# Independent study to examine the technical feasibility and cost of undergrounding the North-South Interconnector

## *Update by the International Expert Commission*

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# Executive Summary

A new North-South electricity interconnector has been proposed for development on the island of Ireland in the form of a 138km 400kV single circuit overhead line (OHL) with the stated purpose of: improving security of supply; removing the bottleneck between the transmission systems thus facilitating the most efficient transfer of power across the island; and facilitating the integration of renewable power sources onto the electricity system. The proposed development has been granted planning approval by the relevant authorities in both the Republic of Ireland and Northern Ireland.

A number of studies have assessed alternatives to an OHL for North-South. The most recent was an independent study by a Government-appointed 'International Expert Commission', conducted in the second half of 2011 and published in early 2012. In that report, the Commission did not recommend any solution as such. However, it recommended against fully undergrounding using an AC cable solution. It noted that, if the option is to underground the connection along the whole, or main part of the route, with the technology available at the time, the best solution would be a voltage source converter (VSC) based high voltage direct current (HVDC) solution combined with cross-linked polyethylene (XLPE) cables. It also stressed that an overhead line still offers significantly lower investment costs than any underground alternative and could also be made more attractive by investing slightly more in new tower designs rather than the classical steel lattice towers, at least for part of the route.

Given the potential for changes in technology and cost since the publication of its previous study in 2012, the International Expert Commission has been re-convened to provide an update. This report fulfils that purpose.

Recent developments in respect of the main technical options for the development of a new interconnection between the Republic of Ireland and Northern Ireland are reported. In line with the earlier report, these are:

1. an AC connection entirely made up of overhead line (OHL);
2. an AC connection comprising a combination of OHL and underground cable (UGC);
3. an undergrounded AC connection using a 'gas insulated line' (GIL);
4. a DC connection entirely made up of OHL;
5. a DC connection of which at least some of the connection uses underground cable, perhaps all of it underground.

The Commission's 2012 report observed that option 1 – an AC connection entirely made up of OHL – has generally been preferred by electricity network owners as it is significantly cheaper than the alternatives. In addition, long sections of high voltage AC underground cable present major technical problems and are generally avoided.

Since 2011, no major new technologies have emerged from the laboratory in a state of readiness for commercial deployment. However, a number of examples of HVDC 'embedded' within an AC system and avoiding the electrical problems associated with long high voltage AC underground cables are either under development or have entered operation. Particular attention is therefore paid to 'embedded' HVDC.

A number of projects in Europe that make significant use of the main alternatives to conventional overhead lines are described in order that these alternatives may be better understood. They include three 'embedded' HVDC projects and two that are planned to use novel OHL tower designs.

An update is presented of the Commission's own, earlier estimate of the cost of developing North-South as HVDC with underground cables as an alternative to an AC development with overhead line. It can be concluded that the costs for both key alternatives, AC overhead line and HVDC underground cables, have gone up. However, the cost relation is still the same: the HVDC option is more than three times more expensive.

Then, as part of the Commission's assessment of the feasibility of an alternative to overhead line development for the new North-South interconnector, its context within the electricity system on the island of Ireland is described.

The Commission's new review of the technical options for enhancing the power transfer capability between the Republic of Ireland and Northern Ireland has concluded that:

- Complete AC undergrounding is not viable; partial undergrounding is possible but with a limited total length of undergrounded sections.
- AC overhead line is viable; it would be possible to build the interconnection using new tower designs that are less visually intrusive but at an extra cost.
- A gas-insulated line (GIL) to cover the entire length would be extremely expensive and is, as yet, unproven anywhere in the world. Partial undergrounding using GIL would also be very expensive.
- The only viable means by which a high voltage interconnection of significant length could be completely undergrounded would be through use of an embedded HVDC link.

Embedded HVDC is not yet common worldwide but operational experience does exist and, within a few years, there will be at least four examples in Europe of comparable size.

Although the Commission regards it as a credible option, there are a number of aspects of the potential use of embedded HVDC in the context of enhancing the interconnection between Northern Ireland and the Republic that would require careful consideration. Among these issues is that a number of parties with which the Commission has consulted have expressed the need for economic development in the areas through which the planned North-South interconnector passes. They have pointed specifically to the possibility of attracting investment in new industrial or commercial facilities that have a need for significant amounts of electrical energy, in particular data centres. However, development of a North-South interconnector as embedded HVDC system would not achieve this.

Strictly limited partial undergrounding of an AC interconnection is possible but the Commission's understanding is that further planning enquiries would be necessary delaying commissioning of a new interconnector by, we understand, at least two years with an annual constraint cost of, according to the transmission system operator in Ireland, EirGrid, between 13 M€ and 20 M€ in the early years. Based on current central estimates, adoption of an embedded HVDC alternative would delay commissioning of a new interconnector by at least 5 years and would add approximately 120 M€ of additional constraint costs to the extra cost of building the link as HVDC compared with the currently planned AC OHL. The Commission's own estimate of the extra capital cost of 1 × 1GW voltage source converter (VSC) based embedded HVDC for a North-South interconnection compared with the planned 400kV AC OHL is 270 M€ giving an estimated total extra cost of 390 M€ or, with 2 × 700MW, 570 M€.

**The Commission's overall finding is that, from a techno-economic point of view, an AC overhead line is the most beneficial way of meeting the need for enhanced power transfer capability between the Republic of Ireland and Northern Ireland.**

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# 1 Introduction

## 1.1 Background

Currently there is one 275 kV double circuit (with a continuous Winter thermal rating of 2 × 881 MVA) plus two 110 kV circuits connecting the transmission networks of the Republic of Ireland and Northern Ireland. For operational reasons, the typical 'secure' level of power transfer between the two areas is 300 MW as a consequence of which they cannot operate as effectively as a single system thus limiting the benefits that can be derived from the Single Electricity Market and the interconnection's ability to contribute to security of supply through access to additional generation capacity in either area [1].

A new 138 km long, 400 kV overhead line (OHL) with a Winter continuous thermal rating of 1500 MVA [2] – the North-South Interconnector – has been proposed to enhance the connection between the transmission networks of the Republic of Ireland and Northern Ireland.

According to EirGrid, the transmission system operator in the Republic of Ireland, the objectives of the proposed North-South Interconnector development are [1]:

- improving security of supply;
- removing the bottleneck between the transmission systems thus facilitating the most efficient transfer of power across the island;
- facilitating the integration of renewable power sources onto the electricity system.

A "non-technical summary" of the proposed development can be found in [3]. From a system operation perspective, the main outcome would be an increase in the secure power transfer capability between the Republic of Ireland and Northern Ireland to, typically, between 1100 and 1300 MW [1].

The section of the proposed North-South Interconnector in the Republic of Ireland received planning approval from An Bord Pleanála (ABP) on December 21st 2016 [4]. However, on February 16th 2017, a Fianna Fáil private members' motion on the interconnector "called on the Government to commission an independent report to examine the feasibility and cost of putting the interconnector underground and to ensure no further work is done on the interconnector until that analysis and a full community consultation are completed" [5]. The motion was passed by 76 votes to 60.

On January 23rd 2018, the Department for Infrastructure in Northern Ireland approved planning permission for the northern element of the North-South Interconnector following a positive recommendation from the Planning Appeals Commission (PAC) [6].

A number of objections to the proposed development were submitted to the relevant planning authorities. As noted in [7], a number of submissions to An Bord Pleanála urged the adoption of an alternative to a new overhead line development, e.g. the undergrounding of any new line. The potential for an underground alternative has been examined in a variety of studies, some independently-commissioned and some commissioned by EirGrid. A number of these studies are summarised in [8]. The most recent independent study by a Government-appointed 'International Expert Commission' was published in early 2012 [9].

Given the potential for changes in technology and cost since the publication of the independent study published in 2012, it was proposed by the Irish Government that the International Expert Commission be re-convened to provide an update on its earlier study, based on the terms of reference below.

## 1.2 Commission membership and Terms of Reference for the review

This report is prepared by the Commission composed of:

- Bo Normark, Chairperson Elimark AB, Sweden;
- Ronnie Belmans, 2BEnergy, Belgium;
- Keith Bell, University of Strathclyde, United Kingdom.

The Terms of Reference for the work were set by the Department of Communications, Climate Action and Environment as follows.

> The Department of Communications, Climate Action and Environment requires an independent study to examine the technical feasibility and cost of undergrounding the North-South Interconnector, taking into account the most recent developments in technology and experience gained from existing projects abroad.
>
> The independent experts will:

- review international literature, recent technology developments, international projects, and cost data in relation to overhead and underground high voltage power lines;
- consult with the Minister, the Commission for Energy Regulation, EirGrid, the ESB, the North East Pylon Pressure Campaign, the County Monaghan Anti Pylon Committee and other bodies as deemed necessary;
- examine the technical merits and construction and operation costs of the proposed project;
- examine the technical feasibility and cost of an underground alternative to the North-South Interconnector which will include technical considerations in the context of the electricity networks of Ireland and Northern Ireland operating effectively as a single system thus increasing the benefits that are derived from the Single Electricity Market, and which will have regard, insofar as possible, to the potential underground route types (e.g. along roadway, cross-country, etc.) for the North-South Interconnector;
- issue a final report within five months of commencing work that will include a comparison of the estimated construction and operation costs, and relative technical merits of the proposed overhead project and an underground alternative; and
- present the results of the study to the Minister and the relevant Oireachtas Committee.

## 1.3 Outline of the report

The report is structured as follows. First, an update is provided on the main technical options for the development of a new interconnection between the Republic of Ireland and Northern Ireland that were reviewed in the earlier Commission report. Then, a number of projects that make significant use of the main alternatives to conventional overhead lines are described in order that these alternatives may be better understood. An update is presented of the Commission's own, earlier estimate of the cost of developing North-South as HVDC with underground cables as an alternative to an AC development with overhead line. Then, as part of the Commission's assessment of the feasibility of an alternative to overhead line development for the new North-South interconnector, its context within the electricity system on the island of Ireland is described. Finally, conclusions are presented.

Although consideration of issues and concerns associated with electric and magnetic fields is outside the scope of the Commission, the Commission recognises the strong interest that stakeholders have in such issues. An appendix to this report is therefore included that summarises electric and magnetic field issues. For a fuller description and assessment, the interested reader is recommended to consult two independent reports commissioned by the Irish Government [10][11] plus EirGrid's submission to ABP outlining its evaluation of alternatives to an OHL.

The Executive Summary from the Commission's previous report is reproduced in a final appendix.

# 2 Main technical options

## 2.1 Technology review: introduction

The International Expert Commission's report on the Meath-Tyrone interconnector published in 2012 reported the Commission's judgement that there are 5 main alternative technologies that could be used for the connection [9]:

1. an AC connection entirely made up of overhead line (OHL);
2. an AC connection comprising a combination of OHL and underground cable (UGC);
3. an undergrounded AC connection using a 'gas insulated line' (GIL);
4. a DC connection entirely made up of OHL;
5. a DC connection of which at least some of the connection uses underground cable, perhaps all of it underground.

No major new technologies have emerged from the laboratory in a state of readiness for commercial deployment, except for a small first try out of high temperature superconductive cable in Essen Germany taken into service in 2014 [12].

Ever since the late 1890s when Nikola Tesla's ideas beat those of Thomas Edison in what became known as the "war of the currents", large, modern power systems all use alternating current (AC). The main advantages are the ability to step voltages up and down and the ease of interrupting fault current. High voltages allow power to be transmitted over long distances with low losses, but have significant electrical insulation requirements. Power is therefore stepped down to lower voltages for distribution to end users. However, since the 1960s, high voltage direct current (HVDC) has received growing attention, initially for two reasons:

- to allow the interconnection of two AC power systems operating at different frequencies of oscillation of the alternating current; or
- to transmit over relatively long distances with reduced losses compared with AC.

HVDC has been enabled by the development of technology that allows conversion between AC and DC and vice-versa at high voltages and powers. Innovation around HVDC has primarily concerned the use of different devices, how they are connected together and how they are controlled. The converter stations also represent both an advantage of HVDC and its main disadvantage. One benefit of HVDC is its controllability. The power carried by an AC OHL or UGC depends on the locations of generators and load on the network and the mesh of parallel routes between them. The power flowing on different lines can only be modified by changing the amount of power being generated or used at particular locations or by installing additional equipment such as phase shifting transformers. In contrast, under normal conditions, the power carried on an HVDC OHL or UGC can be fully controlled. In this way, it can reflect operator or electricity market preferences and can help the total capacity of parallel routes to be optimally utilised. However, the big disadvantage is the extra cost – and physical footprint – of the converter stations at each end of the route.

Along with other reports, the Commission's 2012 report observed that option 1 – an AC connection entirely made up of OHL – has generally been preferred by electricity network owners as it is significantly cheaper than the alternatives. Although the conductors and insulators on an OHL are exposed to the elements and therefore vulnerable to weather-related faults, e.g. due to lightning or in high winds, physical damage resulting in long outage times is rare. Even then, the location of the fault can be easily identified and a repair can normally be carried out quite quickly enabling the line to be returned to service. In the past, once a route has been identified and relevant planning permissions gained, the development timescales of OHL were generally moderate. However, in recent years and in spite of the extra cost, objections to OHLs and delays in the granting of permissions have led to network developers considering undergrounding, often for at least the most sensitive parts of an intended route. Some grid companies use a compensation type of approach in which the construction of new OHL at very high voltages is compensated by undergrounding nearby high voltage lines, e.g. in the Stevin project described in Section 3.5. Another approach was discussed at the CIGRE Symposium in Dublin 2017 concerning the first time that a section of OHL has been replaced for reasons of visual amenity [13].

As will be recalled in section 2.3, long sections of high voltage AC underground cable present major technical problems and are generally avoided. Thus, for distances beyond a few tens of km where an OHL is not an option, e.g. undersea connections or where undergrounding is required, some other technology is required. In 2012, the options were considered to be gas insulated lines (GIL) and HVDC. Both avoid the problems associated with the high susceptance of insulated cables, the former because a high pressure mix of, typically, 20% $SF_6$ and 80% $N_2$ gas is used to provide the electrical insulation, the latter because of the use of direct current.

Since the previous report, no new commercially viable options have appeared representing alternatives to those highlighted by the Commission in 2012. This chapter therefore concentrates on providing an overview of recent developments of the same technologies with which the previous report was concerned, based on reports that have emerged since 2011.

The rest of this chapter comprises the following:

1. an overview of OHL innovative approaches (built and design stage) since 2011;
2. an update on installations and issues associated with AC UGC;
3. an update on GIL;
4. an update on HVDC connections ‘embedded’ within an AC power system.

## 2.2 Overhead line innovations since 2011

The Commission’s report from 2012 described a number of innovations in respect of overhead lines. In general, they are designed to

1. make a more aesthetically pleasing tower;
2. increase the power carried in a given corridor, through use of novel conductors with higher current capacity, through closer monitoring of the conductors relative to their limits or by reducing the width of the physical corridor required for an OHL construction to carry a given amount of power;
3. reduce the number of towers required to carry the OHL;
4. reduce the electro-magnetic field (EMF) associated with the line.

A number of new tower designs were highlighted in the 2012 report [9]. Many of these represented compact designs that use composite materials to provide both electrical insulation and mechanical strength thus avoiding the need for long cross-arms from which insulators and conductors are suspended. The design of the towers of the Stevin project in Belgium is an application of these ideas as discussed in section 3.5. TenneT’s WindTrack in the Netherlands also reduces the magnetic field and is being used in the Randstad project for which a brief update is provided in section 3.6. They might also be regarded as being ‘easier on the eye’ than conventional, steel lattice towers. However, they are more expensive. A good example is the design used for future Hinkley Point C link described in section 3.7.

## 2.3 AC underground cable developments

AC underground cables (UGC) are widely used in urban environments within the lower voltage distribution network. At such low voltages, the major problem with AC UGC is of negligible significance: shunt susceptance. This represents the need for current into a piece of electrical equipment to be used to charge it to a certain voltage before current can pass through the equipment. Similarly, the equipment must be discharged for the current to reverse. In an AC system, this happens repeatedly (every 10 ms at the 50 Hz frequency that is used in Europe). In the case of an overhead line (OHL) or UGC, the charging and discharging must happen along the entirety of its length so that the required charging current is larger for longer connections. The requirement also depends on the equipment's ability to store charge and this, in turn, is a function of the material used to provide electrical insulation. For an OHL it is the air around the conductor; for a UGC it might take the form of specially designed paper impregnated with oil (which must be suitably contained) or, in most new cables, cross-linked polyethylene (XPLE). The susceptance of the materials used in cables is much higher than air. Moreover, it is so high when the cable is operated at a high voltage that some additional equipment is often required to compensate for the effect. In addition, special arrangements may be required to manage the initial charging when a cable is switched in or discharging when it is switched out, either for routine network rearrangement or because of a fault somewhere [14]. Switching of any item of equipment electrically close to the cable can trigger interactions – resonances – between the cable and other network elements to induce such high voltages that there is a significant risk of equipment being permanently damaged and needing to be taken out of service for a long period of time while it is replaced [14]. Furthermore, a long AC cable could amplify harmonics associated with the increasing use of power electronics connected the system [14]. The high voltages associated with uncontrolled resonances also represent a significant safety risk and the currents associated with harmonics can lead to excessive heating of equipment.

