NOTE

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FOR YOUR INFORMATION ☒

FOR DECISION-MAKING ☐

Assessment of possible options to realize the required transmission capacity towards Zeeuws-Vlaanderen

1. Introduction

The use and transport of electricity in the Netherlands has been increasing for the last decades. The high-voltage grid in the Netherlands is becoming increasingly (over)loaded. Due to the energy transition the demand for electricity will continuously grow and even accelerate in the coming years. In Zeeland, especially in Zeeuws-Vlaanderen, the forecasted growing demand for electricity is leading to bottlenecks in the transmission capacity of the high-voltage grid. Further expansion of the existing 150 kV high voltage grid is insufficient to ensure security of supply and facilitate the connection of large industrial consumers to the grid. Therefore, expansion of the 380 kV grid is required. To facilitate all developments a new 380 kV substation near Terneuzen is required, connected to the 380 kV grid in Zeeland by means of 4 new circuits. This will create a new strong grid connection point at Zeeuws-Vlaanderen to facilitate the industrial electrification and reinforce the 150 kV grid there. TenneT and the Ministry of Climate and Green Growth (Ministerie van Klimaat en Groene Groei) have therefore initiated a project called “380 kV Grid Extension Zeeuws-Vlaanderen”.

As it is known that grid expansion towards Zeeuws-Vlaanderen will not be easy to realize, besides technical challenges of crossing the river Westerschelde, it will also have a substantial impact on the spatial and public environment. As one of the first project steps, the concept memorandum “Notitie Reikwijdte en detailniveau 380 kV netuitbreiding Zeeuws-Vlaanderen” [1] has been finalized and established on September 17, 2025. This memorandum (further referred to with NRD) describes the scope and level of detail which all solutions with respect to the required grid extension towards Zeeuws-Vlaanderen shall respect.

Now the need and motivation for the grid extension are concluded, the technical options to realize this grid extension must be determined. TenneT has made an inventory of the available technical options and assessed them with regard to applicability for this project.
High Voltage transmission capacity can basically be realized by means of Alternating Current (AC) or Direct Current (DC) technology. Furthermore, the connections can be made with overhead line, cable, GIL or a combination of them. This memorandum in front of you will further explain these technologies, the resulting technical options to realize the grid extension towards Zeeuws-Vlaanderen. TenneT has assessed all the options and present the outcome in this memorandum.
It is concluded that the option with AC technology, consisting of a partly cable, partly overhead line, is the suitable solution for this project. As the next step DNV is asked to further investigate the preferred solution with respect to operational and electrical reliability and define necessary measures to ensure a robust and reliable high voltage grid towards Zeeuws-Vlaanderen.

2. Explanation of some technical terminology

When discussing the technical possibilities to extend the transmission capacity towards Zeeuws-Vlaanderen, it is necessary to have a basic understanding of the used terminology:

2.1 Units

With respect to the transmission of electricity (electrical energy) the following terms are used:

- Voltage: indicates the level of potential energy in the system. A difference in potential is conditional to allow for a current to flow in a closed circuit. Voltage is expressed in Volts [V], for high values the term kiloVolt [kV; 1000 Volt] is used.

- Current: the amount of electrical charge that moves via a conductor between two points with a voltage difference. Current is expressed in Ampère [A], for high values the term kiloAmpère [kA; 1000 Ampère] is used.

- Transmission capacity: indication for the maximum amount of electrical energy that a connection safely can manage to transport electrical energy between two nodes in the grid. Transmission capacity is determined by the product of voltage and current and is expressed in VA (Volt-Ampère). In the high voltage grid the transmission capacity is usually expressed in MVA [Mega-Volt-Ampère; 1 million VA]

- Active power: the portion of electrical power which is converted into useful work, such as generating heat, light or mechanical energy. It is determined by the product of voltage and current, completed with an efficiency factor (the power factor, usually called the ‘cosinus phi’ (cos φ)). Regularly the power factor shall be between 0,9 and 1,0. Active power is expressed in Watt, for large units MegaWatt [MW; 1 million Watt] is used.

- Reactive Power: the electrical energy that is needed to operate an Alternating Current Grid (AC-grid), i.e. the establishment of the electric and magnetic fields. Reactive power is expressed in var (Volt-Ampère-reactive), for large units Megavar [Mvar; 1 million Volt-Ampère-reactive] is used.

2.2 Alternating current and Direct current

Electrical energy transmission is from physics point of view possible due to the interaction between electrical and magnetic fields (electromagnetic fields, or EM-fields). The fields are generated by the co-existance of capacitances and inductances. The latter are determined by the physical characteristics of equipment.
There are two possible technologies to transmit power between a generator and a consumer. This can be done by means of alternating current (AC) or direct current (DC).

AC

The operation of AC is based on the principle that the polarity of the voltage and the direction in which current flows changes 50 times per second. The number of changes per second is indicated with the frequency, in the European grid the frequency is always 50 Hertz (Hz). Because the polarity of voltage and current changes almost simultaneously, power transmission is possible.

With DC, the polarity does not change, the voltage and current will always have the same direction, which will allow for power transmission.

Alternating current can be converted into direct current and vice versa, this requires however an electrical installation called a rectifier (AC → DC, single direction) or a converter (AC ←→ DC, both directions).

The entire European electricity system – from power plant to power outlet – is based on the principle of alternating current. The physical characteristics of AC technology makes the use of transformers (thanks to the alternating electromagnetic fields) to change to another voltage level, and circuit breakers (thanks to the natural zero crossing of the current) to switch a link in the grid in or out, possible. But furthermore, in the event of a fault in a connection in the AC-grid and the fault is cleared, the current is automatically redistributed over the remaining circuits without any intervention. There is no interruption of the power supply.

An important consequence of the use of AC is that the transmission behavior is dependent on the length of the connection and the choice of the physical components. Due to the constantly changing polarity, the electromagnetic fields must be rebuilt again and again to enable power transmission. The required energy for this is called reactive power and transmission of reactive power leads to losses. The efficiency of AC power transmission is amongst others determined by the voltage level, the length of the connection and the construction (like overhead line or cable). For long connections, the amount of reactive power is becoming so high that it is limiting the transmission capacity for active power. To increase the distance, the voltage level could be increased or additional reactive power compensation (to compensate for the losses) could be installed along the routing.

As mentioned above, the choice of physical components to make a connection between two substations impacts the amount of required reactive power compensation. A connection can basically either be made by overhead line or by underground cable. Both types have very different electrical characteristics (different values for their capacitance and inductance). The capacitance value determines the amount of generated reactive power. In the TenneT 380 kV grid the capacitance per kilometer of underground cable is approx. 30 times higher than the capacitance of an overhead line. A cable section generates therefore more than 30 times more reactive power than an overhead line section with the same length. This has therefore a huge impact on the possible connection length and the need for intermediate compensation.

AC connections are efficient in an meshed grid with relatively short distances (< 100~150 km) between substations. They provide a robust electricity system with a high availability and a high transmission capacity. Due to extensive development and use of AC equipment in electricity grids worldwide, the costs are moderate.

DC

DC power transmission does not have the disadvantage of reactive power, the EM-fields are static and do not need to change continuously to make the transmission of electrical energy possible. The values of the inductance and capacitance do play a minor role in the system design, which enables the use of both overhead line as underground cable for a DC connection. Because there are no reactive power losses, a DC connection makes power transmission over long distances possible and efficient.

