Zeeland 380 kV Cables Project Review

Final Report

JUNE 2026

NOTE

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EPRI prepared this report.

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EXECUTIVE SUMMARY

The Zeeland 380 kV reinforcement project is a strategic grid upgrade required to support the Netherlands' energy transition and secure long-term supply in Zeeuws Vlaanderen. The existing 150 kV network is insufficient to meet future demand, driven by ~700 MW industrial growth in Terneuzen, large-scale electrolyser developments, and integration of offshore HVDC wind connections at Borssele and Haven Vlissingen[1].

Strategic Option Assessment

Three supply pathways were evaluated: Belgium interconnection, local generation, and 380 kV grid expansion. The review confirms that:

- Interconnection cannot ensure domestic security of supply or resolve structural bottlenecks.
- Local generation does not eliminate transmission constraints and lacks certainty in delivery.
- Expansion of the Dutch 380 kV network is the only option that fully meets reliability, capacity, and future-proofing requirements.

Technology Selection: AC vs HVDC

The analysis consistently supports **AC transmission** as the preferred solution:

- Fully aligned with the Netherlands' meshed 380 kV AC system
- Avoids complex and costly converter infrastructure
- Lower capital cost and significantly reduced delivery risk
- Faster implementation (avoids 4–8 year HVDC delays)

HVDC, while technically feasible, introduces **multi-billion-euro cost escalation, large land footprint, higher operational complexity, and no material system benefit** for this application.

Preferred Engineering Configuration

The optimal design is a **mixed overhead line (OHL) and underground cable (UGC) solution**:

- OHL used as the default for efficiency, reliability, and policy compliance
- UGC applied selectively for the **Westerschelde crossing (~7 km)** to address environmental and navigational constraints
- Gas-insulated lines (GIL) were assessed but rejected due to limited operational experience and scalability concerns

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[1] Haven Vlissingen can also be referred to as Sloegebied in some literature that did not form part of this review.

This hybrid approach balances **technical performance, environmental constraints, and constructability**.

Critical Constraint: Reactive Power

A key system challenge is the **high reactive power generated by underground cables**, which places constraints on feasible cable length due to limited substation compensation capacity.

Three routing options were evaluated:

- **Option 1 (~7 km UGC)**
  - Fully compatible with existing compensation capacity
  - No major infrastructure upgrades required
- **Option 2 (~10 km UGC)**
  - Significant reactive power deficits across substations
  - Requires major upgrades or new infrastructure
- **Option 3 (~14 km UGC)**
  - Large and widespread deficits
  - Not viable without substantial system redesign

Feasibility and Risk Assessment

- Only **Option 1** is immediately viable within current system and policy constraints
- Longer underground options exceed technical limits and require complex mitigation measures
- Alternative solutions (e.g., STATCOMs, additional substations, policy changes) introduce **significant cost, land use, and implementation risks**, with no clear near-term pathway

Overall Conclusion

The key outcome is that the preferred solution is an AC-based 380 kV grid expansion using a mixed OHL–UGC configuration, with the shortest underground cable option (~7 km) being the only immediately feasible design from a reactive power and system integration perspective. Longer underground options require significant further investigation and infrastructure enhancements before they could be considered viable.

The review confirms that TenneT's approach is **robust, well-validated, and aligned with international best practice**.

The proposed design solution provides **security of supply, supports energy transition objectives, and minimizes delivery risk**, while keeping future flexibility for system evolution.

ACRONYMS

AC	Alternating Current
BSL	Borssele (substation)
EHV	Extra High Voltage
GIL	Gas Insulated Line
HVDC	High Voltage Direct Current
HVL	Haven Vlissingen (substation)
HV	High Voltage
OHL	Overhead Line
RLL	Rilland (substation)
SMR	Small Modular Reactor
STATCOM	Static Compensator
TNZ	Terneuzen (substation)
UGC	Underground Cable
VSR	Variable Shunt Reactor

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1 INTRODUCTION

The project known as the 380 kV grid extension to Zeeuws-Vlaanderen is driven by the need to strengthen the extra-high-voltage network in Zeeland (refer to Figure 1) so that it can support a rapidly changing electricity system. The existing 150 kV network in Zeeuws-Vlaanderen is no longer considered sufficient, on its own, to guarantee security of supply and to connect large new industrial and energy-transition loads. A new 380 kV connection, together with a new 380/150 kV substation in the Terneuzen area, is therefore being advanced as the strategic reinforcement needed to connect the regional system more robustly to the national 380 kV grid.