The net result of the above is that power network operators are obliged to limit the total length of high voltage UGC in their systems. A recent report by CIGRE Working Group B1.47 [15], reported that a 220 kV UGC commissioned in Australia in 2012 has a world record length of 88 km. It required the installation of additional reactive compensation equipment and 235 joints to be made between sections of cable. UGC does not eliminate electromagnetic field (EMF) issues. In this case, particular arrangements of ducts were needed to minimise them. The Gemini offshore wind farm in the Netherlands was connected in 2016 with around 110 km of 220 kV undersea cable. Higher voltage underground or undersea cables do not reach such a length. The connection to Vancouver Island is operated at 525 kV and has a total cable length of 39 km. The 245 kV connection between Sicily and Malta has a total length of 119 km of AC cable [16].

All cases of high voltage cables of a few tens of km in length require special attention to the susceptance effects. This often results in a need for blocks of shunt reactor compensation plus tuned filters to deal with resonance issues and, perhaps, switched series resistors to limit charging currents when the cable is being energised and 'point on wave' switching [14][17]. Although it usually suffices with shorter cables to have shunt compensation at each end, longer cables may also require it part-way along which means an additional above ground installation. All factors add extra cost. However, if the key resonant frequency is close to 50 Hz, use of filters to manage the condition may be impractical. In addition, the longest examples of AC UGC mentioned above – in Australia and for the Dutch offshore wind farm – are radial connections that would normally be energised from the end connected to the onshore, main interconnected system. Measures for the management of possible resonances and over-voltages can be concentrated on that end. However, the proposed North-South development will be embedded within the interconnected network and, thus, may be expected to be energised from either end.

*Figure 1: Typical shunt reactor for reactive power compensation [15]*

In contrast with OHL, UGC installations are largely protected from the environment and, thus, faults may be expected to occur less often. However, because they are buried, locating where a repair needs to be carried out can be difficult and the repair itself can be time-consuming with the result that overall availability may be comparable with that of an OHL of similar length. Indeed, it is argued in [18] that "long cable lengths impose a higher risk in transmission grids than overhead lines due to the failure rate and repair time". Typically, the part of a cable most vulnerable to failures is where sections are joined together. Because long sections cannot be transported on land, many more separate sections are required for underground cables than for a similar total length of undersea cables. As a consequence, there are many more joints. However, pre-fabricated joints are now available making installation easier and reducing the likelihood of faults. Most joints are put into well accessible joint pits.

Underground cables are typically buried in trenches although, on occasion, dedicated tunnels are dug, e.g. one of 20 km in North London for a 400 kV AC cable. The width of the trench depends on the number of individual cables and whether they are buried side-by-side or one above the other. (See, for example, chapter 6 of the Commission's 2012 report [9]). One option to reduce the susceptance problem would be to use a lower voltage but, to have the same total power transfer capacity, a number of parallel cables would be needed, increasing the cost and increasing the size of trench.

Detailed assessment of the system technical issues arising from use of long AC underground cables in the context of the island of Ireland can be found in [19] and [20]. A further general summary of issues associated with use of underground cables can be found in [21].

## 2.4 Gas-insulated lines (GIL)

A good description of the state of the art of Gas-Insulated-Lines can be found in [22].

Although the technology has major advantages, a real breakthrough for longer length remains to be seen. Siemens is internationally recognized as the top provider of the technology [23].

According to CIGRE Working Group B3/B1.09 [24], 250 km of GIL were in operation in 2008. This CIGRE overview has not been updated since then.

## 2.5 HVDC systems: development of technology and market

Use of underground cables while avoiding the technical problems associated with long, high voltage AC underground cables entails use of HVDC. This, in turn, requires converter stations at each end of the cable-based connection. They are large and expensive but offer benefits in terms of control of power flows.

The two main HVDC converter station options use 'line commutated converter' (LCC) or 'voltage source converter' (VSC) technology. The latter has become increasingly popular in recent years and now represents the majority of HVDC orders. Although the converter station has higher losses than an LCC option, this is due to its extra controllability and the fact that it can operate on a weak network. Between 2012 and 2017, over 2500 km of HVDC cable routes (705 km underground, 1840 km undersea) were installed worldwide using VSC in 18 different projects [26]. Almost all of these made connections between different synchronous areas.

The HVDC market has generally been strong in recent years. The development is following two parallel trajectories.

1. Ultra high voltage DC (UHVDC) projects in Asia, mainly in China where a great expansion is taking place with new projects using ever increasing line capacities. Several systems rated at 800 kV are in operation with capacities up to 8000 MW per line. The world's largest system stretching over 3400 km rated at 1100 kV and 12000 MW is under construction in China [25]. All these systems are built with classic LCC Technology.
2. Voltage Source Convertors (VSC) have become the norm for building smaller systems and are almost always combined with at least some cable technology. The main market has been in Europe.

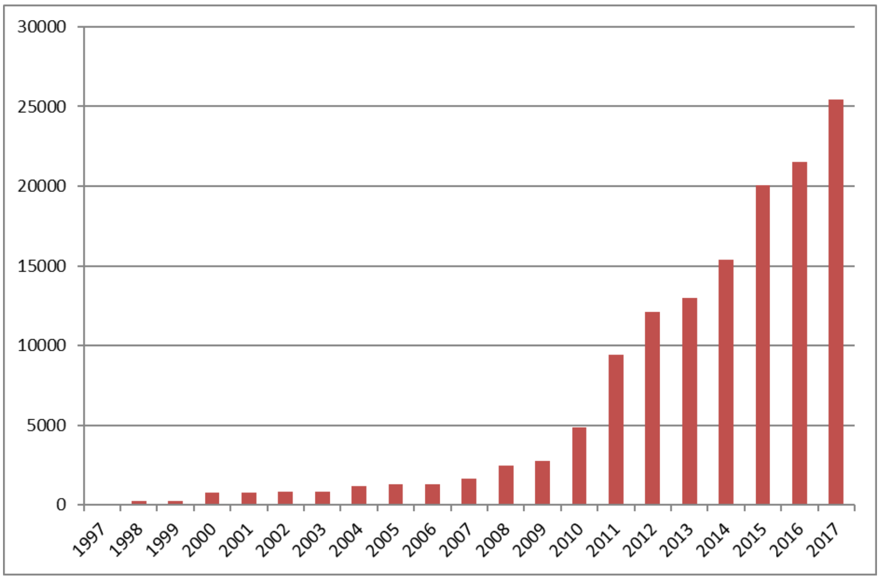

*Figure 2: Accumulated awarded VSC HVDC Projects (Source: Commission's own data).*

Since the Commission's previous work in 2011 that was published in early 2012, the Commission has identified that a total of 19 HVDC projects with cables have been awarded. Europe remains the dominant market for HVDC cable projects. Some observations can be made.

- All new HVDC projects with cables are based on the VSC technology.
- Almost all projects are interconnections or offshore wind connections.
- Two “embedded” links have been awarded since 2011: the ALEGrO project connecting Belgium and Germany and a new project in India.
- Voltage level:
  - 320 kV could be regarded as emerging as a “de facto” standard;
  - 400 kV has been chosen for two projects;
  - 500 kV is the highest VSC voltage in operation;
  - two projects at 525 kV are under construction.
- Power level:
  - 320 kV projects range between 600 MW and 1000 MW per convertor;
  - the two 525 kV projects each have a 1400 MW rating.
- Power losses have been reduced from typically 1 % to typically 0.8 % per convertor. It does not result in a significant change in the basic losses evaluation done in the Commission’s previous report.
- Most cables are subsea cables but there are 6 projects with land cables.
- Total route length of subsea cables in the VSC schemes awarded since 2011 is 3169 km and of land cables is 963 km.
- The dominant VSC suppliers are European: ABB, GE (former Alstom) and Siemens.

Cables are traditionally supplied by the European suppliers NKT (former ABB), Prysmian and Nexans. Two new cable suppliers are now in the European market, J-Cable from Japan and Silec from France.

There is also a pipeline of new projects in Europe. Europe continues to be main market for HVDC cables systems.

*Table 1: HVDC projects with cables awarded since 2011 (Source: Commission’s own review of manufacturers’ press releases; costs are published Engineering, Procurement and Construction (EPC) costs; total project costs are typically 20-30% larger than the EPC costs)*

| **Year order** | **Year in service** | **Project** | **Countries** | **Application** | **Contract Value Meuro** | **MW** | **Voltage kV** | **Distance Total** | **Distance Sea** | **Distance Land** | **MEuro/ MW** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2011 | 2015 | Skagerrak 4 | Denmark/Norway | SubSea | 241 | 700 | 500 | 140 | 140 | 0 | 0,34 |
| 2011 | 2017 | DolWin2 | Holland | Off-Shore | 857 | 916 | 320 | 135 | 45 | 90 | 0,93 |
| 2011 | 2015 | SylWin1 | Holland | Off-Shore | 857 | 864 | 320 | 160 | 160 | 0 | 0,99 |
| 2011 | 2015 | IFA 1 | France - Spain | Landcable | 557 | 2000 | 320 | 65 | 0 | 65 | 0,28 |
| 2012 | 2015 | ÅL-Link | Åland | Submarine | 111 | 100 | 80 | 158 | 158 | 0 | 1,11 |
| 2012 | 2018 | Sydvästlänken | Sweden | Underground + OH | 394 | 1200 | 320 | 190 | 0 | 190 | 0,33 |
| 2013 | 2017 | Dolwin 3 | Germany | Offshore + Land | 866 | 900 | 320 | 162 | 83 | 79 | 0,96 |
| 2014 | 2017 | Maritime Link | Canada | SubSea | 343 | 500 | 200 | 360 | 360 | 0 | 0,68 |
| 2014 | 2018 | Caithness Moray | Scotland | Subsea | 484 | 800 | 320 | 160 | 160 | 0 | 0,60 |
| 2015 | 2021 | NSN | Norway - UK | Subsea | 1257 | 1400 | 525 | 740 | 740 | 0 | 0,90 |
| 2015 | 2020 | Nordlink | Norway - Germany | SubSea | 1200 | 1400 | 525 | 623 | 623 | 0 | 0,85 |
| 2015 | 2019 | NEMO | Belgium - UK | Subsea | 496 | 1000 | 400 | 140 | 130 | 10 | 0,49 |
| 2015 | 2019 | Frejus | France - Italy | Landcable | 1397 | 910 | 320 | 190 | 0 | 190 | 1,53 |
| 2016 | 2019 | Cobra | Denmark - Holland | Subsea | 411 | 480 | 320 | 325 | 325 | 0 | 0,85 |
| 2016 | 2019 | Alegro | Belgium - Germany | Landcable | 399 | 1000 | 320 | 90 | 0 | 90 | 0,40 |
| 2017 | 2023 | Dolwin 6 | Germany | Offshore + Land | 1028 | 900 | 320 | 90 | 45 | 45 | 1,14 |
| 2017 | 2020 | ElecLink | France - UK | Land | 437 | 1000 | 320 | 51 | 0 | 51 | 0,44 |
| 2017 | 2020 | IFA 2 | France - UK | Subsea + Land | 621 | 1000 | 400 | 225 | 200 | 25 | 0,62 |
| 2017 | 2020 | India VSC | India | Land | 446 | 1000 | 320 | 200 | 0 | 128 | 0,44 |
|  |  |  |  |  | 12403 | 18070 |  | 4204 | 3169 | 963 | 0,00 |

*Table 2: New VSC HVDC projects in Europe with cables (Source: Commission's own review of published EPC costs).*

| Year order | Year in service | Project | Countries | Application | Contract Value Meuro | MW | Voltage kV | Distance Total | Distance Sea | Distance Land |
|---|---|---|---|---|---|---|---|---|---|---|
| 2018 | 2021 | Shetland | UK | Subsea + Land | 343 | 600 | 300 | 267 | 257 | 10 |
| 2018 | 2021 | FAB Link | France - UK | Subsea + Land | 848 | 1400 | 320 | 216 | 171 | 45 |
| 2018 | 2021 | Western Isles | UK | Subsea + Land | 0 | 450 | 320 | 156 | 80 | 76 |
| 2018 | 2022 | NorthConnect | UK - Norway | Subsea | 0 | 1400 | 525 | 655 | 655 | 0 |
| 2018 | 2022 | Viking Link | UK - Denmark | Subsea + Land | 0 | 1400 | 400 | 770 | 630 | 140 |
| 2020 | 2024 | Eastern Link | UK | Subsea | 0 | 2000 | 400 | 305 | 305 | 0 |
|  |  |  |  |  |  | 7250 |  | 2369 | 2098 | 271 |

## 2.6 HVDC connections 'embedded' within an AC power system

An HVDC option for making a new interconnection between Northern Ireland and the Republic of Ireland would operate in parallel with AC circuits and be 'embedded' within a single synchronous area. There are 17 examples of embedded HVDC in operation globally of which 11 are in China [26]. One was recently commissioned in Europe between France and Spain – INELFE – and is discussed in section 3.1. Five others are under development in Europe. They include the ALEGrO project between Belgium and Germany discussed (section 3.2) and the South-West Link between Norway and Sweden (section 3.3). In addition, the Western HVDC Link in Britain discussed (section 3.4) is expected to be commissioned in 2018.

The main limiting factor regarding use of HVDC with cables is the rating that can be achieved for the cable. INELFE uses 320kV cables. In order to give the required power transfer capability, INELFE comprises two parallel 1 GW connections. However, the NEMO interconnector between Belgium and Britain using VSC HVDC and undersea cables planned for commissioning in 2019 will operate at 400 kV and Nordlink between Germany and Norway and NSN between Norway and Britain will each be commissioned in 2021 and operate at 525 kV with a power capacity of 1400 MW. Importantly, the use of HVDC underground cables does involve some – though not all – of the issues associated with AC UGC, in particular the high number of joints and the relatively long repair times in the event of faults. (Section 2.3).

Another potential issue with use of HVDC is that a future wish to extend the DC side to, for example, a third terminal would involve multi-terminal operation for which there is little operational experience, the only VSC examples to date being two projects in China, Nan'ao Island and Zhoushan.

The Commission is not aware of any particular operational difficulties that have emerged from the embedded HVDC systems already in operation. However, the system operators on the island of Ireland have no experience with such systems.

## 2.7 Technology review: concluding remarks

The Commission's understanding is that the main objections to the planned and, now, approved development of a new North-South interconnector concern (i) visual impact and (ii) concerns about electro-magnetic fields (EMF). As was noted in section 1, EMF issues are outside the scope of the Commission's Terms of Reference.

In common with the Commission's previous findings published in early 2012, the technology review presented above reveals that the main alternatives to AC OHL development for North-South that promise to reduce the visual impact of the development are:

1. use of underground cables for some or all of the route;

2. use of a novel design of tower for overhead lines that reduces the size of the corridor or improves the appearance of the line.

In respect of 1, the review of the use of AC underground cable suggests that it is not a viable option except, perhaps, for a very limited length, e.g. no more 10km. If the entire length of the connection is to be undergrounded, the problems caused by the susceptance of an AC cable suggest that it should be built to carry direct current (DC) at a high voltage. This would entail the development being one of an ‘embedded’ HVDC system. The significant development in recent years of the market for HVDC using undersea or underground cables and the commissioning or construction of a number of ‘embedded’ HVDC links suggests that this option is commercially viable.

For the purposes of illustration, the next chapter reports on some developments of ‘embedded’ HVDC in Europe. It also reports on one example of a new design of tower being used to improve the appearance of an OHL.

# 3 Illustrative projects

The previous chapter presented an update of the Commission's previous review of the main technology options that might be considered as alternatives to an AC OHL development. It concluded that the main, commercially viable means by which the route might be entirely undergrounded would be by means of 'embedded' HVDC link. It also noted that the appearance of an OHL route might be improved by use of a novel tower design.

This chapter presents short, illustrative summaries of four 'embedded' HVDC projects that are either operational or under development in Europe. It also briefly reports on two AC projects in Europe – Stevin and Randstad – that use short sections of AC underground cable. Both also use a novel design of tower for the overhead line section. Finally, proposals in Great Britain to use a novel tower design for a section of new 400 kV overhead line are described along with the British regulator's published opinion of the cost of such a tower.

## 3.1 Spain-France (INELFE)

Until the installation of the new HVDC link, the Electrical interconnection between Spain and France consisted of four lines, the last of which was built in 1982: Arkale-Argia, Hernani-Argia, Biescas-Pragneres y Vic-Baixas. They have a total commercial exchange capacity of 1400 MW, meaning that they represent only 3% of the current maximum demand in the Iberian Peninsula [27]. It made the Iberian Peninsula to have one of the lowest interconnection ratios in the European Union, thereby limiting the possibilities of helping or receiving assistance in the event that there is a failure in any of the electrical systems. This new interconnection line doubles the level of interconnection between France and Spain from its current 3% to 6%, i.e. it will add on another 1400 MW to reach 2800 MW, still below the 10% recommended by the European Union.

The owners of all interconnections are and will be Red Eléctrica de España and Réseau de Transport d'Electricité (RTE). For this specific new project, a special purpose company has been established, being INELFE (Interconnection Electrical France-Espagna, https://www.inelfe.eu/en ), a joint venture company between RED and RTE, governed by French law. After the first project as discussed here, the company will build the connection Gatika (near Bilbao, Spain) to Cubnezais (near Bordeaux, France) via the Bay of Biscay.