However, direct current has to be made from alternating current and at the end point converted back into alternating current. This is done by means of power electronic installations, called converters, which are installed in the converter stations. There are two main types of power electronic converters: the line commutated converter (LCC) and the voltage source converter (VSC). The LCC converter is very suited to transport huge amounts of power over very long distances in a (mainly) single direction, the VSC converter offers more flexibility in power direction, maintaining power quality and can be designed for multi terminal use. The TenneT 2 GW offshore grid connections systems are of the VSC type.

The Voltage Source Converter type is used as the reference for a converter in this memo. Furthermore, the reference topology of an HVDC connection is a point-to-point connection, which means a series connection of a converter station, a DC connection and a second converter station; between two AC substations, see Figure 1

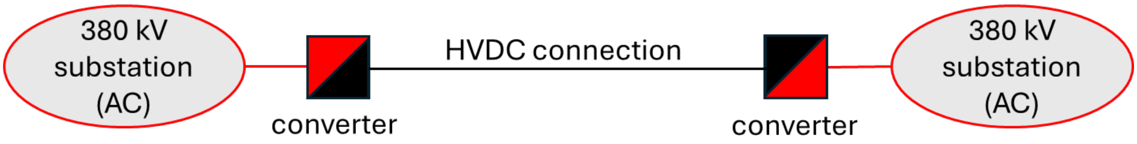


Figure 1: Schematic representation of a single HVDC connection system (point-to-point) between two 380 kV substations

The cost of a converter station is higher than an AC substation. When a large amount of power needs to be transmitted over a short distance, although the cost created by the DC conductors and losses are low, the total cost is higher than using AC due to the high cost in the converter stations. But when the transmission distance is long even (more than a so called ‘breakeven point’), the high cost in the converter station will be compensated by the low cost on the DC conductors and losses, which makes the DC connections more technically and economically efficient. The breakeven point is around 100 km for cables and 500-800 km for overhead lines. Moreover, since the frequency is zero in DC, there is no reactance in the system. This can lead to very fast system dynamics and high fault currents in the system.

DC connections are efficient in use when a large amount of power needs to be transmitted over a long distance (see above), when two non-synchronous grids needs to be coupled, or sometimes when a physical barrier needs to be crossed that is not possible by means of an AC connection.

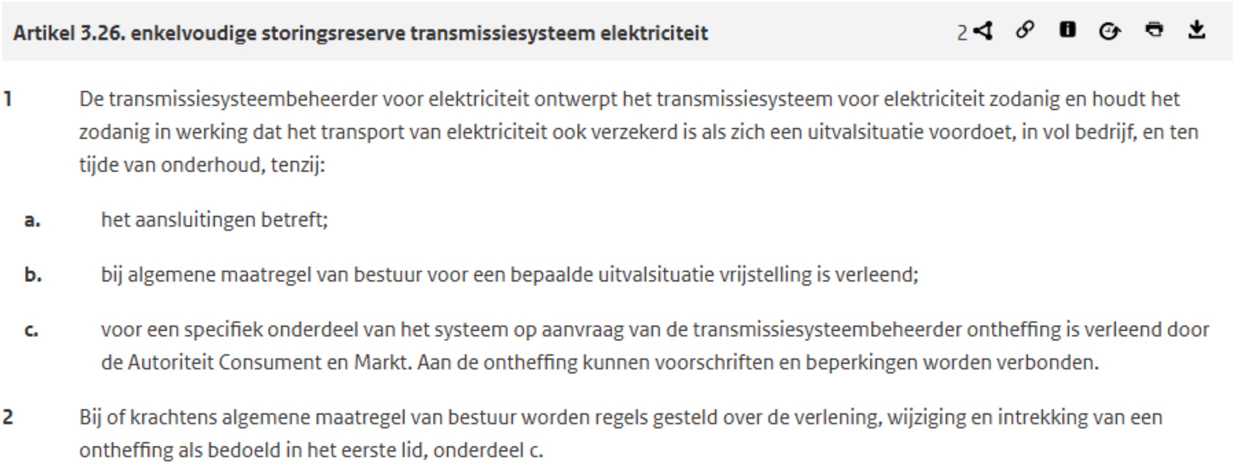
As DC transmission is highly suitable for large power transmission over long distances, the operating voltage is usually increased to 525 kV to maximize the transmission capacity. It has been common to refer to DC transmission systems using the abbreviation HVDC (High Voltage DC). This will therefore also be used in this memorandum.

3. Start conditions for grid design

As indicated in the introduction (can be read in the NRD), there is a motivation to extend the 380 kV grid towards Zeeuws-Vlaanderen. This will therefore not be repeated in this memorandum.
Before discussing the technical solutions, there are some pre conditions with respect to the grid design requirements.

3.1 N-1 / N-2

The grid shall be designed in such a way that any fault shall not lead to an interruption of the transmission of electricity. This is stated in the current Energy Law (Energiewet), article 3.26. (see Figure 2).
This is also referred to as the N-1 design principle: an outage of one grid asset of the total number (N) grid assets shall not lead to interruption.
Next to that, also the N-2 design principle must be respected: in case of a scheduled outage for maintenance, it must still be assured that any fault does not lead to interruption of the supply.



Artikel 3.26. enkelvoudige storingsreserve transmissiesysteem elektriciteit

1 De transmissiesysteembeheerder voor elektriciteit ontwerpt het transmissiesysteem voor elektriciteit zodanig en houdt het zodanig in werking dat het transport van elektriciteit ook verzekerd is als zich een uitvalsituatie voordoet, in vol bedrijf, en ten tijde van onderhoud, tenzij:

- **a.** het aansluitingen betreft;
- **b.** bij algemene maatregel van bestuur voor een bepaalde uitvalsituatie vrijstelling is verleend;
- **c.** voor een specifiek onderdeel van het systeem op aanvraag van de transmissiesysteembeheerder ontheffing is verleend door de Autoriteit Consument en Markt. Aan de ontheffing kunnen voorschriften en beperkingen worden verbonden.

2 Bij of krachtens algemene maatregel van bestuur worden regels gesteld over de verlening, wijziging en intrekking van een ontheffing als bedoeld in het eerste lid, onderdeel c.

Figure 2: Extract from the Energiewet article 3.26 (20-01-2026), in Dutch

3.2 Voltage level

Furthermore, to extend and reinforce the grid towards Zeeuws-Vlaanderen a transmission level must be selected which matches the required capacity increase.

The electrical grid can be split up in different levels indicated with their voltage level. The grid TenneT maintains and operates has two levels: the national level at extra high voltage (EHV) at 380.000 Volt (380 kV) and the regional level at high voltage (HV) at 150.000 Volt (150 kV)[1].

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[1] 220 kV (EHS) and 110 kV (HS) are also voltage levels in the grid of TenneT, but are not located in Zeeland and therefore not further mentioned.

The electrical grid basically consists of nodes and connections between the nodes. The nodes at EHV level are actually the substations at 380 kV level with connections to the regional grid, large power plants, large industrial consumers and offshore located platforms to which the large offshore wind farms are connected. Furthermore at these substations specific installations to support the grid, like reactors, capacitor banks, filters, synchronous condensers, are connected.

