DMR) – a third cable running alongside the two +/-pole cables – obviates all of these disadvantages, although at additional cabling cost.

7.3.4 Flexible circuit rating

AS explained in Section 7.1.3 Limitations, the IGBTs of VSC HVDC systems heat very quickly and, despite their cooling systems, they cannot operate significantly above their nominal rating without the risk of damage. This means that, unlike AC overhead lines and underground cables, the present HVDC systems are strictly limited to their stated continuous ratings and cannot offer significant temporary overload capability.

7.3.5 System restoration capability

As explained in Section 5.3.4, the process of system restoration needs simple transmission connections that require minimum controls, absorb minimum amounts of energy, do not require supplies to be available at both ends of the connection, and are immediately available for service. VSC HVDC links meet some of these criteria and may thus be suited to assisting in the transfer of restoration power across the transmission system to help network and generation operators to restart the national power supply.

As with AC overhead lines and underground cables, VSC HVDC systems with the appropriate controls can offer AC system restoration services. A downside to using a VSC HVDC link for system restoration is that the startup procedure for the link is complex and both converters will absorb useful energy from the weak recovering power system before they transmit any useful power, making system restoration with them more complex than with overhead lines. On the plus side, however, once the VSC HVDC link is operating with a stable power supply at one end, the system operator is able to use it to closely control the AC conditions (voltage, power flow, and reactive power) at the far end.

Relatively new system restoration functionality is also being tested that is unique to VSC HVDC links. Called a ‘soft-start’[47], this capability has the potential to benefit network owners beyond traditional hard-switching methods, as the soft-start can energise sections of network as a whole, by smoothly ramping up the voltage and power. This avoids the network damage from high voltage spikes that can be caused by repeated system shock-loads as circuit breakers reconnect large blocks of customers.

In summary VSC HVDC links are suited to assist with system restoration. The reader should nevertheless understand that HVDC links do not provide any restoration energy themselves; in this role, like the AC overhead and underground alternatives, they simply facilitate the transfer of power from restoration energy sources to other, larger generators needing startup power. It is also important to note that, unlike VSC HVDC Links, the traditional LCC HVDC link technology requires a robust AC supply at both ends before it can start to operate, so it cannot facilitate restoration services in the same way.

7.4 Environmental impacts

This chapter summarises the most prominent environmental impacts to be considered during the manufacturing and construction phase and the operation phase for this archetype. Detailed impacts and mitigation measures can be found in the Appendix 2.

[47] Blackstart from HVDC-connected offshore wind: Hard versus soft energization - Jain - 2021 - IET Renewable Power Generation - Wiley Online Library

7.4.1 During manufacturing and construction

7.4.1.1 Resource efficiency and pollution prevention

The following impacts should be considered for resource efficiency and pollution prevention:

- **Material Consumption:** The construction phase requires significant amounts of materials, including cables, support structures, and equipment. The extraction, processing, and transportation of these materials can have resource implications, particularly for non-renewable resources. Construction activities, such as cable laying, trenching, and installation of support structures, require energy-intensive equipment and processes. The energy consumption during construction contributes to the overall carbon footprint and resource efficiency of the project.
- **Water Pollution:** Construction activities may result in the discharge of sediments, construction waste, and chemical pollutants into marine or coastal waters. These pollutants can have detrimental effects on water quality, marine ecosystems, and aquatic species.

7.4.1.2 Impacts on biodiversity

The following biodiversity impacts should be considered during the construction phase:

- **Seabed Disturbance**: Activities such as cable trenching, anchoring, or installation of support structures can result in physical disturbance of the seabed. This can affect benthic (lowest level of a body of water) habitats, including the presence of sessile organisms (such as corals, mussels, fungi), seabed topography, and sediment composition.
- **Substrate Cover and Composition**: The installation of support structures, such as monopiles or jackets, may alter the substrate cover and composition, potentially affecting the colonisation and distribution of benthic organisms and macrofauna.
- **Hydrodynamic Changes:** The presence of support structures or cable routes can alter local hydrodynamic conditions, including water flow patterns and sediment transport, which may impact local species composition and distribution.
- **Noise and Habitat Displacement:** Construction activities, such as pile driving, can generate underwater noise and vibrations that may disturb or displace marine fauna, including fish, marine mammals, and invertebrates.
- **Collision Risk:** The presence of support structures or cable routes can pose a collision risk for marine species, particularly marine mammals and migratory fish, which may encounter the structures during their movements.
- **Avian Species**: Overhead cable structures (if any are installed onshore to connect with the HVDC) or offshore support platforms may pose a collision risk for avian species, particularly during migration or for species that use the area for foraging or resting. This will likely require a full assessment when forming the route of the cable.

7.4.1.3 Impacts of excess noise and dust

The following impacts should be considered for excess noise and dust in the construction phase:

- **Construction Noise:** The installation of offshore HVDC cables involves activities such as drilling, trenching, and piling, which can generate noise and vibration. These activities may impact nearby communities and sensitive habitats during the construction phase.
- **Air Emissions:** Construction activities can generate air emissions from heavy machinery, transportation, and energy generation. These emissions may include greenhouse gases, particulate matter, nitrogen oxides, and sulphur oxides, contributing to air pollution.

7.4.1.4 Accessibility to site

The following impacts should be considered for site access in the construction phase:

- **Cable Routes:** The presence of offshore HVDC cables and associated support structures may require navigational considerations and potential route restrictions for other marine vessels, including commercial shipping, fishing vessels, and recreational boats.

- **Temporary Exclusion Zones:** During construction activities, temporary exclusion zones may be established to ensure the safety of construction vessels and personnel. These zones may restrict access to certain areas for other marine users.
- **Onshore Infrastructure:** The construction of onshore infrastructure, such as converter stations or substations, may require access roads, construction staging areas, and temporary storage areas. These activities can impact existing access routes and local transportation networks.
- **Cable Landing Points:** The location of cable landing points onshore may require construction activities and associated onshore infrastructure, potentially affecting local access to coastal areas or existing facilities.

7.4.1.5 Climate change impacts

The following climate change impacts should be considered in the construction phase:

- **Construction Machinery and Vehicles:** Construction activities can contribute to GHG emissions, such as transportation of materials and equipment, energy consumption during construction, and construction-related machinery emissions, which contribute to the overall carbon footprint of the project.
- **Energy Consumption:** The energy consumption associated with use of heavy machinery and equipment that consume energy, including excavators, cranes, and vessels can contribute to GHG emissions, especially if fossil fuels are used for energy generation.
- **Material Production and Transportation**: The production and transportation of materials including cables, support structures, and equipment, can generate GHG emissions. The carbon intensity of these materials and their associated production processes can contribute to the climate change impact of the construction phase.

7.4.2 During operation

7.4.2.1 Impacts on biodiversity

During the operation phase, the following impacts should be considered:

- **Physical Disturbance to Seabed and Habitat:** Activities may physically disturb the seabed and associated habitats, leading to potential damage or displacement of benthic organisms and their habitats.
- **EMFs**: Power cables can emit EMFs, which may have potential impacts on marine organisms, including sensitivity to navigation, orientation, or behaviour.
- **Collision Risk for Marine Species:** The presence of maintenance vessels, support vessels, or equipment can pose a collision risk to marine species, including marine mammals, sea turtles, and seabirds.
- **Noise and Vibrations:** Maintenance activities, such as pile driving or other construction-related tasks, can generate underwater noise and vibrations that may disturb or harm marine organisms, particularly sensitive species such as marine mammals and fish.

7.4.2.2 Accessibility to site

During the operation phase, the following impacts measures should be considered:

- **Vessel Traffic:** Regular maintenance activities require the presence of maintenance vessels, crew transfer vessels, or service boats near the offshore HVDC infrastructure. This can result in increased vessel traffic in the area, potentially affecting other marine activities and navigation.

7.4.2.3 Climate change impacts

Offshore HVDC cabling is often used to transmit electricity generated by offshore wind farms, which contribute to the reduction of greenhouse gas emissions and the transition to cleaner energy sources. Nonetheless, the following should be considered:

- **Energy Efficiency**: HVDC technology is known for its efficiency in long-distance electricity transmission, resulting in lower energy losses compared to alternative transmission methods such as High Voltage Alternating Current (HVAC). The specific comparative level of losses can vary depending on the system design, distance, voltage level, and other factors. It is estimated that HVDC transmission can achieve efficiency levels of 95% or higher over long distances, while AC transmission may have efficiencies ranging from 90% to 95%, meaning that HVDC systems can deliver a higher percentage of the generated power to the load, resulting in lower energy losses. Please refer to section 4.2 for further information on losses.
- **Decommissioning and Disposal:** At end-of-life, decommissioning would normally remove all above-ground structures along with some, or all, of the foundations, unless these were to be re-purposed, and proper decommissioning practices will be applied to minimise environmental impact.
- **Life Cycle Assessment:** It is important to consider the full life cycle of offshore HVDC cabling, including its manufacturing, installation, operation, maintenance, and eventual decommissioning, to assess the overall climate change impact.
- **Transfer of Renewable Energy**: One of the positive secondary impacts of the HVDC is that the required network supports the transfer of renewable energy across the country, which allows the UK to increase their renewable energy mix and contribute positively to reducing the impacts of climate change.

7.5 Community impacts

This chapter summarises the most prominent community impacts to be considered during the manufacturing and construction phase and operation phase for this archetype. Detailed impacts and mitigation measures can be found in the Appendix 2.

7.5.1 During manufacturing and construction

7.5.1.1 Land use and community impact

It is important to understand the location of the offshore HVDC line and any supporting onshore infrastructures and the presence of any natural habitats or cultural heritage sites. This should be undertaken during the environmental impact phase of the pre-construction period. The main impacts to be considered:

- **Cable Landing Points:** Offshore HVDC cables require landing points where they connect to onshore infrastructure. These landing points may require land acquisition or use of coastal areas, potentially impacting coastal habitats and land use patterns.
- **Construction Sites and Visual Impact:** Construction activities for the onshore infrastructure, such as converter stations or substations, may require temporary use of land and have associated impacts on the local environment and land use. This infrastructure, as well as offshore cable laying vessels and associated activities can introduce new visible structures and equipment that may have visual impacts on the local landscape and scenic views, particularly in coastal areas.
- **Community Disruption:** Construction activities may temporarily disrupt the daily lives of local communities, particularly in coastal areas near cable landing points or onshore infrastructure sites. Increased traffic, noise, and limited access to certain areas may affect community activities, businesses, and tourism.
- **Employment and Economy:** The construction phase can provide employment opportunities and contribute to the local economy through job creation, supply chain involvement, and ancillary services.
- **Underwater Cultural Heritage:** The installation may require trenching or other activities on the seabed. These activities have the potential to encounter and impact underwater cultural heritage, including shipwrecks, submerged archaeological sites, or other historically significant features.
- **Onshore Infrastructure:** The construction of onshore infrastructure, such as converter stations or substations, may require excavation and ground disturbance. In some cases, this could potentially affect historical sites, structures, or archaeological remains that are present on the land.

- **Urban vs Rural Land Occupation:** The impact of the HVDC cable, being predominantly offshore will have a similar low impact on both urban and rural areas. However, the installation of support infrastructure, such as substations or converter stations will be more favourable in rural areas due to the availability of land.

7.5.2 During operation

7.5.2.1 Visual impact on residential areas

During the operation phase, the visual impact may be minimal in comparison to overhead lines. However, the following impacts should be considered:

- **Cable Burial:** The presence of buried cables may not have a significant visual impact as they are located beneath the ground and seabed. However, cable routes will require beach landings and a cable connection chamber to transition between the onshore and offshore cables, which could be visible depending on the design and location.
- **Converter Stations and Substations:** Onshore converter stations and substations will have visible structures, such as buildings, electrical equipment, and transmission towers, which can alter the visual landscape of the surrounding areas. For high-capacity HVDC systems, converter stations can occupy a significant area, with buildings housing the equipment extending over several thousand square metres. The physical dimensions can also include multiple floors or levels, especially in installations where space is constrained. If the overhead line is being connected to an existing substation, an additional bay will be required which will take up approximately half a hectare (if no spare bay is already available). The construction of a new substation, if required, with modern technology is estimated to occupy approximately six hectares for a 2,000 MW connection. The converter station as part of the substation, may also be as high as 18-20m in height.
- **Cable Landfall Points:** The cable landfall points on the coast may require onshore infrastructure, such as cable terminations or transition pits. These structures can be visible and have visual implications, particularly in areas with sensitive landscapes or designated scenic views. The size of cable landing points can vary depending on the specific requirements of the project but generally include buildings or facilities to house cable terminations, jointing equipment, and control systems. The impact of these is anticipated to be minimal as typically only 1m high and 1m wide throughout the route of the cable line.

  For further insight into the typical dimensions of an HVDC converter, please refer to Fig 7.3 and 7.4.

7.5.2.2 Impacts on neighbouring communities

During the operation phase, the following impacts should be considered:

- **Fishing and Maritime Activities:** The presence of offshore HVDC infrastructure and maintenance vessels can impact traditional fishing grounds and disrupt other maritime activities, potentially affecting the livelihoods and economic activities of coastal communities.
- **Socio-Economic Benefits:** The development and operation can bring socio-economic benefits to local communities, including employment opportunities, local procurement, and infrastructure development.
- **Emergency Preparedness and Safety:** Emergency scenarios can arise and impact nearby communities, such as cable failures, fires, or other incidents.

7.6 Commercial & Supply chain impacts

We refer the reader to Section 5.6 for a short, general discussion of some aspects of the supply chain to the electricity supply industry. In this section we provide a summary table of key supply chain concerns for HVDC submarine links (Table 7.1), with equivalent tables in Sections 5.6 and 6.6 for overhead lines and underground cables, respectively.

Table 7.1: Commercial and supply chain impacts – HVDC submarine links

HVDC Submarine Links	
VSC Convertors	No known concerns, at present, with three major OEMs each having many projects in service. The buildings are normally steel-framed, but are not expected to represent a significant lead-time threat.
Cable systems – Onshore	Raw materials for the conductors, insulators and the cable external protection are all managed by the OEMs. The metals, in particular, will be bought ahead of manufacturing requirements, to attempt to minimise costs as the commodity prices vary. With a number of suppliers, including Prysmian, Nexans, NKT, Sumitomo, Hellenic, LS Cable and Taihan, competition should be healthy. Current indications are that lead times are driven by manufacturing capacity and not availability of materials. This manufacturing capacity is a global constraint, with manufacturers presently expanding production capacity. For example, both XLCC and Sumitomo have approval to build new cable manufacturing facilities in Scotland. Current orders are expected to deliver in 2031 - 2032, depending on specific length and technical requirements of the cables.
Cable systems – Offshore	Regarding the offshore cables – broadly as for onshore. As customers start to place framework orders with cable suppliers, the lead times for other customers increase still further. Regarding cable transport – vessels to transport submarine cable from the manufacturer and lay it on the seabed are in short supply, though more vessels are on order.
Networked HVDC hubs	HVDC circuit breakers, upon which networked 525kV 2000MW HVDC bipole hubs will rely for their operational flexibility, are not expected to be competitively available until mid-2030s, at the earliest, without a stable market to encourage the investment by OEMs. For 525Kv HVDC CBs have not yet been fully tested and could be considered in the TRL 5 – 6 range.

8 COMPOSITE CIRCUITS

Although a particular transmission route will have its own 'leading' archetype, there may be some situations where an alternative technology needs to be employed for specific sections of the route, for example, where an overhead line route cannot easily avoid approaching a community or an environmentally sensitive area, or where the final sections of a predominantly rural route lead into an urban environment. In these cases, it may be perfectly feasible, technically, to employ a mix of technologies on the route, the majority of which could be covered by overhead line, with a relatively short section of underground cable leading through the community or sensitive area. Such solutions are known as 'composite' circuits.

A key factor to note about this approach is the need for one or more transition installations between the archetypes, each with their own environmental, community, and cost impacts. For example, the transition between an overhead line and an underground cable requires a secure compound (known as a 'sealing end compound', or SEC) to be built to accommodate both the overhead line terminal tower (usually larger than normal towers) and the cable sealing ends that take the high voltage overhead line connections below ground.[48] The higher capacity double circuit overhead lines would require twelve cables for the underground section of the route so, to provide enough space for these, the SEC starts to look like a small substation. At the far end of the underground section, a second, similar transition SEC would be required to connect the underground cables back up to the next section of overhead line route.

Other complicating factors associated with the control and protection of the composite circuits cause their costs to rise above levels that might be envisaged simply by 'adding' some underground cable to an overhead line.

The environmental and community impacts of these transition SECs will be characterised by the impacts from both overhead line and underground cable.

[48] Cable sealing end - a rigid insulator stack, some 3m to 4m long mounted vertically on a steel structure that is itself 2m to 3m tall. The end of the underground cable is threaded up through this insulator stack and carefully terminated at the top. From this point the overhead line connections are taken up on to the overhead line tower. Six or twelve such sealing ends would be needed for each SEC

9 OFFSHORE INTERCONNECTION: HUBS & ENERGY ISLANDS

9.1 Archetype description

The energy island (or offshore energy hub) concept is, at its core, an offshore transmission substation that can aggregate, control and distribute electricity to or from shore, from offshore windfarms, and to or from international connections (interconnectors). Typically, the concept also co-locates, with this substation, high-capacity electricity storage plant and high-electricity-demand process industry such as hydrogen production (through electrolysis). This latter function is often referred to as 'power-to-X', 'P2X', or 'PtX'.