*Figure 3: Route of the INELFE interconnector [28]*

The agreement was signed in 2008 in Zaragoza. As a final step in permitting, RED Electrica obtained the Environmental Impact Declaration (EID) of the project on December 13, 2010. In 2014, the works were completed: converter stations, tunnel and underground connections. In 2015 the systems were activated, tested and integrated. Late 2015 the commercial operations on the Baxias-Santa Llogaia line were started.

The overall length of the connection is 64.5 km, 33.5 km in France and 31 km in Spain [28]. The central part of the line crosses the Pyrenees at the Albera massif (Figure 3). An 8.5 km tunnel was built for this section: 1 km in Spain and 7.5 km in France. The rest of the line is buried in a trench.

On the Spanish side, the line crosses the Empordà through the municipalities of Santa Llogaia, Vilafant, Figueres, Llers, Pont de Molins, Cabanes, Biure, Capmany, Darnius, Agullana, and La Jonquera. For the most part, the layout is parallel to the AP-7 motorway and the high-speed railway.

The layout on the French side was the result of 15 months of consultations with representatives and associations from the region. The line passes through the towns of Baixas, Baho, Villeneuve-la-Rivière, Le Soler, Toulouges, Canohès, Ponteilla, Trouillas, Villemolaque, Banyuls dels Aspres, Tresserre, and follows the high-speed railway for most of its layout up to the tunnel entrance, in Montesquieu des Albères (Figure 4). The tunnel then goes under the municipalities of Le Boulou, Les Cluses, and Le Perthus (Figure 5).

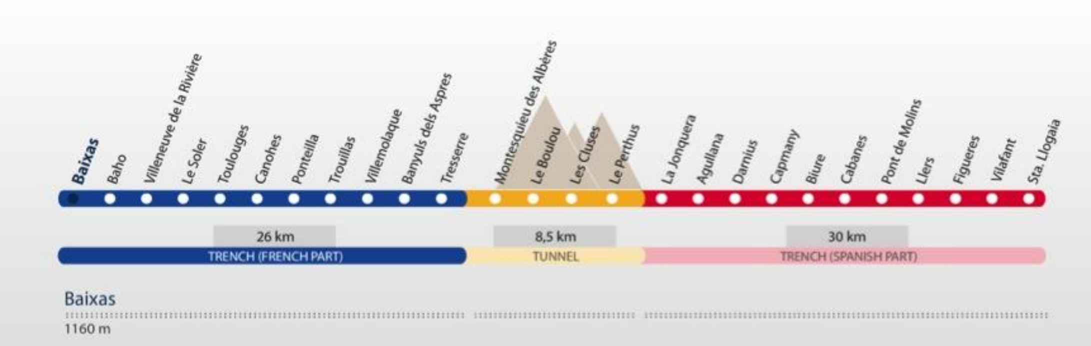

Figure 4: INELFE project: summary of routing and use of tunnel or trenches for underground cable [28]

Figure 5: INELFE project: cables in tunnel section [28]

Siemens' "HVDC Plus" technology is used, based on self-commutated voltage-sourced converters (VSC) in a modular multilevel converter configuration (MMC) that converts alternating current (AC) into direct current and direct current, VSC works with IGBT power transistors that can be switched off enabling the commutation processes in the power converter to run independently of the grid voltage. The very fast control and protective intervention capabilities of the power converters provide for a high level of stability in the transmission system, which primarily serves to reduce grid faults and disturbances in the three-phase AC network. The overall lay-out resembles the Meath-Tyrone interconnector were embedded HVDC to be used: an existing AC overhead line system in parallel with a new connection of similar size.

The converter stations and cables (manufactured by Prysmian) are rated at 320 kV. The rated power is 2000 MW (2 × 1000 MW), with a reactive power capability of ± 300 MVAr. Power reversal is possible in 150 ms. VSC's black-start capability function makes it possible for the HVDC transmission system to restart the affected power grid as quickly as possible in the event of a major disturbance.

Each converter station is comprised of several large buildings covering a total surface area of 4 ha. Two main buildings house the power units constituting the main devices for converting alternating into direct current after massive converter transformers bring the alternating current to the appropriate voltage level, or vice-versa.

The roof of the Baixas station was specially designed by an architect (Figure 6). It rises 17 m in height while that of Santa Llogaia reaches 25 m. Each station consists of two main buildings 17 m in height that house the power units (the AC to DC converters), seven transformers weighing more than 250 ton (whose transport from Germany required special logistics) and an air cooling system. Two smaller buildings house the control equipment. Construction work began in January 2012 on the Spanish side and shortly thereafter on French side. Work was completed in the middle of 2014.

*Figure 6: INELFE project: one of the converter stations [28]*

The overall cost is 700 M€, with the following elements [9].

- The cost of 4 converters including platforms and connections is about 400 M€.
- The cost of the cable including joints, termination and pulling the cable inside pipes is around 110 M€.
- The civil works and drilling is estimated to cost 50 M€ with the 8 km of tunnel costing an additional 120 M€.

The financing is organized in the following way:

- 225 M€ from the European Union within the framework of the EEPR (European Energy Program for Recovery) programs;

- 350 M€ from European Investment Bank (EIB) as a loan;
- 125 M€ from the Owners.

With initial testing, Siemens began commissioning the converter stations for a high voltage direct current (HVDC) transmission link between France and Spain. The HVDC transmission system commenced commercial operation in end of 2015.

## 3.2 Belgium-Germany (ALEGrO)

The ALEGrO (Aachen-Liège-Electric-Grid-Overlay) project connects Germany and Belgium directly [29]. In fact, after World War 2 all direct links between Belgium and Germany disappeared. Two "indirect" links exist. One is via The Netherlands where a double circuit 400 kV link from Maasbracht (the Netherlands) to Kinrooi (Belgium) is split in Maasbracht, half of it going north to The Netherlands, half going east to Germany. The second indirect link is via Luxemburg, where half of the system is within the control area of Elia, the Belgian TSO, the other half is part of Amprion in Germany. The overall situation is shown in Figure 7. North of Belgium, The Netherlands are further coupled to Germany via a number of 400 kV lines; the same holds in the south (Vichy-Uchtelfangen).

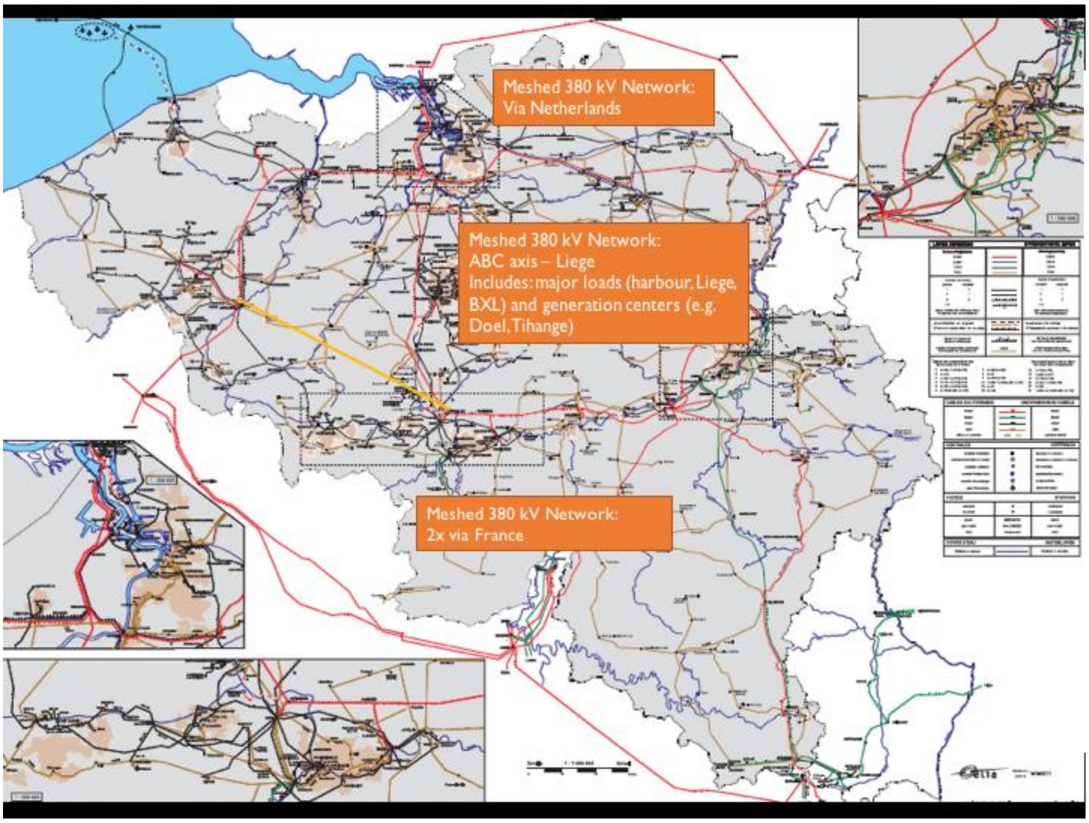

*Figure 7: The Belgian transmission network [30]*

This situation created a lot of loop flows: in Germany the wind energy in the North-East found its way to the load centres in the South-West of the country via the Netherlands-Belgium-France, blocking a lot of the commercial flows. Therefore, Elia has installed (and is further installing) a number of phase shifting transformers (PSTs).

In order to further elaborate the interconnections with the surrounding countries, a number of projects are being executed for the time being, highlighted in Figure 8.

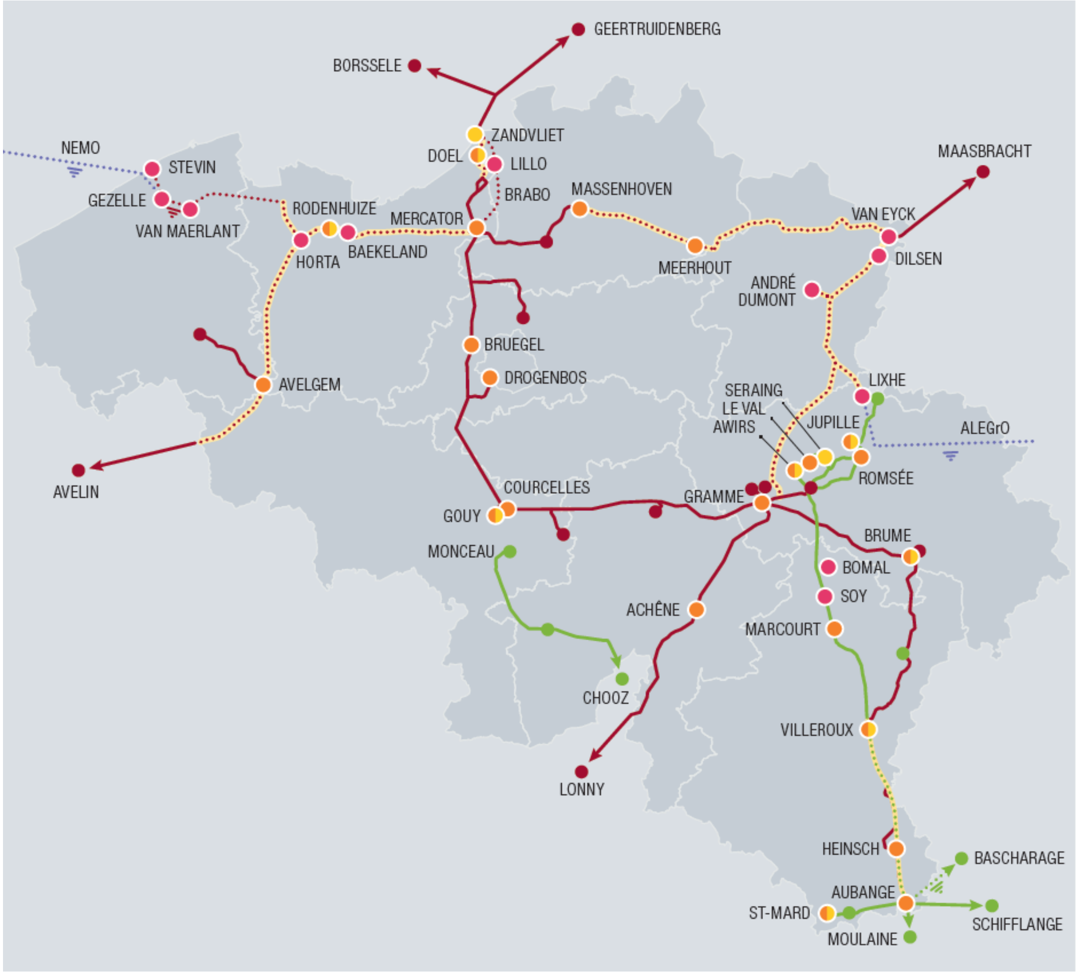

*Figure 8: Major transmission projects in Belgium [31]*

ALEGrO is the direct current link between Germany (Amprion control zone) and Belgium (Elia control zone). On a broad scale, it is a DC link embedded in a fully deployed AC system. It is in parallel with a number of 400 kV lines north of it, mostly controlled by phase shifting transformers and a strong 400 kV corridor south of it with natural flow. It passes through the Ardennes which imposes various environmental restrictions. There are two important infrastructure routes already present in the area: the E40 highway and the high speed train link (Figure 9).

*Figure 9: Railway tunnel entrance in the Ardennes [29]*

The option for the new direct link between Belgium and Germany is to install a 94 km underground cable link between Lixhe (Elia, Belgium) and Oberzier (Amprion, Germany) (Figure 10). 49 km is in Belgium and 45 km in Germany. The transmission capacity is 1000 MW; the generated or consumed reactive power is defined independently by the converters at both ends. The applied voltage is 320 kV DC, with multilevel symmetrical monopole configuration. The cable is HVDC XPLE.

*Figure 10: Connection of the ALEGrO project [29]*

The developers of the project judged that the best technology available for this project was HVDC with VSC converters and cable type conductors. Managing and controlling energy transfers with intermittent behaviour and long-distance undergrounding are regarded by the developers as feasible. The capacity is 1000 MW, i.e. 10 % of the average Belgian electricity demand during the year. At both sites of the DC link, a short AC cable connection is used between the existing AC overhead grid and the converter (Figure 11).

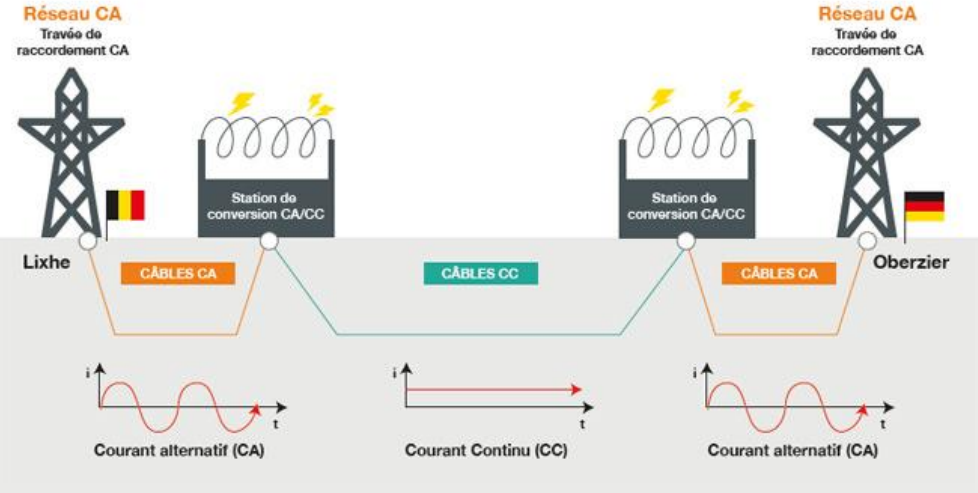

*Figure 11: ALEGrO project: cable sections [29]*

The routing is shown in Figure 12. In Belgium the cable connection will run from the existing substation at Lixhe to the E40 car park at Eynatten (Raeren). The routing is based on the principle described in the Belgian SDER (Spatial Development Rules). Therefore, ALEGrO will mainly use existing infrastructure (towpaths, motorways and railway infrastructure). The route was selected from a number of options in consultation with the local authorities to have the least possible impact on local residents and the environment. It avoids residential zones and areas of important biological interest (Natura 2000).

The cables are laid in the public domain (in or along roads) with limited place available while optimizing the routing using techniques to minimize impact on mobility. An additional advantage is that undergrounding minimizes the visual impact. Several installing techniques are used for the cable: normal trenches, micro tunnels (passing canals and rivers) and directional drilling (crossing of highways, railways, roads, …) (Figure 13).

The converter in Belgium is near a strong substation with several voltage levels. It is placed in a defined zone according to the spatial planning, i.e. a zone intended for industrial use.

The construction time, including commissioning is estimated to be less than 3 years.