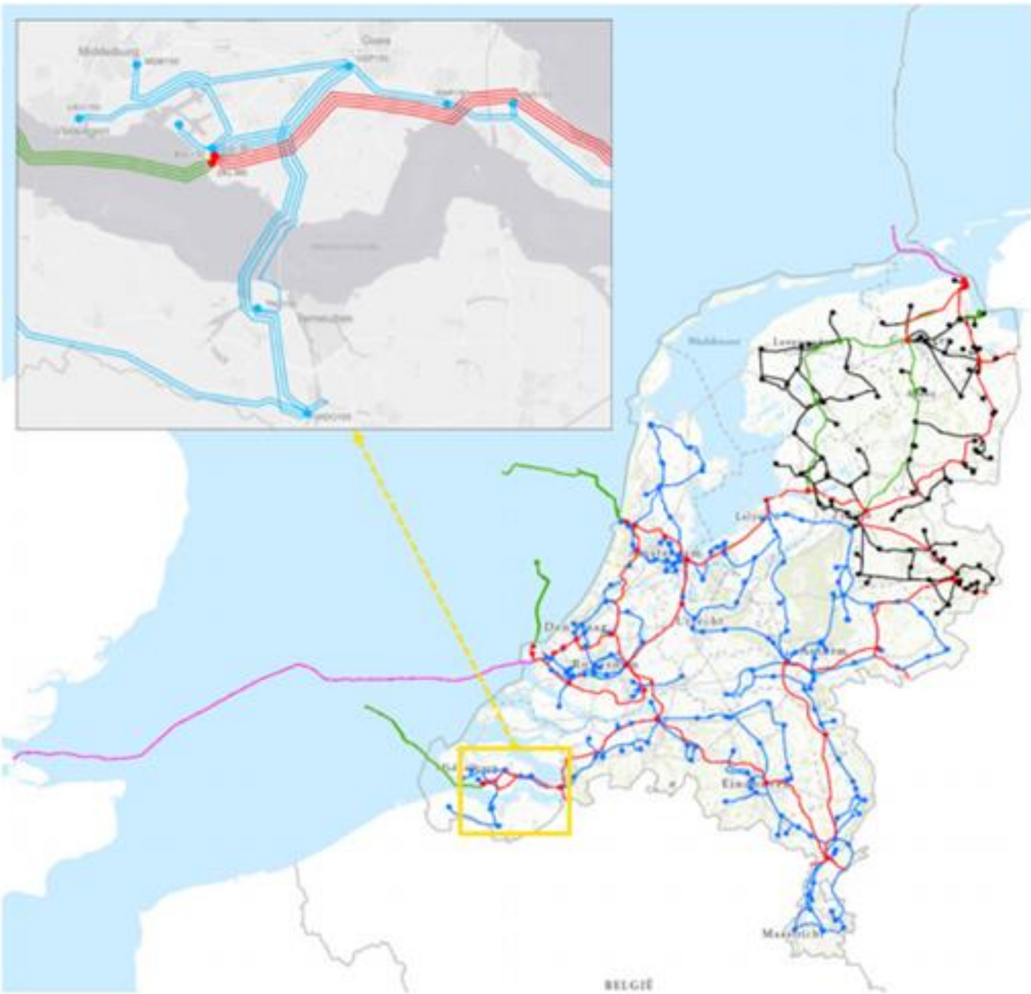

Figure 1 – Locality in Zeeland province as of year 2026.

This report provides a review of several reports, notes, memorandum from TenneT and DNV and establishes an opinion as to the assumptions, analysis, approach methodology, and conclusions in these documents. A list of the reviewed documents follows:

- TenneT, System Impact Study: Zeeland 380 kV Cable connections (BTR) - Input Data Document, Document Reference PU-AMT 24-131, V0.7 dated 28 August 2025.
- TenneT, 380,000 volt grid expansion in Zeeland Flanders: technical choices and feasibility of underground South Beveland, Document Reference 380 kV Zeeuws-Vlaanderen dated 19 February 2026.