The nodes at regional level, the 150 kV substations, facilitate the connections of the regional grid operators, local industrial consumers, solar farms, onshore wind farms and medium sized power plants.

3.3 Connections and circuits

The connections between the nodes are the high voltage connections. They can be made in different manners; depending on the voltage level, the required transmission capacity and possible physical obstructions in the route routing a connection can be made by overhead line (OHL) or underground cable (UGC).

In the 380 kV grid a connection between two substations always consists of two parallel circuits (or sometimes more), which are each other's back up. In case one circuit fails, the other circuit always has spare transmission capacity to take over. In case of an overhead line, the current standard is to install maximum two circuits in one tower.

Next to that, each 380 kV circuit shall have a standard transmission capacity of 2.635 MVA, matching the standard equipment size of 4.000 A.

3.4 Interconnection

The Dutch electricity grid is connected to the grids in our neighboring countries via the so called interconnectors.

There are:

- AC interconnectors to Belgium (2) and Germany (4)
- HVDC interconnectors to the UK, Denmark and Norway.

There are international agreements about the way these interconnectors can be used in the European system. This has been extensively discussed in the TenneT position paper regarding the possibility of an interconnector between Zeeuws-Vlaanderen and Belgium. [2]

3.5 Grid design proposal

The current grid in Zeeland consists of a strong 380 kV connection between the substations Rilland and Borssele. Substation Borssele is located at the area (former island) Zuid-Beveland. This connection has 4 circuits, each circuit has (or will get, but can already conditionally manage) a transmission capacity of 2.635 MVA. See Figure 3 with the grid map in the province Zeeland.

The electricity grid at Zeeuws-Vlaanderen has a voltage level of 150 kV and is connected to the grid in Zuid-Beveland by means of two 150 kV circuits, crossing the river Westerschelde. As this connection already has a transmission capacity bottleneck, a project is ongoing to reinforce this connection with two additional 150 kV circuits.

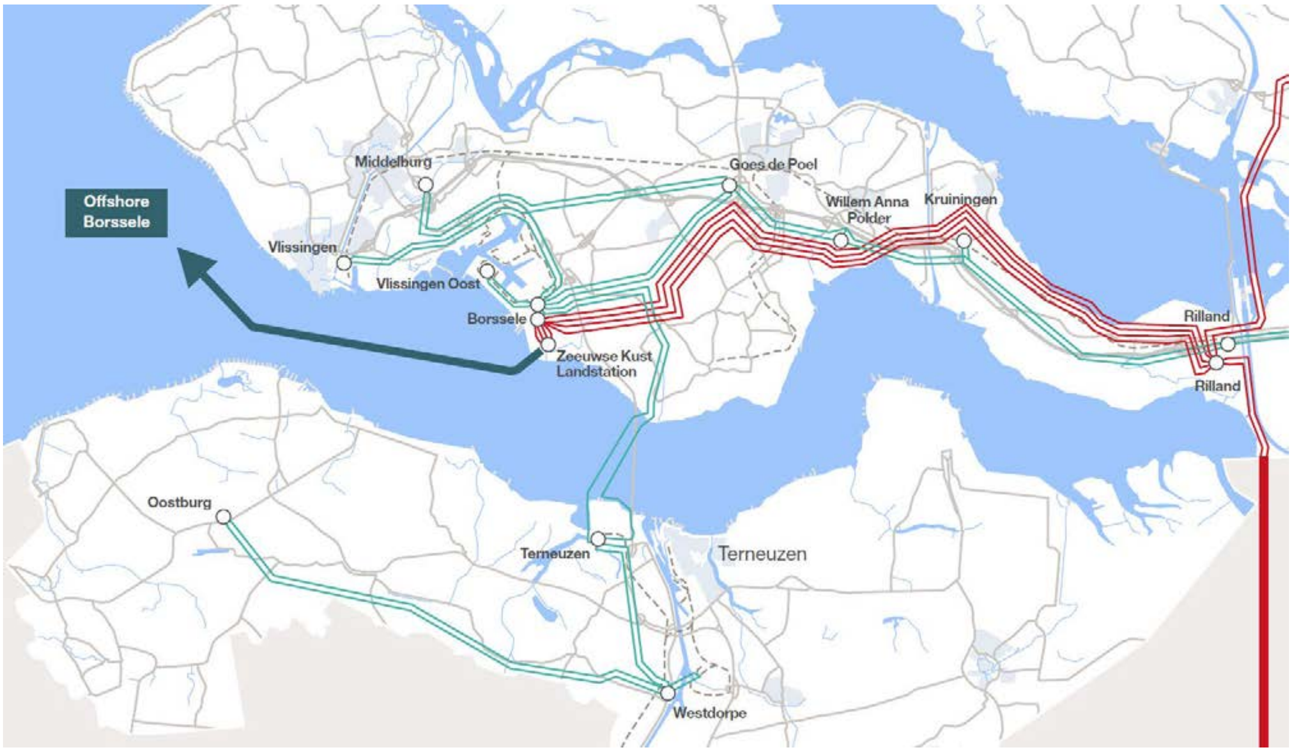

Figure 3: TenneT map with the EHV and HV grid in Zeeland (legend: ○: substation; —: 380 kV circuit; —: 150 kV circuit)

Based on the criteria in the previous sections a proposal for the grid extension has been made, with the starting points:

- Given the required increase of transmission capacity the grid towards Zeeuws-Vlaanderen must be extended with circuits that have a transmission capacity fitting the 380 kV transmission standard.
- To fulfill the N-1/N-2 design criteria more than one connection is required.
- The grid reinforcement must be done within the Dutch grid.

An additional starting point is that the current 380 kV substation Borssele is fully occupied and cannot be extended anymore due to space limitations.

The scope of the grid reinforcement consists of several related parts:

- A new 380 kV substation at Zeeuws-Vlaanderen is required to connect to the existing local 150 kV grid, to facilitate the connection of new large industrial customers and future large power generation plants (offshore wind, nuclear). This substation is provisionally called “380 kV substation Terneuzen”, although there is no location selected yet. This substation will be the node to which the 150 kV grid in Zeeuws-Vlaanderen will be connected to.

- The connections between Zeeuws-Vlaanderen and the 380 kV infrastructure at Zuid-Beveland.

Given the above considerations, the optimal grid design is to loop in the substation Terneuzen in two of the four circuits between Borssele and Rilland, at this moment still irrespective of the way to physically realize this. The schematic view is presented in Figure 4.