*Figure 12: ALEGrO project: cable routing [29]*

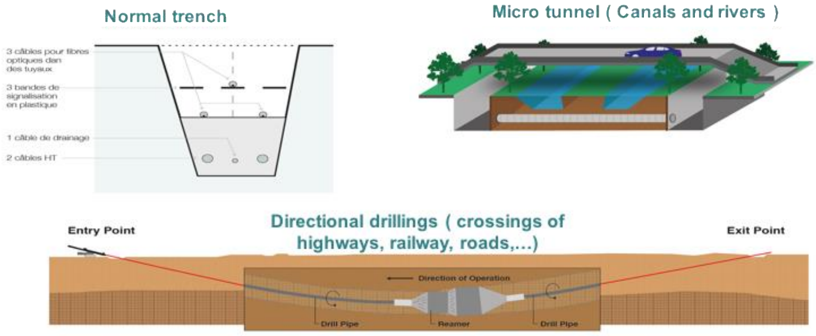

*Figure 13: ALEGrO project: underground cable installation techniques [29]*

*Figure 14: Illustrations of ALEGrO converter stations [29]*

## 3.3 Norway-Sweden (South-West link)

There has for many years been identified a need to reinforce the North–South interconnection capacity in Sweden in order to:

- Improve the market;
- Allow further integration of renewable energy;
- Increase security of supply.

Sweden has many critical sections in the grid. The most southern section has today a total transmission capacity of 4500 MW. The first priority was to increase the transmission capacity in this section by at least 1000 MW.

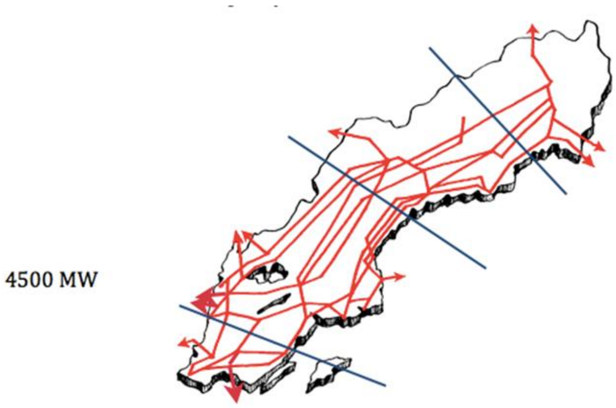

*Figure 15: Main transmission boundaries in Sweden [32]*

The original idea in 2011 was to build a multiterminal HVDC system with one North-South connector in Sweden and a branch connecting Central Sweden and Southern Norway. Shortly after the commencement of the project is was decided not to build the West part of the project so the final layout of the project was to build a North-South Interconnection from Central to South Sweden.

- Contracts for cables and convertors for the South part of the projects were awarded in late 2011 with a scheduled in-service date December 2014. The tenders were close to the budget.
- The rating of the project was finally defined to 2 x 600 MW.

*Figure 16: Location of the South West Link [32]*

## South-West Link, North part

| | |
|---|---|
| Distance: | Hallsberg - Ostansjo - Barkeryd |
| Technology: | OH - AC, 400 kV |
| Route | Mainly replacing existing 220 kV OHL |
| Transmitted power: | 1200 MW |
| Overall length: | 176 km |
| No: Pylons | App 350 |
| Pole height: | App 30 m |
| Approx Cost | 160 M€ |
| In-Service | April 2015 slightly behind schedule |
| | Completed approximately on budget |

## South-West Link, South part

| | |
|---|---|
| Distance: | Barkeryd - Hurva |
| Overall length: | 251 km |
| Technology: | DC, HVDC VSC |
| No: Convertors | 4 x 600 MW |
| Transmitted power: | 2 x 600 MW |
| OH line: | 62 km (on existing 220 kV OHL route) |
| UG cables: | 189 km |
| Approx cost | 570 M€ |
| Planned In-Service | Nov 2014 |
| Expected in-Service | May 2018 |

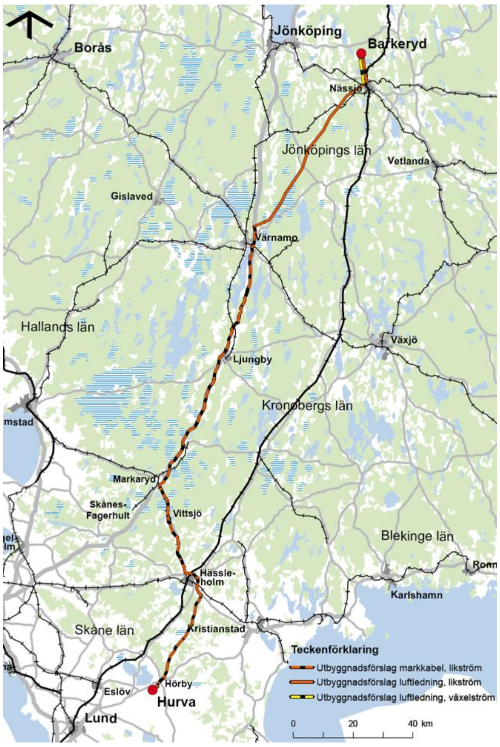

*Figure 17: Detail of the South West Link's location [32]*

The cable installation was completed approximately on schedule in April 2014, but the installation and commissioning of the convertors has experienced severe delays.

At the time of writing, the schedule for completion of the commissioning of the convertors is May 2018 compared to the original schedule of November 2014.

The cost estimation is still close to the budget despite the delay.

## 3.4 Great Britain (Western HVDC Link)

National Grid (owner of England and Wales transmission system, and operator of the GB system[1]) and Scottish Power Energy Networks (owner of the South Scotland transmission system) are jointly developing an 'embedded' HVDC offshore transmission circuit, from Ayrshire in Scotland to Deeside near Chester on the North Wales / Cheshire border: the Western HVDC Link. It will comprise 600 kV DC cables with giving a continuous power transfer rating of 2200 MVA with LCC HVDC converter stations at each end. A total of 385 km of the cable route will be undersea and 37 km underground [33].

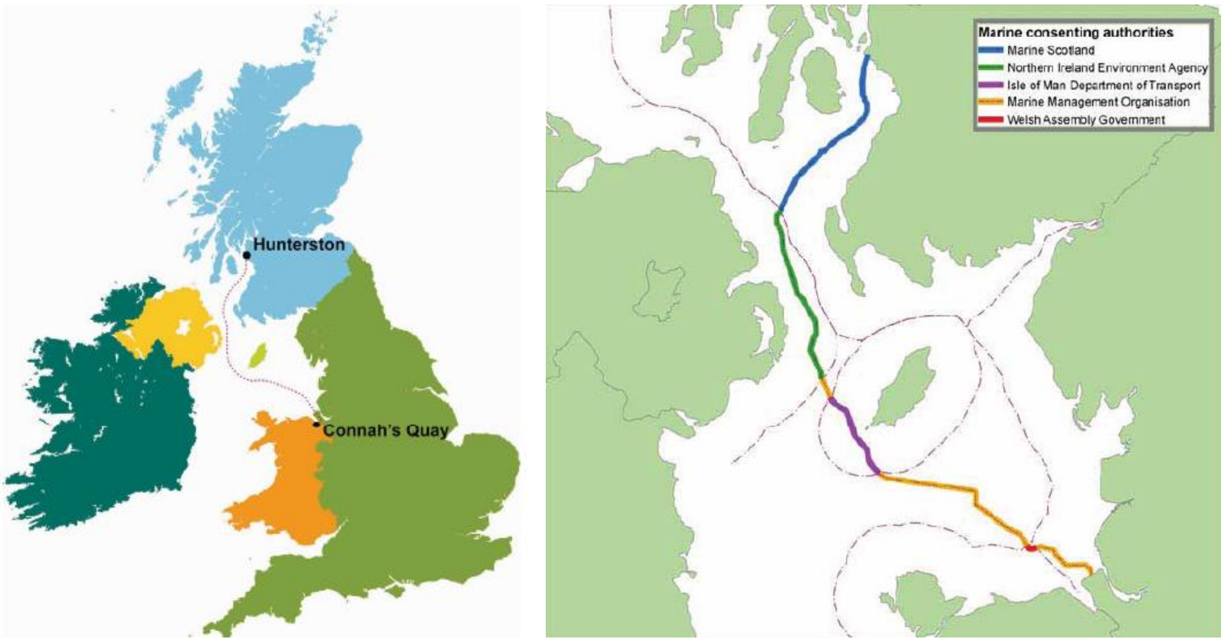

*Figure 18: Location of the Western HVDC Link undersea cable [34]*

Most HVDC links installed internationally are interconnectors, which connect two separate power markets. Investment in them is typically justified on the basis of the economic benefits of enabling flows that exploit the difference in power prices between the two markets. In recent years, interconnectors predicated on security-of-supply benefits are rarer. Unlike an interconnector, the Western HVDC Link lies entirely within the single Great Britain (GB) system and will operate in parallel with the meshed AC network.

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[1] At the time of writing, the system operator (SO) and transmission owner (TO) parts of National Grid are being split. The Western HVDC Link is being developed and will co-owned by the TO part.

*Figure 19: Aerial view of the converter station under construction at Hunterston [35]*

*Figure 20: A section of underground cable under construction on the Western HVDC Link [36]*

When the project was first proposed, there was considerable uncertainty regarding the future background of generation capacity in different parts of GB. If the expected volumes of new wind farm connections in Scotland materialised and most existing thermal plant remained open, investment in significant transmission network export capability from Scotland would be justified from the perspective of reducing the annual cost of curtailing wind generation in the North and running additional plant in the South. However, it remained to be determined what level of enhanced capacity might be justified and what form it would take.

*Figure 21: Cable laying vessel for the Western HVDC Link [36]*

Considerable work has been undertaken in the last decade to increase the export capability from Scotland. This has involved uprating of the two pre-existing 275 kV double circuit overhead lines across the border between Scotland and England to 400 kV operation and reconfiguration and reconductoring of circuits within Scotland. A rotor angle stability constraint that has, historically, limited exports from Scotland has been addressed by means of series compensation installed on the cross-border circuits, a first in Britain and unusual worldwide in that the series compensation connects two large, meshed areas. The cost of these developments included not only the equipment procurement and construction work but also the costs of constraints of power flows while the long construction outages were to allow reconfiguration of reconductoring work to take place. Any further enhancement of export capability would require the building of one or more new lines through areas that are relatively undeveloped but border tourist areas such as the Lake District and Northumberland.

According to what is reported in [37], the scale of development of an onshore overhead line (which would need to be more than 300 km long from Central Scotland deep into Northern England) and the timescales to gain planning consents meant that an onshore overhead line was not regarded a serious alternative to the Western HVDC. The relatively shallow depth of the sea off the coast of Britain and the potential access strong 400 kV bussing points quite near to the coast suggested that an undersea cable link may be viable. With a length of more than 350 km, it would be HVDC. However, the cost of a very long cable plus two HVDC converter stations would be considerable. In advance of running an extensive tender process, the developers estimated capital costs based on discussions with suppliers and intelligence of similar projects world-wide as part of the cost-benefit analysis. The other main elements were the constraint (or congestion) costs saved over the lifetime of the scheme and the reduced costs of network losses.

Compared to the alternative of an onshore AC overhead line development, the Western HVDC Link, being offshore, clearly has major benefits of visual amenity (at least, away from the large converter stations) and, for the vast majority of its length, is very far from any stakeholders who might express concerns about electromagnetic fields.

Confidence in future generation scenarios and the associated benefits in terms of reduced congestion costs took some time to establish with the regulator, Ofgem, from which approval of recovery of the capital expenditure was required. When its development was given outline approval, tenders were invited with value given to maximisation of the power transfer capacity. This led to the use of LCC bipoles rather than VSC. To avoid additional cost, only two cables are being laid each with a world record high rating of 600 kV with no earth return cable. As the use of a ground or seabed return is forbidden in the UK, this means that an outage on one or other of the cables would render the entire link inoperable. However, the converter stations are being configured such that, wherever possible, a fault would still enable monopole operation (with half of the usual power transfer capability). The converter stations have also been 'overrated' relative to the cables' nominal 2.2 GW rating so that the cables' cyclic rating can be used when necessary.

The Link was originally scheduled for commissioning in 2015. However, problems with the manufacture of the cables by Prysmian led to a 2-year delay (and the issue of a profit warning by Prysmian) [38]. In September 2017, a fire on a cable sealing end at the substation at the Northern end [39] led to further delay, estimated to be of the order of 6 months.

As yet, nothing has been published on quite how the Link will be operated once it is commissioned. As has been noted in section 2.5, HVDC offers benefits in terms of controllability: unlike for an AC line operating in parallel with other AC lines, in normal operation the system operator can choose exactly how to dispatch power on the HVDC line. However, the system operator must decide on what basis to make that choice. Exactly what benefits will accrue in terms of reduced congestion cost will depend on that judgement [40].

## 3.5 Stevin project (Belgium)

The Stevin project reinforces the Belgian grid between the cities of Zomergem and Zeebrugge [41].

The overall project is composed of:

- construction of an AC double circuit high voltage connection at 380 kV with a route length of 47 km. The connection is partially overhead, partially cable. The rated power is 6000 MVA.
- three high voltage substations (Zeebrugge, De Spie and Vivenkapelle).
- removal or cabling of existing 150 kV links.

53 km of existing overhead lines at 150 kV will be taken down during the project. A further 35 km of existing 150 kV will be undergrounded after finalising the 380 kV link.

The new 380 kV connection reuses 16 km existing right of way, 10 km is undergrounded including a tunnel for crossing the Boudewijn Channel and 21 km are new overhead lines right of way, totalling a length of 47 km.

The objectives of Stevin are fourfold:

1. improving the security of supply of Belgium as a whole and West-Flanders in particular, even if electric energy demand increases due to the growth of the port of Zeebrugge;
2. connecting new generation units based on renewable energy (on- and offshore wind, solar, biomass, CHP, …) to the main grid.
3. landing the offshore wind energy parks and linking Belgium to a future North Sea grid;
4. enabling the international connection to the UK for import and export, the so-called NEMO link [42].

The project started in 2015 and was expected to take 3 years. At the time of writing, it is under final commissioning.

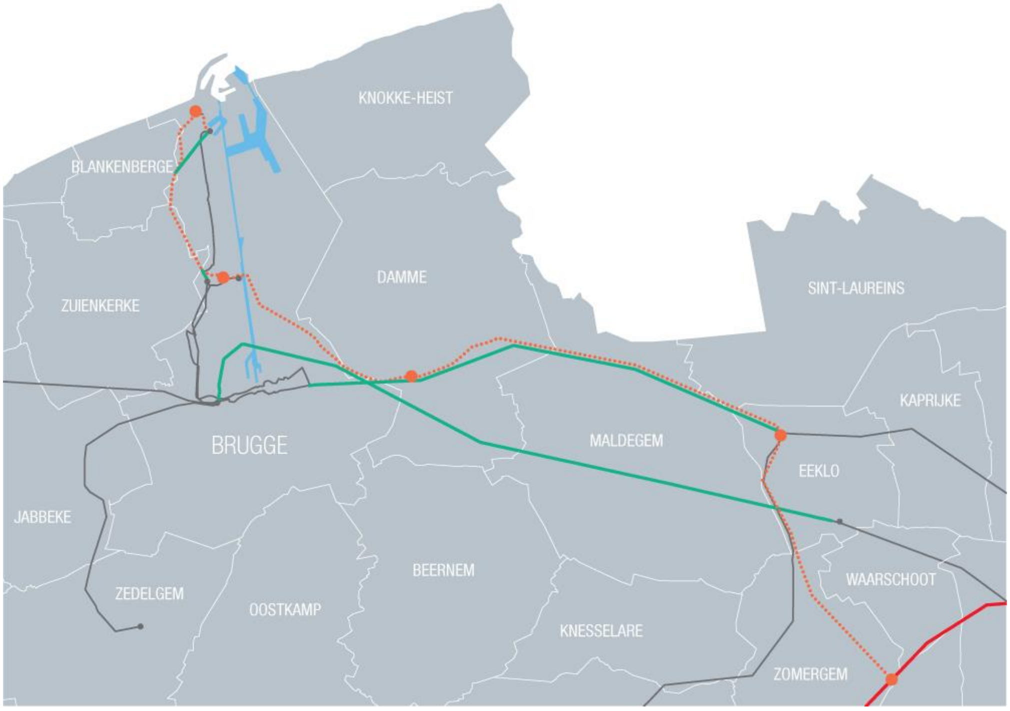

*Figure 22: The route of Stevin project [41]*

FASEN WERKZONE

| FASE | STUK | TIMING |
|---|---|---|
| 1 | J5-J4 | 5/1/16 - 20/5/16 |
| 2 | J4-J3 | 28/1/16 - 1/7/16 |
| 3 | J3-J2 | 3/3/16 - 1/7/16 |
| 4 | J2-J1 | 7/3/16 - 30/8/16 |
| 5 | J1-VM | 11/4/16 - 30/9/16 |
| 6 | J5-J6 | 8/6/16 - 30/11/16 |
| 7 | J6-J7 | TOT 28/2/17 |
| 8 | J7-J8 | TOT 31/3/17 |
| 9 | J8-J9 | TOT 31/3/17 |
| 10 | J9-J10 | TOT 10/7/17 |
| 11 | J11-GEZ | TOT 10/7/17 |
| 12 | J10-J11 | TOT 10/7/17 |

*Figure 23: Stevin project: routing of the AC underground cable showing section joints and installation dates [41]*

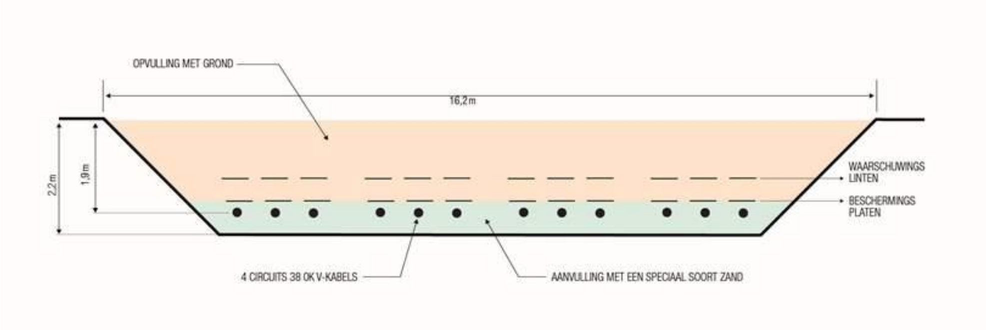

*Figure 24: Stevin project: cross-section of cable trench [41]*

The cable portion of the route consists of 12 cable sections, divided amongst 4 parallel three phase systems. Between each three-phase system is a space of 3 m. The trench is 16 m wide and 2.2 m deep. The overall length is divided in 12 pieces of between 800 and 900 m in length.