In comparison with existing offshore electricity power infrastructure, which mainly comprises point-to-point transmission links, few multi-connection offshore energy hubs, if any, have been constructed to date because the commercial and social benefits are still being established, and the necessary regulatory and financing frameworks have not yet been put in place. Furthermore, as the North Sea Wind Power Hub (NSWPH) Programme[49] points out in its Concept Paper of May 2021, since the capital costs of such projects would be so high, the benefits of offshore energy hubs are likely to be best realised through new levels of international cooperation and cross-energy-vector coordination rather than through national policies alone.

However, despite the high costs and the lack of operating experience of offshore energy hubs to date, the European Cooperation in Science and Technology (COST) organisation notes on its website[50] that offshore energy hubs are attracting great interest around the world (including in the USA, Canada, China and Europe), particularly for their potential to assist in carbon reduction and meeting climate carbon targets. In particular, several European countries and electricity companies bordering the North Sea are fast progressing both the technical plans for the development of energy islands and the associated international agreements and regulatory policies to promote their development.

An offshore energy hub may be established upon a pre-existing natural island in the sea, on a new artificially constructed island, or it may be based upon one or more offshore platform (OSP) modules that may stand on the seabed or float, either singly or in clusters. The nature of the base of the hub would depend entirely upon the purposes to which the hub would be put, its location, and the services it would require to operate. Where the hub functions include, for example, the P2X production of methanol, or where it would act as a construction and maintenance base for nearby wind farms, the hub would also offer some measure of sheltered mooring and port facilities.

For the UK, with its particular characteristics of a heavy north-south electrical power flow and its already well-developed crop of offshore wind farms – each with its own export connection having the potential to impact communities and the onshore environment to various degrees, the offshore energy hub idea has other potential attractions, too. For example, since an offshore energy hub could aggregate future wind farm connections, fewer circuits may need to be brought ashore (although, see also the comment relating to 'Infrequent Infeed Loss Risk' in the notes to the following diagram). Offshore energy hubs might also combine national offshore transmission connections (sometimes referred to as 'bootstraps') with future interconnectors, with their final routes to the GB transmission system being better optimised both for the system itself and for the onshore communities and environment through which they pass. And, of course, the very fact that the energy hubs are offshore means that they take the majority of their connections offshore too, thus reducing the need for further onshore transmission infrastructure.

The following diagram, Figure 9.1 illustrates some of these features, with further notes following the diagram.

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[49] https://northseawindpowerhub.eu/files/media/document/NSWPH_Concept%20Paper_05_2021_v2.pdf

[50] https://www.cost.eu/modenerlands-energy-islands/

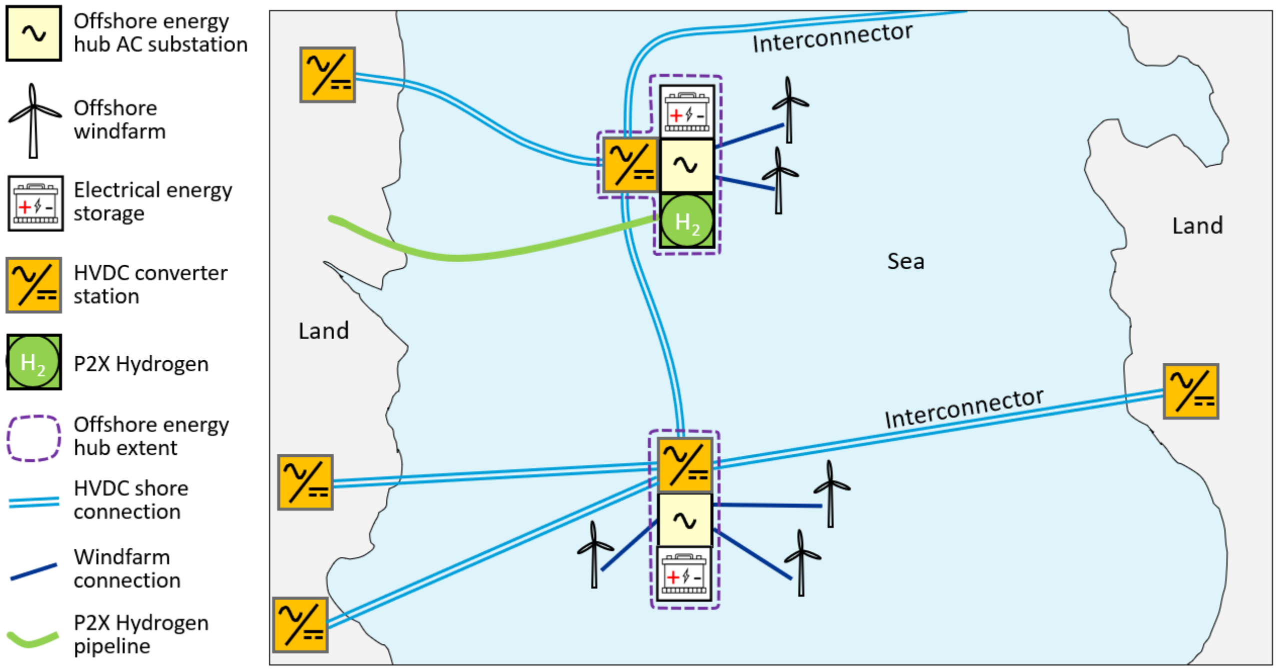

Figure 9.1: Notional example of multiple offshore energy hubs (notes to diagram follow), DNV sourced diagram

Notes to Figure 9.1:

i. AC submarine transmission cables become increasingly inefficient and ineffective with length so, especially for high capacities, the HVDC alternative becomes the optimum solution for connection lengths beyond a few tens of km. Technical limitations of AC submarine transmission cables mandate the use of HVDC connections for interconnectors, regardless of length.

ii. At least 2, and probably 3 cables (positive, negative, and common metallic return) would be expected on most high capacity HVDC connections.

iii. To effectively supply the various on-hub services (for example, energy storage, hydrogen electrolysis, nearby wind farms, mooring/port facilities, as well as logistics and maintenance base and personnel welfare services), each hub would require an **AC transmission substation**.

iv. P2X production of hydrogen (gas) would most likely require a **hydrogen delivery pipeline** to a shore-based gas handling facility.

v. P2X production of ammonia or methanol (liquid) would most likely require mooring facilities for ship transport, and possibly an on-hub storage capacity. These processes may also require **deliveries to the hub**, for example carbon dioxide for methanol, and process catalysts.

vi. The **interconnectors** could, in practice, be routed to the shores of other nations, or to other offshore energy hubs owned and operated by other nations or commercial operators.

vii. Each infeed to the GB transmission network is presently limited, in practice, to a maximum of 1.8GW – see the following Section 9.3.3 ‘Infeed loss risk’.

9.2 Rationale and precedent for building offshore energy hubs

Technology breakthroughs are often paired with 'early adopter' risk. For example, as the first wind turbines were developed, the cost remained prohibitively expensive compared to well-established fossil-fuelled competition. In order to incentivise the deployment of wind turbines and drive down costs, Government established a scheme to stimulate a renewables industry and attract developers by creating a mechanism to ensure a stable return on investment; the Contracts for Difference (CfD) scheme, which offers a 'strike price' – a guaranteed return per MWh of electricity generated, and importantly; decreased exposure to risk. This model attracted huge investment and propelled Britain to the summit of the global offshore wind industry, and in the process has delivered one of the fastest decarbonising power systems in the world.

These early connections conformed to the network planning framework for the transmission system at the time, and indeed offered almost identical characteristics to most onshore generators connecting into the transmission system: radial design, point-to-point connection to the nearest substation, in other words; an electrical connection to the onshore system but extended into the sea. These new links are designed, constructed and commissioned by the developer of the wind farm. Ofgem took the opportunity to auction the ownership and operation of these new offshore transmission assets in a competitive process to drive down costs for consumers, an appointed owner became an Offshore Transmission Owner (OFTO). As more and more wind projects followed, the network planning processes were reformed, to deliver more coordinated and efficient offshore designs. Today, the network planning processes continue to evolve to deliver the needs of a future more flexible and interconnected power system and, looking ahead, the variability of a renewables-based power system and new technologies reaching maturity will pose new challenges and offer new solutions to future network planning regimes.

Deviation from such robust planning mechanisms, which have served consumers with affordable, secure and reliable energy supplies for decades and provided sufficient commercial attractiveness to developers and investors, introduces significant uncertainty, and with uncertainty comes risk; not only for investors but also to network companies, consumers and Governments which oversee new policy. The concept of an interconnected offshore transmission system has been discussed for many years, but negotiations by all stakeholders to 1) ensure robust business case and financial attractiveness for the parties responsible for delivery, 2) manage uncertainty and 3) mitigate risks, presents significant barriers to its development; not least the risk of stranded assets.

9.2.1 Conceptualisation of energy hubs

The idea of an offshore energy hub combining multiple functions has been circulated in academia and industry over the last decade. However, only recently, with the establishment of the North Sea Wind Power Hub consortium of the Dutch and Danish TSOs TenneT, Gasunie and Energinet, has the idea started to materialise in concrete studies, plans and Governments' commitments. The primary factor that stimulated focused work on the topic of offshore energy hubs is the combination of climate ambitions of the countries around the North Sea and the realisation that those ambitions cannot be realised through an uncoordinated, national approach. Offshore energy hubs are thus emerging as a potential solution to reaping the benefits of large-scale offshore wind development coordination, synergies with cross-border electricity trade, and system integration across countries and commodities.

9.2.2 Barriers to financing of energy hubs

In order to understand why not a single offshore energy hub has been implemented so far neither in the UK, nor in the EU, one needs to look at the status quo offshore wind regulatory regimes. Two factors play a role; financial incentive schemes and overall project development process.

The prevailing support regime for offshore wind in the UK is based on the Contracts for Difference scheme which was first introduced in 2014 and since then has been successful in driving the cost of offshore wind development down making the UK a country with the largest installed capacity. Under the CfD scheme, annual auctions are organised for the right to receive a guaranteed revenue from the sales of generated electricity based on the awarded strike price. Developers compete for obtaining the CfD by submitting bids indicating the desired strike price – a guaranteed price per MWh of produced electricity. The lowest bids are awarded the contract until the total CfD round budget is not filled. The CfD scheme fundamentally promotes cost reduction in order for developers to remain competitive. Thus, both the wind farm and the grid connection system optimisation became a priority. Optimisation of grid connection system usually implies seeking connection to the nearest point possible and designing it in a lean way, with the minimal set of equipment required to safely deliver the electricity generated by a particular wind farm to shore. This philosophy is incompatible with the development of capital-intensive energy hub-based offshore grid solutions. The benefits of the energy hubs (described further) are abundant, however mostly accrued by the society. Meanwhile, the additional costs for developing would have to be borne by those developing them[51], and in the case of windfarm developers which operate in a competitive commercial environment, are not justified.

The offshore wind development process consists of a number of steps with a number of public and private stakeholders involved in each. These steps include: maritime spatial planning, where the area for future wind farm developments is assigned by the Marine Agency and Crown Estate; seabed lease process, where Crown Estate allocates licenses to applying offshore wind developers; consenting , where developers who have obtained lease rights in the previous step perform the necessary studies and apply for Development Consent Order (DCO) permit from BEIS; CfD auctions, where developers who have obtained the DCO compete for the state support; construction and commissioning, where the wind farm and grid connection designs are finalised, equipment is procured and projects are built and tested before going online. The overall procedure might take up to 10 years, form the moment where the area for a potential wind farm development is identified, till the first unit of electricity is produced. Integrating an additional step of offshore hub development would significantly raise the complexity, potentially prolonging the lead time of project delivery, raising overall costs and number of interfaces between stakeholders to be regulated and managed. At present, the regulatory framework does not deal with these issues and would have to be significantly re-designed given that the energy hubs often deliver the highest benefits when developed with internationally, thus requiring coordination with neighbouring countries and their regulations.

9.2.3 Proposals for energy hubs in Europe

Currently, there are at least three energy island projects at advanced planning stages, supported by national government commitments. None of these hubs have been constructed. Note that this is a fast-changing environment, and the summary below only gives a ‘flavour’ of the ongoing activities; no attempt is made at a comprehensive view here.

These are:

1) Energy hub in Danish waters of the North Sea (to be built as an artificial island)[52]

   This hub will, in the first phase, accommodate up to 3 GW of offshore wind generation, with a later potential for expansion to 10 GW. Offshore hydrogen production is being considered for this hub, as well. There are intergovernmental agreements to connect this hub to a Belgian offshore hub and to Germany and potential plans to also connect to the Netherlands (or a potential Dutch hub). A recently declared open tender for an artificial island is presently on hold due to cost considerations, with the current focus on offshore platform solutions.

2) Energy hub based on the natural island of Bornholm in the Danish part of the Baltic Sea

   This energy hub will accommodate up to 3 GW of Danish offshore wind and provide connections to Denmark mainland and Germany with potential future expansions to Poland or Sweden. This energy hub will be implemented on the existing natural island of Bornholm, which makes it easier to implement from the technology

[51] Some of the EU countries (e.g. Netherlands, Belgium) take the responsibility for financing and developing the offshore transmission infrastructure away from the wind farm developer, i.e. the state pays for it. This could become a first step to offshore grid coordination, including delivery of capital-intensive and complex offshore energy hub projects.

[52] Throughout this chapter the word island does not necessarily imply a particular support structure. An energy island may be constructed using crushed rock, sand, caisson technology or a number of interconnected steel platforms.

point of view, as it is essentially in an onshore environment. It is also expected that the hub will serve as a logistics and maintenance base, thereby benefiting the local economy and creating new jobs. Hydrogen production is being considered here, as well.

3) Princess Elisabeth Energy Island in the Belgian part of the North Sea (to be built as an artificial island).

This energy hub will accommodate up to 3.5 GW of offshore wind and enable connections at least to GB and to the Danish energy hub in the North Sea. The project will combine HVDC and HVAC transmission; it will accommodate the connection of 2.1GW via 3 x 700MW 220kV AC substations and the connection of 1.4GW by a HVDC station. The energy island will be connected to shore by means of 6 x 220kv AC cables and 1 HVDC cable system. High-voltage infrastructure will be used to evacuate wind farm generation to Belgium's mainland and also serving as a hub for future interconnectors with the UK and Denmark. The island itself will be an artificial island; the outer perimeter will feature concrete foundations placed on the seabed. The area around the foundation will be filled with sand.

The approach that Elia is taking to evacuate offshore wind generation to the mainland is similar to GB's approach in that it is coordinated like GB's Holistic Network Design, and supports the large-scale delivery of electricity generated from offshore wind whilst minimising the traditional radial approach for delivering this electricity to where is needed. The main differences between the Belgium and UK approach is that the former is establishing a first offshore hub in the european plan to have an offshore network in the North Sea. The linking of Princess Elisabeth Island to other countries (e.g., UK and Denmark) helps to establish this as a first step to the european offshore network.

We note that this Princess Elisabeth Island will comply with the Infeed Loss Risk limits for both UK (i.e., 1.8GW) and Europe (i.e.,3GW). We also note that the island will be extendable over time as per the current plans. In this occasion, multiple (separate) onshore links will be required to evacuate the additional power, which should also comply with the Loss Risk Limits.

Table 9.1: Energy Hub in Europe - Summary

	Belgium – Princess Elisabeth Island[53]	**Denmark - North Sea Vindo Island[54]**	**Denmark - Baltic Sea Bornholm[55]**
Capacity	3.5 GW, modular approach, extendable over time	3 GW offshore wind by 2030, extended to 10 GW by 2040	3 GW
Potential offshore energy hub functions	1. Aggregate offshore wind 2. Interconnection to: - GB mainland - DK new energy hub island	1. Aggregate offshore wind 2. Interconnection to: - DE mainland or energy island - BE new energy hub island 3. P2X hydrogen production	1. Aggregate offshore wind 2. Interconnection to: - DE mainland - other Baltic countries 3. P2X to be decided
Nominal delivery date estimates	2026 to 2030	First phase ~2032 A recently declared open tender for an island is presently on hold, with the current focus on offshore platform solutions	To develop in parallel, but lagging, Vindo Island
Finance	Shared between European Recovery & Resilience Fund and Danish TSO Elia	Private / state shared ownership, the Danish state being the majority shareholder (at least 50.15%).	Shared ownership, the state being the majority shareholder.
Landing point	Belgium mainland with a single set of cables, GB & Denmark	Denmark	Denmark, Germany, and elsewhere
Connections	HVDC	HVDC, H_2 pipeline	HVDC

53 https://www.elia.be/en/infrastructure-and-projects/infrastructure-projects/princess-elisabeth-island

54 https://ens.dk/en/our-responsibilities/offshore-wind-power/energy-island-north-sea#:~:text=A%20broad%20majority%20of%20the,to%2010%20GW%20offshore%20wind.

55 https://ens.dk/en/our-responsibilities/offshore-wind-power/denmarks-energy-islands

9.2.4 Potential benefits of energy hubs in the North Sea

Multiple functions to realise synergies between connected systems

The countries surrounding the North Sea are all characterised by different offshore wind potential, domestic electricity (and energy) demand, generation mix, onshore grid topology, level of interconnectivity with neighbours, and offshore grid planning regimes. In this context, an energy hub that *collects* the offshore wind energy where it is generated, *connects* it to the countries where it can be consumed and *converts* the surplus into alternative energy carriers is a solution that maximises the benefits from the offshore wind despite these national differences.

Savings on cross-border and onshore electricity infrastructure

The primary rationale for the Danish energy hub in the North Sea (whose plans are amongst the most advanced in the world) lies in the immense offshore wind potential in the area, more than the country can cost-effectively integrate into its own system. Even with the growing electrification of energy demand, the ratio between peak offshore wind production and domestic demand (assuming full offshore wind potential is realised) would be so high that Denmark would have to curtail its offshore wind generation. Alternatively, Denmark could significantly increase the capacity of interconnectors to neighbouring countries that have offtake potential. However, that is not cost-effective given that the full offshore production would have to be delivered to the onshore system first, flow through it, and then be delivered to a neighbouring system. This would require significant investments both in offshore and onshore grid infrastructure, not to mention the negative impacts on the environment and visual amenity. In this particular case it has potential to save millions of pounds in capital investment cost to directly re-route the surplus electricity from where it is produced to off-taking countries, such as Germany.