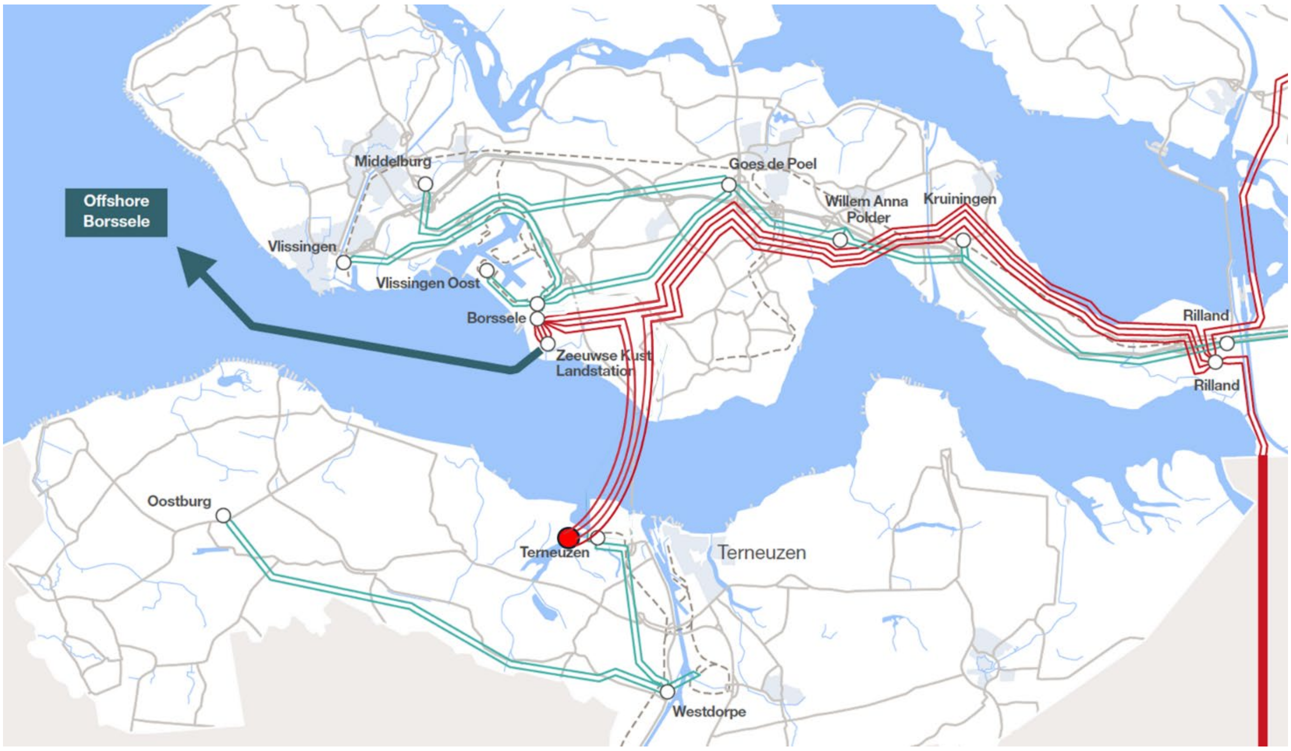

Figure 4: Schematic representation of the proposed EHV grid extension towards Zeeuws-Vlaanderen. The location of substation Terneuzen and the routing of the new connections is only indicative.

This grid design will connect the new 380 kV substation Terneuzen with substation Borssele as well as the substation Rilland. Each connection will have two circuits, every circuit is able to take over the power transmission of the parallel circuit. This grid design respects the N-1/N-2 design requirements, it will establish sufficient transmission capacity to facilitate all expected future developments and does not require extension of existing substations at Zuid-Beveland.

Each circuit in the existing 380 kV connection at Zuid-Beveland has a transmission capacity of 2.635 MVA. To fully utilize this capacity, the connection extension towards Terneuzen shall have the same capacity.

4. Realization alternatives

To physically realize the connections there are a few technical options. This chapter will briefly introduce the options and assess whether it is a suitable option for the projected scope of this grid extension.

Basically the options can be divided into a choice between AC or HVDC, and a choice between overhead line, cable or a third alternative, the so called Gas Insulated Line (GIL, only AC).

4.1 Grid extension with HVDC

Technical aspects

A point-to-point HVDC transmission system consists of two converter stations with an HVDC connection in between. The connection in between can be realized by means of overhead line or cable. The operational DC voltage of the connection in between will be plus and minus 525 kV (the voltage between the plus and minus conductor is 1.050 kV). The overall transmission capacity of a HVDC system is determined by the size of the converters and the capacity of the connection in between. A principal picture is presented in Figure 1 and copied again in Figure 5. The HVDC connection, here indicated with a single black line, consists in reality of three physical conductors: a ‘plus’-conductor, a ‘minus’-conductor and a neutral conductor[2].

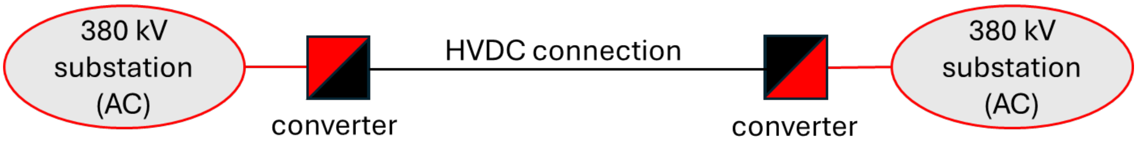

Figure 5: Schematic representation of a single HVDC connection system (point-to-point) between two 380 kV substations

For the connection of large offshore wind farms TenneT has developed a standard HVDC connection system with a transmission capacity of 2.000 MW (also called 2 GigaWatt or 2 GW). This system makes use of HVDC-cable for the connection between the converters. The maximum transmission capacity of this system is 2.000 MW, mainly limited by the cable size. But assumed that the cable size can be increased, the transmission capacity of a single HVDC connection system can be adjusted to closely meet the 380 kV standard transmission capacity of 2.635 MVA. In that case, each circuit towards Terneuzen, as is drawn in Figure 4, could theoretically be replaced by an ‘upgraded’ 2 GW HVDC point-to-point connection system.

In total there are four (point-to-point) HVDC connection systems necessary to realize the proposed grid design, which results in four converters located at Zuid-Beveland and four converters at Zeeuws-Vlaanderen, see Figure 6. In between, a total number of at least 12 cables have to be installed, three per HVDC system. In

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[2] There are different HVDC topologies possible. This memorandum uses the topology with a neutral conductor as it can give a 50% redundancy in case of a fault. This topology is also used in the 2 GW offshore connection systems under construction.

case the transmission capacity is limited by thermal boundaries of the cables, it might be necessary to double the ‘plus-cables’ and the ‘minus-cables’, so 20 cables have to be installed. This requires further study.