Each joint between cable sections has to be accessible for inspection and is 0.5 m below the surface. The access points are illustrated in Figure 25 and Figure 26.

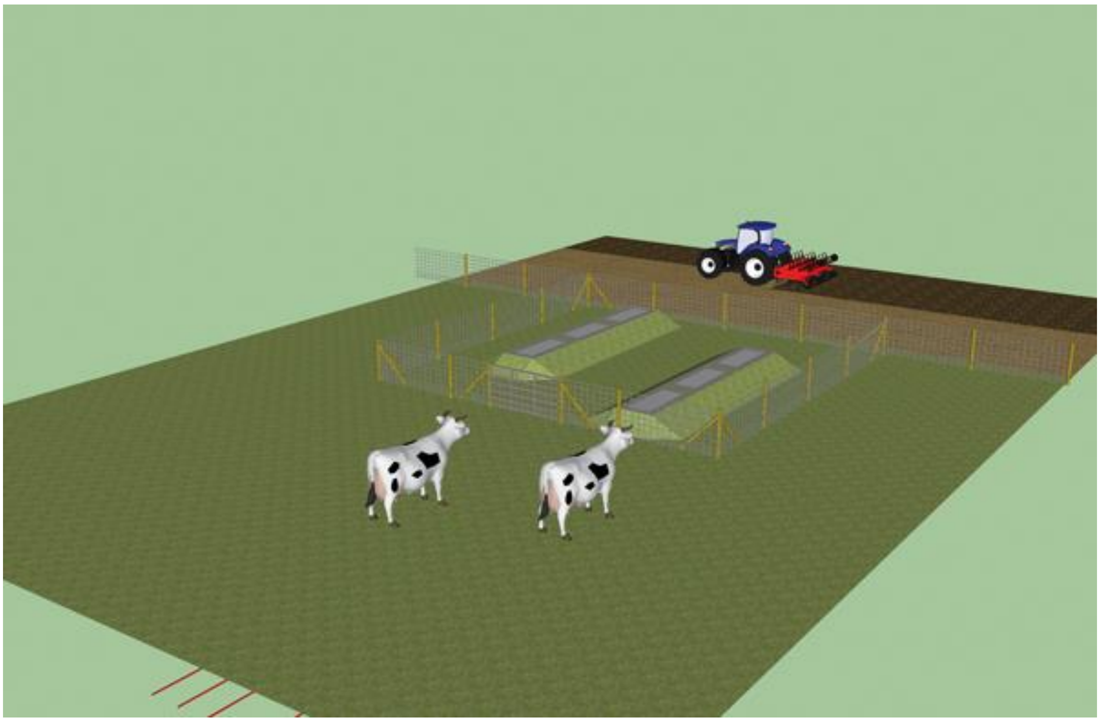

*Figure 25: Stevin project: illustration of cable access points [41]*

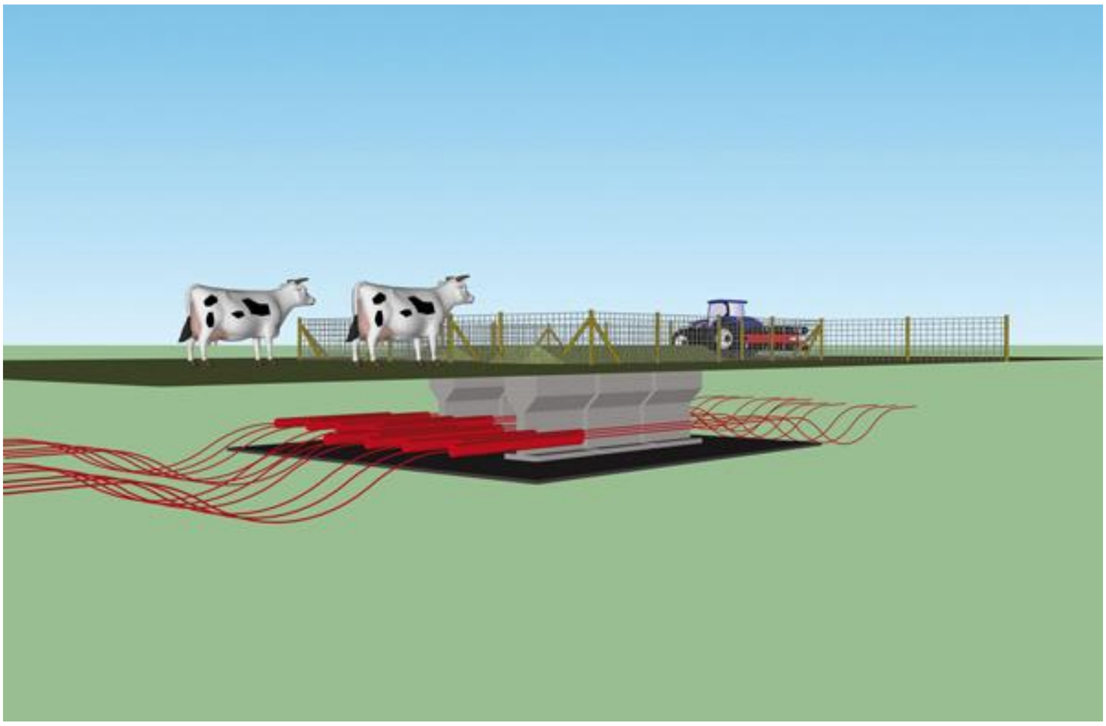

*Figure 26: Stevin project: illustration of underground cable access below ground [41]*

The crossing of Boudewijn Channel is done by a tunnel. The diameter of the vertical shafts is 14 m and each is 32 m deep (Figure 27).

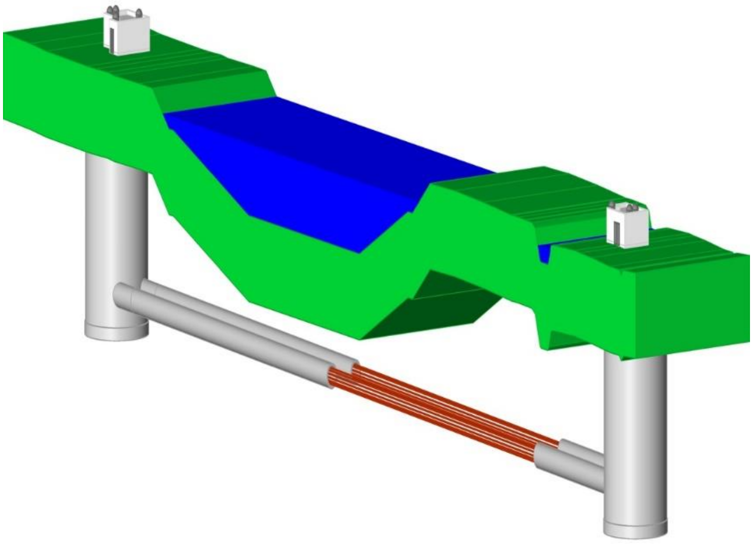

*Figure 27: Stevin project: Boudewijn Channel crossing [41]*

At each side of the cable link a high voltage substation is needed for linking the cable to the overhead line (Figure 28). Gas-insulated switchgear (GIS) is used. Inductors for reactive power compensation are installed.

*Figure 28: Stevin project: substation connecting overhead line and underground cable sections [41]*

The overall cost of the Stevin project (all elements discussed) is estimated to be 270 M€. Although the 10 km cable section represented only 21% of the total route length, the cable portions more than doubled the cost.

## 3.6 Randstad project (The Netherlands)

The project is divided into a north (between Zoetermeer and Beverwijk) and south (between Wateringen and Zoetermeer) ring.

The whole route is around 80 km, where around 20 km of it will be realized with 380 kV AC underground cables. For the overhead lines a new type of pylon has been designed (Wintrack, – Figure 29), which, in tests, produced no magnetic fields beyond 100 m distance from the line corridor centre[2].

*Figure 29: 'WinTrack' towers used for overhead line sections [44]*

The total cable length of the connection is 20 km in two sections. The rated current of the cable is 4000 A with 2 cables per phase, i.e. c. 1000 MVAr at 400 kV[3]. Reactive compensation is foreseen at 380 kV transformers of 11 × 100 MVAr.

The TSO responsible for the project, TenneT, has published a position paper in which the various element of cost are outlined [45]. The cost for a single circuit overhead AC line is reported as 2.3 M€/km and for an AC cable as 12.3 €/km, i.e. roughly 10 M€/km or more than 5-fold difference.

## 3.7 Hinkley Point C link (Great Britain)

Another high voltage network project in Europe proposed to progress using OHL and non-conventional towers is that for the accommodation of Hinkley Point C nuclear power station in the South West of England, planned for commissioning in 2025 [46][47]. A competition for the development of more aesthetically pleasing towers was run by National Grid, the transmission owner in England and Wales, in 2011 and the winner – the T-pylon (Figure 30), which is also 10 m shorter than an equivalent steel lattice tower – has since been further developed and is part of the plans for network reinforcements related to Hinkley Point C's connection [48].

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[2] A good view of the lay-out of the WindTrack design can be seen in a video available here: https://www.tennet.eu/nl/ons-hoogspanningsnet/onshore-projecten-nederland/randstad-380-kv-noordring/

[3] The cable laying process can be seen in a video available here: https://www.tennet.eu/nl/ons-hoogspanningsnet/onshore-projecten-nederland/randstad-380-kv-noordring/

In August 2017, the British office of gas and electricity markets, Ofgem, challenged the costs of the Hinkley Point C connection project highlighting, among other things, the cost of the 116 T-pylons, claimed to be 65 M£ more than if conventional towers were used, a figure made up of 17 M£ of T-pylon development costs attributed to the Hinkley project and 48 M£ of additional steel and foundation costs. On the other hand, National Grid claims visual amenity benefits of between 12 M£ and 39 M£ based on surveys of theoretical consumer 'willingness to pay' [49].

*Figure 30: National Grid's 400kV T-pylon [48]*

# 4 HVDC with underground cable: estimated cost of development

In its report published in early 2012, the Commission expressed its opinion that only viable means by which the North-South interconnector could be fully undergrounded would be through use of ‘embedded’ HVDC. However, the additional cost of doing so, relative to use an AC OHL, should be established.

For the Commission’s 2012 report the cost structures shown in Table 3 and Table 4 were established based on available cost data available in 2011 [9][4].

*Table 3: 2011 estimates of the cost comparison between OHL and VSC HVDC with cables for North-South [9]*

| Concept | Length km | Terminals M€ | Line/ Cable M€/km | Total M€ | Relative Cost |
|---|---|---|---|---|---|
| 400kV OHL 1 × 1400MW | 140 | 20 | 1.05 | 167 | 1 |
| 2 × 700 MW VSC HVDC +<br>2 × 700 MW UG cable | 140 | 310 | 1.36 | 500 | 3.0 |

*Table 4: 2011 estimates of costs of alternatives with reduced ratings [9]*

| Concept | Length km | Terminals M€ | Line/ Cable M€/km | Total M€ | Relative Cost |
|---|---|---|---|---|---|
| 1 × 700 MW VSC HVDC +<br>1 × 700 MW UG Cable | 140 | 160 | 0.9 | 286 | 1.7 |
| 1 × 700 MW VSC +<br>2 × 700 MW cables | 140 | 160 | 1.36 | 350 | 2.1 |
| 1 × 1000 MW VSC +<br>1 × 1000 MW UG Cable | 140 | 210 | 1.2 | 378 | 2.3 |

The Commission’s 2012 report presented an extensive discussion of key factors such as metal prices that affect the cost of transmission network developments. Since 2011 there has been a large number of HVDC systems awarded so there is a good base to update the cost figures for an HVDC based underground alternative.

Data regarding the total cost of most of the contracted projects are available in public sources. However, for many projects there is no breakdown of convertor and cable costs. Table 5 shows a summary of costs for HVDC projects ordered since 2011. Note, however, that these are the EPC costs normally found in media communication from EPC Contractors[5].

To this, project development costs and project related costs borne by the owner / operator must be added. These costs can be assumed to be about 25% of the final project cost.

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[4] As part of its submission to An Bord Pleanála in 2015, EirGrid commented on the International Expert Commission’s cost estimates from the 2012 report. See [8].

[5] “EPC stands for Engineering, Procurement, Construction. The engineering and construction contractor will carry out the detailed engineering design of the project, procure all the equipment and materials necessary, and then construct to deliver a functioning facility or asset to their clients. Companies that deliver EPC Projects are commonly referred to as EPC Contractors” [50].

From Table 5, it is reasonable to assume the following costs including the 25% project development overhead.

Convertors:

- 700 MW: 200 M€ for one set of convertor stations
- 1000 MW: 290 M€ for one set of convertor stations

Cables including installation cost:

- 700 MW: 1 M€/km
- 1000 MW: 1.5 M€/km

*Table 5: Summary of published data on costs of recent HVDC projects.*

| **Year order** | **Year in service** | **Project** | **Countries** | **Application** | **Contract Value Meuro** | **MW** | **Voltage kV** | **Distance Total** | **Distance Sea** | **Distance Land** | **Conv Meuro** | **Conv MEuro/ MW** | **Cable Meuro** | **Cable MEuro/ km** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2011 | 2015 | Skagerrak 4 | Denmark/Norway | SubSea | 241 | 700 | 500 | 140 | 140 | 0 | 154 | 0,22 | 86 | 0,62 |
| 2011 | 2017 | DolWin2 | Holland | Off-Shore | 857 | 916 | 320 | 135 | 45 | 90 | 0 | 0,00 | 0 | 0,00 |
| 2011 | 2015 | SylWin1 | Holland | Off-Shore | 857 | 864 | 320 | 160 | 160 | 0 | 0 | 0,00 | 248 | 1,55 |
| 2011 | 2015 | IFA 1 | France - Spain | Landcable | 557 | 2000 | 320 | 65 | 0 | 65 | 466 | 0,23 | 90 | 3,00 |
| 2012 | 2015 | ÅL-Link | Åland | Submarine | 111 | 100 | 80 | 158 | 158 | 0 | 0 | 0,00 | 0 | 0,00 |
| 2012 | 2018 | Sydvästlänken | Sweden | Underground + OH | 394 | 1200 | 320 | 190 | 0 | 190 | 222 | 0,19 | 137 | 0,72 |
| 2013 | 2017 | Dolwin 3 | Germany | Offshore + Land | 866 | 900 | 320 | 162 | 83 | 79 | 513 | 0,57 | 350 | 2,16 |
| 2014 | 2017 | Maritime Link | Canada | SubSea | 343 | 500 | 200 | 360 | 360 | 0 | 0 | 0,00 | 0 | 0,00 |
| 2014 | 2018 | Caithness Moray | Scotland | Subsea | 484 | 800 | 320 | 160 | 160 | 0 | 0 | 0,00 | 0 | 0,00 |
| 2015 | 2021 | NSN | Norway - UK | Subsea | 1257 | 1400 | 525 | 740 | 740 | 0 | 385 | 0,27 | 869 | 1,17 |
| 2015 | 2020 | Nordlink | Norway - Germany | SubSea | 1200 | 1400 | 525 | 623 | 623 | 0 | 385 | 0,27 | 812 | 1,30 |
| 2015 | 2019 | NEMO | Belgium - UK | Subsea | 496 | 1000 | 400 | 140 | 130 | 10 | 0 | 0,00 | 0 | 0,00 |
| 2015 | 2019 | Frejus | France - Italy | Landcable | 1397 | 910 | 320 | 190 | 0 | 190 | 299 | 0,33 | 479 | 2,52 |
| 2016 | 2019 | Cobra | Denmark - Holland | Subsea | 411 | 480 | 320 | 325 | 325 | 0 | 167 | 0,35 | 244 | 0,75 |
| 2016 | 2019 | Alegro | Belgium - Germany | Landcable | 399 | 1000 | 320 | 90 | 0 | 90 | 274 | 0,27 | 124 | 1,38 |
| 2017 | 2023 | Dolwin 6 | Germany | Offshore + Land | 1028 | 900 | 320 | 90 | 45 | 45 | 0 | 0,00 | 0 | 0,00 |
| 2017 | 2020 | ElecLink | France - UK | Land | 437 | 1000 | 320 | 51 | 0 | 51 | 316 | 0,32 | 120 | 2,35 |
| 2017 | 2020 | IFA 2 | France - UK | Subsea + Land | 621 | 1000 | 400 | 225 | 200 | 25 | 269 | 0,27 | 350 | 1,56 |
| 2017 | 2020 | India VSC | India | Land | 446 | 1000 | 320 | 200 | 0 | 128 | 0 | 0,00 | 0 | 0,00 |

A general observation is that the costs for both the planned AC OHL option and the HVDC, underground cable alternative have increased since 2011. For the present update report, a comparison has only been done with two HVDC alternatives: 2 × 700 MW and 1 × 1000 MW. The overall conclusion is that the cost relation to an AC OHL development is very similar to the estimations done in 2011. (Table 6).