Maximising the value of generated electricity through interconnection

By connecting an energy hub to several neighbouring countries, the system can be operated such that the surplus electricity is directed to where it has the highest value at a given moment. For example, there is a plan to connect the Belgian energy hub to the Danish hub in North Sea as an additional outlet for the surplus wind power. Whilst at first sight it may seem that such a connection is too long and therefore uncommercial, the reasoning here is that, because two countries are widely separated, they will often have different, but complementary, offshore wind generation profiles; that is, over a typical year there will be many periods where one country's wind generation is in surplus whilst the other's is in deficit. An interconnected system of offshore energy hubs would allow both countries to increase their security of supply by relying, from time to time, on generation capacities that are located far away.

A similar situation is observed in the Baltic Sea, where the plan is to connect the offshore wind in the vicinity of Danish Bornholm Island to an energy hub on the island, whilst building electrical connections from the island to Denmark, Germany (and potentially Poland or Sweden in the future). Here, the energy hub would serve as a mid-point where the cross-border flows between the connected systems are optimised together with the offshore wind electricity transmission in a way that electricity is delivered to a market where it has the highest value in a given moment. In this way, such an interconnected system starts resembling the typical onshore grid, where there are multiple pathways for electricity to travel to where it is most needed, which maximises its utility and consequently the socio-economic welfare.

Cross-commodity coupling

In addition to offering cheaper ways to integrate electricity, an offshore energy hub can facilitate energy being directly converted to other energy-carrying commodities, such as hydrogen and its derivatives, which can be transported to the industrial centres where they are most in demand. Further in the future, an energy hub could become a synthetic fuel production base where, for example, maritime fuels would be produced and directly consumed by the maritime industry (that is, the hub could serve as a refuelling station for ships). Again, an energy hub minimises the volume of transmission infrastructure that would otherwise be required to do this and simplifies consenting procedures by removing the need to find space for the electrolysers onshore (although not the space for pipeline landfalls). Power-to-hydrogen (P2H or P2X) electrolysers at a commercially viable scale of several hundred of megawatts can take an area equal to several football fields so, with appropriate pipelines, an offshore energy hub could serve as a coupling element between electricity and gas infrastructure. (Note that, although consenting procedures would thus be simplified, there would still be a significant commercial cost to the electrolyser base – be it artificial island or offshore platform.)

Scale and location benefits

Looking purely at the offshore electricity infrastructure, an energy island can offer certain economies of scale where the offshore wind energy from several relatively small wind farms is aggregated and transported onwards in bulk. This approach is especially relevant for distant wind farms whose individual capacities are less than the onshore system's loss of infeed limit. The latter defines the maximum size of a single connection than can be brought onto the onshore system without jeopardising the security of supply. Thus, in a situation where the total capacity of two or more wind farms is below this value, one can aggregate their total infeed so that, instead of building an individual connection for each single wind farm (which would be the status quo), the energy hub could collect the energy from all the wind farms and bring it to shore through a single large link, which typically costs less, and is less disruptive, than two smaller ones.

Often, where the wind farms are located far from shore, an AC connection becomes too expensive and complex to realise due to the reactive losses in cables. In such situations, HVDC connections are the practical alternative, especially at high power transfer levels, although each such connection requires a large AC-to-DC converter to be placed offshore, and another one onshore. As with electrolysers, the ground footprint area of such converters can be equal to that of several football pitches. An energy hub large enough to install one or more such converters is thus a prerequisite to cost-efficient transmission of power to shore.

Redundancy benefits

Finally, by aggregating multiple wind farms onto a single electrical node that is connected to multiple onshore systems, an additional redundancy for delivering power to shore is created. Where under the status quo a damaged wind farm-to-shore connection would imply that the power cannot be delivered to shore anymore, an energy hub having multiple connections to onshore system (or other hubs) will, all else being equal, have alternative routes for evacuating the offshore power to shore if a failure in one part of the system occurs.

9.2.5 Risks & uncertainties for offshore energy hubs

There are certain risks associated with the development of energy hubs as this is a novel approach. Some of the risks and the areas that require further development were discussed in section 9.2.2. Further considerations are presented below.

Financing & Ownership

There are different available structures for financing and owning an energy hub. For example, it could be a privately-owned structure, which should attract investors' interest because of the potential for high profitability whilst at the same time providing certainty to private investors that the regulatory, commercial and technical arrangements are in place. It could also be a state-owned structure, where the State takes the risk and the responsibility for delivering an energy hub on the basis that it aligns with national policy and targets or it can be a consortium of public and private ownership. Each option has its own risks and benefits and best practice is not available due to the infancy stage of energy hubs.

- When looking at the EU's proposed energy hubs, typically the state enters a consortium with the private sector, whilst the state remains the majority owner of the island. This structure allows the government to be the key decision maker for a critical infrastructure – to the security of supply – whilst it reduces the risk for the private sector. In the UK, the ownership and control of such a structure would still need to be determined as the energy hub will not be the typical OFTO structure. The ownership arrangement requires feasibility assessments and market studies so that all the viable options are considered and the energy hub attracts sufficient private interest. For example, it is not in investors' interests to commission the development of a new interconnector, without confidence that the interconnector will be transporting electricity over its 25-year lifetime to provide a return on investment.

- Closely linked to the ownership of the energy hub, the question of how and who to finance this large infrastructure project should also be considered. Looking into the European examples, Belgian Energy Island will be partially funded by EU's recovery and resilience facility, whilst the Danish State was actively looking for private partners though an open tender which will support the finances of the project in North Sea. However the Danish Energy Agency has delayed a public tender for construction of the island and is now assessing new approaches to energy islands as the current costs and risks are considered too high to continue.

The uncertainties around financing and ownership arrangements could create delays in project planning and delivery, as it is the case of the North Sea energy island.

Commercial Viability of the energy hub

The commercial viability of the various types of offshore energy hubs is still being investigated. Recent Danish studies[56] indicate that their planned investment associated with a new artificial island in the North Sea is not, at present, low enough risk for state support; further studies on offshore platform bases, as an alternative, are ongoing, but these findings are not thought to adversely affect Danish plans for a natural island-based energy hub on Bornholm. The commercial viability of energy hubs is very closely linked to the ownership and financing arrangements. In order for private investors to finance an energy hub, they need certainty that there is a positive business case in building and operating an energy hub. Investors will logically look into increasing their revenue streams compared to only owning offshore wind assets or being OFTOs. For example, the operation of other energy conversion facilities such as P2X and storage facilities would potentially make the business case more attractive.

Co-ordinated delivery of energy hubs with offshore wind farms- Risk of stranded assets

As discussed, the main driver for developing energy hubs is the expected growth in offshore wind generation and the need to evacuate offshore wind power to the mainland in a cost-effective and timely delivered way. This means that the planning process, tendering and delivery of the energy and the offshore wind farms should be aligned in order to avoid the risk of building stranded assets that are not utilised by the time they are built. The process for connecting a wind farm to the network was explained earlier and it was explained that it may take up to 10 years, form the moment where the area for a potential wind farm development is identified, till the first unit of electricity is produced. This lead time suggests a long process which should be well planned in order to be delivered in time. The development of an energy hub is a more complex process which is expected to require at least similar amount of time if not more. For example, in Europe where discussions about the energy hubs are more progressed compared to the UK, the earliest connection date is suggested to be around 2034. Considering these timescales, delivering energy hubs in the UK by 2030 to connect a fraction of the 50GW of offshore wind as per national targets would not be a realistic option.

Construction of energy hubs - Scalability

Another uncertainty mostly because of the lack of good practices is the construction strategy of the energy hubs. It is well understood that Energy hubs require huge investments and their viability is very much reliant on reducing risks and managing future uncertainties. As such it would make send to develop the energy hubs in a modular approach so that they grow and integrate new technologies in alignment with market conditions and industry developments. A modular approach could lead to management CAPEX costs and provide space for further adjustments as the project grows and in conjunction with the market needs. The NSWHP for instance is taking a modular approach in developing the energy hub

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[56] https://en.energinet.dk/infrastructure-projects/energy-islands/news-about-energy-islands/energinet-investigate-north-sea-energy-island-on-platforms/

and associated infrastructure. On the other side, when large infrastructure projects are planned some key decision need to be made at early stage of the development process to avoid additional costs and delays. Whether there is a right or wrong answer, it is still to be determined and international experience on this topic would be useful for GB.

Market Arrangements

This document has already mentioned the benefits of maximising the value of generated electricity through interconnection, which could be a potential usage of offshore wind generation which is connected to the hub. In this case the energy hub would serve as a mid-point and multi-purpose interconnectors (MPIs) would be required for cross-border trading. There is currently a lot of discussion and uncertainty around the market arrangements that will underpin an energy hub and MPIs. Ofgem has been exploring through a consultation on “Market Arrangement for MPIs” the relative merits of two market configurations for these MPIs: the Home Market (HM) model and Offshore Bidding Zone (OBZ) model. Looking at the energy hub, similar processes will be required to understand the impact of the potential market setup on investors in an energy hub. For instance, the European NSWPH is exploring the roll-out of offshore bidding zones, associated risks and mitigation measured. Changing the market setup offshore will results in a change of risks for offshore developers and P2X developers. The allocation of these risks to various stakeholders is a political decision that should be taken prior to tendering so that developers have sufficient clarity and transparency of the process when they assess their business case.

Safety of critical infrastructure

The risk of sabotage of critical energy infrastructures is higher for centralised large infrastructure which can become an easier target with a larger impact on energy security compared to decentralised solutions. For example it would be easier to “blow up” one energy hub and take down several wind farms at once, than to blow up individual wind farm connections. The sabotage against the Nord Stream Executive gas pipe is a reminder that energy infrastructure is a potential target and therefore energy islands must be designed to withstand both cyber and physical attacks.

Limited Precedent

Regarding precedent for offshore energy hubs, whilst none have been contracted for construction yet, a number of countries and organisations have invested in feasibility studies and in the processes of forming partnerships and memoranda of understanding as a precursor to establishing trading agreements that optimise the benefits to be gained from international cooperation on wind energy from the North Sea. However the fact that no energy hubs have been constructed and viably operated yet, means that no good practices are available, GB will have to work on the development of their novel practices, which typically requires more time and involves inherent risks. For example, the first talks of HVDC links at 525 kV and 2 GW power level arose in 2018, as part of the EU research PROMOTioN project. The actual connection at these ratings are planned to be online in early 2030s. This shows that the process from understanding the needs, developing the concept, developing the technology, planning project, procuring equipment, constructing and getting online can easily take more than 10 years.

9.3 Deliverability and Operability

Even in the basic electrical-hub-on-an-offshore-platform form, an offshore energy hub and its associated cable links represent a very large investment – significantly more than most OFTOs today. The investment levels rise much further when artificial island structures are incorporated, so it is vital for investors to understand and accurately size the market(s) that a hub would serve as well as to understand the technology supporting it.

Many factors will affect the deliverability and operability of the early offshore energy hubs. Some of these factors are universally applicable, whilst one or two are GB-specific. A few of the key factors are identified next.

9.3.1 Technology readiness levels

The Technology Readiness Level (TRL) designation for a new technology is a 10-step scoring scale that indicates the amount of progress has been made in the development of that technology. The scale starts at 0 (zero) when the initial idea has been identified, and as the development matures, the scale passes through 8 other steps including technology concept, experimental proof and industrial verification before arriving at a score of 9 for an actual provable system available through competitive supply.

Some technology areas needing further development before offshore energy hubs can be fully exploited are outlined next:

- **Multi-terminal HVDC**, which is an essential technology for forming high capacity long distance offshore power networks, is a developing field. The HVDC link technology to transmit high volumes of submarine power from point to point is already available and proven – it is used by the UK and around the world today. However, the HVDC circuit breaker (HVDCCB) technology to 'knit' these links together to create a highly reliable and available offshore power network, resilient against equipment failure, is still in development.

- Regarding technology readiness, lower voltage HVDCCBs from several manufacturers are already at the system prototype demonstration stage (and so may be considered to be at around TRL 7). However, at 525kV, which is a standard voltage for HVDC links and a necessary voltage to achieve the maximum allowable infeed to the onshore system (see also the following Section 9.3.3), HVDCCBs are still being validated in industrial environments (~ TRL 5/6) and there is uncertainty as to when the first products will becomes commercially available for transmission networks, with estimates ranging from mid 2030s to post 2040[57]. This may coincide with the timing of the first offshore wind hubs but, until HVDCCBs are available, the technology development rate remains a risk to hub designers and potential users.

- Of course, multi-terminal offshore HVDC links with overall capacities of less than 1.8GW (see explanation for this in the following Section 9.3.3 'Infeed loss risk') could be designed and operated without HVDCCBs, on the understanding by all connectees that, in the event of an HVDC link fault, all the HVDC terminals on the link would be simultaneously disconnected to clear the fault. Such an arrangement would, however, significantly reduce the potential benefit of networking the HVDC links.

- **Hydrogen from electrolysis** at GW scale is not yet a commercially developed technology, although it is an active area of research and development. A report for the Scottish Government by Arup in October 2022 indicates that several hydrogen electrolysis technologies have been proven in an operational environment (equivalent to TRL 9), but only at a smaller scale.[58] The report also notes that not all of these technologies can operate flexibly, as would be required by the intermittent nature of wind power. Nevertheless, DNV estimates that offshore energy hub scale converters will be available by the mid 2030s.

- **Methanol from hydrogen and carbon dioxide** at the GW scale is also not yet fully developed, although the shipping industry is looking hard at future-proofing its operations through the adoption of carbon-free propulsion fuels (of which methanol has the highest energy density), and there are already a number of large vessels running on methanol, a report by the Methanol Institute in May 2023 indicates that although E-methanol (that is, methanol produced carbon-free) was not produced for shipping at all in 2020, it is estimated to take half the world market by 2050 We therefore estimate the current development maturity of E-methanol production at the GW scale to be at a TRL of ~4/5. [59]

9.3.2 Link capacities

Shore-to-hub and hub-to-hub link capacities are always limited by the energy transfer capacities offered by the connecting cables – particularly by their operating voltages. Presently, the largest design capacity for an HVDC link (no link of this

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[57] ENTSO-E TYNDP 2024 Offshore Network Development Plans – Tranmission Infrastructure Needs (windows.net)

[58] https://www.gov.scot/publications/assessment-electrolysers-report/pages/2/#:~:text=The%20electrolyser%20technologies%20that%20have,solid%20oxide%20electrolysers%20(%20SOE%20).

[59] https://www.methanol.org/wp-content/uploads/2023/05/Marine_Methanol_Report_Methanol_Institute_May_2023.pdf

size has yet been built) is still only around 3GW, which is dwarfed by the anticipated 10GW or higher expected final wind power generation that might need to be aggregated by some offshore energy hubs. However, even this 3 GW capacity could not be accommodated by the GB transmission system – see the following description of 'infeed loss risk'.

9.3.3 Infeed loss risk

A particular operability factor for electricity transmission is the management of unexpected loss of generation. To help manage this risk in GB, the Security and Quality of Supply Standard (SQSS) stipulates that each infeed to the GB transmission network be limited to a maximum of 1.8GW by a quantity known as the Infrequent Infeed Loss Risk (IILR). This value is chosen to accommodate the largest connected power plant whilst minimising the hour-by-hour costs of operating extra spinning reserve. (To put this in some context, the IILR for the whole of Europe is 3GW, although the continent does not normally operate as a single synchronous AC system.)

The practical impact of the IILR on the connection of offshore energy hubs is that, despite the energy-aggregating capability of energy hubs, infeeds to the main onshore power system greater than 1.8GW would still need to be split and brought ashore through multiple cable connections. These connection routes would need be diversified to minimise the risk that a single event – such as a dragging anchor – could cause an infeed loss greater than the IILR, the implication being that offshore hubs may not significantly reduce the number of landfalls required by offshore wind power.

Note: A factor that could reduce the number of cable landfalls in the medium term is the 'Power-to-X' idea – see the following Section 9.3.5.

9.3.4 Component lead times

Aside from any delays due to technology readiness levels, commercial lead times are already known to be highly extended for some major components of offshore electricity systems due to world-wide demand and limited supply. For example, the Dutch TSO TenneT, considering that it will need many offshore HVDC platforms over the next 10 years and wishing to standardise its equipment for cost, reliability and maintenance reasons, has encountered, during the project planning process, anticipated delivery lead times in the order of 10 years. Offshore cables is another known area of limited supply, we anticipate high international demand for cable raw materials over the next 10-15 years.

A detailed assessment of component lead times for HVDC submarine links is presented in Table 7.1 in Section 7.6.

9.3.5 'Power-to-X'

Power-to-X is the function of converting bulk supplies of renewable electricity to chemical energy (as hydrogen gas, or hydrogen-based liquids). A power-to-X facility on an offshore hub means that electrical energy can be exploited without the electricity even needing to be brought to the mainland. At a high level, therefore, this is a highly attractive idea that could be 'bolted-on' to the basic concept of an offshore electricity aggregating hub. Power-to-X would be essential to uptake large amount of offshore wind electricity without excessive onshore electricity infrastructure. However, for power-to-X to work in practice it would need to overcome a number of hurdles including:

- Power-to-X **processes would require substantial offshore space**, both for the energy conversion processes and, in the case of liquid products, for product storage and for sheltered moorings for transport ships. Even more efficient, where methanol is being produced and transported, could be the simultaneous refuelling of the transport ships – a service that could be extended to any shipping within the nearby busy shipping lanes if the energy island was large enough.
- Power-to-X processes are necessarily bulk operations in order to achieve the benefits of scale, so their investments and installations are not so easily drip-fed over time 'as the market develops'. To avoid stranded assets, therefore, **the markets for power-to-X products would need to be developed in parallel with the offshore energy hub facilities themselves**, possibly using decreasing quantities of carbon-based alternatives as the power-to-X products come online.