- TenneT, Assessment of possible options to realize the required transmission capacity towards Zeeuws-Vlaanderen, Document Reference EPN-2026-004 / V2 dated 09 February 2026.
- TenneT, Definition lengths cable section in study, Document Reference EPN-2026-008 dated 05 March 2026.
- TenneT, Policy 380 kV substation and outlook 150 kV grid Zeeland, Document Reference EPN-2026-010 dated 10 March 2026.
- DNV, System impact study 380 kV cables Zeeland, Document Reference 25-1512, Rev. 4.0 dated 16 December 2025.
- Rijksoverheid, Handreiking - Aanleg-220-380-kV-hoogspanningsverbindingen (Guidance on the Construction of 220/380 kV high-voltage connections), July 2025.
- Elia & TenneT, Position Paper: Een robuuste oplossing voor Zeeuws- en Belgisch Vlaanderen - Waarom Zeeuws-Vlaanderen een toekomstbestendige hoogspanningsverbinding nodig heft (A robust solution for Belgian Flanders - Why Zeeuws-Vlaanderen needs a future-proof high-voltage connection), No date.

1.1 Need Case

According to the 2030–2050 grid development plans, the extension of the 380 kV grid in Zeeland towards Zeeuws-Vlaanderen is required to support the energy transition and to provide the transmission capacity needed for major future developments in the region. There are three main drivers:

1.1.1 Growth in industrial electricity demand in Terneuzen

The first major driver is the expected growth of approximately 700 MW in industrial load in the Terneuzen area, which is currently supplied from the regional 150 kV grid.

1.1.2 Connection of large electrolyser projects at Haven Vlissingen

The second driver is the expected connection of large electrolyser projects between 2030 and 2035 to the new 380 kV substation at Haven Vlissingen (HVL), increasing the need for additional transmission capacity and stronger integration with the extra-high-voltage (EHV) network.

1.1.3 Integration of major offshore HVDC projects into the Zeeland grid

The third driver is the planned realization by 2030 of the two 2 GW offshore HVDC projects IJVER Alpha and Nederwiek 1, connecting at the 380 kV Borssele (BSL) and HVL substations respectively, further increasing the strategic importance of reinforcing the Zeeland 380 kV system.

2 ASSESSMENT

This section will discuss some of the different options and decisions that were made in determining the optimal solution for the system development in the Zeeland area. To aid the discussion, an indicative single line diagram of the 380 kV network under consideration in the system impact study is shown in Figure 2.