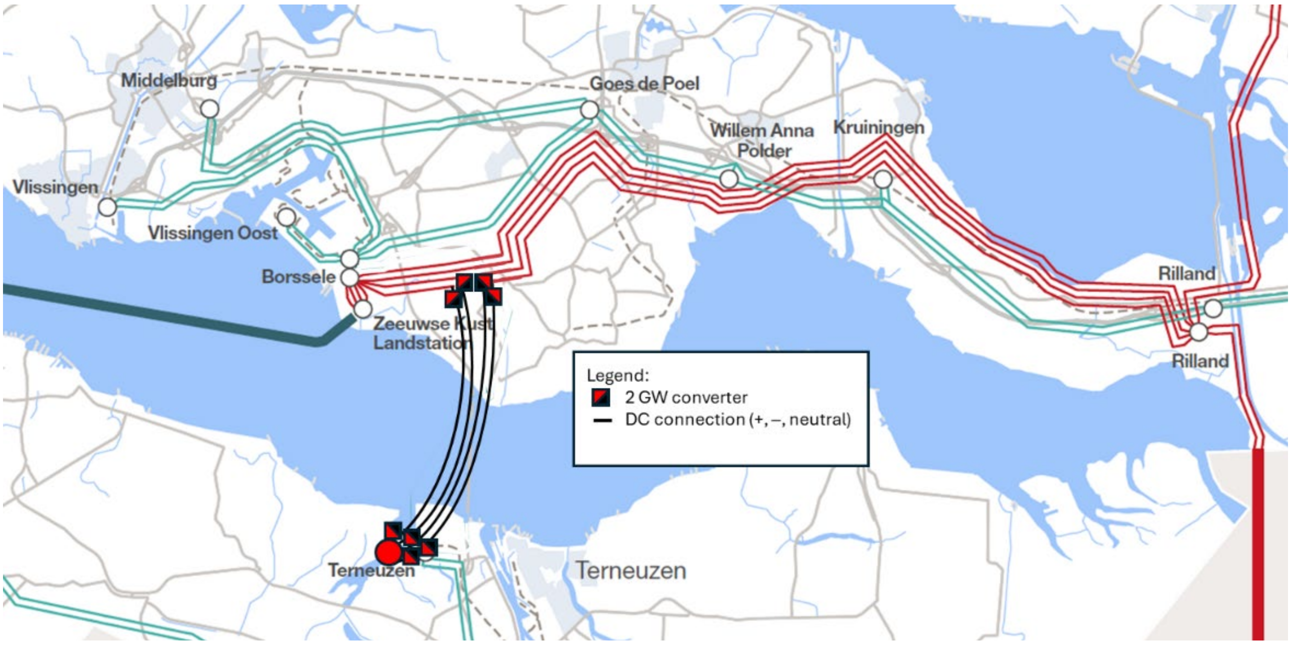

Figure 6: Schematic representation of establishing the proposed grid reinforcement by means of HVDC connection systems. All locations are indicative only.

Installation aspects

A single HVDC converter requires a plot of 5,5 ha. As there are 4 converters necessary in the north and 4 in the south, in total two plots of 4 x 5,5 + 2 = 24 ha (including 2 ha temporary space for building activities) are necessary. Figure 7 shows a realistic view of a single 2 GW converter station (artist impression). The large hall is approximately 25 meters of height.

Figure 7: Artist impression of a single 2 GW converter station.

The conversion of Direct Current into Alternating Current is done by means of power electronic equipment, which will divide the voltage in small fractions and then reconnect them fast in an alternating order. This is done with a speed of a few thousand times per second. Figure 8 shows an example of such an installation.

Figure 8: Example of equipment inside the converter hall.

A high voltage cable basically consists of a central core at high voltage, an insulation layer to withstand the high voltage and an outer earthing shield to provide ground potential and carry fault and leakage currents. Furthermore additional mechanical protection layers are applied. See Figure 9 as an example.

A cable for AC application and DC application do have the same setup, although different materials for the insulation layer are applied. Nowadays the core of a cable is insulated by means of a thick plastic layer (XLPE: cross linked poly ethylene), in the past also paper-wrapped – mass impregnated nsulation is used. The insulation material strongly determines the electrical properties of a cable.

Figure 9: Picture of a 525 kV DC submarine cable (source: www.prysmian.com)

A corridor on land for the DC cable connections shall be broad enough to facilitate the installation of all 12 to 20 cables. Figure 10 shows some examples for the required space for a single DC connection. The exact space requirements are dependent on the thermal ground conditions, and the possible need for doubling the plus and minus cables.

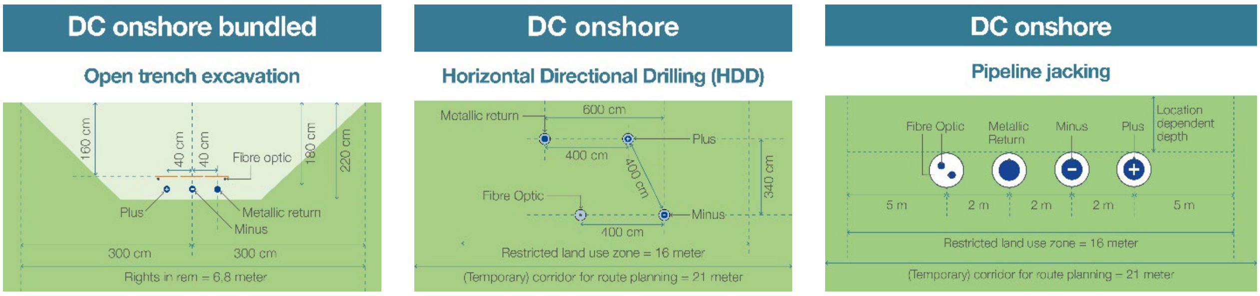

Figure 10: Indication of required distances to install a DC connection in different situations

4.2 Assessment of the HVDC alternative

The applicability of HVDC as a solution to realize the required grid extension is assessed on several criteria:

Technical:

- The DC connection between the converters can be established by underground cable, thus avoiding the installation of new overhead lines.
- Due to the high switching frequency, an HVDC converter introduces a risk on distortion in the grid. It might introduce unwanted electrical interaction between converters and customers like conventional power plants or large industrial facilities. Additional study is required to investigate the need for mitigating measures.
- A converter is a complex technical installation which has an increased risk on disturbances and requires extensive maintenance and inspection on regular intervals.
- A converter has basically the capability to supply additional services to the support grid, when incorporated in the design specification and activated in operation.

Spatial Planning:

- A plot of land at Zuid-Beveland and a plot of land at Zeeuws-Vlaanderen, each approx. 24 ha, is required to build the converters. Each converter consists of a large hall, power transformers and a switching yard. There will be visual and audible impact.
- A corridor for the cable connections has to be found. Depending on the thermal capabilities the corridor shall have sufficient space for 12 to 20 cables.

Financial:

- The costs of a single converter station on land are derived from the ongoing 2 GW projects at TenneT. The costs of one onshore converter station (land, civil works, electrical equipment HVDC and AC, project management) are 750 million Euro. As there are 8 converters necessary, the additional costs will sum up to 5 billion Euro (with ~20% efficiency discount assumed). This must be considered as additional costs compared to other solutions.[3]

Planning:

- The need for additional technical studies, the specification and the design of the HVDC connection systems will introduce a significant delay in the grid extension. A first rough estimation is a shift of the in service date with 4 to 8 years.
- Present demand for HVDC solutions is very high. Which will likely result in additional delays due to OEM related manufacturing and engineering capacity constraints (also between 4 to 8 years).

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[3] The costs of the DC connection are intentionally not mentioned here as a connection is also required for an AC solution.

4.3 Grid extension with AC

Technical aspects

The solution to extend the grid based on AC is a continuation of the current grid philosophy. Two of the four AC circuits between Borssele and Rilland are cut open and a new substation in Terneuzen will be looped in by means of extending the existing circuits, as is indicated in Figure 4.

The next important step is how to realize the new connection extensions. There are basically three technical options:

- Use of overhead line
- Use of underground cable
- Use of Gas Insulated Lines

The next paragraphs will briefly describe these options

The actual policy regarding the choice for overhead line or cable is written down in the policy document regarding the realization of 220/380 kV high voltage connections [4].

Overhead line

This is a worldwide known, robust and reliable solution to realize a high voltage connection. TenneT uses the following starting points when developing a new 380 kV overhead line connection.

- The towers will be made by lattice steel construction.
- To maintain and repair an overhead circuit it must always be accessible without the disconnection of any other circuit. Practically, this limits the number of circuits in a tower to two.
- Parallel towers shall have a certain distance to allow for maintenance activities in a safe way, see Figure 11.