*Table 6: Updated cost comparison between AC OHL and HVDC with underground cable*

| Concept | Length km | Terminals M€ | Line / Cable M€/km | Cable Total M€ | Total M€ | Relative Cost |
|---|---|---|---|---|---|---|
| 400 kV AC OHL 1 × 1400 MW | 140 | | | | 230 | 1.0 |
| 2 × 700 MW VSC HVDC with UG Cable | 140 | 400 | 2 | 280 | 680 | 3.0 |
| 1 × 1000 MW VSC HVDC with UG Cable | 140 | 290 | 1.5 | 210 | 500 | 2.2 |

# 5 System context of planned new North-South interconnector

## 5.1 The situation today

As noted in, for example [3], the electricity system of Northern Ireland is currently interconnected to that of the Republic of Ireland via one 275 kV double circuit between Louth and Armagh with a continuous thermal rating in Winter of 1662 MVA (2 × 881 MVA) and two 110 kV single circuits, one between Donegal and Tyrone and the other between Cavan and Fermanagh each with a winter rating of around 128 MVA [2]. In order to ensure a sufficiently reliable supply, electricity systems around the world are operated in a 'N-1 secure' manner, meaning that, were any single unplanned fault outage event to occur (generator, busbar, transformer, transmission line, …), the majority of demand would still be met and operational limits on individual system assets would still be respected in order that the meeting of the rest of the demand is not threatened.

The critical fault outage affecting power transfers between the Republic of Ireland and Northern Ireland is that of the 275 kV double circuit. Its loss would cause the power to be transferred via the two 110 kV circuits. If the amount of power is too high, both circuits would be overloaded and tripped. In practice, a protection system is installed that, in the event of a loss of the 275 kV route, automatically trips them. This leaves the network in Northern Ireland isolated from that in the Republic: demand in the North must be met exclusively from generation in the North. The loss of the link with the Republic would mean that, if the North was exporting to the South at the time, there would an excess of generation in the North. If the North had been importing, i.e. using some power from the South to help meet demand in the North, there would be a deficit of generation relative to demand.

In any one synchronous area, i.e. a power island, generation and demand must be perfectly balanced. This is normally managed for the whole of the island of Ireland but, with a disconnection between Northern Ireland and the Republic, each power island must be balanced independently. Disturbances such as loss of generation, changes to demand or faults on interconnectors to other systems affect this balance. In order to ensure stable system operation, there should be a rapid response to correct the imbalance. In theory, this could be achieved by changing the demand but, to date, it is has been more common to change generation. However, this depends both on having scheduled enough 'headroom' to increase outputs or 'footroom' to decrease it and on the physical capability of a power plant to change its output sufficiently quickly. When dealing with renewable generation like wind, this is far less evident, however. This leads to a practical limit of power transfers between the Republic of Ireland and Northern Ireland at present of 300 MW [1] . If any more power than that were being transferred and the 275 kV double circuit suffered a fault outage, generation in Northern Ireland would be unable to respond quickly enough to maintain stability of the islanded Northern Irish system. A further connection between North and South would mean that the loss of the 275 kV route would not entail the creation of two power islands. Similarly, if the new route were disconnected due to a fault, the existing 275kV route would remain. With the new line in service, in winter the capacity judged by EirGrid to be required by the market that could be made available would be 1300 MW. Due to the power flows, the 110 kV lines do not currently contribute to a further increase of the capacity.

## 5.2 Embedded HVDC as an option for tomorrow

The discussion of different technologies in section 2 has reviewed different options for the implementation of a new connection between Northern Ireland and the Republic. It has concluded that an AC connection with more than a few km of undergrounding is impractical and that the only means by which a new route of any significant length could be fully undergrounded would be through use of HVDC. In order that the existing interconnections can continue to be used, this would mean the new HVDC route running in parallel with them and being embedded within a single synchronous area.

As discussed in section 2.6, embedded HVDC is not without precedent. Such a connection has been in operation between Finland and Sweden for a number of years and another was commissioned between France and Spain in 2015 (section 3.1). Further embedded HVDC links are under construction or planned, including the Western HVDC Link in Britain (section 3.4) and ALEGrO between Belgium and Germany (section 3.2).

A CIGRE Working Group in 2013 summarised the drivers for development of embedded HVDC as [52]:

1. the ability to overcome practical limitations to the lengths of AC underground or undersea cables;
2. maximisation of power transfer capability through a given physical corridor being able to carry power when operating with DC than with AC; and
3. dependent on the HVDC technology used (LCC or VSC), the ability to offer some advanced control functions within the AC network such as optimal power flow control, voltage control, system transient stability improvement, low frequency damping and the prevention of system cascading failure.

The CIGRE working group also noted some disadvantages of embedded HVDC [52]:

1. Footprint: although, for a given power rating, an HVDC route typically requires a smaller right-of-way than an AC route would need, the converter stations occupy significant space.
2. Synchronisation: in contrast to an AC connection, HVDC does not inherently contribute to maintaining a synchronous link and allowing system frequency management to be naturally pooled between different areas. A dedicated control system must be designed to provide frequency control at the required end of the link.
3. Cost: except for very long distances (typically a few hundred km), HVDC technology is more expensive than HVAC.[6]
4. Sub-synchronous torsional interactions (SSTI): when connected close to generation units, the HVDC link's controls can interact adversely with the dynamics of generation equipment. The HVDC controls must be specifically designed to mitigate this and the nearby generators must have special protection.
5. Multi-point connection: an extension of an HVDC link to tee in other connections is complex and expensive and has been demonstrated at scale in only a few instances worldwide. Control of the multiple terminal also becomes more complex.
6. Flexibility: the flexibility provided by HVDC has a price in terms of complexity which implies dedicated education and training both for system operators and for maintenance teams.[7]

The first thing that limits the power that any given line can carry is the fact that the current carried causes heating. The conductors have strict temperature limits; if, at a certain level of current, the heat cannot be removed, the current and, hence, the power transferred, must be limited. That is, the line, whether is overhead or underground, has a thermal rating[8]. Today it is becoming conventional to equip new HV UGC with temperature measurements all along the cable enabling a real time monitoring of the cable temperature. Given the very high thermal time constants, this allows higher pre-fault loading of cables where any increases in loading following an unplanned outage of another circuit can be reduced in sufficient time by system operator corrective actions.

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[6] The 'break-even' distance at which HVDC is cheaper than HVAC is shorter for cable based systems than for overhead lines.

[7] Maintenance and commissioning is becoming a European business leading to a much less critical situation.

[8] Thermal ratings are typically quoted for different seasons reflecting the different ambient conditions and the ability to move heat away from the conductor.

One of the factors potentially limiting the operation of a number of AC lines operating in parallel is that it is generally not possible to fully utilise the total thermal ratings of all the lines. This is for two reasons:

1. to ensure sufficiently reliable operation of the system as a whole, it is generally regarded as prudent to operate it secure against the unplanned outage of any one line or route;
2. the different effective impedances of 'electrical distances' between the various sources and sinks of power via the different lines gives rise to different levels of power flowing on the different lines. This means that each line's utilisation relative to its thermal rating will be different. As the total power transfer is increased, one of the lines operating in parallel will reach its thermal limit and, regardless of the spare capacity on the other lines, the total power transfer cannot be increased any further.

A major advantage of HVDC is that, by virtue of the controlled switching of the power electronic devices that comprise the converters, the level of power transfer on the HVDC link can be actively controlled. This means that the share of the total power transfer between an embedded HVDC link and the AC lines with which it is operating in parallel can be actively determined with the result that the thermal capacities of each of the lines can be more fully utilised. To achieve a similar end with only AC lines operating in parallel with each other would require the installation of phase shifting transformers or other FACTS (Flexible Alternating Current Transmission System) devices into one or more of the lines though these have a much more limited and slower control range compared with an embedded HVDC link.

## 5.3 Embedded HVDC on the island of Ireland

A new 400 kV AC overhead line (OHL) connecting Meath to Tyrone has received planning permission in the Republic of Ireland. Once in operation, this would operate, in effect, in parallel with the existing 275 kV double circuit and the two 110 kV single circuits. The Commission's understanding is that the secure power transfer capability between the Republic of Ireland and Northern Ireland from South to North is currently around 300 MW, limited primarily by the frequency response capability of generation in the North. Following commissioning of the 400 kV OHL, this capability would increase to 1300 MW as a secured event would no longer lead to the electrical islanding of Northern Ireland and risk of frequency instability. North and South would remain as one synchronous area with frequency management shared across the interconnected system.

The main limiting factor affecting power transfers is what the situation would be following an unplanned fault outage. However, sharing of power between different lines can also be a constraint.

Following commissioning of the 400 kV OHL, the power transfer between North and South would flow over the lowest impedance routes. When the network is intact, these would be the 400 kV line and the 275 kV double circuit. Due to their higher impedances, much smaller amounts of power would be carried on the 110 kV lines. As was noted above, the 275 kV double circuit has a total continuous thermal rating in Winter of 1662 MVA. The new 400 kV has a Winter continuous rating of 1500 MVA. It might be asked whether, given the locations of generation and demand and the effective impedances of the two main routes – the 400 kV line and the 275 kV double circuit – the total, pre-fault power transfer will be shared equally between them. If not, it would not be possible to fully utilise the thermal rating of one or other of the routes. If the sub-optimal utilisation related to the new line, it might be asked whether its particular power transfer capacity was fully justified or whether some additional control capability was needed in order to utilise it. Such a control capability could be provided by a phase shifting transformer which would entail extra cost and physical footprint. However, an embedded HVDC link would have a comparable but larger control capability.

The Commission's understanding is that, in fact, because both the 275 kV double circuit and the new 400 kV OHL are connected into the same relatively strong 275 kV ring in Northern Ireland, the South to North power transfers are very shared between the two routes and the capability to change the power sharing between them is not required.

As has previously been discussed, in spite of its extra cost, an embedded HVDC link might be considered instead of the 400 kV OHL because it would allow its entire route to be undergrounded. The frequency and duration and, hence, the impact of faults needing to be repaired is particularly affected by the large number cable section joints. However, the repair time can be reduced by locating joints in maintenance pits, as is being done in the ALEGrO project. The optical fibre system used for cables temperature monitoring can also be used for fault location.

In common with standard practice worldwide, the power system on the island of Ireland is operated to be secure against any single unplanned fault outage event. In the case of an embedded HVDC link being built to complement the existing lines in enhancing the power transfer capability between North and South, the system should still be stable following a fault either on the HVDC link or on the existing 275 kV double circuit. In the event of the latter, because they would be overloaded, the two 110 kV circuits between Northern Ireland and the Republic would be tripped. This would lead Northern Ireland connected to the Republic only via

a) the Moyle HVDC interconnector to Scotland and then, via the Great Britain transmission system, the East-West HVDC interconnector;
b) the embedded North-South HVDC link.

The Commission's understanding is that part of the purpose of the planned North-South interconnector is to reduce dependency on expensive, fossil-fuelled generation in Northern Ireland to contribute to meeting demand in normal operation and provide frequency regulation following loss of the connection to the South. One advantage of an HVDC link is that the power through it can be quite precisely controlled. However, a disadvantage is that it does not naturally respond to system frequency variations or imbalances. Any response must be designed into the control system. Although the power electronic devices in the converters can themselves be switched very quickly, the measurement of relevant signals from the system and the determination of what a response should be can take time. In order to address the loss of power into Northern Ireland following the loss of the 275 kV double circuit and the two 110 kV single circuits, the HVDC links to the South and/or to Scotland should (a) have some pre-fault 'headroom', i.e. an initial power transfer into Northern Ireland that is less than the link's rating and (b) increase their power transfers into Northern Ireland following detection of a frequency deviation in the Northern Ireland power island. Unlike at present where frequency regulation in Northern Ireland is shared between at least two independent thermal generation units, stable system operation would be dependent on an HVDC control system doing that successfully in a timely fashion. If the response was scheduled on just one HVDC link, there would be a potential single point of failure. While the probability of control system failure may be regarded as small, the magnitude of the impact would be very large. In a future with an embedded HVDC link providing the new interconnection between North and South, the pre-fault power transfer into Northern Ireland would have been, at its largest, 1500 MW. With the HVDC link initially loaded at 1 GW, the imbalance resulting from loss of the 275 kV double circuit would be 500 MW. One or other or a combination of the HVDC links into Northern Ireland must have a 'headroom' – spare capacity relative to its pre-fault loading – equal to that. Failure by the HVDC link(s) to correct that imbalance utilising its pre-fault 'headroom' would, the Commission understands, result in collapse of the system in Northern Ireland with all demand lost. This would be around 1.8 GW at its peak. It may be assumed that it would take between 12 and 36 hours for all demand to be restored.

# 6 Conclusions

In its previous report published in 2012, the Commission did not recommend any solution as such. However, it recommended against fully undergrounding using an AC cable solution. It noted that, if the option is to underground the connection along the whole, or main part of the route, with the technology available at the time, the best solution would be a VSC HVDC solution combined with XLPE cables. It also stressed that an overhead line still offers significantly lower investment costs than any underground alternative and could also be made more attractive by investing slightly more in new tower designs, than the classical steel lattice towers now proposed.

The Commission's new review of the technical options for enhancing the power transfer capability between the Republic of Ireland and Northern Ireland has concluded that:

- Complete AC undergrounding is not viable; partial undergrounding is possible but with a limited total length of undergrounded sections [19][20].
- AC overhead line is viable; it would be possible to build the interconnection using new tower designs that are less visually intrusive but at an extra cost.
- A gas-insulated line (GIL) to cover the entire length would be extremely expensive and is, as yet, unproven anywhere in the world. Partial undergrounding using GIL would also be very expensive.
- The only viable means by which a high voltage interconnection of significant length could be completely undergrounded would be through use of an embedded HVDC link.

Embedded HVDC is not yet common worldwide but operational experience does exist and, within a few years, there will be at least four examples in Europe of comparable size.

Although the Commission regards it as a credible option, there are a number of aspects of the potential use of embedded HVDC in the context of enhancing the interconnection between Northern Ireland and the Republic that would require careful consideration. In particular, following a credible single fault event – the loss of the 275 kV double circuit between Louth and Armagh – it is likely that, as now, Northern Ireland would be left as a separate synchronous area connected externally only via HVDC. With a new HVDC link to the Republic of Ireland, there would be a second asynchronous connection to a neighbouring system in addition to that to Scotland. Control of system frequency and meeting of demand in Northern Ireland would depend on operation of generation within Northern Ireland and/or control of imports via the HVDC interconnectors. With HVDC VSC this can be envisaged. With suitable converter station controls, frequency control, reactive power regulation and even black start are all feasible. There would be major challenges associated with use of wind generation for the purpose of frequency regulation, not least its uncertainty. Other, fossil-fuelled plants could be used but their future in the all-island market is uncertain and reduction of dependency on it is part of the motivation for a new interconnection to the South.

It is the Commission's belief that one or both of the HVDC links could be used to contribute to regulation of a Northern Ireland power island following loss of the Louth-Armagh double circuit. However, this would introduce an additional complexity to their design and operation. Moreover, reliance on one or other would leave all demand in Northern Ireland vulnerable to a fault on it. Global experience of operation of HVDC suggests that such faults are quite rare and the probability of it occurring soon after there has also been an outage of the Louth-Armagh double circuit should be low. However, its impact would be high though little different to that of a fault on the planned 400 kV OHL North-South circuit soon after loss of the 275 kV interconnector. Although either of these 'N-2' circumstances should be very rare (and would be beyond the normal standards to which transmission system operation is secured[9]), not only would demand in Northern Ireland be lost but the sudden loss of what, from the perspective of the system in the Republic of Ireland, would be a very large load may threaten system stability in the Republic. In addition, although the performance of the new HVDC converters would be extensively tested in detailed simulations before entering service, full confidence in new control functionality would not be gained until it has been commissioned and used in the real system context. As noted, failure would have a major impact leading to loss of a large part of the demand for electricity on the island of Ireland with many hours required for restoration.

Finally, Irish experience of the reliability of HVDC to date has not been totally positive. In commercial operation since 2002 with a designed capacity of 500 MW, the Moyle interconnector has suffered a number of fault outages resulting in the capacity to import power into Northern Ireland being reduced by at least 150 MW for a total of 49000 hours up to the end of 2017, i.e. 38% of the time since entering commercial operation [51]. These unplanned outages are dominated by 46000 hours of unplanned unavailability or derating since 2011 due to cable faults, something that, due to the unique design of the Moyle cables, should not be expected to be repeated with any new installation. The unplanned unavailability due to causes other than cable faults has been only 2%. The East-West interconnector suffered four forced outages in 2014/15 and another in 2015/16 though none of these was extensive [53] .

