Independent Report

ASSESSMENT OF TECHNICAL ALTERNATIVES TO STRENGTHEN THE 400 KV TRANSMISSION GRID

DECEMBER 2018

PUBLIC

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ASSESSMENT OF TECHNICAL ALTERNATIVES TO STRENGTHEN THE 400 KV TRANSMISSION GRID

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CONTENTS

TABLES

EXECUTIVE SUMMARY

Background

In order to accommodate power from large scale onshore and offshore wind farms, Energinet, the electric transmission system operator in Denmark, is proposing to reinforce part of the Danish 400kV transmission network along the west coast of Jutland, from Idomlund down to the border with Germany – a distance of approximately 170km. Energinet has proposed to reinforce the network using a solution comprising overhead transmission lines over approximately 91 percent of the proposed route in Denmark and underground cables over the remainder of the route, which has met with significant public opposition.

The Minister for Energy, Utilities & Climate, Lars Christian Lilleholt, has therefore taken the initiative for an independent verification of the proposed solution and whether alternative solutions are viable. The Danish state-owned Transmission Service Operator (TSO), Energinet, has produced a technical report describing the reinforcement requirements, exploring the feasibility of various potential overhead line and underground cable solutions to achieve the required reinforcement, and detailing the consequences of failing to implement or delaying the reinforcement. The Danish Energy Agency (DEA) has appointed WSP to review Energinet's technical report and provide an independent assessment of the findings. This report presents WSP's evaluation of the Energinet report along with their Report Addendum and Presentation on Elaboration of Evaluation Criteria.

It should be noted that WSP has been specifically requested to comment on the technical feasibility of the solutions. The definition of "technically feasible" has been agreed with the DEA as follows: *"Technically feasible covers the establishment and particularly the operation of an installation where there is a strong probability that technical issues will not arise".*

Alternatives Considered

Alternative A is the reference solution. It is understood that this was the solution originally put forward by Energinet. It includes approximately 6% UGC on the Endrup-Idomlund section and 11% of the Endrup-Klixbüll section. Alternative B has an UGC share of 12-15% of the length.

In the answers to clarification questions from WSP, Energinet has stated that Alternatives A and B would require reactive compensation stations at Endrup and Idomlund substations and at a new substation at Stovstrup between Endrup and Idomlund.

Energinet has stated that Alternatives C and D with 50% and 100% UGC would require considerably more compensation as follows:

- Alternative C:
    - Three minor compensation stations between Endrup and the Danish-German border, including expansion of Endrup substation.
    - Five (including two minor) compensation stations between Endrup and Idomlund including expansion of Endrup, Idomlund and Støvstrup substations.

- Alternative D:
  - Four compensation stations between Endrup and the Danish-German border, including expansion of Endrup substation and a new substation at the border.
  - Five compensation stations between Endrup and Idomlund including expansion of Endrup, Idomlund and Støvstrup substations.

Alternative E is a solution based on using 150 kV or 220 kV cable installations with full underground cabling, and alternative F describes a potential HVDC alternative. The use of Gas Insulated Line (GIL) was also considered.

Technical Assessment

In Chapter 2 of this report, WSP presents our appraisal of Energinet's technical evaluations of the different transmission technology alternatives that could be used to construct the required reinforcements. Energinet has considered the use of Overhead Transmission Lines (OHLs), hybrid OHL and UGC lines with varying shares of UGC, full UGC, gas-insulated transmission line (GIL), and HVDC.

A summary of the various considered options is provided in the table below:

Table 1-1 – WSP High Level Comparison of Options

Technology Option	Alternative A	Alternative B	Alternative C	Alternative D	150 kV/ 220 kV cable	HVDC
Capacity	2500 MW per circuit	2500 MW per circuit	2500 MW per circuit	2500 MW per circuit	Not identified	2500 MW
Assumptions	Multiple UGC circuits needed to achieve capacity provided by OHL		Multiple cable circuits needed to achieve OHL capacity; requires ~8-9 reactive compensation stations		Many UGC circuits needed to achieve required capacity	Additional multi-terminal link needed for greater capacity
High Level CAPEX Estimate (mDKK)	2500 + other project related costs	2920 + other project related costs	Not known		Not known	9860 + other project related costs
Timeframe Estimate	2023	2023	2024	2024	Not known	Not known
Technology Risk/ Benefit	Well understood technology with low technical risk	Well understood technology with low technical risk	Risk of technology issues such as harmonics	Risk of technology issues such as harmonics	Risk of technology issues such as harmonics	Multi-terminal solution would have challenges but is not impossible

The table is based on the following assumptions:

- Timeframes assume that public opposition does not lead to any further delays. HVDC timeframe assumes that work could start immediately and there are no subsequent delays;
- Capital cost estimate for Alternatives A and B are provided by Energinet; it is not clear whether sufficient cable circuits have been accounted for in this estimate;
- Capital cost estimate for the HVDC alternative is from WSP; however, this has been interpolated from a derived cost/ MW and is therefore subject to inaccuracy.

It should be possible to deliver Alternatives A or B within the timeframe of 2023, assuming that public opinion does not lead to any further delays. Energinet has ruled out Alternatives C and D on the basis of technical feasibility. WSP agrees with this conclusion in the context of the definition of technical feasibility given in this report. A very high level cost estimate has been provided for the HVDC solution of approximately four times the cost of Alternative A. This is broadly in line with Energinet's estimate of the HVDC solutions being approximately five times the cost of an equivalent solution.

Given that the reinforcements are required by 2023, Energinet has discounted the GIL and HVDC options as unfeasible due to their complexity and their long construction times and has not considered them further in the technical analysis. WSP is in agreement that the GIL solution is technically unfeasible. WSP also agrees that it is not feasible to construct an HVDC solution by 2023 and that the development time for a multi-terminal system of the type that would be required for this reinforcement is likely to be significantly longer than that required for a point to point link.

Energinet also considered a solution based on 150 kV and 220 kV underground cables (Alternative E). This solution was also discounted by Energinet due to the amount of cable circuits that would have to be installed to give the required reinforcement capacity. WSP fully agrees with Energinet's conclusion that trying to reinforce the grid with 150 kV and 220 kV UGC would be unfeasible due to issues with capacity and timescales.

In Section 6 of their report, Energinet explored solutions based on overhead lines with varying shares of UGC to ascertain the maximum amount of UGC that could be included without causing technical issues on the rest of the system. Energinet claims their studies demonstrate a technical limit of approximately 15% share of UGC in the reinforcements. WSP agrees with this assessment for the following reasons:

- At 15% cable share, harmonic amplification is already beginning to "spread" to various substations leading to a great likelihood of mitigation (i.e. filters) being needed at more substations;
- Values of cable share >15% were not studied, because there had already been significant debate as to whether the maximum value should be 10% or 15%. 15% is already pushing the boundaries in terms of global track record;
- Because 4 circuits are required with 3 cables per phase to achieve the required capacity, this represents a significant amount of cable. There are issues for example with modelling cables (modelling accuracy is not very good) which can lead to errors in the modelled results and hence technical issues that are only realised after construction and commissioning of the project. For longer cable lengths, the overall inaccuracy in the model becomes larger and leads to a higher risk of issues; and

- At approximately 19% cable share, additional reactive compensation stations are required which would potentially lead to reduced system reliability and also increase the timescales and costs for the development.

Given the specific technical risks highlighted by Energinet for this particular reinforcement, and the limited global experience in undergrounding long lengths of underground cable, WSP agrees that the 15% limit is reasonable and that Energinet has made efforts to push the limit out from 10% which has fewer technical risks.

Chapter 3 of this report presents WSP's assessment of the environmental aspects considered by Energinet in their report. WSP recognises that environmental impacts were not initially specified as a selection criterion for the reinforcement option, but have nevertheless been referenced. The review was therefore included within the WSP scope of work. Although the level of environmental detail was relatively limited in this report, it is expected that these areas would be examined in greater depth at Environmental Impact Assessment (EIA) stage.

The Report notes that the final selection of the route and transmission solution (combination of OHL and UGC) alternative will need be determined during the EIA phase and should aim to find a solution which limits the environmental impact and alleviates any public concerns as much as possible. This in turn will support a more efficient authorisation process, which is required in order to meet the required project timeframes.

In Chapter 4 of this report, WSP presents our review of the timelines required to construct each reinforcement alternative. As noted previously, the reinforcements are required to be operational by 2023. It is WSP's opinion that it is not possible to construct the reinforcements in this timeframe using the GIL, HVDC, or full UGC (Alternative D) solutions. It is also not possible to give an accurate estimate of the construction times for Alternatives A, B, and C, until the EIA process is complete and the exact route of the proposed transmission lines is known.

Chapter 5 of this report presents our analysis of the costs associated with the different transmission technologies. Overhead lines are the cheapest of the transmission line technology, followed by underground cables, GIL, and HVDC is generally the most expensive. WSP is broadly in agreement with Energinet's high level estimates of the costs of constructing the reinforcements from OHLs and hybrid OHL/UGC transmission lines. It is not possible to give a more accurate estimate of the total costs until the route and technology to be used are known. The high level cost estimate for the HVDC option is approximately four times that of Alternative A, which is broadly in agreement with the five times higher cost estimate provided by Energinet.

It must be kept in mind that, whichever technology alternative is eventually selected, the installation and commissioning of the required transmission grid reinforcements will be a large and extremely complex engineering project, further complicated by the relatively short timeframe in which the reinforcements are needed. There will be no easy solution. Nevertheless, WSP agrees with Energinet's conclusion that constructing the required reinforcements using OHLs will be the technically most robust, simplest, quickest to construct, and cheapest option from the available technology alternatives. This assumes that there are no further delays due to public opposition.

In conclusion, it is WSP's opinion that, considering the required additional transmission capacity and the timescale of 2023 in which the reinforcements must be commissioned, the most likely feasible option is to use 400 kV double circuit overhead lines with sections of UGC up to a maximum proportion of 15% of the total reinforcement. It should be noted that the timeframe of 2023 is dependent on their being no further delays due to public opposition.

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1

INTRODUCTION

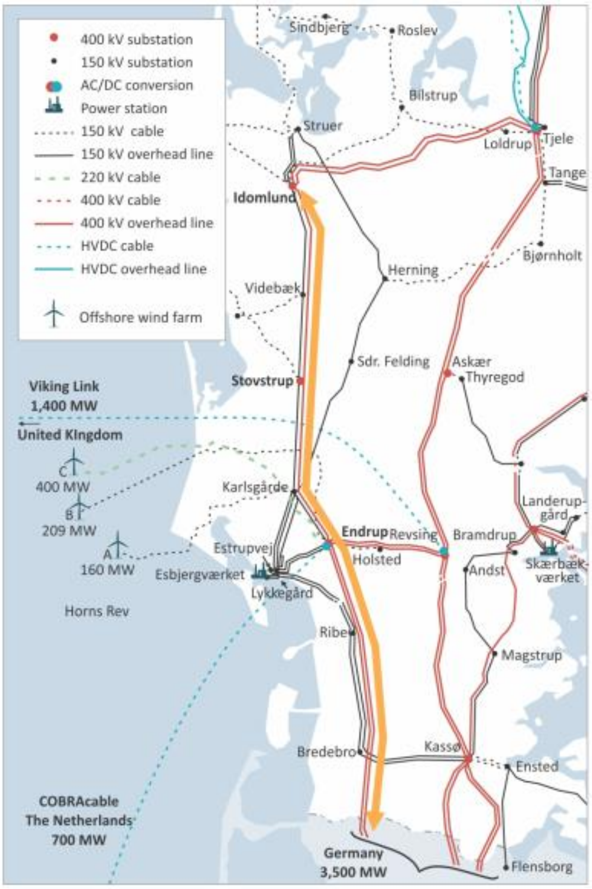
1 INTRODUCTION

1.1 PROJECT BACKGROUND

The proposed 400 kV transmission line from Idumlund to Tønder on the Danish/German border is a critical investment in the strengthening of the Danish national electricity grid that is necessary to meet future developments in production and consumption of energy in Denmark and via interconnectors to UK, Norway, Sweden, and Germany.