For both of these power-to-X hurdles (both the investment in large offshore spaces, and the imperative of producing green fuels in bulk) the offshore platform alternative to an artificial island would severely diminish the prospect of mooring ships for transport or refuelling. However, the Danish government has already judged the present cost estimates of an artificial island to be beyond the prudent level of investment for their state, so **spearheading hub development by national governments and international cooperation** may be vital to reap the full power-to-X benefits of offshore energy hubs. We would advise the new National Energy System Operator (NESO), Ofgem, and the UK Government, to seize the opportunities of the presently forming North Sea investigations and cooperations to develop GB policy on production and export of hydrogen and its derivatives and provide some certainty for investors.

9.4 Policy Outlook

This section is looking at the policy outlook of certain areas that can impact the development of energy hubs. This section discusses:

- The role of existing connections in developing energy hubs;
- The recent classification by the Government of offshore wind as critical national priority;
- The policy around multi-purpose interconnectors which is a potential option for increasing the attractiveness of energy hubs and offering an additional route for evacuating the generated electricity of offshore wind.

9.4.1 Planning for existing connections

When considering the development of the energy hubs, we should also consider their impact on connections that have already granted permission and are progressing through the planning system. Decisions on how to connect an offshore wind farm are typically made at early stages of a project development, and once made, cannot be changed. As such, the development of an energy hub should not interfere or change existing or potential connections for which the design and planning processes are irreversible. Thus, the energy hub (being part of transmission infrastructure) and the wind farms (generation infrastructure) must be planned and designed in coordination from the beginning of the planning process.

As discussed in section 9.2.5 the process from understanding the needs, developing the concept, developing the technology, planning project, procuring equipment, constructing and getting online is a highly time-consuming process. According to Ofgem[60], the time to build new transmission infrastructure averages between 12 to 14 years from the identification of the system need through to commissioning. Hence, agility of the network planning processes and infrastructure commissioning is important to ensure that infrastructure is in place in time for connecting new generation. Changing any plans would introduce additional level of complexity and critical delays, resulting in a sub-optimal outcome for electricity customers. As per a recent report from the Electricity Networks Commissioner[61] "The implications of being able to build wind generation faster than the associated connections to customers will be serious: very high congestion costs for customers, and clean, cheap domestic energy generation standing idle, potentially for years.".

Moreover, costs incurred from any changes, postponement or cancellations to in-flight projects would remain recoverable from consumers and would therefore substantially increase total delivery cost of new infrastructure. The development of new public infrastructure relies on attracting and securing private investment, and any retrospective changes to new transmission projects would arguably have a longer-term impact on investor confidence in the sector, particularly during a time where huge investment in electricity infrastructure and private-sector initiatives are required in coming years.

9.4.2 Critical national priority

The recent National Policy Statement for Renewable Energy Infrastructure (EN-3) specified that there is a critical national priority (CNP) "for the provision of nationally significant offshore wind development and supporting onshore and offshore

[60] https://www.ofgem.gov.uk/publications/ofgem-welcomes-focus-grid-connections-and-transmission-network-build-autumn-statement

[61] https://assets.publishing.service.gov.uk/media/64c8e96e19f5622360f3c0f0/electricity-networks-commissioner-letter-to-desnz-secretary.pdf

network infrastructure and related network reinforcements". The impact of this classification indicates government's ambition to accelerate the growth of offshore wind and remove barriers due to concerns of residual impact of CNP infrastructure. The impact of this classification on energy hubs is twofold :

1) Energy hubs are structures that can facilitate the growth of offshore wind and therefore creating and standardising regulatory, policy and market arrangement could be high in the energy agenda in the years to come.

2) The longer timescales for the construction and operation of energy hubs indicated that energy hubs will not be a 2030 solution for GB's energy system, as accelerating offshore wind connections is a priority.

9.4.3 Multi-purpose interconnectors (MPIs)

Multi-purpose interconnectors consist of a new, innovative asset which until recently was not defined in law and was not licensable by Ofgem. Ofgem defines MPIs as "*assets connected to an offshore generator in GB, which will conduct interconnection activities in GB and the connecting state as well as offshore transmission activities in GB (and optionally in the connecting State)*".[62] The reason that MPIs are discussed separately in this section is because it is highly likely that MPIs will be connected to the energy hub and offshore wind farms. In 2023, the GB government introduced MPIs as a new licensable asset class under the Energy Act 2023. According to the act, only licensed parties can participate in the operation of an MP and Ofgem is the responsible entity to grant the MPI licence.[63] Introducing MPIs as a licensable activity is a first positive step into establishing the regulatory framework of MPIs and indicates Government's aims to provide certainty to investors and developers, enabling them to make decisions regarding future MPIs projects.

As a next step, Ofgem is developing special licence conditions containing provisions on the applicable revenue regulation regime. Ofgem distinguishes MPIs from Non-Standard Interconnectors (NSIs), which are assets "*connected to an offshore generator in the connecting jurisdiction but not in GB, and which will conduct interconnection activities in GB and the connecting jurisdiction as well as offshore transmission activities only in the connecting state*". Ofgem is exploring MPIs regulatory framework in order to support the development of these assets and on the basis that MPIs (and NSIs) are a unique asset type with differing risk profile to interconnectors, meaning that the current "cap and floor" regime may not be suitable for MPIs.

Ofgem is also exploring potential market arrangements for MPIs, in particular bidding zone configuration and cross-border trading arrangements. [64] All such steps taken by the UK government and Ofgem are positive steps towards the establishment of MPIs and aim to provide certainty to investors that policy, regulation and market arrangements will support the business case for MPIs. Pilot MPIs projects are also under development which are providing useful insights during the process. However all these projects and the arrangements require time and support long-term planning objectives for the UK – post 2032. [65] In summary, MPIs might be the future for the UK and Europe, but regulatory, policy and market arrangements need to be developed first to provide sufficient certainty to investors.

9.5 Conclusions on energy hubs in the UK context

Offshore energy hubs (energy islands) are a capital-intensive infrastructure concept that has not yet been realised in the western world. Their utility, and their potential investment payback, lies within a complex area of renewable energy aggregation (from local wind farms), the flexible marshalling and onward transmission of bulk energy (from distant wind farms and interconnectors), and the conversion of a portion of this energy to hydrogen or its derivatives ('power-to-X') to supply carbon-free or carbon neutral fuels (for example, for heating and transport). The electricity could be imported to

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[62] https://www.ofgem.gov.uk/sites/default/files/2023-06/Consultation%20on%20the%20Regulatory%20Framework%20for%20Offshore%20Hybrid%20Assets-%20Multi-Purpose%20Interconnectors%20and%20Non-Standard%20Interconnectors.pdf

[63] https://www.legislation.gov.uk/ukpga/2023/52/enacted, 2023 CHAPTER 52, Paragraph 205

[64] Market Arrangements for Multi-Purpose Interconnectors (ofgem.gov.uk)

[65] Pilot Projects were considered eligible if they submit evidence of a GB connection agreement prior to the end of 2032.

GB's main interconnected transmission system (MITS) or exported to interconnected countries, as required. Equally, the power-to-X energy products could be imported to GB or exported, as markets dictate.

A major social benefit of this flexible, multipurpose concept is the full exploitation of North Sea wind energy through multiple uses and through facilitating international energy trading to optimise energy value; if applied widely across the North Sea it has the potential to greatly facilitate GB and European governments' progress towards net zero. (Quantification of this benefit is beyond the scope of this analysis) A second benefit of offshore energy hubs could be the reduction of onshore transmission reinforcement delays by instead paying the extra costs of developing an offshore transmission network. A third advantage could be that, compared to performing the power-to-X conversions onshore, the same conversions offshore would incur fewer consents issues and require significantly fewer electrical cables to be brought ashore in the future (though it would be most unlikely to reduce the number of shore connections currently in place or in planning now). An important general advantage of promoting the GB production of hydrogen and its derivatives is an improved national energy security (less dependent upon remote sources of gas and fuel oil) – although this, of course, would be a national benefit whether the production was based on offshore energy hubs or at onshore sites (for example those sites previously used to refine oil).

However, the investment required to establish an offshore energy hub and its associated connections to the MITS would be very high (probably exceeding most OFTO investments to date) and, so far, there is no clear incentive for a commercial investor to build and operate an offshore energy hub. Given the size of the investment needed, its success would depend upon reliable long-term revenues. However, the possible sources of revenue would depend upon many diverse drivers: national ambitions to import and export wind power, national ambitions to import and export hydrogen and its derivatives, windfarm developer plans for the area around the chosen hub site, transmission system topology and development, maritime restrictions on selection of hub sites, ability to minimise connection lengths to shore and to hubs operated by others, international offshore energy trading agreements, domestic trading agreements and regulatory constraints, to name but a few.

In addition, the electrical energy flows to shore are restricted by infeed loss limits (1.8GW for Britain, and 3GW for Europe), so although the offshore energy hub can aggregate power inputs to total many GW of supply capacity, the electricity that is imported to the GB MITS would need to be brought onshore through many connections, each of up to 1.8GW capacity. Power-to-X energy conversion on-hub somewhat reduces this need for electricity import cables but, with the advent of high-power offshore energy hubs, there will be the need to consider whether the infeed loss limits should be raised, or augmented with other measures (such as specific demand-side management measures).

No investor consortium would currently be in a position to influence all the above-mentioned factors that would affect the success of an investment. Indeed, noting Denmark's recent judgement that a hub based upon an artificial island would presently be beyond the prudent level of investment for their state, the investment is arguably too difficult even for some states. Accordingly, to take full advantage of the energy resources of the North Sea, we consider that states and energy organisations bordering the North Sea would need to work together with electricity network organisations urgently and imaginatively. We note various existing memoranda of understanding on energy and decarbonisation between GB and neighbouring countries, the bilateral offshore energy trade agreements between European countries, and the December 2022 landmark agreement on renewable energy cooperation between GB and EU and North Seas countries, so we would advise the new National Energy System Operator (NESO), Ofgem, the UK Government, and opposition parties[66] to seize the opportunities to exploit these opportunities to exploit the North Sea investigations and cooperations and establish national policy regarding:

- National ambitions for the production of hydrogen and its derivatives;

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[66] We note Denmark's example of establishing cross-party agreements on the way ahead for protecting the environment: https://ens.dk/en/our-responsibilities/offshore-wind-power/energy-island-north-sea/political-background-denmarks

- Provisions for security of the national electricity supply (through the SQSS) as offshore power capacities rise; and
- National (socialised) financial support for investment in, and regulation of, North Sea offshore energy hubs, including anticipatory investment.

APPENDIX 1 GLOSSARY

Alternating current (AC)	Electricity transmission in which the voltage varies in a sinusoidal fashion, resulting in a current flow that periodically reverses direction. In Great Britain the direction is reversed 50 times each second, which is known as a frequency of 50 Hz.
Back-to-back connections	In HVDC terms, links used to connect neighbouring grids are often referred to as “back-to-back” connections, indicating that the distance between the two grids is minimal. Such connections can link independent power grids, including those operating at different frequencies or voltage, and enable power to flow from one grid to another. A DC/DC convertor is a form of back-to-back connection where there is no intermediate conversion to AC power.
Bipole	The combination of two converter poles, one positive voltage, the other negative voltage, so that the pole conductor of each pole also acts as the return circuit path for the other pole.
British Electrotechnical and Allied Manufacturers Association (BEAMA)	BEAMA indices track the cost of labour and materials in the Electrical and Mechanical engineering industries on a monthly, quarterly and annual basis.
Capacitor (also referred to as a condenser)	A multi-purpose device that can store electrical charge in the form of an electric field. It is used, for example, for power factor correction in (inductive) AC circuits. Capacitors are used to buffer electricity (smooth out peaks) and to guard against momentary voltage losses in circuits (when changing batteries, for example).
Capital expenditure (CAPEX)	Funds used by a company to purchase or upgrade assets such electricity transmission equipment, control systems, and the land on which these are installed
Line commutated converter (LCC)	Well-established conventional or ‘classic’ technology that converts electric power from AC to DC or vice versa, using thyristor power electronics systems.
Committee for Climate Change (CCC)	An independent, statutory body with the aim to advise the UK and devolved governments on emissions targets and to report to Parliament on progress made in reducing greenhouse gas emissions.
Composite circuit	A transmission circuit that comprises a mix of overhead line and underground cable. Every transition between overhead line and underground cable requires a sealing end compound.
Conductor	A material or structure that is designed to carry electric current, typically made of metals with good electrical conductivity such as copper or aluminium.
Converter	An electrical device, comprising a rectifier and inverter, used to alter the voltage and frequency of incoming alternating current in an electrical system. The term may also refer to inverters, rectifiers or frequency converters
Converter station	Special equipment is needed to convert electricity from alternating current (AC) to direct current (DC), or vice versa. High-voltage DC (HVDC) converter stations use power electronic devices to make these conversions.

Dedicated metallic return (DMR)	Dedicated metallic return is used to return current through a separate metal conductor instead of through the earth or ground.
Direct current (DC)	Electrical current that moves in one direction only.
Development Consent Order (DCO)	A Development Consent Order is the means of obtaining permission for developments categorised as Nationally Significant Infrastructure Projects.
Double circuit	A double circuit transmission line has two independent circuits on the same structure with each circuit made up of three sets of conductors.
Electricity System Operator (ESO)	The ESO is the electricity system operator for Great Britain. The control room moves electricity around the country second by second to ensure that the right amount of electricity is where it's needed, when it's needed – always keeping supply and demand in perfect balance.
Electromagnetic field (EMF)	Electromagnetic fields are a combination of invisible electric and magnetic fields of force. They are generated by natural phenomena like the Earth's magnetic field but also by human activities, mainly through the use of electricity. Nowadays, they represent one of the most common and fastest growing environmental issues.
Energy Island	See 'offshore energy hub'
Environmental Health and Safety (EHS)	Environment, health and safety is the set that studies and implements the practical aspects of protecting the environment and maintaining health and safety at occupation.
Environmental impact assessment (EIA)	A process of evaluating the likely environmental impacts of a proposed project or development, taking into account inter-related socio-economic, cultural and human-health impacts, both beneficial and adverse.
Flashover	A flashover is an electrical short-circuit (often between a high-voltage conductor and the ground, or something connected to the ground) that results in a very high-energy spark that can cause danger to property, people and animals.
Flexibility	The ESO considers 'flexibility' to be the capacity for a technology to quickly change its outputs to suit network needs whilst complying with operating standards and without relying on other equipment capacities.
GB transmission network owners (GB TOs)	A collective term used to describe the three electricity transmission asset owners within Great Britain, namely National Grid Electricity Transmission, Scottish and Southern Electricity Networks Transmission and SP Transmission plc.
Habitat Regulations Assessment (HRA)	A process that competent authorities must undertake to consider whether a proposed development plan or programme is likely to have significant effects on a European site designated for its nature conservation interest.
HVAC	High-voltage alternating current (HVAC) – a method of transmitting electrical power with voltages above 110kV that (in Great Britain) alternate at 50Hz.
HVDC	High-voltage direct current (HVDC) – a method of transmitting electrical power with steady positive and negative polarity voltages above 110kV.