Although, in the view of the Commission, an embedded HVDC option would be feasible, the combination of the system operator’s unfamiliarity with it, the control complexity and the risks – not just probability but also impact – associated with failure may, when combined with the extra cost of HVDC, be unattractive to the majority of electricity system users on the island of Ireland.

One particular factor relevant to the potential use of embedded HVDC in the context of North-South is worthy of note. A number of parties with which the Commission has consulted have expressed the need for economic development in the areas through which the planned North-South interconnector passes. They have pointed specifically to the possibility of attracting investment in new industrial or commercial facilities that have a need for significant amounts of electrical energy, in particular data centres. These, the Commission has been told, would bring jobs particularly in the construction sector but also for maintenance and operation. However, the investment would likely only come if access to sufficient, reliable electric power was not prohibitively expensive. At present, network constraints mean that only certain locations would meet this criterion. Development of the North-South interconnector would extend the set of viable locations to include the counties of Monaghan, Cavan and Meath. However, development of a North-South interconnector as an embedded HVDC system would not achieve this at an acceptable cost. While ‘teeing’ into an HVDC link is technically feasible, at the time of writing it has been demonstrated at scale using voltage source converter technology only in two, very new instances in China. It would also be very expensive requiring the construction of a third converter station and new cable joints at the ‘tee’ point. The whole multi-terminal HVDC system would need to be configured in a very particular way to provide the minimum ‘N-1’ security that a data centre would require.

Strictly limited partial undergrounding of an AC interconnection is possible but our understanding is that a further ABP enquiry would be necessary. This would add greatly to the cost, not so much in terms of the cost of people’s time to develop a new proposal and submit to and conduct the enquiry (which would be significant) but in terms of continued operation of the all-island electricity market at a much higher cost than would have been the case had the power transfer capability been enhanced at the date currently planned. The Commission’s understanding is that a further ABP enquiry would add at

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[9] Transmission systems worldwide are typically operated to ‘N-1’ security.

least two years to the development time with an annual constraint cost of, according to EirGrid, between 13 and 20 M€ in the early years. A requirement to deliver the enhanced power transfer capability as embedded HVDC would, the Commission has been advised, add at least 5 years to the delivery timescales. Based on current central estimates, this would add approximately 120 M€ of additional constraint costs to the extra cost of building the link as HVDC compared with the currently planned AC overhead line (OHL)[10]. The Commission's own estimate of the extra capital cost of 1 × 1GW VSC embedded HVDC for a North-South interconnection compared with the planned 400kV AC OHL is 270 M€ giving an estimated total extra cost of 390 M€ or, with 2 × 700MW, 570 M€. In addition, experience from a number of recent HVDC projects, in particular offshore projects and the South-West Link project in Sweden, shows significant delays relative to the planned timescales. However, it may also be noted that not all HVDC projects have experienced delays, e.g. the new NEMO interconnector between Belgium and GB is on schedule, and delays are more likely when a 'first of a kind' technology or its first implementation by a particular manufacturer is being used. In addition, delays are not unique to HVDC projects.

It has not been within the Commission's scope to review either the routing of the approved 400 kV OHL or stakeholders' concerns about electro-magnetic fields (EMF). We note that reputable other studies have addressed EMF questions. Our understanding is that no concerns have been flagged by these studies. Here, we note our understanding that the planned development of the 400 kV OHL North-South fully complies with international standards regarding minimum distance from dwellings.

The Commission's overall finding is that, from a techno-economic point of view, an AC overhead line is the most beneficial way of meeting the need for enhanced power transfer capability between the Republic of Ireland and Northern Ireland. Other alternatives exist any of which would significantly delay enhancement of the network and add to the cost. The option of embedded HVDC with underground cable is the most credible in respect of extensive undergrounding. However, this would add significantly to the cost while providing only one notable benefit: that of hiding the line itself entirely from view.

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[10] The estimate is based on quotes of additional annual energy costs of €20m in 2020 and €40m in 2030 [1] with an assumed linear rise in the intervening years.

# 7 References

[1] EirGrid, “The Need for a second North-South Electricity Interconnector”, *North-South 400 kV Interconnection Development Environmental Impact Statement*, submission to An Bord Pleanála, Volume 3B - Appendices (Appendix 2.1), May 2015.

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# A. Electric and magnetic fields

As several parties present electric and magnetic fields as an element in the choice for potential undergrounding of the connection, we provide an overview of the technical elements here, in order to clarify the situation.

Electric and magnetic fields are everywhere in our modern society as they surround all active applications of electric energy and data processing (computers, mobile phones, microwave ovens, cooking furnaces, light, ….).

High voltage installations generate so-called Extremely Low Frequency electric and magnetic fields. A lot of questions have been raised over the last decades on their potential impact, for instance:

- What is the difference between electric and magnetic fields?
- Do they have an impact on the health of people living nearby?
- What are the values?
- Are standards and regulations available?

## A.1 Basic physics

Electric and magnetic fields are everywhere around us. We are constantly exposed to them. The notion of “fields” is introduced in physics to indicate the influence of an object on its surroundings. An example is the “gravitation field”, describing, for example, the mutual attraction of the Earth and other objects such as the Moon. A thermal field surrounds a heat source (for instance an infrared lamp).

The electric field describes the attraction and repulsion forces between electric charges that are present in an area (electrons, ions, …). The field strength is higher when more charges are present and when they are closer to each other. Electric fields are present in nature for instance high in the atmosphere. At the Earth’s surface in general, it is rather small. During thunderstorms, the field may be extremely high, leading to lightning strikes.

The electric field is linked to charges. The unit is the V/m (Volt/metre) indicating that the voltage is the driver: the higher the voltage, the higher the electric field. The field weakens as the distance to the source increases.

The magnetic field is generated by a displacement of electric charges, i.e. a current. The best-known example is the Earth’s magnetic field, used to orient the needle of a compass to the (magnetic) North Pole; it is a result of electric currents, flowing in the kernel of the Earth.

The magnetic field is linked with currents, the unit for the field strength H is A/m (Ampère/metre). Often Tesla is used as unit, being the magnetic flux density B. (The ratio between B and H in air is a constant, $B=\mu_0 \times H$. $\mu_0$ is the so-called permeability of vacuum (or air) indicating that B and H are proportional). Magnetic flux density values encountered in practice around high voltage systems are in the order of one millionth of 1 T, being μT. The higher the current in a conductor, the higher the magnetic field. The field becomes weaker as the distance to the conductor increases.[11]

As electric and magnetic fields both are linked with the presence of electric charges, they do interact. They are part of our everyday life. Radio, television, mobile phones, WiFi, Bluetooth, … all use electromagnetic waves for the transmission of data. Electric charges create an electric field that exerts forces on other charges in their surroundings. The latter may start to move due to these forces, generating a current, producing a magnetic field, that in its turn produces a force on other currents, ….

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[11] In older texts, sometimes the Gauss is used as unit for the magnetic flux density. 1 Gauss= 1G = 10 μT

These interactions have been formulated in a mathematical model by James Clerk Maxwell in 1864, probably the physics researcher with the largest impact on society ever.

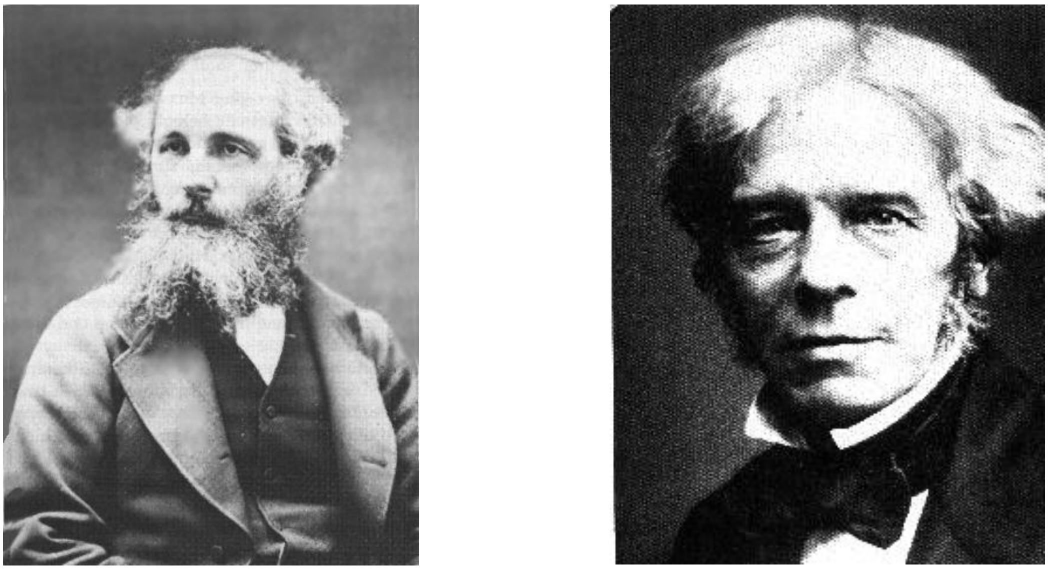


*Figure 31: James Clerk Maxwell (left) and Michael Faraday (right)*

At high frequencies, the fields are traveling as waves in space, called radiation. The wavelength is the distance a wave travels during one full cycle of the oscillation. Frequency and wavelength are coupled: the higher the frequency, the lower the wavelength. If the frequency is very low, as is the case with power systems, the wavelength is extremely high. At such frequencies, the interactions between electric and magnetic fields are very small, and both phenomena can be treated independently.

The unit to the describe the speed of change of an oscillation, i.e. the frequency, is Hertz (Hz).

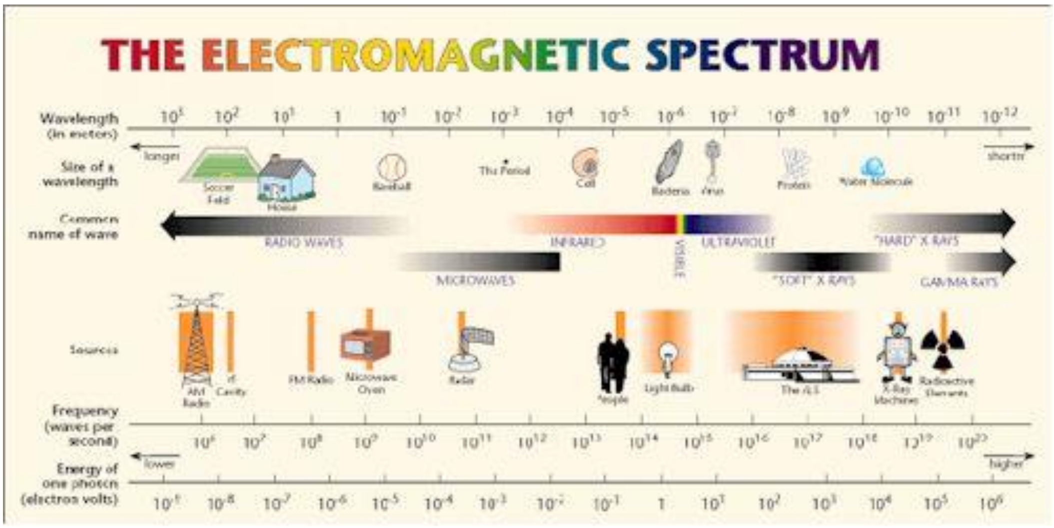


*Figure 32: The electromagnetic spectrum*

## A.2 Living nearby a high voltage line

In our everyday life, we are continuously exposed to electric and magnetic fields of natural or artificial origin. The human being as such has no receptor to "feel" them. However, we can notice some nuisance generated by the fields, mostly due to the electric, rather than the magnetic field.

### A.2.1 How do we notice electric fields?

We may feel some itching of the skin caused by vibrations of the hair on the head or on the arms/legs. Studies have shown that human beings can sense in this in 50-60 Hz fields of power systems with a value of 20 kV/m, only a limited number do sense fields of 5 kV/m. Values above 10 kV/m are only present in space where the general public is not allowed to enter.

Indirectly the electric fields may be noticed too. For instance, a biker passing beneath a 380 kV line may sense a current when touching the frame/handlebars: the equilibrium that is built up by the electric field under the line is disturbed leading to a very small, non dangerous current flowing through the person. Touching the metal portion of the handlebar and not the handles, when passing the line solves the problem.

When touching a metal body, for instance a large vehicle, standing under a high voltage line, light shocks may be felt, comparable to electrostatic discharges in extra dry weather conditions. Such shocks are not dangerous, but somewhat unpleasant. The problem may be solved by earthing the metal parts.

Near to a high voltage line in wet weather conditions (drizzling rain, fog, snow), a crackling noise may be noticed. This phenomenon is known as corona effect: the electric field generates small electric discharges, ionising the surrounding air molecules. This effect is amplified by moisture and dust. The high electric fields close to the conductor are causing the discharges.

When discussing electric fields nearby high voltage lines, the fields are rather low due to screening by natural elements like trees, plants and buildings. Every high voltage line creates an electric field. The strength of the field of a high voltage overhead line depends on a number of parameters:

- Voltage
- Configuration of the line (mutual placement of the phases, conductor type: bundles or single, distance between conductors)
- Distance between measuring point and the line

The mean value of the electric field under a 380 kV line at 1.5 m above the ground is roughly 4 kV/m and decreases rapidly as the distance to the line increases. At around 20 m, the field is 10 times weaker. At lower voltages (220, 150, 110, 70 kV) the electric field values are much lower.

### A.2.2 How do we notice magnetic fields?

Using up-to-date technology, no situations are left in which effects by magnetic field can be noticed. As a mere illustration, we mention two examples from past technology that illustrate the impact of magnetic fields.

Older pacemakers could be disturbed by magnetic fields, but new types are better shielded and no longer susceptible to these problems. Classical screens (TV sets and computer monitors using cathode ray tubes) where disturbed by magnetic fields, but their substitutes LCD and LEC screens show no interactions with them.

Magnetic fields are hard to reduce using natural screens. The magnitude depends on the current and the distance to the conductor. Also, classical household equipment produces magnetic fields. Table 7 gives an overview of some appliances.

The magnetic field of a high voltage line depends on the current it is carrying. As with the electric field, the magnetic field depends on the layout of the line and the distance. As the voltage is high (380 kV) given the rated power, the magnetic field is not extremely high, normally not above 4 $\mu$T and decreases fast as the distance increases.

*Table 7: Magnetic fields produced by domestic appliances*

| Appliance | Magnetic field generated by the appliance (μT) | | |
|---|---|---|---|
| | Distance 3 cm | Distance 30 cm | Distance 100 cm |
| Microwave oven | 10 to 100 | 1 to 10 | <1 |
| Hair dryer, mixer, drilling machine, vacuum cleaner, … | 10 to 100 | 0.5 to 5 | <0.5 |
| Furnace, vapor extractor in kitchen | 1 to 50 | 0.1 to 5 | <0.5 |
| Washing machine, tumbler dryer, dish washer | 0.5 to 10 | 0.1 to 5 | <0.5 |
| Clock radio, bed light | 0.5 to 5 | <0.5 | <0.1 |
| Television (LCD), computer | <0.5 | <0.2 | <<0.1 |

## A.3 General health and electric and magnetic fields

More than 40 years of research has not led to a formal proof that electric and magnetic fields at extremely low frequencies may cause health risks. It is scientifically impossible to exclude interactions as such, causing anxiety and confusion with part of the general public. Therefore, research continues to look for potential short and long term effects.

Electric and magnetic fields may produce forces on charged particles in the body, leading to electric fields within the body and generating small electrical currents. These induced currents may cause biological effects in the body, categorized as short term effects. Small electric currents are present in our body. They for instance flow in the nerves to provide signals. An induced current might impact this, if it is larger than the natural levels. Therefore, the nervous system would be the most susceptible to field effects. It has been shown that for field values, much higher than the ones found in every day applications, human beings can see light flashes as the retina contains very sensitive nerves. At even higher field strength, uncontrolled muscle contractions can be noticed. These effects are reversible: when the field disappears, the effect goes away. They have no impact on health conditions.

A biological effect is a noticeable change as a consequence of a change in the environment or an activity. Our body is capable of adapting to these activities and influences by a number of very difficult to analyse mechanisms. The effect of this type is mostly reversible: if the trigger disappears, the effect does too. The compensation mechanisms of the body have their limitations. Major changes put pressure on the organism and may lead to health risks.

Scientists take into account results of epidemiological studies and animal and cell tests before analysing potential health effects. Whether a biological effect leads to risks of the health of the population depends on intensity and duration. In order to protect the general public, exposure limits are defined.

With regard to electric fields, no indications are found on long term effects. This unanimity does not exist amongst scientists regarding magnetic effects. From epidemiological studies, it is found that there is a very weak, though significant, statistical relationship between long term exposure to extra low frequency magnetic fields of a high voltage line and an increased risk of childhood leukaemia. It is discussed for residential situations over a long period with field values on average above 0.3 to 0.4 μT.

At present the answers of scientists contains many nuances. The numerous studies on cells and animals performed since 1980 have not confirmed the results mentioned above and therefore, on causal relationship between exposure to magnetic fields and increased risk on childhood leukaemia. As there is no explanation for the statistical link given by epidemiological research, no study has been able to exclude this risk so far.