The transmission line is an integral part of the transmission infrastructure required for the two North Sea Interconnectors Cobra Cable and Viking Link as well as the transmission of the power generated from the planned offshore and near shore windfarms in the Danish Sector of the North Sea e.g. Horns Rev 3, Vesterhav Nord and Vesterhav Syd. The recent energy agreement (29th June 2018) commits to establishing 2,400 MW of additional offshore wind production that will undoubtedly be located in the North Sea, which will also be dependent on the strengthened transmission grid in western Jutland. The proposed reinforcements are denoted by the orange line in Figure 1-1 below.

Figure 1-1 - Expected route of new reinforcements



The strengthened transmission grid is also a response to expected changes in energy consumption. Jutland and Funen are seeing the arrival of six hyperscale datacentres that have all been attracted to Denmark by Europe's second highest levels of security of supply, relatively cheap electricity prices, high proportion of “green energy”, and excellent fibre connections to Europe and the US. Second tier datacentre developers following in the wake of the hyperscale datacentres are having to accept lower levels of security of supply and some redundancy whilst the Danish transmission net is being strengthened (expected completed 2023).

The 400 kV transmission line and potential routing corridors have been presented to the public and despite routing alignments being through relatively thinly populated areas of western Jutland the project has received a large amount of public opposition. Overhead transmission lines will invariably be viewed negatively due to visual, environmental, and economic impacts; however, the public opposition also needs to be seen in the light of the fact that the Danish Energy TSO, Energinet, has previously committed to burying 150 kV/ 220 kV OHL throughout the country. There is therefore a public misconception that OHL throughout Denmark are being buried, and that now Energinet is proposing installing new OHLs based on the least cost solution with the expectation that they will be buries at a later date.

The Minister for Energy, Utilities & Climate, Lars Christian Lilleholt, has therefore taken the initiative for the independent verification of the proposed 400 kV transmission line and whether alternative solutions are viable.

1.2 SCOPE OF REPORT

In order to accommodate power from large scale onshore and offshore wind farms, Energinet, the electric transmission system operator in Denmark, is proposing to reinforce part of the Danish 400 kV transmission network along the west coast of Jutland, from Idomlund down to the border with Germany – a distance of approximately 170km. Energinet proposes to reinforce the network using a solution comprising overhead transmission lines over approximately 91 percent of the proposed route in Denmark and underground cables over the remainder of the route.

The Danish Ministry of Energy, Utilities, & Climate has requested a second opinion from international experts as to whether the use of UGCs would be a feasible option. Energinet has produced a technical report describing the reinforcement requirements, exploring the feasibility of various potential OHLs and UGC solutions to achieve the required reinforcement, and detailing the consequences of failing to or delaying the reinforcement. The DEA has appointed WSP to review Energinet’s technical report and provide an assessment of the findings.

The requirement for the report from Energinet, requested by the DEA, was provided as follows[1]:

A technical report will be prepared, providing a description and quantifying the total need for expansion and the systematic task to be performed in the future by the electricity infrastructure in Western and Southern Jutland, as regards integration of renewable energy, maintaining security of supply, and facilitating the electricity market at the transmission level. The report will describe the

[1] Appendix A: Requirements concerning the deliverables, “Assessment of technical alternatives to strengthen the 400 kV transmission grid”, provided by Danish Energy Authority, 15th October 2018.

structural composition of the electricity system in Denmark and examine the relationship between the existing system and the need to expand the 400 kV electricity transmission grid. Lastly, the report provides a review of Danish and international practices relating to the use of cables at the transmission level.

The technical report will clarify the potential use of the following technical solutions in connection with the realisation of the identified need for expansion in Western and Southern Jutland:

- *The approved 400 kV overhead line solution (Reference/ Alternative A)*
- *The approved 400 kV overhead line solution – with an increased cable share without the need for establishing additional compensation stations (alternative B)*
- *The approved 400 kV overhead line solution – with an increased cable share and resulting need for establishing additional compensation stations (Alternative C)*
- *Full underground cabling of the current 400 kV connection (Alternative D)*
- *Perspectives for using 150 kV or 220 kV cable systems with full underground cabling (alternative E)*
- *Perspectives for using direct current connections (HVDC) with the laying of necessary cable systems underground or offshore (Alternative F)*

The technical report must describe technical solutions, including options for the use of an increased 400 kV cable share for the current system project, which can be carried out within the framework of the existing timeline. The report will also describe the consequences of delayed expansion of the transmission grid in Western and Southern Jutland in relation to the approved expansion of the Viking Link connection between England and Jutland, and the related expansion of the 400 kV grid in Denmark, and its impact on the possibility of realising the energy policy objectives on increased integration of renewable energy, maintaining security of supply and facilitation of the electricity market.

The technical report must clarify the technical, financial and timeline implications and the systematic limitations in connection with the potential utilisation of the above-mentioned technical alternatives.

WSP has been requested by the DEA to assess the following sections of the Energinet report as follows (hereafter referred to as the Report):

- Section 4: Transmission Line Alternatives;
- Section 5: Project-specific considerations regarding the choice of transmission line alternatives; and
- Section 6: Technical performance issues introduced by the application of long HVAC cables

It should be noted that WSP has been specifically requested to comment on the technical feasibility of the solutions. The definition of "technically feasible" has been agreed with the DEA as follows: *"Technically feasible covers the establishment and particularly the operation of an installation where there is a strong probability that technical issues will not arise".*

During the process of report review, WSP has been provided with additional information from Energinet in the form of an Addendum to the initial report (referred to as the "Addendum") and a presentation on "Technical Issues related to new Transmission Lines in Denmark – Elaboration of Evaluation Criteria" referred to as the "Presentation".

It has therefore been assumed that the need for the reinforcement has been established and is accepted, and this has been confirmed via email correspondence with Energinet[2].

"A need for extensive reinforcements of the transmission grid in Western and Southern Jutland was identified in connection with the preparation of business cases for the current 400 kV projects and subsequent grid analyses. Thus, the need for grid reinforcements is an accepted fact, and the scope of the report was defined accordingly as a study of possible technical solutions to alleviate this established need for grid reinforcements, including the perspectives of using 150 kV and 220 kV cable alternatives and HVDC solutions. Therefore, the external review should include Energinet's conclusions on these technical solutions."

This project has therefore been carried out with reference to the requirements provided to Energinet by the DEA. As such, WSP's review has been structured as follows:

- Chapter 1 provides the introduction to the reinforcement and to this report;
- Chapter 2 provides a review of the technical aspects of the Report;
- Chapter 3 gives an assessment of the environmental considerations in the Report;
- Chapter 4 is a review of the timescale aspects of the various options, and provides an independent review of the timescales;
- Chapter 5 reviews the cost information provided in the Report and provides an independent cost for the options; and
- Chapter 6 sets out the conclusions of this report.

[2] email response received from Lars Nielson, Chief Engineer, Grid Planning on 25th October 2018

2

TECHNICAL REVIEW

2 TECHNICAL REVIEW

2.1 INTRODUCTION

In Chapters 4 and 5 of the Report, Energinet has given an overview of the characteristics, merits, and disadvantages of four different technical alternatives that have been considered for the required West Jutland 400 kV transmission grid reinforcement.

In Chapter 4, Energinet describes the four main transmission line technologies that they have considered for the transmission grid reinforcement project. The technologies considered in this high-level assessment were as follows:

- 400 kV HVAC overhead lines (OHL)
- 400 kV HVAC underground cables (UGC)
- 400 kV HVAC gas-insulated transmission lines (GIL)
- High voltage direct current (HVDC)

Chapter 5 of the Report comprises a high-level technical assessment of the four transmission technologies for the proposed project. The technologies were evaluated in terms of:

- Usability
- Technical considerations
- Construction schedule
- Environmental impact
- Cost

It should be noted that WSP has not been asked to comment on the need for the reinforcement. However, the new transmission capacity required was also not clear from the report. Generally, when new reinforcements are being considered, it would be expected that the reinforcement capacity required would be clearly identified using generation scenarios and carrying out contingency analysis of the network. A discussion on this point was undertaken with Energinet in which Energinet stated that whilst the exact location of the offshore wind farms is not currently known, the worst case capacity assumptions and taking into account N-1 requirements the calculations show that around 2030 the maximum capacity provided by a 400 kV overhead line is starting to be exceeded. Energinet is therefore looking into whether utilisation of a second 400 kV circuit of the Northern reinforcement (Endrup-Idomlund) will be needed by 2030.

The following Subsections of this report present WSP's appraisal of Energinet's evaluations of the four different technical alternatives.

2.2 ALTERNATIVES CONSIDERED

In Chapter 5 of the Report, Energinet has presented an assessment of the relative merits of each of the four transmission technologies and provided reasons why some technologies and reinforcement options should be discounted from further consideration.

The results of that assessment are presented in Table 2-1 and the scoring system used by Energinet is presented in Table 2-2. Energinet's conclusion was that the HVAC OHL solution achieves the highest score in all categories apart from Environmental Impact. The Report notes however that the evaluation was of a qualitative nature and that more detailed development and design is needed to fully investigate the impact.

Table 2-1 - Relative merits of different transmission technologies (reproduced)

Technology / Criterion	HVAC OHL	HVAC UGC	HVAC GIL	HVDC
Usability	5	3	3	2
Technical Considerations	5	1	3	1
Construction Schedule	5	4	1	1
Environmental Impact	1	4	3	4
Financial Aspects	5	3	1	1

Energinet report Section 5.6

Table 2-2 – Energinet's scoring system for transmission technology assessment (reproduced)

Rating	Description
1	Least preferred, high difficulty, unacceptable
2	Major technical challenges, difficult, poor acceptability and very risky
3	Known technical challenges, difficult, limited acceptability and high risk
4	Known technical challenges, acceptable and some risk
5	Preferred, no technical challenges, fully acceptable and low risk

Energinet report Section 5.6

The Report notes that GIL has some technical advantages compared with underground cables. The GIL solution is however rejected in the Report due to:

- Lack of operational experience for the type of application, i.e. directly buried in open landscape and areas of special environmental interest
- Lack of experience of long horizontal drilling techniques for GIL purposes or the establishment of tunnels for GILs under these areas
- Timescales – not considered feasible to construct by 2023
- Costs – estimated at 2-3 times the cost of the underground cable solution.

The Report also rejects the HVDC solution on the basis of:

- Lack of robustness compared with HVAC solutions

- Limitations for future expansion and integration of renewables
- Increased cost – roughly 5 times the cost of the “equivalent” HVAC solution.

It is noted that it is not clear from the report in what respect the HVDC solution is equivalent, as the total capacity provided by HVDC is less than the maximum HVAC capacity. This is all subject to N-1 transmission system studies which are not included within the report.

Although not covered in the table above, the Report also considers an alternative based on 150 kV and 220 kV UGCs with full undergrounding. The Report rejects this solution as it would require numerous circuits in order to achieve the required transmission capacity and would require major restructuring of the transmission grid in Jutland.

Having rejected the GIL, HVDC, and 150/220 kV based solutions, the Report then considers four alternatives based on combined use of OHL and UGC with a share of UGC ranging from 6% to 100%. The Report notes that the locations and exact lengths of the individual cable sections are to be defined during the environmental impact assessment.

The share of UGC and OHL for each of the four alternatives is given in Section 5.7 of Energinet’s Report. Note that the distance from Endrup to the border with Germany is approximately 75 km and therefore the part of the line within Germany is approximately 16 km, which will all be OHL.

Alternative A is the reference solution. It is understood that this was the solution originally put forward by Energinet. As indicated below, it includes approximately 6% UGC on the Endrup-Idomlund section and 11% of the Endrup-Klixbüll section.

Alternative B has an UGC share of 12-15% of the length.

In the answers to clarification questions from WSP, Energinet has stated that Alternatives A and B would require reactive compensation stations at Endrup and Idomlund substations and at a new substation at Stovstrup between Endrup and Idomlund. It is understood that in Energinet’s view, Alternative B represents the solution with the maximum possible share of UGC without requiring additional compensation stations (beyond those required for Alternative A).

Energinet has stated that Alternatives C and D with 50% and 100% UGC would require considerably more compensation as follows:

- Alternative C:
  - Three minor compensation stations between Endrup and the Danish-German border, including expansion of Endrup substation.
  - Five (including two minor) compensation stations between Endrup and Idomlund including expansion of Endrup, Idomlund and Støvstrup substations.
- Alternative D:
  - Four compensation stations between Endrup and the Danish-German border, including expansion of Endrup substation and a new substation at the border.
  - Five compensation stations between Endrup and Idomlund including expansion of Endrup, Idomlund and Støvstrup substations.