HVDC cable link	A technology developed during the 1950s to move large amounts of power over substantial distances by either underground or submarine cables. An HVDC link takes electrical power from an AC network, rectifies it to DC at a converter station and transmits it to the receiving point(s) as HVDC, where (an)other converter station(s) convert it back to AC. The conversion is carried out with high-power, high-voltage semiconductor electronic switches. (Refer to Section 7)
Horizontal Directional Drillings (HDD)	Horizontal Directional Drilling is a construction technique whereby a tunnel is bored under a waterway or other designated area, and a pipeline or other utility is pulled through the drilled underground tunnel.
IGBT	Insulated-gate bipolar transistor (IGBT) - an electronic semiconductor switching device that is particularly suited to high voltage and high current applications, such as HVDC converter stations
Institution of Engineering and Technology (IET)	The Institution of Engineering and Technology (IET) is a multidisciplinary professional engineering institution. IET - Institution of Engineering and Technology (theiet.org)
Inductive reactor	Inductive reactors can perform more than one function on a transmission network but, in the context of this document, they are a source of 'reactive compensation', (see glossary entry) providing electric currents that counteract the effects of cable charging currents on the power network. For this function they are normally connected at the ends of the cable although, in the case of a long cable circuit, they may also be connected at an intermediate location part-way along the circuit.
International Finance Cooperation (IFC) Performance Standards	The Performance Standards provide guidance on how to identify risks and impacts and are designed to help avoid, mitigate and manage risks and impacts as a way of doing business in a more sustainable way.
Inverter	An HVDC converter station operating in its control mode that converts direct current (DC) into alternating current (AC).
kilovolts (kV)	kilovolts, 1,000 volts
kilowatt (kW)	kilowatt, 1,000 Watts
kilowatt-hour (kWh)	kilowatt-hour, the energy delivered by 1 kW over the course of 1 hour
LCC	HVDC Line-commutated converters (LCC), also called current-source converters, convert electrical power from AC to DC, and vice versa, using thyristor-based power electronic switches. LCCs can presently be designed to handle greater volumes of electrical power than the alternative VSCs (see glossary entry).
Megavolt ampere (MVA)	Megavolt ampere; 1,000,000 volt ampere, a measure of reactive power.
Megawatt (MW)	Megawatt, 1,000 kW.
MITS	Main Interconnected Transmission System (MITS) is defined within the SQSS as comprising all 400 and 275kV supergrid elements of the onshore Great Britain transmission system and,

	in Scotland, the 132kV elements of the onshore transmission system operated in parallel with the supergrid.
MIPs	Multi-purpose interconnectors
Modular multi-level converter (MMC)	A modular multilevel converter is an advanced design of HVDC VSC that offers advantages in control flexibility whilst minimising the need for AC filters.
MWh	Megawatt-hour, the energy delivered by 1 MW over the course of 1 hour
National Grid Electricity Transmission (NGET)	Transmission owner in England and Wales.
Nationally Significant Infrastructure Project (NSIP)	Nationally Significant Infrastructure Projects are large scale developments (relating to energy, transport, water, or waste) which require a type of consent known as "development consent".
Office of National Statistics (ONS)	The Office for National Statistics is the executive office of the UK Statistics Authority, which reports directly to the UK Parliament.
Offshore Transmission Network Review (OTNR)	The OTNR was launched in July 2020 with the objective to address the barriers in increasing offshore wind capacity to achieve net zero and ensure that the transmission connections for offshore wind generation are delivered in the most appropriate way. This aims to find the appropriate balance between environmental, social and economic costs.
Offshore energy hub	The energy island (or offshore energy hub) concept is, at its core, an offshore transmission substation that can aggregate, control and distribute electricity to or from shore, from offshore windfarms, and to or from international connections (interconnectors). .
Operational expenditure (OPEX)	The ongoing costs for running a product, business, or system throughout its operational life.
Overhead line (OHL)	Electrical conductors, supported by steel towers (pylons), that transmit power from power stations, via high voltage substations, to consumers. (Refer to Section 5)
Power-to-X P2X	Typically, the concept of an offshore energy hub includes, with the electricity substation and convertor stations, high-electricity-demand process industry such as hydrogen production (through electrolysis). This process converts excess electrical energy from nearby windfarms to an alternative type of energy carrier, and this conversion function is often referred to generally as 'power-to-X', 'P2X', or 'PtX'
Reactive compensation	The automatic adjustments to voltages and currents in an AC power system that help to maintain its voltages, currents and stability within acceptable limits. The compensation may be provided intrinsically, by passive components such as capacitors and reactors, or through the automatic controllers of active components such as static var compensators, generators, and VSC HVDC links.
Reactive power	The frequency-related loss of useful power in an AC system resulting from the unavoidable production of electric and magnetic fields during the transmission of electricity. Reactive

	power is measured in Volt-Amps-Reactive (VAR) and is significant because it must be continuously provided to control the voltages and currents on the AC transmission network.
Reliability, availability, maintainability (RAM)	Reliability, Availability, and Maintainability (RAM) are design attributes of a system or an asset. Reliability is the probability of zero failures over a defined time interval. Availability is the percentage of time a system is considered ready to use when required. Maintainability is a measure of the ease with which a system can be restored to operational status following a failure.
Restoration services (formerly 'black start')	The services providing stand-alone energy (from sources such as, for example, diesel generators, batteries, renewable generators, if available) so that, in the (rare) event of a total shutdown of the national electricity transmission system, key generating site operations may be restored so that they, in turn, can enable general electricity supplies to be re-established. An important element of system restoration is a set of transmission circuits that can, themselves transmit the restoring supplies without, themselves, absorbing much of the supplies through losses. Restoration services used to be termed 'black start'.
SEC	Sealing end compounds (SEC) safely accommodate the high-voltage connections between underground cables and overhead lines. A SEC is always required at every overhead line / underground cable interface on composite circuits.
Short circuit	An electric contact between parts of an electric circuit, which causes a very high current, increases in temperature and potentially fire, if the circuit is not properly protected. This can occur if two live wires come into contact with each other, perhaps because of worn insulation. The term is also used when defining the safe operating conditions for electrical devices. If a device is said to have a short-circuit resilience of 400 amps (A), that means that it can be subjected to up to 400 A before it will shut itself down.
Strategic environmental assessment (SEA)	A process by which public bodies and private companies operating in a public character, such as utility companies, are required to assess, consult on, and monitor the likely impacts their plans, programmes and strategies will have on the environment.
Switchgear	The term used to describe components of a substation that can be used to carry out switching activities. This can include, but is not limited to, isolators/disconnectors and circuit breakers.
UGC	Underground cables (UGC) can be used as an alternative to overhead lines for the provision of electrical power. (Refer to Section 6)
Valve stacks	In HVDC converters, the IGBTs are arranged in columns, one above another, that allow them to work together to control HVDC voltages as high as 525kV DC. These columns, or stacks, are sometimes called 'valve' stacks as a colloquial throw-back to the days when HVDC control was performed with mercury valves instead of power electronics.
VSC	HVDC voltage-source converters (VSC) convert electrical power from AC to DC, and vice versa, using insulated-gate bipolar transistor (IGBT) power electronic switches. VSCs can offer greater power control versatility than the alternative LCCs.

APPENDIX 2 ENVIRONMENTAL AND COMMUNITY IMPACT

Appendix 2 lists the environmental and community impact and corresponding mitigation measures during both construction and operational phases.

AC OVERHEAD LINE: ENVIRONMENTAL IMPACT

Table 1 – Summary of environmental impacts during construction of overhead lines

Potential impacts source:	Mitigation measures:
Resource efficiency and pollution prevention	
• **Raw Materials Consumption:** The construction of overhead lines requires significant amounts of materials (steel, aluminium etc), including conductors, insulators, support structures, and hardware, which can lead to resource depletion and environmental impacts associated with material extraction, manufacturing, and transportation. • **Energy Consumption:** Energy-intensive activities, such as manufacturing components, transportation of materials and equipment, and installation processes, which contribute to greenhouse gas emissions and energy consumption, especially if produced by coal fired power plants. • **Waste Generation:** Generation of various types of waste, including packaging materials, construction debris, and discarded or replaced components, leading to increased landfill waste and potential pollution. • **Soil and Groundwater Contamination:** There might be some changes in the soil properties resulting from the soil replacement for the foundations and from construction of the overhead line. There might also be some impacts on the soil at the project site resulting from accidental leaks of wastes or oils used by the construction machinery. Whilst, such spills are expected to be limited, there could be an impact on nearby groundwater sources.	**Resource Efficiency:** • Optimise material use by selecting sustainable and recyclable materials, promoting the use of recycled or reclaimed materials, and implementing efficient design practices to reduce material waste. • Consider the life cycle assessment of materials to identify environmentally preferable options. • Implement responsible sourcing practices and prioritise suppliers with sustainable manufacturing processes. **Energy Efficiency:** • Improve energy efficiency during construction activities by optimising construction schedules and logistics to minimise transportation distances, adopting energy-efficient equipment and machinery, and utilising renewable energy sources where feasible. • Promote the use of energy management systems to monitor and reduce energy consumption on construction sites. **Waste & Soil Management:** • Excess soil is being used for other purposes (if applicable); either land levelling or in other nearby properties or be transferred to a landfill to be used for daily cover of waste in coordination with the landfill staff. • Arrange for delivering any waste oils to an authorised company for appropriate disposal. Waste oils should be adequately labelled and stored in designated locations of the construction site until being collected. • Use dedicated waste bins in certain locations around the construction site, so as no open storage of domestic solid waste would be allowed. The contractor should regularly transfer waste, or subcontract a waste collector, to the nearest authorised waste disposal. • Recyclables, such as plastics, woods and metals, should be separately collected for reuse in other sites by the contractors or sold to recycling dealers. • It is recommended to develop a waste management plan for the size, including hazardous and non-hazardous waste storage and collection. • Spill kits should be available throughout the site. Workers shall be trained in spill prevention and handling.
Impact on biodiversity	
• **Habitat Loss and Fragmentation:** Construction activities may result in the clearance of vegetation, including trees, shrubs, and other plant species, leading to the loss of habitat for various plant and animal species. The linear nature of	**Studies & Management Plans:** • Implement measures to minimise habitat loss and fragmentation, such as conducting pre-construction surveys

overhead lines can also cause fragmentation of habitats, hindering the movement of wildlife. • **Disturbance to Wildlife:** Construction activities, including noise, vibration, and increased human presence, can cause disturbance to wildlife species. This disturbance can lead to altered behaviour, displacement, or temporary abandonment of nesting or breeding sites. • **Soil Erosion and Sedimentation:** Construction activities can lead to soil erosion, particularly during site grading and vegetation clearance, which can result in sediment runoff into nearby water bodies. Increased sedimentation can negatively affect aquatic habitats and species. • **Watercourse and Wetland Impacts:** Construction activities may involve crossing or working near watercourses, wetlands, or other aquatic habitats, leading to potential impacts on aquatic ecosystems, water quality, and associated species. • **Invasive Species Spread**: Construction activities and the associated disturbance can create opportunities for the spread of invasive plant species, which can outcompete native vegetation and negatively impact biodiversity. • **Collision Risk:** Birds may be at risk of collision with overhead lines or associated infrastructure during construction, particularly if they are not properly marked or made visible. • **Risk of Electrocution:** Overhead lines can pose a risk of electrocution to birds if appropriate measures are not in place to prevent them from perching or nesting on the equipment. • **Nesting Site Replacement:** Construction activities may result in the direct removal or destruction of bird nests. Displacement from nesting sites can disrupt breeding patterns and affect reproductive success.	to identify sensitive habitats and species and avoiding or minimising impacts on critical habitats. Consider re-vegetation or habitat restoration programs to compensate for any habitat loss, promoting connectivity between fragmented habitats where feasible. • Conduct pre-construction surveys to identify sensitive species and their breeding or nesting periods. Schedule construction activities to minimise disturbance during critical periods, such as breeding or nesting seasons. Establish buffer zones around sensitive areas to minimise disruption. Implement best practices for minimising noise, using visual barriers, and reducing vibration levels to minimise disturbance to wildlife. • Develop and implement invasive species management plans to prevent the spread of invasive species during construction. Conduct surveys to identify and remove invasive species before construction commences. Implement appropriate measures to prevent the introduction and establishment of invasive species during restoration and revegetation activities. **Erosion & Sediment Control:** • Implement erosion and sediment control measures, such as sediment barriers, sediment ponds, or erosion control blankets, to prevent or minimise soil erosion and sediment runoff. Properly manage construction site runoff to prevent contamination of nearby water bodies. Implement erosion and sediment control plans consistent with local regulations and best management practices. • Comply with regulations and guidelines regarding the protection of water bodies and wetlands. Implement appropriate measures, such as using sediment barriers, temporary bridging, or elevated platforms, to minimise direct impacts on water bodies. Avoid or minimise disturbance to sensitive aquatic habitats and species. **Reducing Impact on Birds:** • Implement measures to minimise the risk of bird collisions, such as using bird diverters or markers on the overhead lines to increase their visibility. Install bird flight diverters and perch deterrents near the lines to reduce the chances of bird collisions. Monitor bird behaviour and mortality during construction to assess and mitigate collision risks. • Install bird guards, nesting prevention devices, or insulating materials on the equipment to prevent birds from perching or nesting in hazardous areas. Regularly inspect and maintain the equipment to ensure its integrity and effectiveness in mitigating electrocution risks. • Conduct nesting surveys prior to construction to identify active nests and breeding sites. Implement measures to avoid or relocate active nests, ensuring that appropriate timing and methods are used to minimise disturbance. Provide alternative nesting structures or nearby suitable habitats to compensate for any loss of nesting sites.
Impact of excess noise and dust	
• **Construction Equipment and Machinery:** The use of heavy machinery and construction equipment such as cranes, excavators, and pile drivers can generate significant noise levels and create excessive dust during the installation of towers, and other infrastructure. • **Construction Activities:** Construction activities, including excavation, foundation work, and material handling, can	**Noise Mitigation:** • Implement measures to minimise noise emissions, such as using noise barriers or enclosures around noisy equipment, selecting quieter equipment where feasible, and adhering to noise control guidelines and regulations.

create noise and dust, particularly during the assembly and erection of overhead line structures. • **Traffic and Transportation:** Increased traffic and transportation associated with the delivery of construction materials, equipment, and personnel to the construction site can contribute to noise and dust generation. • **Noise Monitoring and Compliance:** Inadequate monitoring and failure to comply with noise control regulations can result in excessive noise levels that negatively impact nearby communities. • **Airborne Emissions:** Impacts to air emissions expected during the construction of the project will be due to airborne dust resulting from earthworks, in addition to the emissions of different construction machinery such as power generators, excavators, loaders, vehicles, etc. Additionally, dust particles can settle on vegetation, soil, and water bodies, leading to reduced air quality and potential harm to ecosystems and nearby communities. Excess dust will also contribute to the overall emissions generated as part of the project which is highlighted as part of the climate change impact section below.	• Schedule noisy activities during daytime hours and consider the proximity of noise-sensitive areas, such as residential areas or educational institutions. • Employ construction practices that reduce noise, such as using advanced construction techniques and equipment that minimise noise emissions. Implement noise control measures, such as the use of acoustic barriers, soundproof enclosures, or damping materials around construction sites. • Communicate with nearby residents or businesses to inform them of construction activities and potential noise impacts. • Develop and implement traffic management plans to minimise noise from construction-related vehicles. Use designated routes and consider scheduling deliveries during off-peak hours to reduce the impact on nearby communities. Utilise noise-reducing technologies, such as low-noise vehicles or vehicle routing systems, where feasible. **Dust Control Measures:** • Water Spraying: Implement water spraying techniques to suppress dust emissions during activities such as excavation, material handling, and site preparation. • Dust Screens and Barriers: Use physical barriers or screens to prevent dust from spreading to adjacent areas or sensitive receptors. • Soil Stabilisation: Implement erosion control measures such as covering exposed soil with mulch, geotextiles, or stabilising agents to minimise dust generation.
Accessibility to site	
• **Construction access:** During the construction phase, access routes to the transmission line site need to be planned and constructed. This involves considering the width and condition of roads or tracks, bridges, and access points for construction vehicles and equipment. • **Public safety and security:** Accessibility impacts also extend to considerations of public safety and security. Appropriate signage, barriers or fencing should also be installed to discourage general public from accessing the construction site.	**Construction access:** • Design and construct access routes that can accommodate construction vehicles and equipment, ensuring appropriate width, stability, and load-bearing capacity. • Implement erosion control measures to minimise the environmental impact during construction. • Coordinate with local authorities to ensure compliance with any road permits or restrictions. • Establish traffic management plans to minimise disruption to local communities and ensure safe access. **Public Safety and Security:** • Install appropriate signage, barriers, or fencing to discourage unauthorised access to dangerous areas and ensure public safety. • Implement security measures, such as surveillance cameras or alarms, to deter vandalism, theft, or unauthorised entry into transmission line infrastructure.
Climate change impact	
Greenhouse gas emissions: • **Direct Emissions:** Construction activities involve the use of heavy machinery, vehicles, and equipment that can generate direct emissions, primarily from the combustion of fossil fuels. These emissions contribute to the overall carbon footprint of the project. • **Indirect Emissions:** The production and transportation of construction materials, such as steel, concrete, and insulators, can result in indirect greenhouse gas emissions.	**Emissions reduction:** • Use of Efficient Equipment: Opt for energy-efficient machinery and equipment, including low-emission vehicles, to reduce direct emissions during construction activities. • Alternative Fuels: Promote the use of cleaner fuels, such as biodiesel or electric-powered equipment, to reduce greenhouse gas emissions from construction operations.

The extraction of raw materials, manufacturing processes, and long-distance transportation can all contribute to these emissions. **Energy consumption:** • **Construction Operations:** The construction phase requires significant energy consumption for powering machinery, equipment, and temporary facilities on-site. The energy sources used, such as diesel generators, can impact overall energy efficiency and carbon intensity. • **Material Production:** The production of construction materials, such as steel and concrete, requires energy-intensive processes that contribute to indirect energy consumption and associated emissions. **Land use change:** • **Soil Disturbance:** Construction activities can result in soil compaction, erosion, and disruption of natural soil processes, which can have negative consequences for soil health, nutrient cycling, and carbon storage.	• Emissions Monitoring and Reporting: Implement monitoring systems to track and report construction-related emissions, enabling the identification of areas for improvement. **Sustainable material selection:** • Material Efficiency: Optimise material use by minimising waste, recycling materials where feasible, and using sustainable sourcing practices. • Low-Carbon Materials: Prioritise the use of low-carbon or recycled materials for construction, such as eco-friendly concrete or steel produced with lower emissions. **Sustainable land management:** • Soil Conservation: Implement erosion control measures, such as sediment barriers, vegetation cover, or soil stabilisation techniques, to minimise soil disturbance and erosion during construction activities. • Reclamation and Rehabilitation: After construction, implement land reclamation and rehabilitation measures to restore disturbed areas and promote ecological recovery.