A circuit in an overhead line uses the surrounding air for isolation, therefore the lines are hanging high above ground, see Figure 12 with an example of such a conductor. This results in a low capacitance value, which influences the electrical behavior in the system: when an overhead line circuit is low loaded, it generates some reactive power, when it is high loaded it requires reactive power.

The worldwide experience over the last decades with overhead lines continuously confirms the high reliability of this construction.

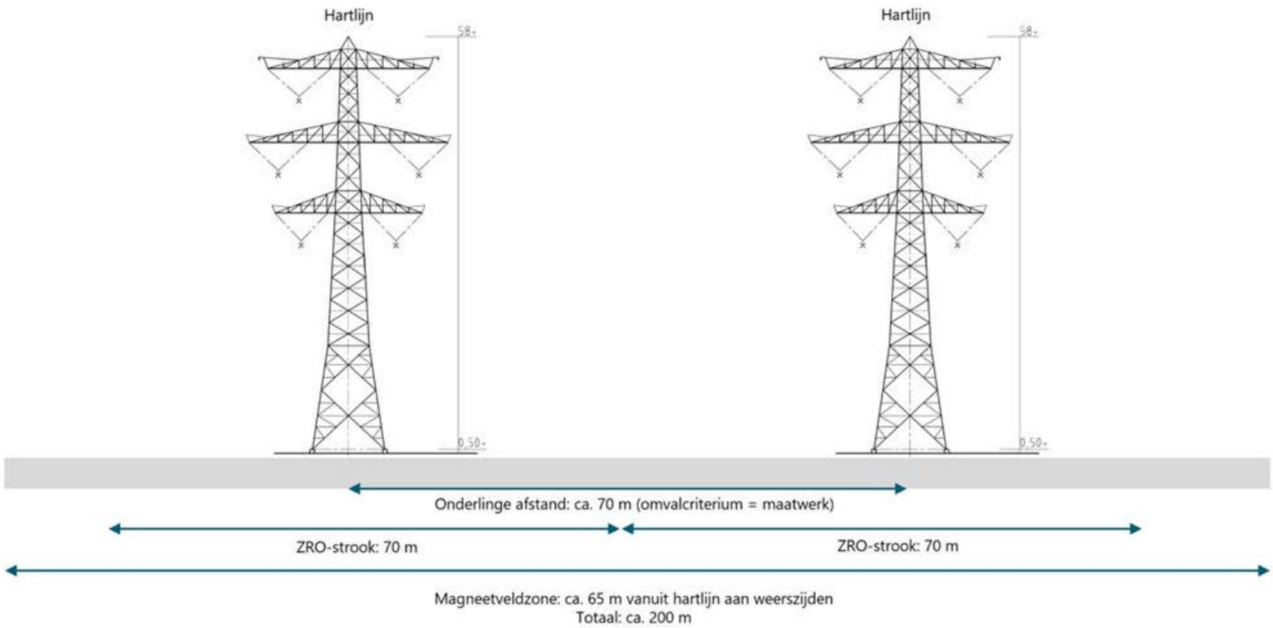

Figure 11: Visual with two parallel 380 kV connections. Minimum distance between towers subjected to further research. (from IAE project Noord-Holland-Noord Concept-IEA - Deelproduct kabels en leidingen - 380 kV Netuitbreiding Noord-Holland Noord).

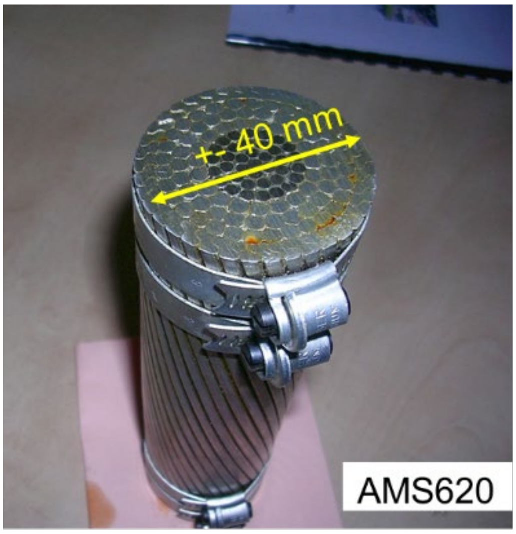

Figure 12: Example of a conductor used in an overhead line connection

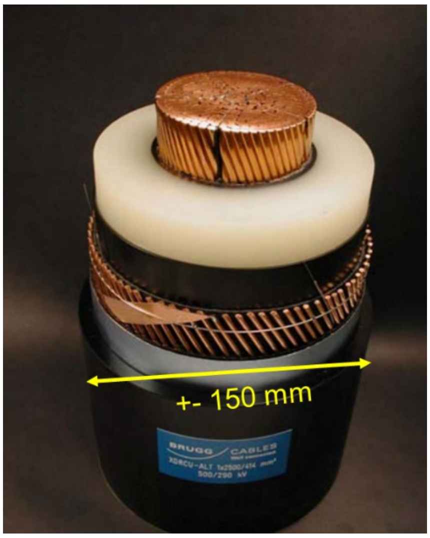

Figure 13: Example of a 420 kV cable

Cable

The use of cable for high and extra high voltage connections requires more careful considerations about the applicability at the foreseen location in the electricity grid. The cable technology for AC applications has nowadays reached the proven technology readiness level for voltages up to 420 kV. Nevertheless, the following points must be taken into consideration when applying an AC cable section in an EHV connection.

- The physical construction of a cable results in different electrical properties of a cable compared to an overhead line. Due to the thick plastic insulation layer, see Figure 13 as an example, a cable has a much higher capacitance and will always generate reactive power when energized (see also section 2.2).
- The losses generated in cable will heat up the cable. As a cable has a maximum allowable temperature, the heat must be dissipated by the surrounding ground. To establish a transmission capacity matching the 380 kV standard of 2.635 MVA, more than one cable per phase is required. The policy of TenneT is to use two cables per phase and make use the thermal capacity of the cables to manage the variations in loading.
- To install a cable section in a connection, several separate cable lengths must be joined as it is not possible to transport infinite lengths. Normally a length of approx. 1,5 km fits on a drum that can be transported over the road.
- Each joint or cable - overhead line transition in a circuit introduces additional failure risks. Repair is a specialist job and requires proper preparation and craftmanship. It can take up to several weeks to repair a failed cable.

The application of cable in the 380 kV grid has a significant impact on the electrical behavior of the system. Due to the high capacitance a risk on resonances at low frequencies is introduced, which might require the use of additional filters. Furthermore, a cable has the disadvantage that it can amplify harmonic distortion in the grid, which might affect the proper functioning of customer installations.
Due to its high capacitance a 380 kV cable section generates much reactive power in the connection. As this will increase the operational voltage, which must be kept within the grid code levels, measures are necessary. There are some options to compensate for this reactive power. It can be done by separate reactors, by power electronic means (Statcom) or it can be compensated by conventional power plants. In the latter case it must be procured from market parties. Nevertheless, compensating reactive power shall be done at or closely near the location where it is generated.

The policy of TenneT is to compensate the reactive power by means of reactors, owned by TenneT. A reactor in the TenneT 380 kV grid has a specified maximum rating of 150 Mvar, to prevent unacceptable voltage variations when energizing it. Figure 14 shows an example of a 380 kV reactor.