Energinet has not considered an UGC share of between 15% and 50% because the technical challenges and risks associated with a length of 15% are already becoming significant. It was therefore concluded that there would be limited value in understanding these intermediate cable shares.

2.2.1 400 KV HVAC OVERHEAD LINES

A brief overview of the characteristics of HVAC OHLs is given in Section 4.1 of the Energinet Report.

Figure 10 shows a comparison of the visual impact of 150 kV and 400 kV OHL towers. The figure seems to show that OHL spans would be the same length, which, in WSP's experience, would not be the case in reality. The spans of the 400 kV OHL would be approximately twice the length of the 150 kV OHL, meaning there would be approximately half as many towers for the 400 kV solution.

Energinet states in Subsection 4.1.4 that it normally takes around 100 hours to repair and return to service a 400 kV OHL that has been taken out of service due to a fault. This seems somewhat pessimistic to WSP; in our experience, we would expect this to be possible in less than 48 hours, given that the proposed transmission lines will be traversing mainly agricultural land and not inhospitable terrain such as mountains.

In Subsection 4.1.5, Energinet has only considered the visual impact of OHLs; no mention has been made of issues such as bird strikes or disruption to local communities and farmers. WSP understands that most of the terrain of the proposed transmission line routes is arable land. Transmission towers would therefore reduce the area under cultivation along the proposed route and add a degree of complexity to farming operations, along with there being a small but increased risk of farm equipment colliding with the towers.

Energinet has not included a comparison of the span lengths for 400 kV OHLs relative to 150 kV OHLs in Subsection 4.1.5. It seems that only the Thor tower design has been considered. WSP understands that this tower design was selected by the Danish public during a consultation on different OHL tower designs, but perhaps other tower designs could also be considered. Modern composite OHL towers can be significantly smaller than traditional steel towers with much lower visual impact and space requirements.

In terms of loadability, the diagram given in Section 4.2.2 of the Report states that a capacity of 2000 MW can be provided per 400 kV OHL circuit. In a clarification question raised to Energinet, it was noted that the standard conductor system rated at 3600A will have the capability to carry 2500 MW, hence a double circuit overhead line would have capacity to carry 5000 MW in total. WSP agrees with these values in terms of maximum overhead line rating that can be achieved.

2.2.2 400 KV HVAC UNDERGROUND CABLES

2.2.2.1 Cable Design and Cable Rating

In section 4.2.1 of the Report it is stated that the conductor for an underground power cable is "aluminium or occasionally copper". For higher rated circuits, WSP notes that copper conductors are normally used rather than aluminium since copper has a lower electrical resistivity and therefore can carry higher ratings. A copper conductor cable carries a rating which is approximately 20% higher than a cable with the same cross-section of aluminium conductor, assuming the same size and laying configuration. Aluminium is frequently used for the lower rated circuits due the lower cost.

The Energinet Report states that "in order to match the capacity ratings of 400 kV OHLs, more parallel cable circuits are normally required". Carrying the full rating associated with the Viking Link project (i.e. 1400 MW) is not possible using just one HVAC cable circuit, but it would be feasible to carry this rating using two circuits. Assuming a load factor of 0.9, each of the circuits would be required to carry a current of 1123 A and this could be achieved by using 2 x 400 kV XLPE cable circuits with either a 1600 mm^2 aluminium conductor size cable or a 1000 mm^2 copper conductor size cable.

This is assuming the following parameters:

- A cable depth of 1000 mm
- A cable axial spacing of 300 mm
- Ground temperature of 15 Deg.C
- Ground thermal resistivity of 1.2 K.m/W
- Cable sheaths specially bonded
- Each circuit thermally independent.

Both the conductor sizes stated above are within the normal manufacturing range for 400 kV XLPE insulated cables. The required construction width for these two circuits would be approximately 23 metres, as shown in Figure 2-1. This construction width is less than the 36 metre construction width shown in Figure 14 of the Report.

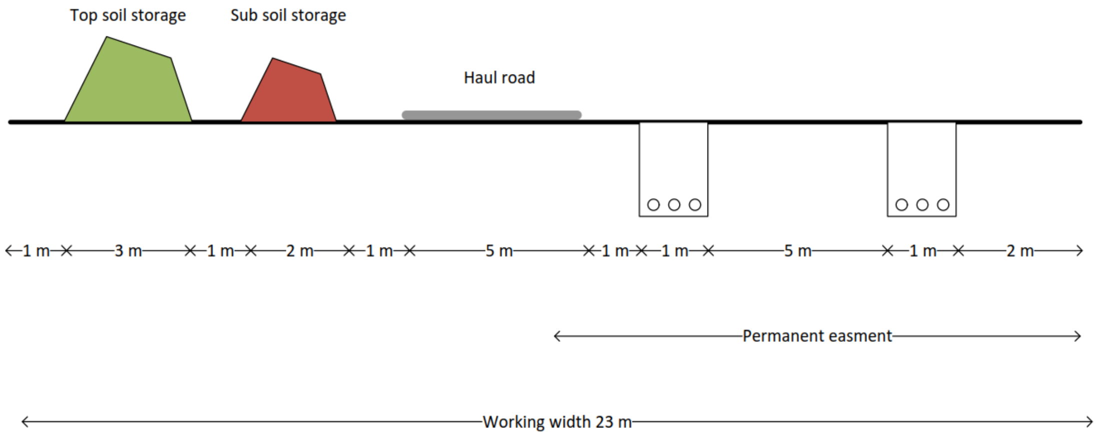


Figure 2-1 - Estimated Construction Width for Two Circuits (each carrying 700 MW)

It should be noted that the arrangement shown above in Figure 2-1 is for a standard trench. There would be sections along the route where the cable depth would increase (i.e. railway crossings, crossing existing services, river crossing etc). In these areas cable and circuit spacings would increase and a more complex installation arrangement may be required (e.g. horizontal directional drills, pipe jacking etc).

However, whilst carrying 1400 MW is possible using two parallel circuits, further circuits would be required to achieve the full 2500 MW capacity that Energinet state will be needed to accommodate the new renewable generation in addition to the rating associated with Viking Link. In order to replicate the capacity of the 400 kV overhead line, i.e. 2500 MW per circuit, up to eight cable circuits might be required in total. The proposed design for the UGC parts of the reinforcements is not provided in the Report.

2.2.2.2 EHV Cable Systems in Service

The survey details that are included in section 4.2.4 are taken from a CIGRE document (i.e. Technical Brochure 338 - Statistics of AC Underground Cables in Power Networks) that is 10 years old and is a little misleading. The total number quoted for installed EHV cables (i.e. 1397 km – the total of Table 1) are for the circuit length and therefore the total cable length is 3 x 1397 = 4191 km (as three cables are required per circuit). This value would be the total quantity of EHV cables and would include:

- XLPE insulated cables
- Self-contained fluid filled cables
- High pressure fluid filled cables.

A survey compiled by CIGRE in 2005 (i.e. Technical Brochure 379 - Update of Service Experience of HV Underground and Submarine Cable Systems) indicated that XLPE insulated cable consisted of approximately 23% of the total cable installed globally at this voltage level. Fluid filled cables are gradually being replaced by XLPE cables and therefore the percentage of XLPE insulated cables should now be a far higher percentage than the value quoted in Technical Brochure 379.

2.2.2.3 Reliability of EHV Cables

Section 4.2.7 of the Report refers to “limited experience of 400 kV underground cable systems in operation”. There is in fact considerable experience of cables operating at 400 kV and this has demonstrated that underground cables at this voltage level are very reliable. XLPE insulated cables have been used very successfully since the 1980s at voltage levels up to 132 kV, since the 1990s at voltage levels up to 275 kV and since the late 1990s at a voltage level of 400 kV.

In CIGRE Technical Brochure 379 in Table 11 it is stated that there is a failure rate for XLPE cables in the 220 kV – 500 kV range of 0.133 failures / year 100 cct.km. Based on the statistical information from CIGRE for one circuit with a length of 170 km it is estimated that 9 or 10 faults would occur over the period of 40 years. Note that this failure is considering both the internal origin of failures and external origin of failures.

2.2.2.4 Conclusion about the practicality of using cables

In general, WSP agrees with the comments detailed in section 4.2.6, i.e. high voltage cables are used in the following areas:

- In urban areas
- For river crossings
- When crossing an area of special environmental interest.

It is possible to construct very long HVAC cables circuits with reactive compensation, but it would be significantly more expensive to supply and install compared to an overhead line. Also, the duration to manufacture and install long lengths of 400 kV cables would be far longer than the same process for overhead lines. The amount of reactive compensation required would be very significant, with Energinet estimating that 9 reactive compensation stations would be required for the complete reinforcement. This is equivalent to constructing 9 transmission substations, as opposed to the 3 transmission substations required for an overhead line solution.

An estimate of the installation rate for cables per metre would be:

- Rural environment 100 m per day
- Urban environment 30 m per day

2.2.3 400 KV HVAC GAS-INSULATED TRANSMISSION LINES

2.2.3.1 General Comments

Within section 4.3.1, it is stated that the GIL is filled with an insulating gas mixture consisting mainly of nitrogen and a smaller proportion of sulphur hexafluoride (SF_6). It is also stated that these gases were “non-toxic and non-flammable insulating materials”. Nitrogen is non-toxic but SF_6 gas is an extremely potent green-house gas and when electrical discharge occurs within SF_6 (i.e. an electrical arc) the by-products that can be produced which are considered cancerous. However, WSP would therefore not consider SF_6 as non-toxic per se.

Section 4.3.2 states that the longest directly buried section in service is 1 km in length. It is accepted that this technology could be used for selected short routes with limited installation challenges; however, to extend to use the GIL for a circuit length of 170 km would be a significant risk. Along a route of 170 km it anticipated that there would be certain obstacles to be crossed (e.g. rivers, major roads, railways, wet-lands etc) and crossing these would be difficult with GIL.

Section 4.3.4 states that GIL is “predominantly installed in tunnels” and buried GIL has only been used to a “limited extent”. Section 5.3.4 of the Report recognises the use of buried GIL as “very risky”. WSP agrees that there is little track record for the installation of long lengths of GIL, and that installing GIL of the length required for this reinforcement would be difficult and risky.

2.2.3.2 Conclusion about the practicality of using GIL

The Energinet Report notes that GIL has some technical advantages compared with underground cables. The GIL solution is however rejected in the Report due to:

- Lack of operational experience for the type of application, i.e. directly buried in open landscape and areas of special environmental interest
- Lack of experience of long horizontal drilling techniques for GIL purposes or the establishment of tunnels for GILs under these areas
- Timescales – not considered feasible to construct by 2023
- Costs – estimated at 2-3 times the cost of underground cable solution

WSP agrees with the statements made in the final paragraph of 5.3.4, there is a lack of operational experience with GIL and there would be a significant increase in cost and the constructional schedule. Therefore, it is WSP's opinion that GIL does not present a feasible solution to the extension of the transmission grid.

2.2.4 HIGH VOLTAGE DIRECT CURRENT

This section of the Report considers the technical, environmental, timeline and cost issues associated with Alternative F: Perspectives for using high voltage direct current (HVDC) connections, with the laying of necessary cable installations underground or off-shore.

This is one of six interconnector options discussed in the Energinet Report. Specifically, this Report considers the possibility of a HVDC link from Idomlund to Endrup and from Endrup to the German border. The total length of the link would be about 170 km. As such this would be a link embedded within a synchronous network, unlike other HVDC links in Denmark which interconnect asynchronous networks.

It is noted that the agreed connection to Germany is via 400 kV AC circuits. Therefore, it is assumed that any HVDC link would terminate within Denmark and not become an international interconnector. Of significance in the possibility of a HVDC link is the future presence of the Cobra HVDC link from the Netherlands, rated at 700 MW at ±320 kV, and the Viking HVDC link from Great Britain, rated at 1400 MW at 515 kV. Such schemes in close proximity to any North-South interconnector would need to be considered in detail as they create a concentration of HVDC converters in the Endrup/Revsing region. Co-ordination studies would be required to ensure stable operation between the control systems provided by multiple manufacturers.