Table 2 – Summary of environmental impacts during operation of overhead lines

Potential impacts source:	Mitigation measures:
Impact on biodiversity	
• **Collisions:** Birds in flight may collide with power lines, especially during low visibility conditions or when the lines are not clearly visible. • **Nesting:** Birds may build nests on or near transmission structures, putting them in close proximity to live electrical equipment. This increases the risk of nest failure due to electrical hazards or the destruction of nests during maintenance activities. • **Habitat fragmentation:** The construction of overhead transmission lines can lead to habitat fragmentation, and restricting the movement of wildlife, particularly arboreal species such as birds and arboreal mammals. This can disrupt breeding patterns, migration routes, and access to food and shelter. Additionally, vegetation clearance and maintenance activities around overhead line can result in the removal of trees, shrubs, and other vegetation that provide habitat and food sources for wildlife. • **Electromagnetic fields (EMFs):** There is some evidence to suggest that there some adverse impacts on birds from EMF, specifically around, behavioural effects, magnetic field sensitivity, health effects and species variability.	**Avian markers and deterrents:** • Adding visual markers, such as bird flight diverters or reflective devices, can increase the visibility of power lines to birds and reduce collision risk. These markers can help birds perceive the presence of the lines and avoid them. **Insulation and separation:** • Retrofitting transmission infrastructure with insulating materials or using bird flight-safe designs can minimise the risk of electrocution when birds come into contact with the lines or structures. **Nest management:** • Conducting thorough surveys and monitoring of transmission line routes to identify active nests and implementing nest relocation or construction of alternative nesting platforms can reduce the risk of nest failures or destruction during maintenance activities. **Strategic line routing:** • When planning new transmission lines, avoiding sensitive bird habitats and important migratory routes can help minimise the impact on bird populations. **Research and technology development:** • Continued research into bird behaviour, flight patterns, and the effectiveness of different mitigation measures can inform the development of more bird-friendly transmission line designs and operational practices. **Electromagnetic fields (EMFs):** • As the research into this subject is not yet definitive, it is advised to apply avian protection measures (such as bird flight diverters) and continue monitoring the research undertaken within this field.

Accessibility to site	
• **Maintenance and inspection:** Accessibility for routine maintenance and inspection activities is crucial to ensure the ongoing reliability and safety of the transmission line. • **Vegetation management:** Vegetation growth around the transmission line can impede access and pose safety risks. • **Security and restricted access:** It is essential that security measures are in place to avoid unauthorised access. • **Access during an emergency:** Access to the transmission line during an emergency needs to be clear and convenient for any emergency services.	**Maintenance and inspection:** • Safe and efficient access should be provided to all components of the line, including towers, conductors, insulators, and other equipment. Consideration should be given to the design of access roads, walking paths, and working platforms to facilitate regular inspections and maintenance work. **Vegetation management:** • Implement a vegetation management plan that includes regular pruning or clearing of vegetation within the transmission line corridor to maintain clearances and ensure safe access. **Security and restricted access:** • Conduct training programs for personnel involved in the operation, maintenance, and security of the transmission line to ensure they understand and adhere to security protocols. **Collaboration with emergency services:** • Maintain regular communication and collaboration with local emergency services to familiarise them with access routes, equipment, and emergency protocols specific to the transmission line.
Climate change impact	
• **Extreme weather events**: Climate change is leading to an increase in the frequency and intensity of extreme weather events. These events can cause physical damage to transmission lines and potentially causing them to collapse. • **Increased temperature and heatwaves**: Higher temperatures can increase the electrical resistance in transmission lines, leading to increased power losses during transmission. • **Sea-level rise and coastal erosion:** Rising sea levels due to climate change pose a threat to coastal transmission lines. Saltwater intrusion can corrode metal components, while erosion can undermine the stability of transmission towers. • **Changes in precipitation patterns:** Changes in precipitation patterns can affect the stability of the ground on which transmission towers are built. Increased rainfall or prolonged periods of rain can saturate the soil, increasing the risk of landslides or destabilisation of the ground, which can compromise the structural integrity of the transmission lines. • **Decommissioning and Disposal:** At end-of-life, decommissioning would normally remove all above-ground structures along with some, or all, of the foundations, unless these were to be re-purposed, and proper decommissioning practices will be applied to minimise environmental impact. • **Life Cycle Assessment:** It is important to consider the full life cycle of the overhead line, including its manufacturing, installation, operation, maintenance, and eventual decommissioning, to assess the overall climate change impact. • **Transfer of Renewable Energy:** One of the positive secondary impacts of the overhead line is that the network supports the transfer of renewable energy across the	**Climate-resilient design and engineering:** • Incorporating climate change considerations into the design and engineering of transmission infrastructure can improve its ability to withstand future climate conditions. This includes accounting for factors like increased temperatures, changes in precipitation patterns, and sea-level rise in the planning and construction phases. **Enhanced monitoring and early warning systems:** • Deploying advanced monitoring technologies, such as sensors and weather forecasting systems, can help detect potential risks and provide early warnings. Real-time monitoring allows for timely responses and proactive measures to prevent or mitigate damage to transmission lines. **Vegetation management**: • Regular maintenance of vegetation around transmission lines is essential to minimise the risk of damage caused by falling trees, branches, or debris during storms or high winds. Clearing vegetation in a controlled and planned manner reduces the chances of outages and potential fire hazards.

country, which allows the UK to increase their renewable energy mix and contribute positively to reducing the impacts of climate change.	

AC OVERHEAD LINE: COMMUNITY IMPACT

Table 3 – Summary of community impacts during construction of overhead lines

Potential impacts source:	Mitigation measures:
Land use and community impacts	
• **Visual Impact:** The construction of overhead lines involves the installation of towers and associated infrastructure, which can alter the visual landscape of an area. This change may be perceived as unsightly or intrusive by the local community. • **Land Use Disruptions:** Construction activities may require temporary land use changes, including access roads, construction staging areas, and storage of construction materials. These changes can disrupt existing land uses and activities in the area. Dust and noise impacts may also be significant on nearby communities as well as increased traffic inflow due to transportation of materials. • **Community Engagement and Communication:** Lack of effective communication and community engagement during the construction phase can lead to community dissatisfaction, misinformation, and potential conflicts. • **Electromagnetic (EMF) Exposure:** overhead lines emit electromagnetic fields that decrease in intensity with increasing distance from the lines. The community living or working in close proximity to the overhead lines may experience higher levels of exposure to EMFs compared to those farther away. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has established guidelines for limiting exposure to EMF. These guidelines provide reference levels for both electric and magnetic fields. The reference levels are designed to protect the general public from any known adverse health effects of EMF exposure. Compliance with these guidelines helps ensure that EMF levels near communities are within acceptable limits. • **Disturbance of Archaeological Sites:** Construction activities associated with AC overhead lines, such as excavation for foundations or installation of support structures, can disturb archaeological sites of cultural significance. • **Employment and Economy:** The construction phase can provide employment opportunities and contribute to the local economy through job creation, supply chain involvement, and ancillary services. • **Urban vs Rural Land Occupation:** Whilst it is unlikely that the overhead line will be routed through a high-density urban population, the installation and operation of the OHL will have a significantly larger impact on urban areas due to the need for resettlement, visual impact, reliability, and safety. Thus, it is anticipated that rural areas will hold less impact for such an installation, as the visual impact will be lower, and typically agricultural activities, forestry, and other rural land uses can usually coexist. However, does not exclude the possibility of potential resettlement or land reallocation.	**Community Engagement:** • Implement design considerations that minimise visual impacts, such as selecting appropriate tower and pole designs that blend with the surrounding landscape. Consider landscaping and vegetation screening to help visually integrate the overhead lines into the environment. Engage with the community and local stakeholders to address concerns and seek input on design aspects where feasible. • Develop comprehensive construction plans that minimise disruption to existing land uses. Coordinate with local authorities and stakeholders to identify suitable locations for temporary facilities and minimise conflicts with other land uses. Communicate with the community and affected stakeholders to provide information about construction plans, timing, and potential impacts. • Establish a proactive and transparent communication strategy to engage with the community and stakeholders. Provide timely and accurate information about construction plans, timelines, and potential impacts. Address community concerns, solicit feedback, and involve stakeholders in decision-making processes where feasible. Implement mechanisms for addressing and resolving complaints or issues raised by the community. **EMF Information:** • Implement measures to minimise EMF exposure to the community, such as establishing appropriate setback distances between the overhead lines and residential areas or sensitive locations, as per relevant regulatory guidelines or international standards. Use design techniques that minimise magnetic field strengths, such as optimising conductor arrangements or using phase-shifting techniques. **Archaeological Studies:** • Conduct thorough archaeological surveys and assessments prior to construction to identify and protect any significant archaeological sites. Implement appropriate mitigation measures, such as archaeological monitoring, salvage excavations, or rerouting of the overhead lines to avoid impacting sensitive cultural heritage sites.

Table 4 – Summary of community impacts during operation of OHLs

Potential impacts source:	Mitigation measures:
Visual impact	
• **Visual impact:** A new overhead transmission line would have a persistent visual impact on people who would see the line from their homes, and it would also be likely to affect the aesthetics of the landscape through which it passes by intruding upon the natural views of nearby communities. In doing so, it would potentially impact property values. National Grid Electricity Transmission would take a whole system approach when assessing the visual impacts of their electricity transmission proposals on local communities, taking into consideration infrastructure development plans from local and national authorities to minimise the likelihood of unexpected negative socio-economic impacts from the project. Part of their planning process would be to model the likely levels of visual impact from the proposed overhead line and its associated substation terminating structures and present the results of this analysis as part of a community engagement process to arrive at a final transmission proposal.	**Vegetation screening and landscaping:** • Planting trees, shrubs, and other vegetation strategically along transmission line corridors can help mitigate the visual impact of overhead lines and improve the aesthetics of the surrounding area. **Innovative tower designs:** • The use of innovative tower designs that are aesthetically appealing can help reduce the visual impact of overhead transmission lines.
Impacts on neighbouring communities	
• **Electromagnetic fields (EMFs):** Overhead transmission lines produce electromagnetic fields due to the flow of electrical current. Concerns have been raised regarding potential health effects associated with prolonged exposure to EMFs. • **Safety considerations:** Communities living near transmission lines need to be aware of the potential risks associated with high voltages, the infrastructure and adhere to safety guidelines. There are additional risks associated with additional installations (such as antennas) on the overhead line, which increase EMF exposure. Effective communication and engagement with the community are crucial to address concerns, build trust, and ensure that community members feel heard and involved in decision-making processes. • **Noise Generation:** AC overhead lines can generate audible noise due to electromagnetic fields interacting with conductors and other components, as well as electrical arcing or corona discharge (which is when high-voltage transmission lines ionize the surrounding air, creating a bluish glow and a hissing noise). • **Noise Propagation:** Noise can propagate to nearby residential areas, potentially causing disturbance to residents. The nearby communities should be made aware of such potential impacts, and relevant mitigation measures should be implemented to reduce this impact. • **Land/Property Value:** The accumulation of the impact's discussion in the above section, including visual, noise and EMF may influence the land/property value in the nearby communities depending on people's perception of the infrastructure and the proximity of the structures to residential areas, urban centres, schools, recreational facilities, and other amenities.	**Electromagnetic field management:** • Monitoring and adhering to national guidelines (for high-voltage AC lines (e.g., ≥132 kilovolts), Public Health England) recommends a separation distance of around 50 meters from the centreline of the line to comply with the reference level) on electromagnetic field exposure can help address concerns related to EMFs. Implementing engineering measures to minimise EMF levels, such as proper grounding and insulation, can provide additional reassurance to nearby communities. **Safety and education programs:** • Providing information on safety precautions, such as maintaining a safe distance and avoiding unauthorised access to transmission infrastructure, can promote community safety. **Noise Management:** • Implement measures to reduce noise generation, such as using low-noise design principles, optimal conductor configuration, and insulation materials. • Apply noise barriers or enclosures around substations or equipment to attenuate noise propagation. • Conduct regular maintenance and inspections to identify and repair any sources of excessive noise. • Conduct noise modelling studies to assess the noise propagation patterns and identify areas where noise levels may exceed acceptable limits. • Implement noise mitigation measures such as vegetation buffers, noise barriers, or retrofitting noise-damping materials on existing structures to reduce noise propagation.

Table 5 – Summary of environmental impacts during construction of underground cables

Potential impacts source:	Mitigation measures:
Resource efficiency and pollution prevention	
Resource Efficiency: • **Material Usage:** Underground cable installations require various materials, including cables, conduits, insulators, and backfill materials, which can sometimes result in excess waste. • **Energy Efficiency**: Construction activities, such as trenching, drilling, and installation, should aim to maximise energy efficiency by using modern, well-maintained equipment and employing energy-saving practices during construction operations.	**Waste Management:** • Waste Minimisation: Promote waste minimisation through efficient material use, recycling, and waste management practices. Encourage the use of recycled or reclaimed materials wherever feasible. • Construction Waste Recycling: Establish procedures for sorting, recycling, and appropriate disposal of construction waste materials, such as excess cables, packaging materials, and debris. **Erosion and Sediment Control:** • Erosion Prevention: Implement erosion control measures, such as sediment barriers, silt fences, or erosion control blankets, to minimise soil erosion and sediment runoff during construction activities. • Stormwater Management: Develop and implement stormwater management plans to capture and treat runoff water, reducing the potential for pollution and protecting nearby water bodies. **Spill Prevention and Response:** • Spill Prevention: Develop spill prevention plans and provide training to construction personnel on proper handling, storage, and transport of construction materials to minimise the risk of spills. • Spill Response: Establish spill response protocols and ensure that appropriate spill response equipment, such as containment booms and absorbent materials, are readily available on-site
Impact on biodiversity	
Habitat Loss and Fragmentation: • **Excavation Activities:** The trenching or directional drilling required for installing underground cables can result in the loss and fragmentation of habitats, especially if the project traverses areas with existing vegetation or natural habitats. • **Soil Disturbance:** Construction activities can disturb the soil, potentially affecting the viability of plant species and disrupting soil-dwelling organisms. **Vegetation and Ecological Disturbance:** • **Vegetation Removal:** Clearing vegetation along the cable route can result in the direct loss of plant species, including trees, shrubs, and understory vegetation. This can impact the food sources, shelter, and nesting habitats of various wildlife species. • **Disturbance of Ecological Processes:** Construction activities may disrupt natural ecological processes, such as seed dispersal, pollination, and nutrient cycling, which are important for the maintenance of local biodiversity. **Wildlife Displacement and Barriers:** • **Disruption of Wildlife Movement:** Construction activities and the presence of underground cables can disrupt the movement patterns of wildlife, including terrestrial and arboreal species. This can lead to	**Habitat Conservation and Restoration:** • Habitat Assessment: Conduct thorough ecological assessments prior to construction to identify important habitats, endangered species, or ecologically sensitive areas along the cable route. • Habitat Restoration: Develop and implement habitat restoration plans to mitigate habitat loss. This may involve replanting native vegetation, establishing wildlife corridors, or creating new habitat areas. **Wildlife Protection:** • Wildlife Surveys: Conduct wildlife surveys to identify the presence of protected or endangered species. This information can inform the development of appropriate mitigation measures. • Timing Restrictions: Schedule construction activities to avoid critical periods for breeding, nesting, or hibernation of sensitive wildlife species. • Wildlife Passages: Install wildlife passages or underpasses where feasible to facilitate the movement of wildlife across the underground cable infrastructure. **Soil Stabilisation:**

isolation of populations and limit their access to essential resources or breeding grounds.

- **Barrier Effect:** Underground cable installations may act as barriers for small mammals, reptiles, or amphibians that cannot easily move through or beneath the infrastructure. This can impact population dynamics.

- Implement erosion control measures to help protect soil health and preserve the viability of plant species and soil-dwelling organisms.

Environmental Monitoring:

- Incorporate adaptive management approaches to address unforeseen biodiversity impacts during construction and make necessary adjustments to mitigate these impacts effectively.

Impact of excess noise and dust

- **Air Quality:** Dust generation from excavation or construction machinery can contribute to air pollution. Effective dust control measures, such as water suppression or dust screens, should be implemented to minimise airborne dust emissions.
- **Noise Pollution:** Construction activities can generate significant noise levels, potentially impacting nearby communities. Proper planning, use of noise-reducing equipment, and adherence to noise regulations can help mitigate noise pollution.

Dust Suppression:

- Use water sprays, dust screens, or other appropriate dust suppression techniques to minimise airborne dust emissions during construction activities.

Noise Mitigation:

- Implement noise mitigation measures, such as using noise barriers or scheduling noisy activities during less sensitive times, to minimise noise impacts on nearby communities.

Accessibility to site

Access Restrictions:

- **Construction Area:** The construction activities associated with underground cable installations may result in restricted access to certain areas of the site. This can affect the movement of vehicles, pedestrians, and machinery within and around the construction zone.
- **Road Closures/ Traffic Disruptions:** Depending on the location and extent of the construction activities, temporary road closures, lane restrictions, or traffic diversions may be required. This can impact local transportation routes and accessibility for nearby communities.

Temporary Infrastructure:

- **Construction Site Infrastructure:** The construction phase may involve the establishment of temporary infrastructure, such as site offices, storage areas, or construction laydown yards. These temporary facilities can occupy space and potentially affect access to surrounding areas.
- **Material Transportation:** Transporting construction materials, equipment, and machinery to the site can temporarily impact access routes, especially if the project requires large deliveries or specialised vehicles.

Traffic Management:

- Traffic Control Plans: Develop and implement traffic management plans to minimise congestion and ensure safe access for both construction vehicles and local traffic. This may involve using designated routes, scheduling deliveries during off-peak hours, or providing alternative access routes when necessary.
- Communication and Notifications: Provide timely and clear communication to affected stakeholders, such as local residents, businesses, and emergency services, about road closures, traffic diversions, and alternative access routes.

Construction Site Layout:

- Optimise the layout of the construction site to maintain adequate access for vehicles, pedestrians, and emergency services. Consider the placement of temporary infrastructure and the arrangement of equipment to minimise access restrictions.

Stakeholder Engagement:

- Engage with local communities, businesses, and relevant stakeholders to understand their concerns, preferences, and specific accessibility needs. Incorporate their feedback into the project planning and implementation to ensure their needs are considered.