Figure 14: Example of a 380 kV reactor with a rating of 150 Mvar

A cable section in a 380 kV circuit (2 cables per phase) generates approximately 20 Mvar/km reactive power. In the proposed grid topology, see Figure 4, there are four circuits presented to extend the grid towards Terneuzen. So each kilometer of the extended circuits that would be realized by means of cable will jointly generate 80 Mvar, which must eventually be compensated.

As indicated the reactive power shall be compensated at the location where it is generated. For cable sections with a limited length (double circuit 7-10 km) the compensation can usually be installed at the 380 kV substations of that connection. For longer lengths it might be necessary to compensate also at intermediate locations of the cable sections to control the voltage level along the connection.

Installation aspects

Combined OHL cable connections

It is possible to introduce a transition from an overhead line to a cable in a connection. The transition from a double circuit overhead line to a double circuit cable requires a plot of land of approx. 50 x 100 meters, see Figure 15 as an example. For two connections, two plots of land are needed.

If it becomes necessary to install reactors at the transition points (along the route), these points shall then be extended to a small substation to connect the reactors to the cable. The required plot size will increase from 2 times 50 x 100 m (see Figure 15) to roughly 400 x 200 m.

Figure 15: Overhead line - cable transition point, double circuit (connection Bleiswijk - Vijfhuizen 380 kV, Wintrack towers)

Each transition in a circuit introduces an insulation failure risk. Switching actions or lightning strikes can introduce high overvoltages due to the use of equipment with different electrical properties. Therefore TenneT limits the number of cable sections in a connection between two substations to three.

Crossing of the river Westerschelde

The river Westerschelde is an important water way which may not be obstructed by any infrastructure. At the proposed location for the extended 380 kV connections, the river is approx. 7 km wide and has two important shipping lanes. Although it is technically possible to cross the river by means of an overhead line, this has been ruled out due to the exceptional high towers that would be required. The visual impact, the difficult maintainability and still the concerns regarding possible obstructions of the shipping lanes are motivations to select a crossing by means of underground cable. TenneT has earlier investigated the consequences and concluded that, if appropriate measures are taken, this can be facilitated.

The way the cable crossing can be realized (for instance by a tunnel, direct dredging, horizontal directed drilling) has basically no impact on the electrotechnical behavior of the connection and therefore not decisive with respect to the analysis in this memorandum.

Cable installation on land

As has been indicated in section 3.5 each circuit will have a transmission capacity of 4.000 A. To realize this with cable, two parallel cables per phase will be necessary. For each circuit there will be 6 single core cables required. For 4 circuits, the total number is 24. As a first indication a corridor of 40 meters width will be required, excluding the additional space during installation, see Figure 16

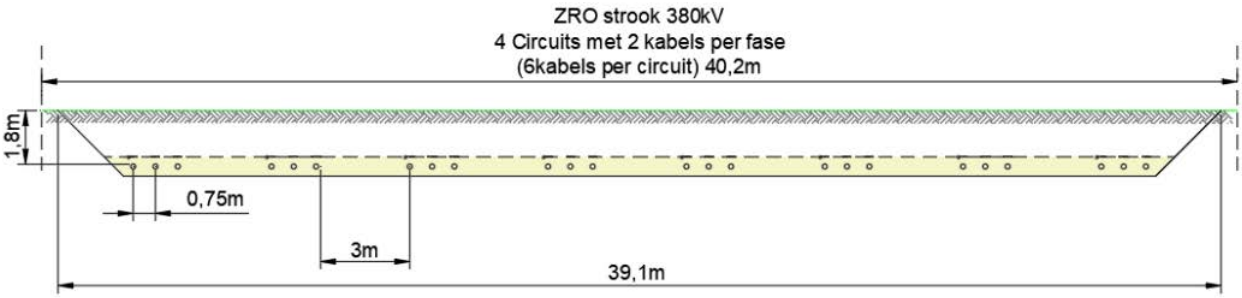

Figure 16: Indication of required corridor for four 380 kV cable circuits (excluding building area). (from IAE project Noord-Holland-Noord Concept-IEA - Onderzoeksrapport techniek - 380 kV Netuitbreiding Noord-Holland Noord)

Gas insulated lines

In 2021 DNV performed an exploring investigation to the options to cross the river Westerschelde [3]. In this report also the Gas Insulated Line (GIL) has been assessed to evaluate whether it would be an alternative for a cable connection.

A Gas Insulated Line consist of a conductor inside a steel tube, filled with insulating gas under pressure, see Figure 17. Up to now the most applied insulation gas is SF_6, a strong greenhouse gas. As the use of this gas will not be allowed in the future anymore, manufactures are developing alternative insulation gasses.

Figure 17: Inside view of a GIL (GE)

Figure 18 shows some typical examples of the application of GIL. GIL is mainly used for short distances (few 100’s of meters) in situations where local obstructions do not allow for an open air solution.

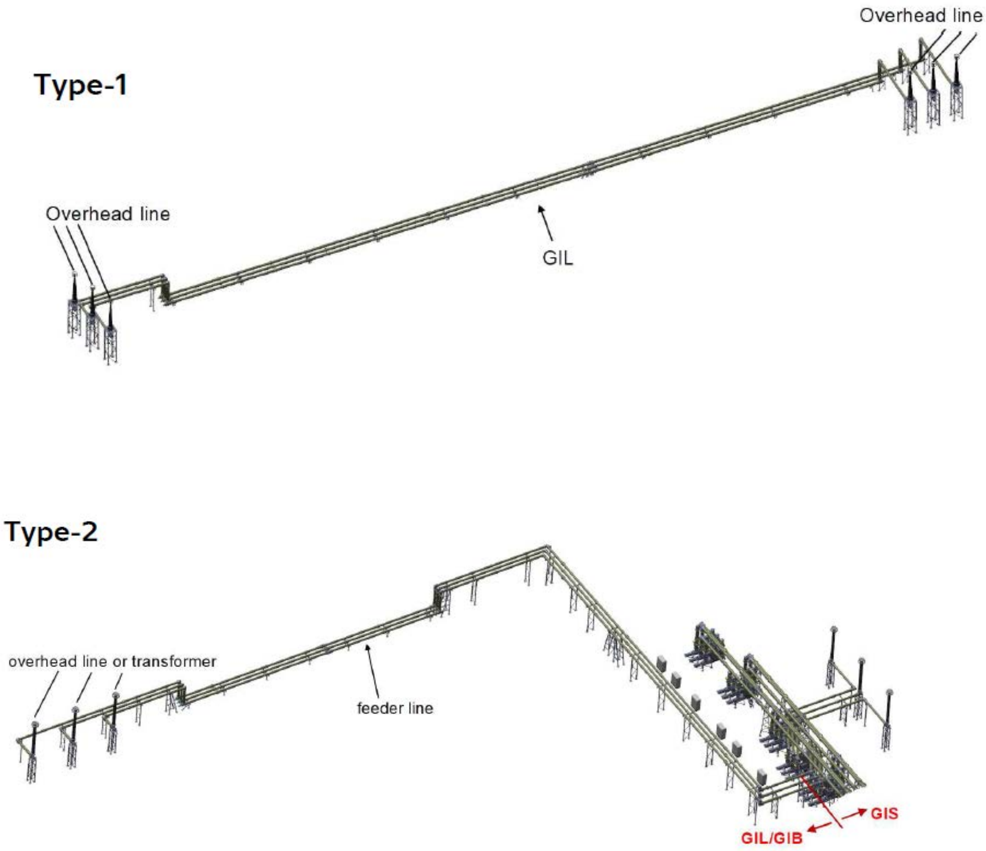

Figure 18: Examples of GIL application (Hitachi)

An advantage of GIL compared to cable are the improved electrical properties. A GIL has an electrical behavior close to the behavior of an overhead line. There is no need for extensive reactive power compensation measures.