2.2.4.1 Topology Choices

The Energinet Report (Section 4.4.1) states that Voltage Source Converter (VSC) technology would be the most suitable for such an interconnector. WSP agrees with this assessment. Although Line Commutated Converter (LCC) technology is more mature, has lower costs and lower operating losses, the functionality benefits of VSC technology, such as reactive power control, smaller footprint, lower harmonic emissions, black start capability, etc., make it a more suitable choice for such an embedded link. With the exception of the Western Link project in the UK and the Italy – Montenegro project, all HVDC schemes in planning or construction in Europe are now using VSC technology.

Section 4.4.1.2 of the Energinet Report describes the possible topologies available for the HVDC link. Based on the dimensioning contingency in the Danish transmission grid of 700 MW loss, WSP initially considered two potential options:

- **Twin symmetrical monopoles, each rated at 700 MW operating at a DC voltage of around ±225 kV**. This is the same topology as used for the INELFE link between France and Spain (2 x 1000MW at ±320 kV), the South-West link in Sweden (2 x 700 MW at ±300 kV) and the France to Italy link (2 x 600 MW at ±300 kV).
- **A bi-pole with dedicated metallic return, rated at 1400MW operating at a DC voltage of around ±450 kV**. This is similar to the topology used for the NSL link (1400 MW at ±525 kV) and proposed for the Viking link (1400 MW at ±515 kV). However, both links use a rigid bi-pole topology.

A solution with twin monopoles would require 4 off high voltage underground cables, adding significantly to the project costs and requiring a wider construction corridor along the length of the link. However, the loss of a converter station or cable results in only the loss of 50% of the power transfer capacity. This would be the most expensive of all options considered in the Energinet Report and is not considered further.

A rigid bi-pole link would require only 2 off high voltage cables, but any fault in a converter to cable would result in the loss of 100% of the transfer capacity. The forced outage rate of a single pole is typically 3 – 5 times per year. Without a metallic or ground return path the complete bi-pole would trip, which would compromise the 700 MW loss limit. If the fault were in the converter, the healthy pole could be returned to service very quickly, in seconds or minutes depending on the choice of DC switchgear used. A cable fault would mean a complete loss of the link until a repair could be executed. Such a solution would not be recommended.

A bi-pole with ground return is unlikely to be acceptable in Denmark due to environmental concerns about prolonged operation during a cable fault. There is almost no precedence for the use of ground electrodes in Europe. Such a solution would not be recommended.

The optimal solution is considered to be a bi-pole with a Dedicated Metallic Return (DMR) conductor. This requires the installation of 2 off high voltage cables plus 1 off medium voltage cable, the latter with the same current carrying capacity as the HV cables. In the event of a converter fault or cable fault the loss of power transfer capacity would be 50%. This would be the recommended topology for an embedded link in Denmark.

On further consideration of the report and discussion with Energinet, it would appear that a further HVDC reinforcement would be necessary to handle grid-related contingencies which would be implemented between Revsing and Tjele. This would increase technical complexity of the solution in addition to cost and development time.

2.2.4.2 Multi-terminal solution

To match the AC alternatives, the HVDC link should link Idomlund, Endrup and the German border which would logically lead to a multi-terminal network, as discussed in Section 4.4.1.2.4 of the Energinet Report. This would avoid the need to build two separate point to point links, thus saving the cost of one complete converter station, i.e. at Endrup.

Multi-terminal VSC schemes are in operation in China and in planning/construction in Europe. The South-West link in Sweden was designed for future 3rd terminals in Norway. The Caithness – Moray link in Great Britain (rated at 800 MW at ±320 kV) is designed for a future connection to the Shetland Isles, increasing the final capacity of the receiving station (Moray) to 1200 MW. When extended to 3 terminals the scheme will be known as Caithness – Moray – Shetland (CMS). The Ultranet project in Germany will develop a 2000 MW at ±500 kV link using a multi-terminal solution.

It must be noted that all multi-terminal schemes in operation use symmetrical monopole topology. The first multi-terminal scheme using a bi-pole topology is presently under construction in China, rated at 3000MW at ±500 kV. This scheme, known as Zhangbei, is a 4-terminal meshed network, using overhead transmission lines.

Hence operational experience of multi-terminal schemes is increasing all the time and although such a solution would have challenges it cannot be considered impossible to achieve.

To achieve flexibility of operation the connection of the mid-point station (at Endrup) or future additional stations would need to be more complex than indicated in Figure 24 of the Energinet Report. A DC switching station would need to be established to allow 2-terminal and 3-terminal operation of monopole and bi-pole connections. Such a DC switching station is shown in Figure 2-2.

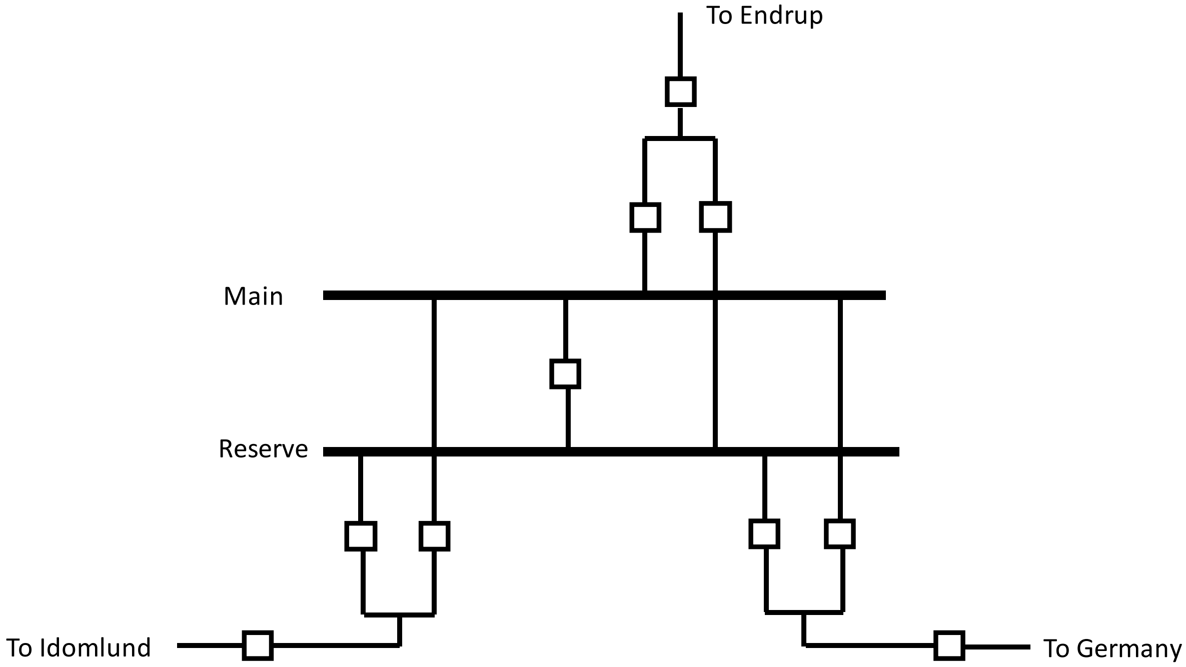


Figure 2-2 - Single line diagram of a DC switching station

Adopting a simplified version of an AC switching station, this example has main and reserve busbars, with a bus coupler between them. This provides the flexibility to operate in 2-terminal mode (3 options) or 3-terminal mode. Depending on the speed of change-over required switching between states could be achieve by simple disconnects (in minutes) or fast acting switches, based on AC circuit breakers (in seconds). All of the security and safety equipment of an AC switching station, i.e. isolation switches, ground switches, would be required. In Figure 2-2 DC switchgear is indicated in a simplified form. Measurement equipment would be required in the switching station to establish protection zones, to allow detection and discrimination of faults. The switching station would require its own small building for control and protection systems. Such a switching station is being constructed for the Caithness – Moray link at the mid-point station (Caithness). This also allows for the future expansion of the station to connect two additional HVDC systems, from off-shore windfarms. The cost of such a switching station must be factored into the overall costs of a HVDC alternative.

To date the protection philosophy for multi-terminal schemes subject to faults on the DC system, is to shut down the whole system and re-start the healthy parts. For a bi-pole system this would mean shutting down all three terminals of one pole, while the other pole remains healthy. Depending on the DC switchgear used the healthy parts of the pole can be re-started in seconds or minutes. DC circuit breakers have now been developed which could isolate a faulted section within 5ms, without shutting down healthy sections of the scheme. Such DC circuit breakers have been developed and tested, but not yet deployed on a commercial project in Europe. DC circuit breakers will be installed on the Zhangbei multi-terminal project in China, which is due to come into service in 2021. Energinet would need to undertake a risk assessment on the choice of protection system used on a multi-terminal system.

2.2.4.3 Control functions

For an embedded HVDC link the key functionality is that the link can emulate the performance of an AC link. Traditionally HVDC links operate as bulk power transmission systems, with controls designed to connect generation sources to load centres. However, there are now many examples of HVDC links which link variable generation sources (such as off-shore wind farms in the German North Sea)) to load centres, or are embedded within well meshed synchronous systems, such as the Alegro project between France and Belgium (1000 MW at ±320 kV) and France to Italy link. The Energinet Report in Section 5.4.4 quotes the example of the INELFE link which uses phase angle measurements at each end of the link to determine the required level of power flow.

It is clear that Energinet would need to develop a control methodology specific to the AC systems connected at each terminal of the HVDC link. This would need to consider the steady state load flows in the AC networks to ensure that thermal loading conditions were controlled and also consider the stability issues on the AC systems. These may effectively be achieved by installing, if not already installed, Phasor Measurement Units (PMU) within the AC networks and using the resultant phase angle signals, or an aggregated signal, as a control input to the HVDC controller.

In addition, before implementing more advanced multi-terminal HVDC installations, the existing eight HVDC links in operation in Western Denmark must be considered.

Today, existing interconnectors between Jutland and the Nordic region, Zealand and the Netherlands, respectively, are regulated automatically. The input to the HVDC control systems is an automatically generated exchange schedule with a 5-minute resolution, based on ELSPOT and intraday market trades. In addition, several of the HVDC interconnectors are equipped with emergency control, initiated from external inputs, to be activated in the event of critical grid or generation contingencies in Denmark or the Nordic region.

If an additional automatic control scheme of an advanced HVDC multi-terminal solution is to be implemented, designed to respond to fluctuating power infeed from wind power generation and varying power exchange on the other converters (including Viking Link) as well as to the planned or unplanned disconnection of transmission lines, there is a great risk of introducing critical errors to such a control algorithm. Hence, a HVDC controller failure can lead to widespread operational consequences for the Danish power system as well as Northern Germany and the Nordic region.

2.3 POWER SYSTEM STUDIES

2.3.1 GENERAL OBSERVATIONS

In Chapter 6, Energinet has presented high-level indicative studies to evaluate the technical merits of four different alternatives for the required reinforcement of the 400 kV transmission grid along West Jutland. The studies focus on assessing the amount of UGC that it will be technically feasible to accommodate on the Danish transmission grid as part of the required reinforcements. As such, only reinforcement Alternatives A, B, C, and D have been studied here.

Overall, Chapter 6 is well-written and informative; nonetheless, WSP initially had some concerns about the chapter in its current form. For example, in Section 6.6.2.7 it was not possible to understand whether the level of harmonic amplification identified meant that harmonic mitigation (or "action" i.e. filters) would be needed. Energinet subsequently explained within their Presentation that a red colour meant that action would be needed and that orange meant that action may be needed. In addition, they presented further study cases which provided additional understanding of the harmonics issue.