Signage and Safety Measures:

- Clear Signage: Install clear and visible signage to provide directions, information, and warnings regarding access changes, detours, or potential hazards.
- Safety Measures: Implement appropriate safety measures, such as pedestrian walkways, temporary barriers, or lighting, to ensure the safety of pedestrians and maintain accessibility in and around the construction area

Climate change impact

- **GHGs from Construction Machinery and Vehicles: The** use of construction machinery, vehicles, and equipment during the installation of underground cables can generate greenhouse gas emissions, primarily

Energy Efficiency:

carbon dioxide (CO_2) and other pollutants, which contribute to climate change. • **GHGs from Material Production and Transportation:** The production of construction materials, such as cables, conduits, and insulators, can involve energy-intensive processes that emit greenhouse gases. Additionally, transportation of these materials to the construction site contributes to carbon emissions. • **Energy Consumption from Construction Activities:** Construction activities, such as excavation, trenching, and drilling, require energy for equipment operation and lighting. The energy consumed during these activities may contribute to increased greenhouse gas emissions if it comes from fossil fuel-based sources. • **Deforestation and Vegetation Loss:** The construction phase of underground cable installations may require the removal of vegetation along the cable route. Deforestation and vegetation loss contribute to reduced carbon sequestration capacity and the release of stored carbon dioxide into the atmosphere	• Equipment and Machinery: Utilise energy-efficient construction machinery and equipment to minimise energy consumption and associated greenhouse gas emissions. • Lighting: Use energy-efficient lighting systems, such as LED lights, during night-time construction activities to reduce energy usage. **Renewable Energy:** • Where feasible, utilise renewable energy sources to power construction activities. This can include using solar panels, wind turbines, or grid-connected renewable energy. **Sustainable Material Selection:** • Low-Carbon Materials: Choose construction materials with lower carbon footprints, such as those made from recycled or sustainable sources. This can help reduce emissions associated with material production. • Local Sourcing: Prioritise locally sourced materials to minimise transportation distances and associated carbon emissions. **Carbon Offsetting:** • Consider participating in carbon offset programs by investing in projects that reduce greenhouse gas emissions or enhance carbon sequestration. This can help mitigate the construction-related emissions that cannot be avoided. **Environmental Management Systems:** • Implement robust environmental management systems that include monitoring and reporting mechanisms to track energy consumption, greenhouse gas emissions, and other climate-related impacts during construction. This can help identify areas for improvement and facilitate ongoing reduction efforts.

Table 6 – Summary of environmental impacts during operation of underground cables

Potential impacts source:	Mitigation measures:
Impact on biodiversity	
• **Substation Sites:** Substations associated with underground cable systems may occupy small areas of land and could potentially result in habitat fragmentation or alteration. However, these impacts are typically localised and limited in scale. • **Cable Access Points:** Access points, such as manholes or cable pits, may be present along the cable route. Vegetation clearance around these access points may be required to ensure proper access and maintenance, which can affect local vegetation and small-scale wildlife habitat. • **Indirect Impacts:** The operation of AC underground cable systems is connected to energy generation sources, which may have indirect impacts on biodiversity through associated infrastructure, such as power plants or renewable energy installations.	**Vegetation Management:** • Habitat Restoration: Implement habitat restoration initiatives in areas surrounding substations or access points, if feasible, to compensate for any vegetation clearance during installation or maintenance. • Native Planting: Promote the use of native vegetation and landscaping practices in and around substations and access points to provide habitat and support local biodiversity. **Wildlife Protection:** • Protected Species Surveys: Conduct surveys and assessments to identify the presence of protected or sensitive species in the vicinity of substations or access points. Implement measures to protect these species and their habitats during operation and maintenance activities. • Wildlife-friendly Practices: Incorporate wildlife-friendly design features, such as nesting boxes or wildlife corridors, into the design and management of substations and access points, where appropriate. **Environmental Monitoring and Reporting:** • Implement robust environmental management systems to monitor and report any potential impacts on biodiversity during the operation phase. This includes regular inspections and

	assessments to ensure compliance with applicable regulations and best practices.
Accessibility to site	
• **Access Restrictions for Substations:** Underground cable systems require substations for the conversion of electricity between high and low voltages. Depending on their location, substations may have restricted access areas or security measures in place to ensure the safety and integrity of the electrical infrastructure. • **Access Restrictions for Cable Access Points:** Access points, such as manholes or cable pits, may be present along the cable route. These access points may require covers or markers to indicate their presence, which can be located within public spaces or private properties. • **Maintenance and Repair:** Access may be required to perform maintenance, inspections, or repairs on the underground cable system. This may involve temporary disruptions or limited access to certain areas while work is being carried out.	**Stakeholder Communication:** • Foster positive communication and collaboration with stakeholders and provide clear and timely information to affected stakeholders, such as property owners, tenants, and local communities, about access restrictions, maintenance schedules, or any temporary disruptions that may occur. **Maintenance Planning:** • Plan maintenance and repair activities in a way that minimises disruptions to access and considers the needs of the surrounding area. This may involve coordinating with local authorities, businesses, and residents to minimise inconveniences. **Safety and Security:** • Signage and Barriers: Use appropriate signage, barriers, or safety measures to clearly indicate restricted areas or hazards associated with substations or access points. • Security Measures: Implement security measures around substations or access points to prevent unauthorised access and ensure public safety.
Climate change impact	
• **Energy Losses:** AC underground cables can experience some energy losses due to resistance, resulting in heat dissipation during transmission. While these losses are generally low, they contribute to increased energy consumption and associated greenhouse gas emissions from the power generation sources. • **System Efficiency:** Underground cables may require cooling systems, such as circulation of insulating fluids or refrigeration, to maintain optimal operating temperatures. These cooling systems consume energy, which contributes to indirect greenhouse gas emissions. • **Decommissioning and Disposal:** At end-of-life, decommissioning would normally remove all above-ground structures along with some, or all, of the foundations, unless these were to be re-purposed, and proper decommissioning practices will be applied to minimise environmental impact. • **Life Cycle Assessment:** It is important to consider the full life cycle of the underground cable, including its manufacturing, installation, operation, maintenance, and eventual decommissioning, to assess the overall climate change impact. • **Transfer of Renewable Energy:** One of the positive secondary impacts of the underground cables is that the network supports the transfer of renewable energy across the country, which allows the UK to increase their renewable energy mix and contribute positively to reducing the impacts of climate change.	**Energy Efficiency:** • System Design: Optimise the design and specifications of the underground cable system to minimise energy losses during transmission. • Insulation Materials: Select and utilise insulation materials with high efficiency to reduce energy losses and heat dissipation during cable operation. **Renewable Energy Integration:** • Increase the integration of renewable energy sources, such as solar, wind, or hydro, into the electricity grid. This reduces the overall carbon intensity of the energy supply and offsets the greenhouse gas emissions associated with the energy losses in the cable system. **Monitoring and Maintenance:** • Regular Inspections: Conduct regular inspections and maintenance activities to ensure optimal performance and minimise energy losses in the cable system. • Leakage Prevention: Implement measures to prevent or minimise leakage of insulating fluids, which can reduce the need for additional energy consumption to compensate for fluid losses. **Transition to Low-Carbon Technologies:** • As new and more energy-efficient technologies become available, consider upgrading or retrofitting existing AC underground cable systems to reduce energy losses and improve overall system efficiency.

AC underground cable: community impact

Table 7 – Summary of community impacts during construction of underground cables

Potential impacts source:	Mitigation measures:
Land use and community impacts	
Construction Impacts: • **Excavation and Trenching:** Underground cables require extensive trenching or directional drilling to lay the cables. This process can disrupt land use and temporarily impact areas where the cables are being installed. • **Right-of-Way Requirements**: Underground cable systems may require a dedicated right-of-way, which can involve land acquisition or easement agreements with landowners. • **Spatial Requirements:** Underground cables typically require wider corridors than overhead lines to accommodate the size and depth of the cables, which can impact land availability and land use planning. • **Substation Infrastructure:** Underground cables may necessitate the construction of substations or distribution hubs, which can have additional land use implications. **Community Impacts:** • **Construction Disruptions:** The installation of underground cables involves construction activities that can disrupt local communities, including noise, dust, traffic congestion, and restricted access to certain areas during the construction phase. • **Visual Impact:** While underground cables are less visually prominent compared to overhead lines, the construction and maintenance of substations and associated infrastructure can still have visual impacts on the surrounding area. • **Socioeconomic Effects:** The construction of underground cables may affect local businesses, agriculture, or residents who rely on the affected land for their livelihoods. • **Community Engagement:** Engaging with local communities throughout the planning and construction phases can help address concerns, provide information, and involve community members in decision-making processes. • **Employment and Economy:** The construction phase can provide employment opportunities and contribute to the local economy through job creation, supply chain involvement, and ancillary services. • **Urban vs Rural Land Occupation:** The installation and operation of the underground cable in urban areas will have a higher impact due to the presence of other utility infrastructure, dense population and limited available space. The installation will also likely cause temporary road and traffic disruptions during the construction phase. In rural areas, the impact is anticipated lower, as the underground cable can be installed more easily due to the availability of space and fewer infrastructure conflicts. **Disturbance to Archaeological Sites:** • **Excavation Activities:** The trenching or directional drilling required for installing underground cables can	**Strategic Planning** • Strategic Route Planning: Conduct thorough studies and assessments to identify the most suitable route for underground cables, considering existing land use, environmental sensitivities, and community preferences. This can help minimise impacts on important land uses, such as agriculture or ecologically sensitive areas. • Co-location with Existing Infrastructure: Explore opportunities to co-locate underground cables with existing infrastructure corridors, such as roadways or utility corridors, to minimise the need for additional land acquisition or disruption. • Compact Design: Optimise cable designs and trenching techniques to minimise the spatial requirements of underground cables, allowing for more efficient land use and reducing the impact on surrounding areas. • Consideration of Landowners and Community Needs: Engage in open dialogue with landowners and affected communities to understand their concerns, consider alternative route options, and develop mitigation strategies that address their specific needs. **Archaeological Surveys and Assessments:** • Prior Assessment: Conduct thorough archaeological surveys and assessments to identify any known or potential archaeological sites along the proposed route of the underground cables. • Site Avoidance/ Modification: Adjust the cable route, where feasible, to avoid known or high-potential archaeological sites. If avoidance is not possible, consider modifying construction techniques or implementing additional archaeological investigations and monitoring to minimise impacts on sensitive areas. **Archaeological Monitoring and Mitigation:** • On-site Monitoring: Assign and train personnel to monitor construction activities during trenching or drilling to identify and document any archaeological remains encountered. This allows for prompt mitigation measures to be implemented if necessary. • Salvage Excavations: If significant archaeological remains are discovered, undertake salvage excavations and archaeological mitigation measures to record and preserve the cultural heritage before construction proceeds. **Collaboration with Heritage Authorities:** • Engage with relevant heritage authorities, archaeological experts, and local communities to seek their input, expertise, and recommendations throughout the planning and construction phases.

potentially disturb archaeological sites, including buried artifacts, features, or structures. • **Soil Disturbance:** Construction activities can cause soil disturbance, which may result in the disruption or destruction of archaeological layers and deposits. • **Chance Finds:** During construction, unexpected archaeological discoveries may occur. These chance finds need to be appropriately managed and reported to preserve and document any cultural heritage that may be encountered.	

Table 8 – Summary of community impacts during operation of underground cables

Potential impacts source:	Mitigation measures:
Visual impact	
Access Points and Infrastructure: • **Cable Terminations:** Cable terminations are always placed within securely fenced-off areas to ensure safety of the public. Within the context of a substation, therefore, although the cable terminating structures can be several metres high, visual impact is normally minimal. • **Cable Joint Access Points:** Access points for underground cable joints, such as manholes or cable pits, may be present along the cable route, but not necessarily so. These access points may require covers or markers to indicate their presence, which can be visible at ground level. Alternatively, cable access points may be approximately 1m high and 1m wide in occupancy and will be present every 800 - 900m throughout the length of the cable route. • **Composite Route Transition Points:** For a composite route comprising sections of overhead line interspersed with one or more sections of underground cable, above-ground transition points bring the overhead line connections down to the cables at the start of each underground cable section. A second transition point at the far end of the cable brings the connections back out of the ground and up to the overhead line. Such transition points ('sealing end compounds') safely and securely fence–off the high voltage cable ends and overhead line connections and vary in area between around 0.2 and 0.4 ha (0.5 to 1 acres). Their local visual impact, unmitigated, can thus be similar to that of a small substation, however, National Grid Electricity Transmission works hard with local communities to effectively place and screen these installations from public view. **Landscaping and Vegetation:** • **Swathe Management**: Depending on the location, there may be periodic vegetation management activities, such as tree trimming or clearing around access points, to ensure the integrity and accessibility of the underground cables. These activities may have temporary visual impacts.	**Screening and Visual Integration:** • Implement appropriate landscaping strategies, such as the planting of trees, shrubs, or other vegetation, to visually integrate infrastructure elements, such as substations or surface installations, into the surrounding environment. **Community Engagement:** • Engage with local communities and stakeholders to communicate the visual design considerations and any potential impacts. Seek their input and address concerns to the extent possible, considering their preferences for visual integration or mitigation measures. **Environmental Planning and Design:** • Develop and adhere to design guidelines or standards that aim to minimise visual impacts during the installation and operation of underground cable systems. This can include considerations for equipment placement, surface installations, and landscaping.
Impact on neighbouring communities	
• **Information Dissemination:** Effective communication with the local community is essential to ensure	**Community Engagement:** • Engage with local stakeholders, community groups, and residents through regular consultations, public meetings, or

awareness of the underground cable system, its operation, and any potential impacts. • **Public Engagement:** Engage with the community, stakeholders, and local authorities to address any concerns, provide updates on maintenance activities, and ensure transparency throughout the operation phase. • **EMF Impact:** The community should be informed of the potential EMF impact from the underground cable, which should be considered during the design phase and may impact both humans and biodiversity, however with strategic planning may have no impact at all. The EMFs decrease rapidly with distance, so the immediate vicinity of the cables experiences higher levels of EMF compared to areas further away. The exact levels depend on factors such as the type of cable, current flow and laying formation of the cables.	workshops to address concerns, gather feedback, and ensure community involvement. **Safety and Security:** • Implement appropriate safety measures around substations, access points, or any visible infrastructure to ensure the safety and well-being of the community. Maintain necessary security measures around substations or access points to prevent unauthorised access and protect the integrity of the underground cable system.

HVDC link with offshore cable: environmental impact

Table 9 – Summary of environmental impacts during construction of HVDC

Potential impacts source:	Mitigation measures:
Resource efficiency and pollution prevention	
• **Material Consumption:** The construction of offshore HVDC cabling requires significant amounts of materials, including cables, support structures, and equipment. The extraction, processing, and transportation of these materials can have resource implications, particularly for non-renewable resources. • **Energy Consumption:** Construction activities, such as cable laying, trenching, and installation of support structures, require energy-intensive equipment and processes. The energy consumption during construction contributes to the overall carbon footprint and resource efficiency of the project. • **Water Pollution:** Construction activities may result in the discharge of sediments, construction waste, and chemical pollutants into marine or coastal waters. These pollutants can have detrimental effects on water quality, marine ecosystems, and aquatic species.	**Sustainable Material and Energy Use:** • Resource Optimisation: Implement measures to optimise material use, considering factors such as material efficiency, recycling or reuse options, and sustainable sourcing practices. • Energy Management: Promote energy-efficient practices during construction activities, such as using low-emission equipment, optimising energy consumption, and utilising renewable energy sources where feasible. **Pollution Prevention:** • Sediment and Waste Management: Implement proper sediment and erosion control measures to prevent sediment runoff into water bodies. Establish waste management plans to ensure proper handling, recycling, or disposal of construction waste and hazardous materials. • Spill Prevention: Develop spill response plans and implement preventive measures to minimise the risk of accidental spills or leaks during construction, ensuring prompt containment and clean-up if incidents occur. **Environmental Monitoring and Compliance:** • Establish environmental monitoring programs to assess and track the impact of construction activities on air quality, water quality, and noise levels.
Impact on biodiversity	
Marine and Coastal Habitats: • **Seabed Disturbance**: Activities such as cable trenching, anchoring, or installation of support structures can result in physical disturbance of the seabed. This can affect benthic habitats, including the presence of sessile organisms, seabed topography, and sediment composition. • **Substrate Cover and Composition**: The installation of support structures, such as monopiles or jackets, may alter the substrate cover and composition, potentially	**Pre-construction Surveys and Impact Assessments:** • Conduct comprehensive baseline surveys to identify and assess the presence of sensitive habitats, protected species, and important biodiversity areas. Evaluate the potential impacts on biodiversity and develop appropriate mitigation measures based on the findings of the impact assessments. **Habitat Protection and Restoration:**

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affecting the colonisation and distribution of benthic organisms and macrofauna.

Hydrodynamic Changes: The presence of support structures or cable routes can alter local hydrodynamic conditions, including water flow patterns and sediment transport, which may impact local species composition and distribution.

Marine Fauna:

Disturbance and Habitat Displacement: Construction activities, such as pile driving, can generate underwater noise and vibrations that may disturb or displace marine fauna, including fish, marine mammals, and invertebrates.
Collision Risk: The presence of support structures or cable routes can pose a collision risk for marine species, particularly marine mammals and migratory fish, which may encounter the structures during their movements.

Avian Fauna:

Avian Species: Overhead cable structures (if any are installed onshore to connect with the HVDC) or offshore support platforms may pose a collision risk for avian species, particularly during migration or for species that use the area for foraging or resting. This will likely require a full assessment when forming the route of the cable.

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Design cable routes and support structures to avoid or minimise impacts on sensitive habitats, taking into account ecological connectivity and the preservation of important biodiversity areas.
Implement habitat restoration measures in impacted areas, such as seabed rehabilitation or creation of artificial habitats, to enhance biodiversity and compensate for any loss of habitats.