Again we need to stress that the discussion is dealing with potential effects of extremely low frequency electric and magnetic fields, and not in the higher frequency range, where known health impacts are scientifically proven.

## A.4 International standards and recommendations

Governmental organisation and public services use multidisciplinary research teams of experts to find out the results of recent studies. A number of key international organisations are discussed here.

### A.4.1 International Commission on Non-Ionizing Radiation Protection (ICNIRP)

ICNIRP is an internationally recognised body, composed of independent experts that develops recommendations for the workforce and the general public dealing with potential damaging effects of non-ionising radiation.

In 1998, ICNIRP published its recommendations on electric and magnetic fields by introducing a 100 μT reference value for the maximum value of public exposure to extremely low frequency (ELF) magnetic fields, starting from proven effects.

ICNIRP does a close follow-up from the scientific developments in the field. When IARC International Agency for Research on Cancer in 2001 classified ELF magnetic fields as “potential cause of cancer”, ICNIRP argued that there was sufficient scientific evidence to change its recommendations.

The new recommendations were published in 2010, defining the exposure as “induced electric field strength” and no longer “induced current density”. The equivalent reference value was increased from 100 to 200 μT due to the improved simulation tools and the therefore lower safety factor needed compared to the previous version.

ICNIRP states that in spite of the statistical associations indicated in epidemiological studies, the longterm effects as childhood leukaemia are not included in the recommendations as no experimental studies are available to support these effect or to point to causal relation.

### A.4.2 IARC – International Agency for Research on Cancer

IARC – International Agency for Research on Cancer is part of the WHO (World Health Organisation). Its mission is the coordination and steering of research of cancer with human beings. The agency is involved in epidemiological and laboratory studies. It evaluates all agents suspected to be cancer related, and therefore has also dealt with the thematics of magnetic fields.

*Table 8: IARC cancer categories*

| | | |
|---|---|---|
| Group 1 | **Carcinogenic to humans"** There is enough evidence to conclude that it can cause cancer in humans. | 109 agents, e.g. asbestos, tobacco |
| Group 2-a | **Probably carcinogenic to humans"** There is strong evidence that it can cause cancer in humans, but at present it is not conclusive. | 65 agents, e.g. exhaust of diesel engines, solar radiation (also artificial) |
| Group 2-b | There is some evidence that it can cause cancer in humans but at present it is far from conclusive. | 275 agents as (ELF and radio frequency) electromagnetic fields, coffee, glass fiber, pickles, exhaust from petrol agents, medical implants |
| Group 3 | **Unclassifiable as to carcinogenicity in humans"** There is no evidence at present that it causes cancer in humans. | 503 agents |
| Group 4 | **Probably not carcinogenic to humans"** There is strong evidence that it does not cause cancer in humans. | 1 agent |

IARC has categorized ELF magnetic fields in category 2-B "potentially cancer generating". This category has been appointed based on limited epidemiological indications and the presence of insufficient and non-conclusive indications from experimental research and two epidemiological meta-analyses done in 2000. They showed a weak statistical effect between child leukaemia and ELF magnetic fields at higher values.

For all other types of cancer the IARC considers the indications as insufficient and non-coherent. IARC states that science has not been able to show the mechanism between the development of cancer under influence of ELF magnetic fields [54].

### A.4.3 WHO World Health Organisation

In 2007 the WHO presented a wide synthesis of the scientific knowledge on potential health effects of ELF fields (monography 238) annex a number of advices (factsheet 322) [55]

WHO states that, in spite of the categorization of ELF field in Group 2-a by IARC, other explanations can be found for the link between exposure to these fields and childhood leukaemia.

WHO stresses the information and communication need between scientists, politics, civil servants, general population and the relevant industry. It suggests to take the concerns of the general public into account when building new high voltage lines. Information and consultation of the general public is key.

WHO strongly advises not to lower the limits arbitrarily in the framework of the precautionary principle.

### A.4.4 European standards – Council of Europe

Based on ICNIRP, IARC and WHO, the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) evaluated all results. The committee does not see any reason for changing the advice given in 1999.

The present values are for the magnetic field 100 μT and the electric field 5 kV/m. Both values are maximum values, also known as reference values not to be passed for exposure to the general public.

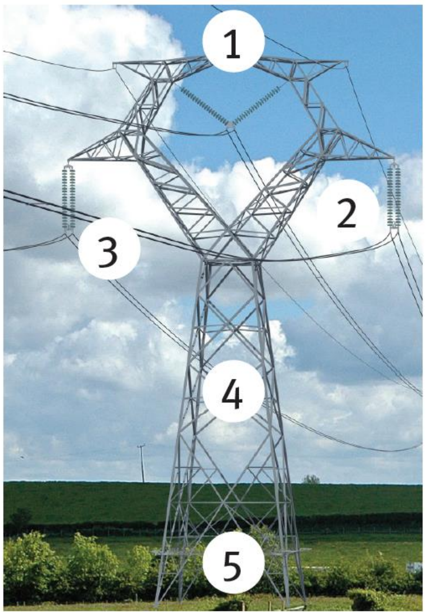
## A.5 Technical adaptations

When looking at a high voltage connection, and discussing with the general public the biological and medical arguments are often used to ask for a different design and even cabling.

The design as proposed by EirGrid is a basic lattice tower design. New designs of overhead lines, where the different conductors are closer to each other, thus reducing the magnetic field on the ground are found more and more. This can be done nowadays by using composite, non-conducting construction materials, narrowing the right of way in a significant way. In general, more compact designs lead to lower magnetic fields as the field of the three phases cancel each other better.

The design of the overhead line for the planned North-South development is basic, with no attempt to use somewhat more advanced techniques as available these days to tackle some of the problems that are mentioned when dealing with overhead lines like magnetic fields or visual impact.

Using tower heads in composite material, the size of a 6 GVA connection at 380 kV becomes comparable to the size of a classic, lattice tower 150 kV line, as shown by the Stevin project in Belgium. (Figure 34).



1. Earthwire / Shield wires (to protect the circuit below from lightning strike)
2. Insulators (to separate the current carrying conductors from the steel tower structure)
3. Conductors (the lines carrying the electrical current)
4. Tower (the structure supporting the conductors and other apparatus)
5. Concrete foundation for each tower footing (to ensure the strength and integrity of the tower)

*Figure 33: General Arrangement of an IVI Tower proposed for use in the North-South interconnector [3]*

*Figure 34: Tower design used in the Stevin project [41]*

Also in Sweden, more compact designs are found. (Figure 35)

*Figure 35: Compact tower design used in Sweden [9]*

When using special design towers, the lines can even be smaller and furthermore the magnetic field is reduced drastically. The Windtrack design by TenneT is very well known for this purpose and is used in the Randstad project (the Netherlands). (Figure 36).

*Figure 36: Tower design used in the Randstad project [44]*

In theory one could think of GIL (Gas insulated lines; Figure 37). The conductor current induces in the enclosure a reverse current of the same size. Consequently, the electromagnetic field outside the GIL is negligible. Such an approach is not feasible in this project due to the very high cost.

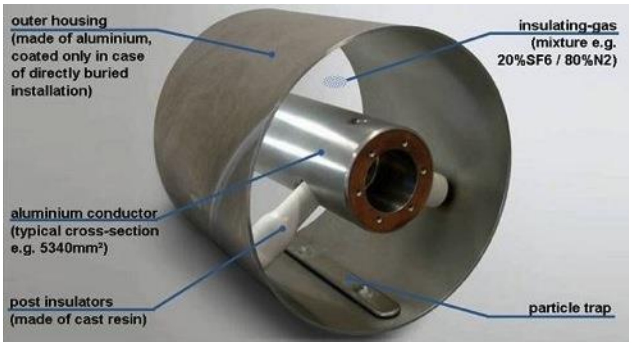


*Figure 37: Section of a gas-insulated line (GIL)*

For example, putting the cables next to each other increases the magnetic field and pushes towards the use of shielding (see Stevin project Belgium, section 3.5) and requires the uses of transposition (exchanges the place of each single-phase cable every kilometre, increasing costs). In general in comparison with overhead lines: underground cables lead to a higher field strength but with a very much narrower impact along the line.

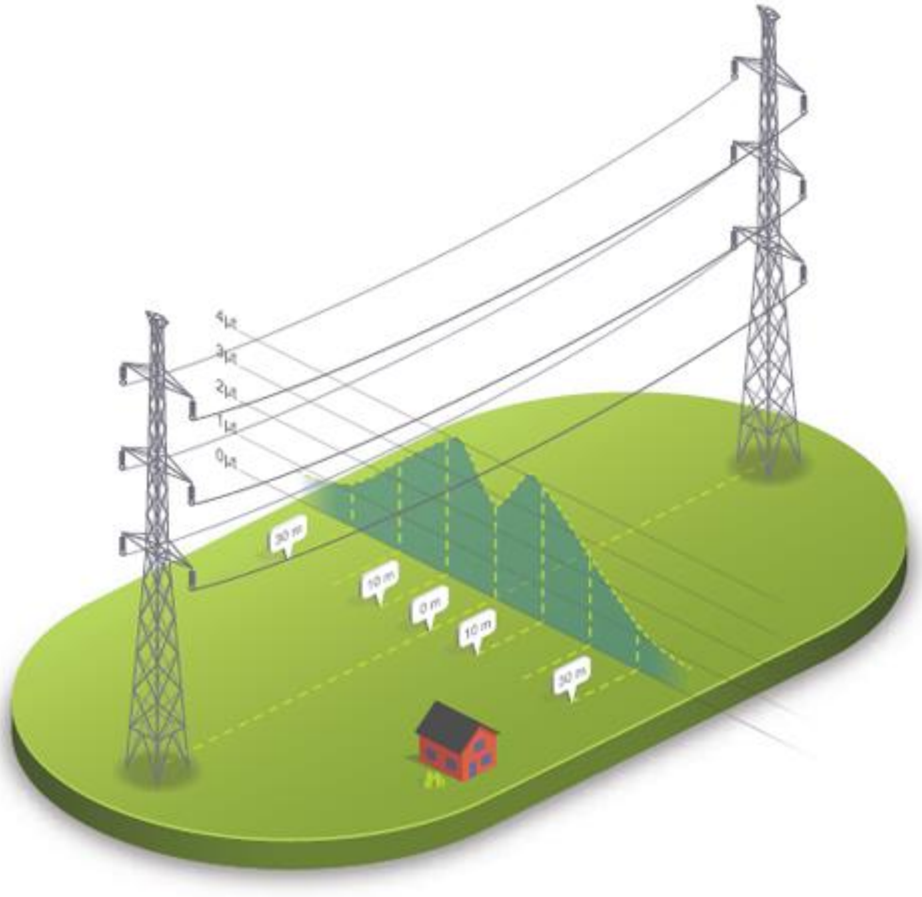


*Figure 38: Field strengths at different locations relative to an overhead line*

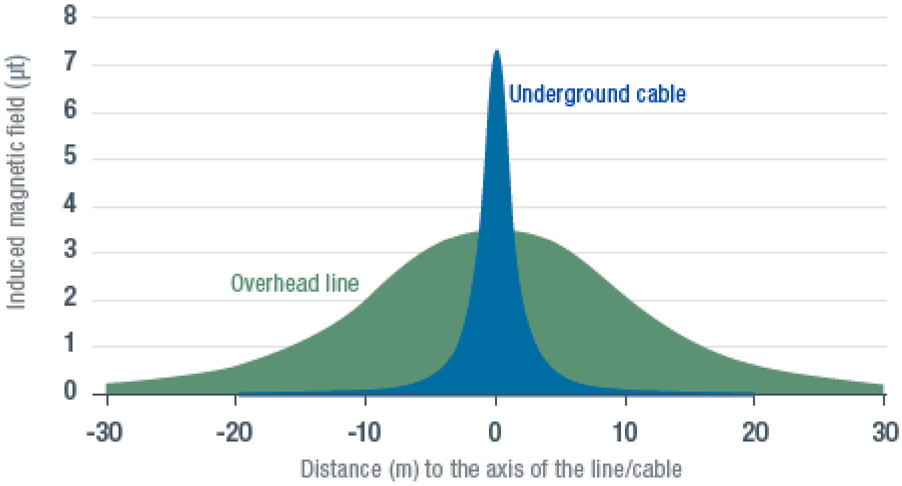


*Figure 39: Magnetic field relative to the centre of an overhead line or underground cable*

## A.6 Conclusions

Power systems including high voltages lines generate extremely low frequency (ELF) electric and magnetic fields. Their impact on human beings in their surroundings is described in literature.

There are no conclusive interactions on the potential health risks given the values of electric and magnetic fields found in practice, even when using classical designs.

The potential use of underground cables to substitute an overhead high voltage line in general results in a higher, but narrower in space magnetic field, and thus is not at all an argument to use this more expensive approach.

# B Meath–Tyrone International Expert Commission, Executive Summary, 2012

The Minister for Energy Pat Rabbitte, on July 5, 2011 announced that the Cabinet had agreed on his proposal to establish an international commission of experts to review and report, within six months, on a case for, and cost of, undergrounding (all or part of) Meath-Tyrone 400KV power link.

The appointed members of the Commission have professional background experiences from the Electrical Supply Industry, Transmission System Operations and Academic Knowledge in Power Systems.

There have already been performed several studies on the project by specialists appointed by organizations representing different aspects of and options for the Meath – Tyrone Project. The Commission wishes to build upon and add to the content and knowledge available in the various reports by studying the system from various angles. In this respect, the commission tries to find an answer to the following question:

- How do different stakeholders look at the project? What are their main concerns and their main suggestions?
- How does the Meath–Tyrone Project fit in a European perspective?
- What can we learn from previous reports on the Meath–Tyrone Project?
- What is the present state of the art of technologies already implemented or commercially available?
- What are the development trends in transmission technologies?
- Using a benchmark approach, what can be learned from recent project in Europe under construction or decided? What are the cost elements for different options today?
- What are the implications on cost and technical performance of possible alternatives for the Meath–Tyrone Project?

By looking at the Meath-Tyrone project from a wider perspective, and checking the arguments from the different reports within an international framework, the NIMBY (Not In My BackYard) elements can be overcome, which are a generally found weak element in almost all reports on a project written from a stakeholder specific angle.

The approach to include the examination of on-going projects in Europe is particularly relevant given the fact that there have been significant changes in technology, suppliers and costs the very last years.

The Commission has spent considerable effort on collecting data from five reference projects all relevant for the Meath–Tyrone project. These projects have ended up in different choice of technology, confirming that there is no single “right” solution. Each project must be judged on its own merits and hybrid solutions, i.e. combining different technologies, have been applied in many cases, for instance partially undergrounding a link. A specific technical solution must be derived accounting for local conditions.

Given the fast technological and market developments over the last years, some of the conclusions drawn in reports on the Meath-Tyrone project reflect the technology status as available a couple of years ago, using information available at the time. Therefore, given the project targets and boundary conditions, the conclusions may be different today compared to the results found at the time of writing of the reports.

Examples are the development of VSC HVDC technology and its deployment in transmission projects and the introduction of new tower designs for overhead lines. Given these major changes in the market it appears relevant to look at near-term trends, i.e. systems that can be bought of the shelf.

Detailed studies were made before the final solution was defined in each of these cases and these experiences are of great value for the Meath–Tyrone project. Examples are:

- Overhead lines can be rendered more acceptable by using new tower designs, new conductor types and other measures to reduce the visual impact, and in some cases also reduce EMF. Short distances may also be covered using underground AC cables.
- When considering undergrounding, a.c. cables are not the best choice when longer connections are to be covered. D.C. technology becomes a viable option as the cable itself is comparable in cost to an advanced overhead line, while major steps forward are seen in both costs and losses in the converter stations.

The Commission is not recommending any solution as such. However, it recommends against fully undergrounding using an a.c. cable solution.

If the option is to underground the connection along the whole, or main part of the route, with today's technology the best solution is a VSC HVDC solution combined with XLPE cables. The best cable route is most likely following existing infrastructure such as large freeways or railroads, or through farmland, as the width of the trajectory is far less than that needed for a.c. cables. In difficult terrain for undergrounding d.c. overhead lines can be used.

The commission wants to stress that an overhead line still offers significantly lower investment costs than any underground alternative and could also be made more attractive by investing slightly more in new tower designs, than the classical steel lattice towers now proposed.

For cost estimations, values found in real projects under execution are the most reliable source, although the high market activity and large fluctuations in key cost parameters such as metal prices can have a major influence that may be different given the technical option chosen.

Operational costs for different alternatives e.g. losses, will depend upon the power flowing to the link. This is an assessment outside the scope of this report. All alternatives have different characteristics, but are rather close making the assessments of lowest "life cycle losses" rather irrelevant, certainly when considering that the price of energy is very difficult to estimate over the say 60 years of life of the project.

The commission appreciates the open and constructive approach taken by all stakeholders. This has made it possible to get a good understanding of the specific conditions of the Meath–Tyrone project. The commission is grateful that all organisations involved made themselves available on short notice. This has made it possible to complete the work with-in the limited time available.

The report will not discuss EMF, the potential impact of the line on property value or landscape devaluation, as none of the Commission members have the appropriate knowledge.

The commission hopes that the report makes a valuable contribution to the overall discussion about the Meath Tyrone Project.

For the Commission

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