It was not initially clear from the Report why Energinet claims that only up to 15% cable share for the proposed transmission lines is technically feasible. It did not appear that values of cable share in the range of 15%-50% had been studied and reason for choosing 15% appeared to be arbitrary. However, further explanation was provided by Energinet in their Addendum to the Report and within their Presentation, "Elaboration of Evaluation Criteria". Key points relating to the 15% maximum cable share value were as follows:

- At 15% cable share, harmonic amplification is already beginning to "spread" to various substations leading to a great likelihood of mitigation (i.e. filters) being needed at more substations;
- Values of cable share >15% were not studied, because there had already been significant debate as to whether the maximum value should be 10% or 15%. 15% is already pushing the boundaries in terms of global track record;
- Because 4 circuits are required with 3 cables per phase to achieve the required capacity, this represents a significant amount of cable. There are issues for example with modelling cables (modelling accuracy is not very good) which can lead to errors in the modelled results and hence technical issues that are only realised after construction and commissioning of the project. For longer cable lengths, the overall inaccuracy in the model becomes larger and leads to a higher risk of issues; and
- At approximately 19% cable share, additional reactive compensation stations are required which would potentially lead to reduced system reliability and also increase the timescales and costs for the development.

Little information about the methods or assumptions made in order to carry out the studies was provided in the Report. However, additional information was given in discussions and in the Presentation. It was found that, given the timeframe and the early stage of development, studies were robust and assumptions had been considered carefully.

The studies carried out thus far should be treated as a first iteration of indicative studies only. More in-depth studies will need to be carried out as the design progresses and decisions are finalised, for example within the EIA process.

WSP's view is that the technical analysis presented in this Report would have benefited from using a base case of a transmission line fully comprised of OHL from which to evaluate the four reinforcement alternatives.

The studies carried out in Chapter 6 (voltage and reactive power control, harmonic impedance and TOV analysis, line energisation and de-energisation, and power quality issues) are appropriate for the high-level indicative studies that it is possible to carry out at this stage of the reinforcement process. As pointed out by Energinet, more in-depth studies should be carried out as the process proceeds and more design detail becomes available. It is appropriate to neglect studies involving trapped charge, fault clearance and transient recovery voltages, induced voltages, and voltage unbalance at this stage, but these studies should be completed in due course. WSP would strongly recommend that lightning impact studies also be undertaken when the final design of the transmission line is known.

From their technical analysis, Energinet have concluded that Alternatives C and D are technically unfeasible. The Report, along with the Presentation and Addendum provides sufficient evidence that Alternative C and D are technically unfeasible, in the context of the definition of “technically feasible” applied to this study.

WSP does recognise that it is not possible, at this stage, to carry out the extensive detailed studies needed to give a definitive answer to the question of how much cable share can be accommodated as part of the proposed transmission grid reinforcements, but that further high level studies would provide a better indication of what might be possible. WSP also understands that Energinet were severely time-constrained during production of the Report, with the result that the technical studies presented in Chapter 6 are high-level.

2.4 ANALYSIS OF OPTIONS

A very high-level performance matrix is provided in Section 5.6 of the Report which compares the four main options considered, i.e. OHL, UGC, GIL and HVDC. However, it would be expected by WSP that a more rigorous approach would be applied to the selection of the preferred option for the new transmission reinforcement. For example, National Grid (in the UK) has a two-stage process, - “approach to the design and routing of new electricity transmission lines”. Stage 1 of this approach is the selection of a preferred Strategic Option. Stage 2 is the identification of outline routing and siting. Subsequent stages relate to more detailed routing/siting and the planning application. Within Stage 1, an options appraisal is carried out in which options are assessed against four criteria: technical, environmental, socio-economic and cost.

S Similarly, Eirgrid has recently announced its new framework for planning strategic reinforcements. The framework involves six stages, including significant stakeholder engagement, as follows:

Top Level Engagement: National, Regional & Local;

- Preliminary Phase: The Technical Basis for the Project;
- Phase One: The Information Gathering Phase;
- Phase Two: The Evaluation Phase;
- Phase Three: The Route Confirmation Phase; and
- Phase Four: The EIS and Application Preparation Phase.

Both the National Grid and Eirgrid frameworks make use of decision making tools such as cost-benefit analysis, least-worst regrets, detailed performance matrix and willingness to pay. The tools and processes still allow for expert judgement to be made, and may ultimately be the basis on which a decision is reached, but the views may be informed by decision making tools.

In response to WSP’s comment that the summary analysis matrix is high level with little detail, Energinet has stated:

The objective of the report was to review the applicability of each of the defined transmission technologies, identify the relative advantages and disadvantages of each option and then assess these against the requirements of the current grid expansion projects in Western and Southern Jutland in order to identify any technically feasible alternatives. The summary analysis matrix is meant to give a final overview of the different technologies. The review is based on a qualitative evaluation and is therefore, to a certain degree, influenced by subjectivity. This evaluation approach has allowed a reasonably objective assessment of the different transmission technologies across a range of potential impacts and identification of the technology with the least negative impact. As for the cost/benefit analyses mentioned, this is not the main theme of the report, given the scope of preparing a technical report to evaluate feasible transmission alternatives.

Transmission Operators are beginning to apply more rigour to transmission reinforcement optioneering, partly driven by public opposition to major new transmission lines. It does not appear that Energinet currently has such a framework in place in order to assist in making decisions on transmission reinforcement, but this is something that could be considered for the future.

3 ENVIRONMENTAL REVIEW

3.1 INTRODUCTION

The Energinet Report was prepared in order to review transmission solutions for the proposed grid expansion in Western and Southern Jutland, with particular focus on examining the merits of using UGC as part of the approved grid expansion and the alternatives associated with this solution. While the scope of the Report was to clarify *the technical, financial and timeline implications, and the systematic limitations in connection with the potential utilisation of the… technical alternatives*, Energinet makes reference to environmental impacts associated with the various transmission solutions, and in certain cases references the consideration of environmental impacts in the selection of the preferred alternative.

WSP has reviewed the applicable sections within the Report to determine the extent to which environmental aspects and impacts have been considered, and provide an opinion as to whether the information provided is considered sufficient to inform the alternatives selection at the current stage of the project. Recommendations are then provided on aspects which need further consideration, which may impact on final route and transmission solutions.

3.2 CONSIDERATION OF ENVIRONMENTAL ASPECTS AND IMPACTS

This section highlights references to environmental aspects and impacts relating to support of the alternatives assessment. Introductory sections of the Report initially refer to reviewing the transmission solutions based on technical characteristics, reliability, operations, and financial impacts. Environmental impacts as a criterion for assessment of the alternatives is clearly not stated.

It is WSP's understanding that one of the primary drivers of the local community concerns relates to visual impacts. While Energinet notes that the reference technology for electricity transmission at 400 kV is OHL, which is based on the national principles for the establishment of transmission lines, the mandate for the Energinet Report is to study the applicability of the use of UGC, intended to mitigate the visual impact. This supports the consistent reference to visual impacts of the various alternatives, with little focus on any other typical potential impacts.

With reference to Section 4 of the Report, reference to impacts include the following.

3.2.1 400 KV HVAC OVERHEAD LINES

Reference is made to the configuration of new 400 kV overhead lines being chosen in order to reduce acoustic noise (Section 4.1). This is achieved through the construction of the overhead lines using a triple bundle configuration of conductors, as opposed to the double bundle alternative. This has the added benefit of reducing losses, which makes up the difference between the costs of the respective options.

A visual comparison is made between the existing 150 kV OHL on the route between Endrup and Idomlund and a visualisation of the proposed new 400 kV line, assuming that the towers are placed in the same locations (Section 4.1). The comparison indicates that there will not be a significant change from the status quo (visually), provided that the same locations for the masts are used; this is attributed to the mast design and reduced height in comparison to alternative 400 kV overhead lines. There is however no indication that the spacing of the masts will remain the same as the current 150 kV OHL; spacing is typically greater with the use of 400 kV OHL, which would reduce the number of masts and therefore, presumably the visual impact.

Section 4.1.5 refers to visual amenity being one of the key drivers in the design. This resulted in the revision of the previously used designs, and the development of the Thor tower design, which is constructed using pipes instead of the angled iron. This design allows for more space between rods, removing sharp edges, resulting in a less dominant overall visual impression. The tower design is lower than previous designs, with a maximum height of 32 m from the ground to the cross arm and 36 m from the ground to the tip of the earth wire bearings. The typical distance between towers will be about 330 metres on average (maximum 360 metres). Notwithstanding the design change, the lines will still be visible in the landscape. While the Thor design is presented as the preferred alternative, having been designed for the proposed reinforcement project, no alternative designs have been considered within the Report. Consideration of alternative designs may need to be given in the EIA phase, as stakeholder preference may vary, depending on, for example, their proximity to the OHL.

It is noted that there is no indication that the new towers will be able to be erected within the existing footprints, thereby minimizing disturbance caused by the establishment of the new towers. Maximising usage of the existing corridor would be advantageous and should be assessed further within the EIA.

3.2.2 400 KV HVAC UNDERGROUND CABLES

Section 4.2.2 dealing with loadability indicates that the use of UGC would have a significant environmental impact and restrictions along the route. This is based on the underground cable requirements needed to match the rated capacity of a 400 kV double-circuit OHL. A work zone of 36 metres wide would be needed; the construction of buildings or roads or terrain changes would only be permissible in exceptional circumstances.

Specific consideration would need to be given within the EIA as to where UGC should be used; given the work zone, the use of UGC may not necessarily present a suitable alternative through sensitive environments. However, as noted in Section 4.2.6, this could be negated by the use of horizontal directional drilling. More detail is required in the EIA reporting as to what distances are feasible for horizontal directional drilling, when determining which section would be selected for UGC.

Additional visual impacts are mentioned in Section 4.2.8, where UGC is noted as having a lower visual impact than OHL, however consideration would still need to be given to those portions of the cable system still visible above the ground, namely the terminal ends between the OHL sections and the reactive compensation stations.

Although not explicitly discussing environmental impacts, Section 5.2.2.2 notes that full undergrounding of the 400 kV transmission lines from the Danish-German border to Idomlund would require the establishment of several compensation installations, each of approximately 80-100,000

m^2. While this is not qualified against other solutions, this still presents extensive development with associated impacts to be included when considering the use of UGC.

Chapter 5 briefly mentions the lower impact that UGCs will have on property value, but this is not further qualified in the Report.

3.2.3 400 KV HVAC GAS-INSULATED TRANSMISSION LINES (GIL)

The environmental impacts description of GILs is limited to comparison to UGCs during the construction phase, however there is no consideration of the width of the work zone (noted as 36 m for UGC), and whether the impact would be reduced by using GIL. The comparison of similar scale project using GIL is ostensibly not possible, as to date GIL systems have predominantly been installed in tunnels, with a limited extent of commercial solutions where GIL has been buried in the ground. There is a noted lack of experience with long horizontal directional drilling for GIL purposes or the establishment of tunnels for GILs in wetlands.

Reference is made to the health and safety impacts related to working with GIL systems. Due to the nature of the SF_6 gas used, which while a relatively non-toxic gas used for its inert qualities, toxic by-products can be produced by electrical discharges occurring within SF_6-filled equipment. The consideration of health and safety aspects of the alternatives is not consistent through the respective alternatives and would need to be assessed further should this be part of the alternatives assessment. This also applies to the reference to SF_6 as a potent greenhouse gas – the significance of this would require additional consideration, but appears to not have been possible due to limited application of GIL systems worldwide.

3.2.4 HIGH VOLTAGE DIRECT CURRENT (HVDC)

The description and comparison of environmental impacts of HVDC in Section 4 is limited to the substations, which are noted as being comparable to existing 400 kV substations, depending on the technology employed. However, further impacts are expected regarding the noted requirements for an additional embedded HVDC link between Revsing and Tjele, as well additional links being required in conjunction with new offshore wind power plants.

The offshore-based HVDC reinforcement is considered in Section 5.4.5, but no mention is made to environmental impacts, only the fact that the technical considerations are the same as that of the onshore option.

Undergrounding the DC cables between three converter stations will remove the environmental impact on the landscape of transmission towers and conductors. The environmental issues related to the underground cables are discussed in another Subsection 3.2.2 of this report. This section of the report considers some of the more significant environmental impacts of the converter stations.

In Subsection 4.4.4 of their Report, Energinet provide a typical footprint for a bi-pole converter station. This is considered to be a good estimate of the area required for the station. The visual impact of the station in the landscape will be dominated by the mass of the converter valve halls. These could be of the order of 100 m x 50 m x 25 m (height). The height of the building being dictated by the choice of DC voltage, here assumed to be 450 kV. Converter station suppliers may be able to offer an optimised solution with a lower building height, but at the expense of a longer building. Energinet would need to liaise with the Local Authorities to agree the details of the buildings, including shape and colour, which is required to receive planning consent. Mitigation measure may include earth bunds, which retain excavated soil on site, and extensive tree planting.