Construction Practices and Techniques:

Implement best practices to minimise underwater noise and vibrations during construction activities, including the use of noise mitigation measures and construction methodologies that reduce disturbance to marine fauna.
Implement collision risk mitigation measures, such as effective deterrent systems, monitoring, and operational procedures, to minimise the potential for bird and marine mammal collisions.

Monitoring and Adaptive Management:

Implement comprehensive monitoring programs to assess the effectiveness of mitigation measures and to detect any unexpected impacts on biodiversity.
Apply adaptive management principles to adjust construction practices and mitigation measures based on the monitoring results and scientific knowledge.

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Construction Noise: The installation of offshore HVDC cables involves activities such as drilling, trenching, and piling, which can generate noise and vibration. These activities may impact nearby communities and sensitive habitats during the construction phase.
Air Emissions: Construction activities can generate air emissions from heavy machinery, transportation, and energy generation. These emissions may include greenhouse gases, particulate matter, nitrogen oxides, and sulphur oxides, contributing to air pollution.

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Noise and Vibration Control:

Implement noise and vibration control measures, such as using appropriate equipment, scheduling construction activities during less sensitive periods, or providing noise barriers, to minimise disruptions to nearby communities and sensitive habitats.

Emission Controls:

Employ technologies and practices to minimise air emissions, such as using low-emission machinery, implementing dust control measures, and managing exhaust emissions.

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Navigation and Vessel Traffic:

Cable Routes: The presence of offshore HVDC cables and associated support structures may require navigational considerations and potential route restrictions for other marine vessels, including commercial shipping, fishing vessels, and recreational boats.
Temporary Exclusion Zones: During construction activities, temporary exclusion zones may be established to ensure the safety of construction vessels and personnel. These zones may restrict access to certain areas for other marine users.

Offshore Infrastructure and Onshore Access:

Onshore Infrastructure: The construction of onshore infrastructure, such as converter stations or substations, may require access roads, construction staging areas, and temporary storage areas. These activities can impact existing access routes and local transportation networks.

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Navigation and Vessel Management:

Coordination and Communication: Collaborate with maritime authorities, shipping companies, and relevant stakeholders to ensure effective coordination and communication regarding cable routes, temporary exclusion zones, and navigational safety.
Marking and Signalling: Implement appropriate marking and signalling measures, such as buoys or navigational aids, to clearly indicate the presence of cables and support structures and assist vessel navigation.

Construction Planning and Management:

Traffic Management: Develop traffic management plans to minimise disruptions to local communities and existing transportation networks during the construction phase. Consider alternative access routes, temporary road diversions, or scheduled construction activities during off-peak hours.
Stakeholder Engagement: Engage with local communities and stakeholders throughout the construction phase to provide information, address concerns, and ensure transparency

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• **Cable Landing Points:** The location of cable landing points onshore may require construction activities and associated infrastructure, potentially affecting local access to coastal areas or existing facilities.	regarding access restrictions, traffic changes, and any temporary disruptions. **Environmental and Social Impact Assessments:** • Conduct thorough assessments to identify potential accessibility impacts during the construction phase, including impacts on marine navigation, coastal access, and local community access. • Develop appropriate mitigation measures to address these impacts and ensure effective stakeholder engagement in the decision-making process.
Climate change	
• **Greenhouse Gas Emissions:** The construction phase involves various activities that can contribute to greenhouse gas emissions, such as transportation of materials and equipment, energy consumption during construction, and construction-related machinery emissions. These emissions can contribute to the overall carbon footprint of the project. • **Energy Consumption:** Construction activities require the use of heavy machinery and equipment that consume energy, including excavators, cranes, and vessels. The energy consumption associated with these activities can contribute to greenhouse gas emissions, especially if fossil fuels are used for energy generation. • **Cable and Support Structure Materials:** The production and transportation of materials used in offshore HVDC cabling, including cables, support structures, and equipment, can generate greenhouse gas emissions. The carbon intensity of these materials and their associated production processes can contribute to the climate change impact of the construction phase.	**Energy Efficiency and Renewable Energy:** • Use energy-efficient machinery and equipment during construction activities to minimise energy consumption and associated greenhouse gas emissions. • Explore the use of renewable energy sources, such as wind or solar power, for construction activities, where feasible, to reduce reliance on fossil fuel-based energy. **Emission Reduction Strategies:** • Implement emission reduction strategies, such as optimising construction schedules to minimise the duration of activities, optimising transportation routes to reduce fuel consumption, and utilising low-emission machinery and equipment. • Encourage the use of low-carbon and recycled materials in the production of cables, support structures, and equipment, thereby reducing the carbon intensity associated with these materials. **Carbon Offsetting:** • Consider carbon offsetting initiatives to compensate for the greenhouse gas emissions generated during the construction phase. This can involve investing in projects that help sequester or reduce carbon emissions, such as reforestation or renewable energy projects.

Table 10 – Summary of environmental impacts during operation of HVDC

Potential impacts source:	Mitigation measures:
Impact on biodiversity	
• **Physical Disturbance to Seabed and Habitat:** Activities may physically disturb the seabed and associated habitats, leading to potential damage or displacement of benthic organisms and their habitats. • **EMFs:** Power cables can emit EMFs, which may have potential impacts on marine organisms, including sensitivity to navigation, orientation, or behaviour. • **Collision Risk for Marine Species:** The presence of maintenance vessels, support vessels, or equipment can pose a collision risk to marine species, including marine mammals, sea turtles, and seabirds. • **Noise and Vibrations:** Maintenance activities, such as pile driving or other construction-related tasks, can generate underwater noise and vibrations that may disturb or harm marine organisms, particularly sensitive species such as marine mammals and fish.	**Avoiding Disturbance:** • Implement measures to minimise physical disturbance, such as using appropriate installation techniques, employing precise positioning systems to minimise the footprint of maintenance activities, and applying soft-start procedures to reduce potential impacts on marine life. **EMFs:** • Design and install HVDC cables with appropriate insulation and shielding techniques to reduce EMF emissions. Consider routing options that minimise exposure to sensitive areas, such as important habitats or migration corridors. **Collision Mitigation:** • Implement measures to reduce collision risks, such as maintaining appropriate vessel speeds, monitoring marine mammal presence with dedicated observers, implementing vessel routing measures to avoid critical habitats or migration routes, and adhering to guidelines on minimising interactions with protected species.

	Noise Mitigation: • Employ noise reduction techniques such as bubble curtains, underwater noise barriers, or low-noise equipment to minimise the propagation of noise. Establish exclusion zones or implement timing restrictions to reduce the potential for disturbance during sensitive periods, such as breeding or migration seasons.
Accessibility to site	
• **Vessel Traffic:** Regular maintenance activities require the presence of maintenance vessels, crew transfer vessels, or service boats near the offshore HVDC infrastructure. This can result in increased vessel traffic in the area, potentially affecting other marine activities and navigation.	**Access Routes and Navigation:** • Design access routes that minimise disturbance to sensitive areas and ecosystems, such as avoiding important habitats or areas with high ecological value. • Coordinate with relevant maritime authorities to establish designated navigation channels and zones to prevent conflicts with other marine activities and ensure safe passage for maintenance vessels. **Vessel Traffic Management:** • Implement vessel traffic management plans to regulate the movement of maintenance vessels and minimise their impacts on marine ecosystems and other users of the sea. • Consider time restrictions, speed limits, and appropriate vessel behaviour to prevent collisions, noise disturbance, and disruption to marine life. **Training and Certification:** • Ensure that maintenance personnel receive proper training and certification in environmental awareness, including understanding the sensitivity of marine ecosystems and the importance of minimising impacts during access to site activities. • Promote adherence to industry standards and codes of practice for maintenance operations to ensure consistent and responsible practices.
Climate change impact	
• **GHG Emissions:** Offshore HVDC cabling is often used to transmit electricity generated by offshore wind farms, which contribute to the reduction of greenhouse gas emissions and the transition to cleaner energy sources. • **Energy Efficiency:** HVDC technology is known for its efficiency in long-distance electricity transmission, resulting in lower energy losses compared to alternative transmission methods such as High Voltage Alternating Current (HVAC). The specific comparative level of losses can vary depending on the system design, distance, voltage level, and other factors. It is estimated that HVDC transmission can achieve efficiency levels of 95% or higher over long distances, while AC transmission may have efficiencies ranging from 90% to 95%, meaning that HVDC systems can deliver a higher percentage of the generated power to the load, resulting in lower energy losses. • **Decommissioning and Disposal:** At the end of the operational life of offshore HVDC cable, proper decommissioning and disposal practices need to be followed to minimise environmental impacts. • **Life Cycle Assessment**: It is important to consider the full life cycle of offshore HVDC cabling, including its manufacturing, installation, operation, maintenance, and	**Renewable Energy Promotion:** • Encourage the use of offshore HVDC cabling for the transmission of renewable energy, particularly from offshore wind farms. This promotes the integration of clean and sustainable energy sources into the electricity grid, reducing reliance on fossil fuels and mitigating climate change. **Energy Efficiency and Loss Reduction:** • Optimise the design and operation of the HVDC system to maximise energy efficiency and minimise energy losses during transmission. This can be achieved using advanced converter technology, optimal cable sizing, and efficient control systems. **Decommissioning and Disposal:** • Develop environmentally responsible decommissioning plans that consider the proper disposal and recycling of materials used in the HVDC system. This minimises potential greenhouse gas emissions and other environmental impacts during the decommissioning process. **Life Cycle Assessment:** • Conducting a life cycle assessment helps evaluate the cumulative environmental impacts, including greenhouse gas emissions, associated with the entire life cycle of the cable.

eventual decommissioning, to assess the overall climate change impact. • **Transfer of Renewable Energy:** One of the positive secondary impacts of the HVDC is that the required network supports the transfer of renewable energy across the country, which allows the UK to increase their renewable energy mix and contribute positively to reducing the impacts of climate change.

HVDC link with offshore cable: community impact

Table 11– Summary of community impacts during construction of HVDC

Potential impacts source:	Mitigation measures:
Land use and community impacts	
Land Use and Coastal Areas: • **Cable Landing Points:** Offshore HVDC cables require landing points where they connect to onshore infrastructure. These landing points may require land acquisition or use of coastal areas, potentially impacting coastal habitats and land use patterns. • **Construction Sites**: Construction activities for the onshore infrastructure, such as converter stations or substations, may require temporary use of land and have associated impacts on the local environment and land use. **Visual Landscape:** • **Onshore Infrastructure:** The construction of converter stations or substations can introduce new visible structures and equipment that may have visual impacts on the local landscape and scenic views, particularly in coastal areas. • **Cable Laying Vessels:** Offshore cable laying vessels and associated activities during construction may be visible from the coastline, potentially affecting the visual aesthetics of the area. **Socio-Economic Impacts:** • **Community Disruption:** Construction activities may temporarily disrupt the daily lives of local communities, particularly in coastal areas near cable landing points or onshore infrastructure sites. Increased traffic, noise, and limited access to certain areas may affect community activities, businesses, and tourism. • **Employment and Economy:** The construction phase of offshore HVDC cabling can provide employment opportunities and contribute to the local economy through job creation, supply chain involvement, and ancillary services. • **Urban vs Rural Land Occupation:** The impact of the HVDC cable, being predominantly offshore will have a similar low impact on both urban and rural areas. However, the installation of support infrastructure, such as substations or converter stations will be more favourable in rural areas due to the availability of land. **Cultural Heritage:** • **Underwater Cultural Heritage:** The installation of offshore HVDC cables may require trenching or other activities on the seabed. These activities have the potential to encounter and impact underwater cultural heritage, including shipwrecks, submerged	**Environmental and Social Impact Assessments:** • Conduct thorough assessments to identify potential impacts on land use and the local community and develop mitigation measures to address these impacts. • Engage with stakeholders, including local communities, to gather input, address concerns, and ensure transparency throughout the construction phase. **Site Selection and Design:** • Consider environmental and social factors during the selection of cable landing points and onshore infrastructure sites to minimise impacts on sensitive habitats and existing land use patterns. • Design onshore infrastructure with visual considerations, such as landscaping, architectural design, and screening, to minimise visual impacts and integrate the infrastructure with the surrounding environment. **Stakeholder Engagement:** • Communicate and engage with local communities and stakeholders to provide timely and accurate information about the construction activities, their duration, and potential impacts. • Address concerns and establish grievance mechanisms to address any community issues that may arise during the construction phase. **Cultural Heritage and Archaeological Surveys:** • Conduct thorough surveys, assessments, and archaeological investigations before construction begins to identify and evaluate potential cultural heritage sites or underwater archaeological features. • Collaborate with heritage authorities, archaeologists, and relevant stakeholders to ensure comprehensive assessments and develop appropriate mitigation strategies. **Site Design and Construction Planning:** • Route Selection: Consider alternative routes that avoid or minimise impacts on known cultural heritage sites or areas of archaeological sensitivity. • Onshore Infrastructure: Design onshore infrastructure, such as converter stations or substations, to avoid or minimise disturbance to cultural heritage sites. If avoidance is not possible, consider incorporating design features that protect or preserve any identified cultural heritage elements.

archaeological sites, or other historically significant features. • **Onshore Infrastructure:** The construction of onshore infrastructure, such as converter stations or substations, may require excavation and ground disturbance. In some cases, this could potentially affect historical sites, structures, or archaeological remains that are present on the land.	**Monitoring and Mitigation:** • Construction Monitoring: Implement monitoring programs during construction activities to identify any unexpected archaeological discoveries or encounters with cultural heritage sites. • Mitigation Strategies: Develop and implement appropriate mitigation measures, such as adjusting construction methodologies, rerouting cables, or implementing protective measures, in consultation with heritage authorities and archaeologists if cultural heritage sites are encountered during construction. **Collaboration and Consultation:** • Heritage Authorities and Experts: Engage in consultation and collaboration with relevant heritage authorities, archaeological experts, and local communities to ensure that cultural heritage and archaeological considerations are adequately addressed throughout the construction phase. • Public Awareness: Promote public awareness of the cultural heritage and archaeological significance of the area, fostering appreciation and understanding of the importance of protecting and preserving these resources.

Table 12 – Summary of community impacts during operation of HVDC

Potential impacts source:	Mitigation measures:
Visual impact	
Cable Routes and Subsea Infrastructure: • **Cable Burial:** The presence of buried cables may not have a significant visual impact as they are located beneath the seabed. However, cable routes near the shore or in shallow waters may require beach landings or nearshore infrastructure, which could be visible depending on the design and location. **Onshore Infrastructure:** • **Converter Stations and Substations:** Onshore converter stations and substations will have visible structures, such as buildings, electrical equipment, and transmission towers, which can alter the visual landscape of the surrounding areas. For high-capacity HVDC systems, converter stations can occupy a significant area, with buildings housing the equipment extending over several thousand square metres. The physical dimensions can also include multiple floors or levels, especially in installations where space is constrained. If the overhead line is being connected to an existing substation, an additional bay will be required which will take up approximately half a hectare (if no spare bay is already available). The construction of a new substation, if required, with modern technology is estimated to occupy approximately six hectares for a 2,000 MW connection. The converter station as part of the substation, may also be as high as 18-20m in height. • **Cable Landfall Points:** The cable landfall points on the coast may require onshore infrastructure, such as cable terminations or transition pits. These structures can be visible and have visual implications, particularly in areas with sensitive landscapes or designated scenic views. The size of cable landing points can vary depending on the specific requirements of the project but generally include buildings or facilities to house cable terminations, jointing equipment, and control systems. The impact of	**Design Considerations:** • Cable Routing: Optimise cable routing to minimise visual impacts, considering factors such as avoiding sensitive landscapes, scenic views, or areas with high public visibility. • Subsea Infrastructure: Explore design options that minimise the visual impact of subsea support structures, such as using low-profile or submerged structures, where feasible. • Onshore Infrastructure: Design onshore converter stations, substations, and cable landfall points to blend harmoniously with the surrounding landscape, considering visual aesthetics and minimising the visual intrusion. **Screening and Landscaping:** • Vegetation and Landscaping: Incorporate vegetation and landscaping strategies around onshore infrastructure to help visually screen or integrate the facilities into the surrounding environment. • Visual Barriers: Consider the use of visual barriers, such as fencing, vegetation, or natural landforms, to minimise the visibility of above-ground equipment and structures associated with converter stations or cable landfall points.

these is anticipated to be minimal as typically only 1m high and 1m wide throughout the route of the cable line.	
Impact on neighbouring communities	
• **Fishing and Maritime Activities:** The presence of offshore HVDC infrastructure and maintenance vessels can impact traditional fishing grounds and disrupt other maritime activities, potentially affecting the livelihoods and economic activities of coastal communities. • **Socio-Economic Benefits:** The development and operation can bring socio-economic benefits to local communities, including employment opportunities, local procurement, and infrastructure development. • **Emergency Preparedness and Safety:** Emergency scenarios can arise and impact nearby communities, such as cable failures, fires, or other incidents.	**Community Engagement:** • Engage with local fishing communities and relevant stakeholders during the planning and design phases to understand their concerns and identify measures to minimise impacts. • Consider alternative fishing grounds or provide compensation measures to mitigate economic losses. • Establish communication channels to coordinate with fishers and ensure their safety and access to fishing areas during maintenance operations. • Develop local employment and training programs to maximise job opportunities for nearby communities. • Encourage local procurement and collaboration with local businesses to support the regional economy. • Develop comprehensive emergency response plans and ensure coordination with local emergency services. Conduct safety drills, provide public awareness campaigns, and establish clear communication channels to keep communities informed and prepared for potential emergencies.