DNV concluded in 2021 that due to lack of experience with long GIL connections worldwide, the reliability for long connection lengths cannot be quantified. To use GIL in the connections towards Zeeuws-Vlaanderen over a distance of 7 kilometers of even more would be a step too far.
In 2025 TenneT conducted a market exploration to the possibilities of using GIL inside a possible tunnel under the river Westerschelde. Based on the responses from the market parties, it is concluded that the challenges regarding installation, reliability and maintainability are still huge. This also affects the availability of the circuit, which is considered a critical criterium in the comparison of possible alternatives.

On land a GIL shall be built on supports above ground, to allow for expansion of the tubes, maintaining the corrosion protection and accessibility for inspections. A GIL can be installed under ground level, but only in a duct. See Figure 19 and Figure 20 with two examples.

Figure 19: Example of concrete duct under construction for GIL installation (GE)

Figure 20: Example of several parallel GIL circuits (GE)

4.4 Assessment of the AC alternative

The grid reinforcement towards Terneuzen by means of extending the current AC circuits is also assessed on several criteria:

Technical:

- The AC technology to build the connections (overhead line, cable) is commonly available. TenneT has extensive experience with that.
- The use of cable sections in 380 kV circuits shall, as a starting point, be avoided if an overhead line

solution is possible, in line with the policy [4]. The crossing of the river Westerschelde is marked as a location where the use of cable will be needed to realize the connections.

- If the use of cable is unavoidable compensating measures are required. Reactors to compensate for the reactive power must be installed, the required amount and locations must be determined in a technical study, specifically investigating the steady state operation. As a starting point, reactors are installed at the substations, but for long cable sections, intermediate compensation might be required.
- The need for installing filters will be determined in the transient part of the technical study. But in any case space shall be reserved in at least at the future substation Terneuzen 380 kV.
- The use of GIL is ruled out because the challenges with respect to installation, reliability and maintainability are huge.

Spatial Planning:

- Given the fact that the crossing of the river Westerschelde will probably be realized with cable, at least space for two OHL-Cable transition points in Zuid-Beveland will be required. If no additional compensation equipment has to be installed at these points, two plots of approx. 50 x 100 m are required. If the cable section would be extended with a longer routing on land, intermediate compensation might be required. Then the transition points have to be extended with reactors and some switching gear, resulting if a small substation of approx. 400 x 200 m.
- A routing for two connections has to be developed from a point at the existing overhead line Borssele-Rilland 380 kV to the point where the crossing of the Westerschelde will start. This will require a certain corridor fit for either two OHL connections or to install all cables.

Financial:

- The realization of the connections by means of AC is already part of the project scope. Depending on the cable length above 7 kilometers that will eventually be required to realize the connections, a number of extra reactors must be installed. This might require an additional budget of 265 million Euro per intermediate compensation station.

Planning:

- A choice for an AC solution is already input for the current project planning.

4.5 Assessment summary

In the table below a brief overview of the separate assessments is presented.

	HVAC			HVDC		
	overhead line	**cable**	**GIL**	**overhead line**	**cable**	**converter**
Technical	++ Technology is commonly available.	+ Technology is commonly available.	o Technology is available.	+ Technology is available.	+ Technology is available.	+ Technology is available.
	++ Extensive experience within TenneT available.	o Cable sections generate reactive power that requires additional compensation measures	– Only effciently applicable for short distances. No mature solution for long distances.	o No experience within TenneT.	+ DC cable technology will be used in 2 GW grid connection systems under construction.	o VSC converter is available, but is a complex technical installation which requires extensive maintenance and regular inspections.
	– – Extremely high towers required for crossing the river Westerschelde.	– Cable sections might require additional filters to mitigate the impact of cable on the harmonic behavior of the grid.	– – Crossing of the river Westerschelde requires installation in a tunnel.		– Cable joints introduce risks on reduced operational availability.	– Additional technical studies are required to define all specifications.
		– Cable joints introduce risks on reduced operational availability.			o Complex installation methods regarding the crossing of river Westerschelde.	
		o Complex installation methods regarding the crossing of river Westerschelde.				
Spatial planning	o Visual impact.	– Free corridor needed, introducing limitations on land use.	– – Free corridor for ducts needed, introducing significant restrictions on land use.	o Visual impact.	– Free corridor needed, introducing limitations on land use.	– – Large plots of land required for the converter stations.
	o Limited impact on use of land (only at tower locations).	– Additional compensation stations might be required at Zuid-Beveland. Approx. 8 ha per station.				
Financial	++ Part of the project scope.	– Installation of cable is more expensive than an OHL. Additonal cable sections on land requires measures for reactive power compensation. (265 million Euro per substation).	not investigated.	not investigated.	o Installation of cable is more expensive than an OHL.	– – Huge additional investment required (5 billion Euro).
Planning	++ Fits in the project planning.	– Depending on the installation method, risk on delay is high.	not investigated.	not investigated.	– Depending on the installation method, risk on delay is high.	– – Delay of several years (4 - 8) due to design change and limited market capacity.

5. Conclusion and next steps

Considering the outcome of the assessment of the AC and HVDC options to extend the 380 kV grid towards Zeeuws-Vlaanderen, the HVDC alternative is rejected as a robust and efficient solution. This solution is, although technically possible, extreme expensive (+ 5 billion Euro) and introduces several technical risks that require extra study. Furthermore, this solution requires a lot of land to build the converters and will delay the in service date of the grid reinforcement towards Zeeuws-Vlaanderen with at least 8 to 12 years.

The AC alternative scores much better on all assessed aspects and is therefore the preferred method to build the grid extension.

Following the design principle that 380 kV infrastructure will be realized with overhead line and only locations where an overhead line is not possible (from any perspective: technical, spatial planning, legal) the use of 380 kV cable could be considered, the preferred solution is to extend two of the four circuits between Borssele and Rilland by means of overhead line and investigate whether the river Westerschelde can be crossed by means of cable. An earlier conducted analysis has confirmed that, but it is recommended to repeat the transient technical study with the latest detailed project information.

In case cable section longer than 7 km has to be applied, a technical study must be conducted to determine the impact on the grid and investigate whether the impact can be mitigated. This study should cover the following subjects:

- Load flow to assess thermal overloads
- Short circuit calculations
- Steady state voltages (reactive power compensation)
- Transient overvoltages during energization, switching, faults.
- Power Quality topics
- Rapid voltage changes
- Voltage unbalance
- Harmonic distortion
- Stability
- Possible impact on Black start conditions
- In addition, as part of detailed design studies the impact on components shall be checked (e.g. in case of discharge of the cable, circuit breakers)

References

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[2] Position Paper TenneT: “Een robuuste oplossing voor Zeeuws- en Belgisch Vlaanderen”
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[4] Handreiking Aanleg 220/380 kV hoogspanningsverbindingen
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