Adjacent to the converter station will be a secure construction “lay-down” area of at least 100m x 100m. This can be returned to “nature” once the station enters commercial service.

Audible noise emissions which comply with Environmental Protection Agency limits, typically at the closest properties, may require expensive mitigation measures, especially on the interface transformers and the valve cooler banks.

The electromagnetic environment around the converter station will need to be defined in some detail such that the station supplier can design their equipment to comply with all appropriate regulations. Modern VSC converter stations create far less harmonic distortion than LCC technology, but over a greater frequency range, normally from 100 Hz to 5000 Hz. Power quality issues on the AC networks and interference with telecommunication systems close to the DC networks will need to be studied. The use of cables buried in the ground does not remove all issues related to interference with telecommunications.

3.3 ENVIRONMENTAL AUTHORISATION REQUIREMENTS AND TIMEFRAMES

The proposed activity is listed within Annex 1 of the Environmental Assessment of Plans and Programs and Projects (EIA Act): "*21. Construction of high-voltage overhead electrical power lines with a voltage of 220 kV or more and a length of more than 15 km*." As the clause is broad, the authorisation process viz. an EIA, would be applicable to all technical solutions and therefore not a driver in terms of alternative selection. The duration of the authorisation process may nevertheless vary depending on the level of complexity of the alternatives.

However, the consideration of the authorisation process as a selection criterion for the preferred alternative will be relevant when considering the implications of the stakeholder engagement process. Stakeholder opposition to the project, and any insufficiencies in addressing these, could potentially lead to a protracted authorisation process. The visual impact is one of the primary concerns which stakeholders have, and the preferred solution would need to meet all parties’ expectations in terms of impacts and project objectives.

There could also be deviations in terms of dispensations and environmental permissions (and their associated timeframes) as different options could allow for avoiding sensitive areas to varying degrees. This would become more apparent during the EIA Phase when assessing routes and solutions to minimize environmental impacts.

3.4 DISCUSSION

The summary in Section 4.5 indicates that the choice of technology for expanding the transmission grid includes environmental considerations. Based on the summary of environmental aspects and impacts presented above, this was not found to be the case. While WSP does not dispute the environmental impacts identified, the aspects and impacts of each alternative are not however comprehensively and consistently compared.

The discussion in Section 5.6 provides an overview of the review of the applicability of the respective transmission technologies. It is stated that the review is based on a qualitative assessment of criteria defined in Chapter 5; the environmental impact, with an associated qualitative score, is listed as a criterion, however the basis for the scoring has not been described. Based on the rating system and score assigned to HVAC OHL, this technically preferred option is considered “least preferred, high difficulty, unacceptable”, which is not consistent with the limited reference to environmental impacts earlier in the Report, and with the knowledge that OHL is the reference technology for electricity transmission at 400 kV. While Section 4, and to a very limited extent Section 5, briefly allude to the various environmental impacts (specifically visual, noise and property values), the description of the environmental aspects and impacts is considered insufficient and should not be considered as one of the selection criteria in the Report discussion and summary.

Based on the summary matrix, the HVAC OHL transmission lines, as a combination of OHL and UGC in areas of environmental interest, are concluded to be the preferred transmission technology when assessed against the selection criteria. This was therefore the focus of a more technical review, with the objectives of the study to identify the technically acceptable maximum share (length) of 400 kV UGCs that can be adopted for the grid reinforcements projects in Western and Southern Jutland. The Report then goes on to state that the environmental impacts of the project depend on the characteristics of the crossed areas, noting that UGC may have significant local impacts and OHLs a more dominant visual impact. The Report notes a comprehensive assessment of the environmental impacts and determination of the route and technology alternative (viz. combination of OHL and UGC) would only be able to be undertaken in the EIA Phase during the definition of the location and exact length of the individual UGC sections; which was stated as being outside the scope of the Report. The Report's conclusion recognizes that the consideration of environmental impacts is primarily limited to visual impacts, and that further conclusions should only be reach based on the EIA.

3.5 CHAPTER CONCLUSIONS

The mandate of the Report was to review the feasibility of the alternatives in terms of the technical, financial and timeline aspects. WSP recognizes that environmental impacts were not initially specified as a selection criterion, but have nevertheless been referenced. The review was therefore included within the WSP scope of work. Although the level of environmental detail was relatively limited in this report, it is expected that these areas would be examined in greater depth at EIA stage.

The Report notes that the final selection of the route and transmission solution (combination of OHL and UGC) alternative will need be determined during the EIA phase and should aim to find a solution which limits the environmental impact and alleviates any public concerns as much as possible. This in turn will support a more efficient authorisation process, which is required in order to meet the required project timeframes.

3.6 RECOMMENDATIONS

In support of a comprehensive assessment of environmental impacts, WSP recommends that the following broadly identified aspects and impacts be included in the EIA reporting when considering the combined use of OHL and UGC, and specifically where the respective solutions should be used. The merits of each solution should be examined by assessing how sensitive receptors are impacted, and which solution will minimize or avoid impacts related to that specific section. This list is not considered exhaustive, and additional site-specific impacts should be considered during the EIA process. The selection of alternatives and solutions to minimize or avoid impacts should incorporate and consider public comments and areas of public concern.

The significance and the duration (e.g. limited to the construction phase and therefore short term, or alternatively long term related to the operational phase) of impacts is not defined, as this will be dependent on selection of the preferred route, the technical solution i.e. OHL or UGC, and the mitigation measures available. The impacts listed are potentially applicable to both OHL and UGC; only cases where a clear distinction can be drawn has been noted.

3.6.1 CORRIDOR SHARING

Utilising existing corridors should be considered to the greatest extent feasible, provided that it is consistent with economic and engineering considerations, reliability of electric system, and protection of the existing environment. This includes using existing utility corridors, and existing transport corridors, with the creation of new corridors being the last option. When properly evaluated as part of routing decisions, corridor sharing can be a useful method in mitigating environmental, property, and community impacts of a new transmission line. There are potential negative aspects associated with corridor sharing, and the project specific merits would need to be evaluated.

3.6.2 AESTHETICS

Assessment of the aesthetic impacts, primarily related to OHL, should consider:

- The physical relationship of the viewer and the transmission line (distance and sight line)
- The activity of the viewer (e.g. living in the area, driving through, or sightseeing)
- The contrast between the transmission structures and the surrounding environment, such as whether the line stands out or blends in.

Mitigation measures to be considered include routing to avoid areas of scenic value (e.g. preferable to pass through commercial or industrial areas or along land use boundaries) or sensitive areas based on surrounding land-use i.e. residential; modifying the design to minimize aesthetic impacts (this has been noted in the technical assessment); or using UGC.

3.6.3 ECOLOGICAL

Ecological considerations should include:

- Impact to, or removal of, habitats, particularly sensitive habitats and those protected by virtue of their species composition, or support of rare, threatened, or protected fauna viz. Ramsar sites, Natura 2000, Bird Protection Zones etc.
- Impacts to watercourses - direct changes to the physical features (e.g. channel width), change in plant cover, water quality, as well as adjacent construction works leading to increased erosion potential and sediment release (especially during rainfall events). Mitigation measures may include rerouting lines away from sensitive watercourses, adjusting mast placements, alternative construction methods etc.
- Impacts to wetlands – temporary or permanent drainage or changes to water flow quantity and direction, loss of vegetation, soil compaction, habitat disturbance (e.g. sediment creation) and impacts to fauna. Mitigation measures may include rerouting lines, adjusting mast placement to avoid or limit wetland access, construction vehicle and method selection.
- Impacts to woodlands and forested areas through fragmentation leading to an increase in edge species and invasive species, reduction in species diversity and suitable habitats. For example, OHL may be the preferred option in wooded areas, which UGC may be favourable in arable areas.
- Habitat creation and proliferation of invasive plant species through site disturbance, and soil and vegetation removal.
- Excavation and subsequent handling of soil leading to the potential for mixing of top- and sub-soils, as well as erosion during rainfall events.
- Bird and bat collision related to OHL.

3.6.4 NOISE

Evaluation of noise should consider:

- Noise generation by construction equipment and activities (incl. vegetation removal, vehicles and equipment, drill rig, construction vehicles, cranes etc.)
- Noise generation during the operational phase during periods of high humidity caused by ionization of electricity in the moist air near the wires of OHL.

3.6.5 WATER AND SOIL CONTAMINATION

Consideration of water and soil contamination should include:

- Release of ochre where ground water levels are altered.
- Run-off from excavations and erosion of stockpiled soil.
- Impacts related to drilling operations of UGC e.g. release of drilling fluids.
- Rainfall run-off from OHL masts, cables etc. may contain zinc and aluminium and potentially heavy metals.

3.6.6 EMF

Electric and magnetic fields (EMF) occur whenever and wherever electricity is used. While the risks associated with exposure to EMF have not been conclusively established, a precautionary approached is typically taken and consideration needs to be given to proximity to residential areas.

3.6.7 SOCIO-ECONOMIC

Assessments of the socio-economic impacts of the proposed transmission lines should include:

- Impacts to land use such as agricultural operations – planning should be undertaken with agricultural landowners early in the design process as possible to identify potential operational and environmental impacts and identify mitigation measures such as changes to mast routing and location, construction timing, compensation measures etc.
- Potential reduction in land value due to visual and noise impacts, and perceived impacts from EMF as well as land ownership due to expropriation. Early planning and discussion is needed to minimize conflicts and form agreements on compensation measures if applicable.
- Impact to recreational areas (e.g. areas visited for the aesthetics of the natural surroundings, altering types of wildlife found in areas by creating more edge habitat etc.).

3.6.8 ARCHAEOLOGICAL AND CULTURAL / HISTORICAL RESOURCES

Damage and/or loss due to excavation, construction, and service road establishment through the use of heavy machinery, removal of trees and exposing sites to erosion etc.

3

TIMELINE REVIEW

4 TIMELINE REVIEW

4.1 INTRODUCTION

Energinet's Report states that the new reinforcement must be in operation by 2023 due to the commissioning of the Viking Link, the HVDC link that will connect Great Britain with Denmark. It is not clear from the Report why this is the case; however, in response to a WSP request for clarification, Energinet explained that full utilisation of the Viking Link is dependent on this reinforcement. The Viking Link is a rigid bipole with a 1400 MW rating – when the new reinforcement is put in place it will be able to withstand the 1400 MW trip. Until the new reinforcement is in place, the Viking Link will not be able to run to its full 1400 MW capacity because of the risk to the Danish system.

The Report also states that the transmission grid must be developed due to the renewable generation that is planned to connect. The timing of the new renewable generation sources coming online is presented in the Report, and the total change in renewable generation connections is provided in Section 2.6.1 as presented in Table 4-1.

Table 4-1 - Total change in renewable energy sources power generation capacity

Total power from renewable energy sources (MW)	2018	2024	2028	2031	2040
2017 assumptions	6,307	9,655	10,292	11,197	16,744
2018 assumptions	6,477	9,307	10,794	12,840	20,209

Energinet report Section 2.6.1

Since the business case for the Jutland reinforcements was approved, further wind farms, which were not part of the original planning assumptions, have been given approval to connect to the north of Denmark. The offshore wind farms have subsequently been added to the updated planning assumptions and are therefore included in the load flow calculations conducted for the Report. The year of commissioning of the wind farms in the table in Chapter 2 of the Energinet Report has now moved 1-3 years ahead, meaning that they will be in full operation by 2026, and thus the grid needs to be ready in 2024. WSP understands that a total offshore wind capacity of 2400 MW is due to be commissioned by 2030.

Whilst there is some uncertainty in the assumptions, it can be seen that, in general, the amount of renewable generation requiring connection is increasing substantially. Much of the prospective wind farm capacity is to be connected in the north of Denmark and will need to be transported south via the new reinforcement. It is not clear from the Report how much of this capacity can be accommodated via the existing transmission system and the capacity that will be required to accommodate the additional energy. In response to a clarification from WSP, Energinet stated that the standard conductor system rated at 3600A is the requirement for the southern connection from the German side; the system will, therefore, have the capability to carry 2.5 GW from north to south.

The exact location of the offshore wind farms is currently not known, but in terms of worst case capacity assumptions and taking into account N-1 requirements, Energinet has stated that their calculations show that around the year 2030 the maximum system capacity will start to be exceeded.

The Report states the specific transmission capacity requirements, as well as the optimal time for the commissioning of these 400 kV transmission lines, will be analysed in more detail as part of the upcoming RUS plan 2018.

Regarding relevant planning processes, WSP understands that a first public consultation meeting has taken place, which revealed significant public opposition to the use of OHLs. The second public meeting has now been postponed until Autumn 2019, due to the publication of this Report. The EIA process started in March 2018 and EIA permission is expected in the first quarter of 2020. After this, landowner negotiations and substation construction work will start. The reinforcement projects are now due to be finished in 2023, which is one year later than originally planned.

The EIA process is two processes running in parallel, for the two reinforcements – Endrup-Idomlund and Endrup-Klixbüll. Based on the conclusions of the Report and statements, the Minister will then make a final decision on the construction of the reinforcement. With political support, Energinet expect that the projects can be completed within the adjusted timeframe.

4.2 PROJECT DEVELOPMENT SCHEDULES

Estimated construction times have been provided within Chapter 5 of the Energinet Report. However, it is noted that other project development time has not been included, for example the time required for planning, consenting and procurement. It appears that commissioning has been included within the construction timeframe provided. The construction times given are reproduced below.

Table 4-2 - Comparison of construction times for the options

Option	Construction Time	Note
400 kV HVAC Overhead Line	2½ - 3 years (i.e. 30 – 36 months)	Appears to assume 100% overhead line (no undergrounding)
400 kV HVAC Underground Cable	39 months	From granting of permissions to commissioning Global cable production capacity is stated to pose a risk
400 kV HVAC Gas-Insulated Transmission Line (GIL)	5 km can be installed and commissioned within 3 years	Stated that installation and commissioning of the entire length within the timeframe seems unlikely
High Voltage Direct Current (HVDC)	More than 5 years	Not including analysis, design, approval, and environmental impact study. Installation and commissioning of multi-terminal HVDC within timeframe seems very unlikely.

An independent review and comparison of each option is given in the following sections.

4.2.1 400 KV HVAC OVERHEAD LINE

In Subsection 5.1.3 of the Report, Energinet state that the full route of the proposed reinforcement from Idomlund to the German border could be constructed within 2 ½ - 3 years. This schedule estimate appears to be based upon the assumption that all required permissions will be granted and there will be no delays due to public opposition. It is already known that there is significant opposition to the use of OHLs and in WSP's experience, legal processes and appeals can add considerable delays to OHL construction projects.

It is not clear from Subsection 5.1.3 whether the estimated timescale to construct the OHL is based upon the whole route comprising of OHL or whether UGC sections have been included. Energinet should clarify if this schedule estimate applies to Alternatives A and B and how including significant sections of UGC would affect the schedule.

WSP is of the opinion that, with the required political support and permissions, that a double circuit OHL of sufficient capacity could be installed and commissioned within the specified timeframes.

4.2.2 400KV HVAC UNDERGROUND CABLE

In Subsection 5.2.3 of the Report, Energinet state that Alternative C (50% UGC) could be constructed in around 3 ½ years from receiving the relevant permissions. It is not clear whether this estimate includes time for constructing the required compensation stations or it only takes into account the laying of the cables.

As noted in Subsection 2.2.2.4 of this report, WSP estimates that the installation rate for 400 kV cables per metre would be:

- Rural environment 100 m per day
- Urban environment 30 m per day.

In Subsection 5.2.3, a construction schedule estimate is given for Alternative C only. It would have been informative if the estimated timescales to construct Alternatives A, B, and D were also given here for comparison.

Unknown worldwide cable production capacity is said to pose an additional risk to the schedule for constructing Alternative C. However, it is not clear what research has been carried out or what experience Energinet have drawn upon to justify this assertion. Energinet should clarify why they believe cable manufacturing capacity may pose to Alternative C and state whether they believe that the same risk would apply to Alternatives A and B.

4.2.3 400 KV GAS-INSULATED TRANSMISSION LINES

Energinet has not presented a detailed breakdown of the timeframes involved with installing GIL instead of UGC for Alternatives A, B, C, or D. However, Energinet do state that they estimate that 5 km of GIL could be installed within approximately 3 years. It is not clear whether this timeframe is assuming the GIL will be installed in tunnels or directly buried, or if it includes time for substation expansion and reactive compensation installation.

Given that the transmission network reinforcements are necessary by 2023, WSP agrees that GIL is not a feasible option due to the long construction times.

4.2.4 400 KV HIGH VOLTAGE DIRECT CURRENT

The development of an HVDC project can take around 8 to 12 years from the initial feasibility studies through to commercial operation. This can be broken down into stages, some of which will overlap, as follows:

1. Feasibility studies to determine the scheme rating plus system interaction studies – 1 to 2 years
2. Location of converter stations, cable route surveys, environmental impact assessments – 1 to 2 years
3. Planning consents from local authorities - 1 to 2 years
4. Supplier pre-qualification, request for proposal, tender adjudication to contract award – 1 to 2 years
5. Design and construction of the converter stations and cables for a multi-terminal system up to commercial operation – 4 years

For a multi-terminal HVDC system with the complexity required for this reinforcement, it is envisaged that development could take significantly longer than the timescales provided above for simple point to point links. It is therefore WSP’s view that no HVDC solution could be delivered to meet the target timescale of the interconnector to enter service by 2023.

4

COST REVIEW

5 COST REVIEW

5.1 INTRODUCTION

In this Section 5.5 of the Report, Energinet has presented high-level cost estimates for the construction of the different reinforcement alternatives.

Calculating the cost of different transmission technologies involves many different factors, including terrain, route length, and power capacity. These costs must be balanced against visual and other environmental impacts by the transmission system owners when they are evaluating new transmission lines or grid reinforcements. It is important to keep in mind that it is very difficult to put a monetary price on environmental factors, such as visual impact, disruption to local communities, and impacts on local flora and faunae.

The cost of sustaining an electricity transmission grid comprises the coast of new equipment comprises capital expenditure (CAPEX) and operational costs (maintenance and losses) over the lifetime of the equipment. This cost is ultimately supported by electricity consumers through their electricity bills. Therefore, more expensive construction projects will mean higher electricity bills for consumers.

To estimate costs for each reinforcement alternative for the West Jutland reinforcement project, Energinet have only considered high-level CAPEX costs. Due to the uncertainty surrounding the final design of the reinforcements that will be eventually used and the short timescales available to produce the Report, it is perfectly reasonable that Energinet has not, at this stage, considered maintenance costs and capitalised losses in the cost estimates.

Energinet has not stated whether the cost estimates include traversing any major obstacles in the terrain for each technical alternative, such as rivers, forests, roads, railway lines, and so forth. It is also unclear if the cost of the planning process has been included in Energinet's cost estimations. Lengthy legal processes and appeals during the planning stage can add significant costs to transmission network reinforcement projects, particularly those including OHLs. However, it is extremely difficult to include such cost estimates at this stage in the process.

As stated above, the cost of sustaining the electricity transmission grid is ultimately borne by electricity consumers. So far, there seems not to have been any assessment of what the Danish public would be prepared to pay to avoid the reinforcements being comprised of OHLs. WSP understand that there is significant public opposition to Energinet's proposal to construct 400 kV OHLs in West Jutland, hence the DEA requested Energinet to prepare the Report in question. It is WSP's opinion that all of the technical alternatives are technically feasible with sufficient investment. Thus, the DEA and Energinet should consult with the Danish public as to how much they would be prepared to see their electricity bills increase in order to avoid the construction of OHLs.

In the next section, WSP presents our own estimations of the costs of different 400 kV transmission line technologies.

5.2 COMPARISON OF COSTS FOR 400 KV TRANSMISSION LINES

In 2012, WSP (formerly Parsons Brinkerhoff) in conjunction with Cable Consulting International and the Institution of Engineering and Technology (IET) produced a report comparing the costs constructing 400 kV transmission lines from OHL, UGC, GIL, and HVDC technologies[3]. The report was reviewed by National Grid (the UK transmission system operator), who found that it was broadly in agreement with their own estimations of such costs. The costs in that report are now over 6 years old, but can still be used to give a rough approximation of the costs for each transmission line technologies, and the cost ratios between the different technologies is still applicable.

As noted in the previous section of this report, Energinet has only considered CAPEX costs in their cost comparisons and has omitted operational costs, which comprise maintenance costs and losses. WSP recognises that it would be extremely difficult for Energinet to include these costs at this stage and that such costs have relatively little impact on the overall lifetime cost for each technology. However, maintenance and operational costs do have a significant impact on the ratio between total lifetime costs of different technologies. For example, the CAPEX cost of installing a 400 kV UGC is around 10 times greater than the CAPEX cost of the equivalent 400 kV OHL; however, broadly similar operational costs mean that, over the lifetime of the transmission line, that ratio is reduced to around 5:1. Thus, a comparison of cost ratios between different technologies can be misleading, as illustrated in the table below, which shows the costs associated with constructing the same transmission line from either OHL or UGC. Therefore, WSP recommends that comparison of financial costs, as opposed to cost ratios, is used when making investment decisions.

Table 5-1 - Comparison of CAPEX and lifetime costs for OHL and UGC[3]

	Capital Build Cost (per km)	Lifetime Cost (per km)
Overhead Line	£1.6m	£4.0m
Underground Cable	£16.7m	£18.9m
Cost Difference	£15.1m	£14.9m
Cost Ratio	Approximately 10:1	Approximately 5:1

[3] Parsons Brinckerhoff in association with Cable Consulting International Ltd. ‘Electricity Transmission Costing Study – An Independent Report Endorsed by the Institution of Engineering and Technology’. April 2012.

In general, when constructing 400 kV transmission line, overhead lines are by far the cheapest option, followed by underground cables, then gas-insulated transmission lines, and HVDC is generally the most expensive.

However, it should be noted that:

- losses and reactive compensation requirements for GIL are much lower than for the equivalent UGC
- Long HVDC lines are proportionally more efficient that short lines.

Costs for all technologies per kilometre tends to fall proportionally to the route length and increase with circuit capacity. Where the HVAC cables, GIL, or HVDC cables are installed in deep tunnels, as opposed to directly buried in the ground, the tunnel becomes the largest construction cost.

Different technologies are more appropriate under different circumstances and so financial cost cannot be used as the only factor when choosing which transmission line technology to use.

The following sections of this report present WSP's appraisal of Energinet's cost estimates for the different reinforcement alternatives.

5.3 400 KV HVAC OVERHEAD LINE

In Subsection 5.5.1, Energinet gives an estimate of the cost of reinforcing the transmission grid using OHLs only as:

- Endrup – Idomlund: 1540 mDKK
- Endrup – German Border: 960 mDKK

These costs are broadly in line with WSP's estimates for the capital cost of constructing double circuit 400 kV OHLs. However, Energinet states that these estimates also include costs for the required substation expansions, compensation to land owners, and "all other related project costs". It is not clear what is meant by "other related project costs" or how they have been calculated. WSP would expect that other project costs, including substation reinforcement and relevant compensation, would be additional to the costs given above.

Energinet also give an estimate of 800-1000 mDKK for the cost of undergrounding parts of the 150 kV network along with the 400 kV reinforcements and state that this constitutes the main part of the cost of the transmission network upgrades. It is not clear to WSP if Energinet are stating that these costs form part of the costs given above or would be additional to them. It is also not clear whether these costs would apply to the other reinforcement alternatives.

5.4 400 KV HVAC UNDERGROUND CABLES

In Subsection 5.5.2, Energinet presents estimates of the costs of including UGC sections as part of the required network reinforcements. Energinet states that only broad estimates of the construction costs can be given at this stage because the final design of the transmission lines is not known. WSP agrees with this assertion; further detailed costing will be required in due course.

Energinet have not provided cost estimates for Alternatives C and D because they are said to be technically unfeasible. WSP agrees that in the context of the agreed definition of "technically feasible" that Alternatives C and D are not feasible for this reinforcement.

The total costs of constructing the proposed transmission lines with UGC sections for technology Alternatives A and B are given in the Energinet Report as:

- Alternative A – 2920 mDKK
- Alternative B – 3300 mDKK.

As with the OHL only option in Section 5.1 of this report, these costs are broadly in line with WSP's estimate for the capital costs for constructing hybrid transmission lines. However, as there is very limited cost breakdown, the cost for the UGC sections versus the OHL sections is not clear. It is assumed that in order to replicated the capacity provided by the OHL, multiple UGC cable circuits would be required, and therefore these estimates may be low.

It is not clear from the Report if Energinet has included other project costs – such as substation reinforcement and land owner compensation – in these estimates; WSP would expect that such costs would be additional to those quoted.

5.5 400 KV HVAC GAS-INSULATED TRANSMISSION LINES

In Subsection 5.5.3 of the Report, Energinet does not provide an actual cost estimate for GIL but states that the cost of GIL would be 2-3 times greater than for the equivalent UGC. As noted, in Section 5.2 of this report, WSP urges caution in the use of cost ratios as these can be misleading.

As Energinet point out in their Report, there is little experience worldwide of directly buried GIL, and it is likely that a GIL transmission line would require the construction of significant lengths of underground tunnel, which would lead to significant increases in the construction costs.

It is not clear from the Report whether Energinet have taken into account factors such as higher capacity, lower losses, and reduced reactive compensation requirements when comparing GIL with UGC.

5.6 HIGH VOLTAGE DIRECT CURRENT

Based on WSP's experience of the HVDC market and recent project prices we would estimate that the price for one bi-pole converter station rated at 1400 MW at a DC voltage of ±450 kV would be 1500 mDKK. Thus, for a 3-terminal system as discussed in this section, the total price would be estimated to be 4500 mDKK. This price estimate excludes the inevitable costs related to any extension of existing 400 kV sub-stations to accommodate two new bays for connection to the HVDC converter station. Any reinforcements of the existing grid, e.g. re-conductoring of overhead lines, additional reactive power compensation, etc. is also excluded.

As discussed in Subsection 2.2.4.2, a multi-terminal system will require a DC switching station at Endrup to allow flexible and secure operation of the system. There is no published information on the costs of such switching stations, as there are few examples in the world today. However, making an estimate based on the prices of an equivalent 400 kV AC switching station, we would consider a price of 100 mDKK to be reasonable.

Such high-level indicative price estimates should be subject to a tolerance of ±20%. Thus, an upper price level of 1.2 x (4500 mDKK + 100 mDKK) should be considered for budgetary purposes at this early stage in the project, i.e. a total of approximately 5520 mDKK for a 1400MW system.

However, it is noted that the full capacity of a 2500MW overhead line solution will be required. Whilst this HVDC solution has not been costed, if a simple cost/ MW is applied, then a 2500MW system would have a cost in the order of 9860 mDKK.

6

CONCLUSIONS

6 CONCLUSIONS

The Danish electricity transmission grid in Jutland requires significant reinforcement to accommodate the Viking Link HVDC connection to Great Britain and large amounts of energy from offshore wind farms connecting to the grid in the north of Denmark. Reinforcements must be installed before the Viking Link is commissioned in 2023 to enable the full capacity of the Viking link to be realised. In discussions, Energinet has stated that the 2400 MW of additional transmission capacity will required by the year 2030, with subsequent further reinforcements likely to be required in the years following. However, the requirement for this amount of capacity is not clear from the report.

Energinet has put forward plans to construct two 400 kV transmission reinforcements, from Idomlund-Endrup and Endrup-Klixbüll, which will provide the necessary additional transmission capacity from the north of Denmark down into Germany. The initial plan is to construct the transmission reinforcements mainly from overhead lines (OHL) with some sections of underground cable (UGC). However, these plans have met with considerable public opposition to the use of OHLs, resulting in the Danish Energy Agency requesting Energinet to produce a report exploring the use of other transmission technologies with less visual impact. WSP was engaged by the DEA to provide an independent third-party evaluation of Chapters 4, 5, and 6 of Energinet's report.

WSP understands that Energinet was time-constrained in the production of the Report, which means that the Report is not as detailed as would generally be required for a feasibility study for a project of this magnitude.

In Chapter 2 of this report, WSP presents our appraisal of Energinet's technical evaluations of the different transmission technology alternatives that could be used to construct the required reinforcements. Energinet has considered the use of Overhead Transmission Lines (OHLs), hybrid OHL and UGC lines with varying shares of UGC, full UGC, gas-insulated transmission line (GIL), and HVDC.

A summary of the various considered options is provided in Table 1-1 below:

Table 6-1 – WSP High Level Comparison of Options

Technology Option	Alternative A	Alternative B	Alternative C	Alternative D	150 kV/ 220 kV cable	HVDC
Capacity	2500 MW per circuit	2500 MW per circuit	2500 MW per circuit	2500 MW per circuit	Not identified	2500 MW
Assumptions	Multiple UGC circuits needed to achieve capacity provided by OHL		Multiple cable circuits needed to achieve OHL capacity; requires ~8-9 reactive compensation stations		Many UGC circuits needed to achieve required capacity	Additional multi-terminal link needed for greater capacity
High Level CAPEX Estimate (mDKK)	2500 + other project related costs	2920 + other project related costs	Not known		Not known	9860 + other project related costs
Timeframe Estimate	2023	2023	2024	2024	Not known	Not known
Technology Risk/ Benefit	Well understood technology with low technical risk	Well understood technology with low technical risk	Risk of technology issues such as harmonics	Risk of technology issues such as harmonics	Risk of technology issues such as harmonics	Multi-terminal solution would have challenges but is not impossible

The table is based on the following assumptions:

- Timeframes assume that public opposition does not lead to any further delays. HVDC timeframe assumes that work could start immediately and there are no subsequent delays;
- Capital cost estimate for Alternatives A and B are provided by Energinet; it is not clear whether sufficient cable circuits have been accounted for in this estimate;
- Capital cost estimate for the HVDC alternative is from WSP; however, this has been interpolated from a derived cost/ MW and is therefore subject to inaccuracy.

It should be possible to deliver Alternatives A or B within the timeframe of 2023, assuming that public opinion does not lead to any further delays. Energinet has ruled out Alternatives C and D on the basis of technical feasibility. WSP agrees with this conclusion in the context of the definition of technical feasibility given in this report. A very high-level cost estimate has been provided for the HVDC solution of approximately four times the cost of Alternative A. This is broadly in line with Energinet's estimate of the HVDC solutions being approximately five times the cost of an equivalent solution.

Given that the reinforcements are required by 2023, Energinet has discounted the GIL and HVDC options as unfeasible due to their complexity and their long construction times and has not considered them further in the technical analysis. WSP is in agreement that the GIL solution is technically unfeasible. WSP also agrees that it is not feasible to construct an HVDC solution by

2023 and that the development time for a multi-terminal system of the type that would be required for this reinforcement is likely to be significantly longer than that required for a point to point link.

Energinet also considered a solution based on 150 kV and 220 kV underground cables (Alternative E). This solution was also discounted by Energinet due to the amount of cable circuits that would have to be installed to give the required reinforcement capacity. WSP fully agrees with Energinet's conclusion that trying to reinforce the grid with 150 kV and 220 kV UGC would be unfeasible due to issues with capacity and timescales.

In Section 6 of their report, Energinet explored solutions based on overhead lines with varying shares of UGC to ascertain the maximum amount of UGC that could be included without causing technical issues on the rest of the system. Energinet claims their studies demonstrate a technical limit of approximately 15% share of UGC in the reinforcements. WSP agrees with this assessment for the following reasons:

- At 15% cable share, harmonic amplification is already beginning to "spread" to various substations leading to a great likelihood of mitigation (i.e. filters) being needed at more substations;
- Values of cable share >15% were not studied, because there had already been significant debate as to whether the maximum value should be 10% or 15%. 15% is already pushing the boundaries in terms of global track record;
- Because 4 circuits are required with 3 cables per phase to achieve the required capacity, this represents a significant amount of cable. There are issues for example with modelling cables (modelling accuracy is not very good) which can lead to errors in the modelled results and hence technical issues that are only realised after construction and commissioning of the project. For longer cable lengths, the overall inaccuracy in the model becomes larger and leads to a higher risk of issues; and
- At approximately 19% cable share, additional reactive compensation stations are required which would potentially lead to reduced system reliability and also increase the timescales and costs for the development.

In addition, a review of the literature supports this view. The published literature considers that relatively short sections of cable in the order of up to 20km when discussing partial undergrounding in a meshed network. For example, the ENTOSE's paper[4] on partical undergrounding discusses a case study with a reinforcement incorporating 7.5km of underground cable. It also states that considerations such as harmonic resonance, switching sequence and reactive compensation can be relevant but gives no further details. National Grid's document on undergrounding high voltage transmission lines[5] states that reactive compensation may be needed for lengths of cable greater

[4] "Joint Paper: Feasibility and technical aspects of partial undergrounding of extra high voltage power transmission lines", ENTSOE/ Europacable, 2011

[5] "Undergrounding high voltage electricity transmission lines: The technical issues", National Grid, 2015

than 5km. There is no information provided on other challenges such as harmonics. This therefore reinforces the point that there is limited experience in undergrounding 400kV cables, including the associated technical risks. Given the specific technical risks highlighted by Energinet for this particular reinforcement, and the limited global experience in undergrounding long lengths of underground cable, WSP agrees that the 15% limit is reasonable and that Energinet has made efforts to push the limit out from 10% which has fewer technical risks.

Chapter 3 of this report presents WSP's assessment of the environmental aspects considered by Energinet in their report. WSP recognises that environmental impacts were not initially specified as a selection criterion for the reinforcement option, but have nevertheless been referenced. The review was therefore included within the WSP scope of work. Although the level of environmental detail was relatively limited in this report, it is expected that these areas would be examined in greater depth at EIA stage.

The Report notes that the final selection of the route and transmission solution (combination of OHL and UGC) alternative will need be determined during the EIA phase and should aim to find a solution which limits the environmental impact and alleviates any public concerns as much as possible. This in turn will support a more efficient authorisation process, which is required in order to meet the required project timeframes.

In Chapter 4 of this report, WSP presents our review of the timelines required to construct each reinforcement alternative. As noted previously, the reinforcements are required to be operational by 2023. It is WSP's opinion that it is not possible to construct the reinforcements in this timeframe using the GIL, HVDC, or full UGC (Alternative D) solutions. It is also not possible to give an accurate estimate of the construction times for Alternatives A, B, and C, until the EIA process is complete and the exact route of the proposed transmission lines is known.

Chapter 5 of this report presents our analysis of the costs associated with the different transmission technologies. Overhead lines are the cheapest of the transmission line technology, followed by underground cables, GIL, and HVDC is generally the most expensive. WSP is broadly in agreement with Energinet's high level estimates of the costs of constructing the reinforcements from OHLs and hybrid OHL/UGC transmission lines. It is not possible to give a more accurate estimate of the total costs until the route and technology to be used are known. However, the high-level cost estimate for the HVDC option is approximately four times that of the HVAC option, which is broadly in agreement with the cost estimate provided by Energinet. It should be noted that the transmission capacity provided for this cost is significantly lower than that provided by the HVAC option. One reason for the difference in cost may be the assumption by Energinet that an additional 1000 MW HVDC link is required which may be to provide the "equivalent" solution in terms of capacity.

It must be kept in mind that, whichever technology alternative is eventually selected, the installation and commissioning of the required transmission grid reinforcements will be a large and extremely complex engineering project, further complicated by the relatively short timeframe in which the reinforcements are needed. There will be no easy solution. Nevertheless, WSP agrees with Energinet's conclusion that constructing the required reinforcements using OHLs will be the technically most robust, simplest, quickest to construct, and cheapest option from the available technology alternatives. This assumes that there are no further delays due to public opposition.

In conclusion, it is WSP's opinion that, considering the required additional transmission capacity and the timescale of 2023 in which the reinforcements must be commissioned, the most likely feasible option is to use 400 kV double circuit overhead lines with sections of UGC up to a maximum proportion of 15% of the total reinforcement. It should be noted that the timeframe of 2023 is dependent on their being no further delays due to public opposition.

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