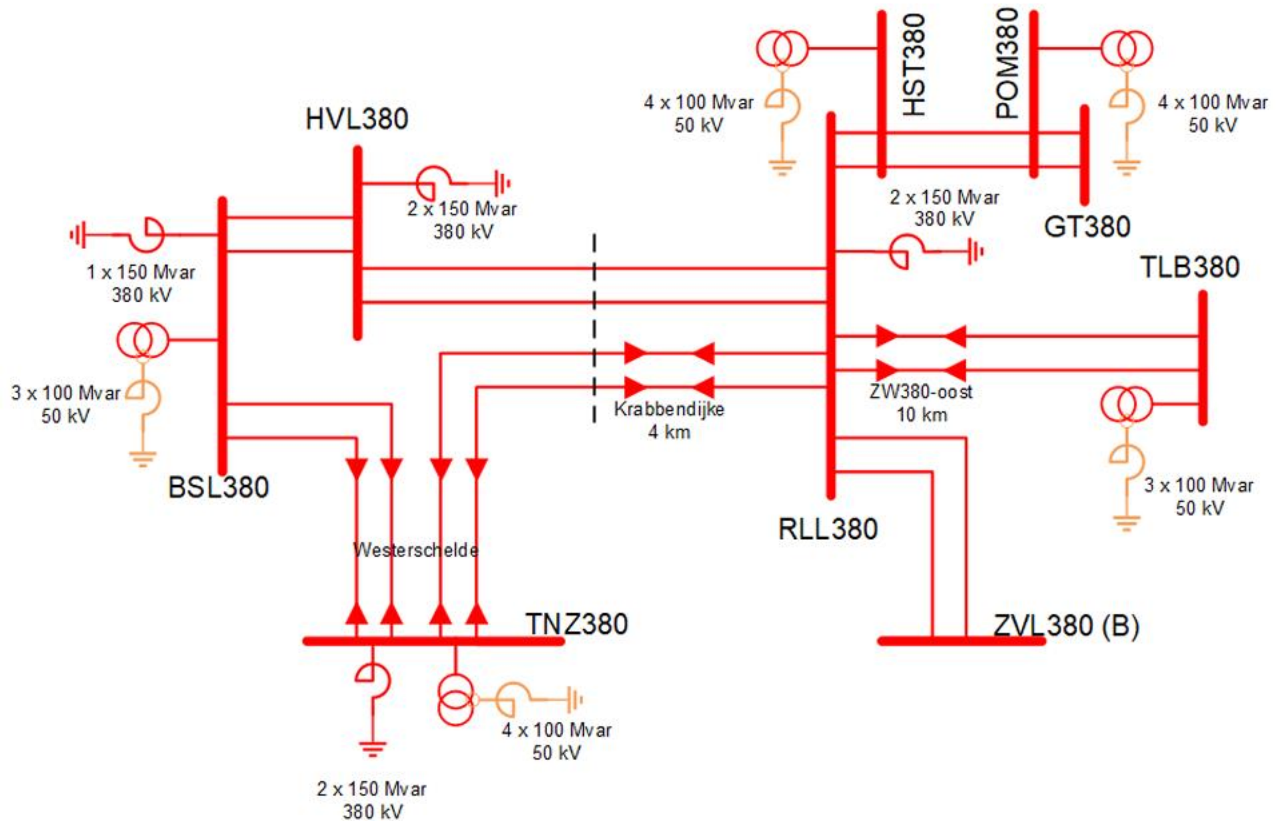

Figure 2 – Single line diagram of the modified 380 kV network with TNZ connected[2]

2.1 Zeeland Supply Options

The Zeeland region—particularly Zeeuws-Vlaanderen—faces growing electricity demand driven by industrial expansion near Terneuzen, upcoming large-scale electrolyser projects, and integration of offshore HVDC connections. A robust solution must ensure regional security of supply, adequate transport capacity, and future-proof integration into the national EHV grid.

The development approach identified three principal supply options:

- Interconnection with Belgium,
- Local generation, and

[2] the diagram is included to show connectivity between substations and not intended for reactive power compensation information.

- Grid expansion of the existing 380 kV Netherlands network.

Interconnection with Belgium

An interconnection with Belgium is technically possible and was jointly explored by TenneT and Elia to assess potential additional cross-border exchange capacity. However, some limitations with an interconnection to Belgium have been identified and these can be highlighted as:

- not being able to replace the need for a robust domestic 380 kV grid,
- not being able to future-proof the Zeeuws-Vlaanderen regional connection to the national grid,
- not being able to provide guaranteed regional security of supply, and
- being intended primarily for market-based international electricity exchange and not for internal Dutch power system transport needs.

It is mentioned in the position paper by Elia and TenneT that, while Corsica is sometimes cited to demonstrate that a region can be supplied with electricity via a cross border connection, this is a flawed comparison as Corsica is a semi-isolated island grid dependent on imported electricity and the interconnection with Italy is required to ensure security of supply; it was not installed with the purpose of resolving local bottlenecks such as the case with Zeeuws-Flanders.

In conclusion, interconnection can be beneficial for European market efficiency (and can play a role when security of supply is an issue such as with Corsica), but it cannot serve as a structural solution for Zeeland's internal supply challenge. It may be complementary in the long term but cannot replace domestic grid expansion.

Local Generation

Introduction of local generation could be a viable solution for the increased demand. Local generation may include renewable plants or technologies such as small modular reactors (SMRs). Some limitations were identified with this approach, including:

- it does not resolve transport capacity bottlenecks — even large-scale local generation requires strong integration with the national 380 kV grid for both imports and exports,
- there remains significant uncertainty in planning, permitting, spatial integration, and public acceptance (especially for SMRs), and
- it cannot guarantee security of supply, as local sources still depend on the wider grid for balancing and redundancy.

In conclusion, local generation may support sustainability goals, but it cannot replace the need for a strong backbone connection. Therefore, it is deemed unsuitable as a standalone solution for regional adequacy or transport needs.

Grid Expansion of the Existing 380 kV Netherlands Network

Eliminating the interconnection with Belgium and the introduction of local generation leaves the only choice as the expansion of the existing 380 kV grid to accommodate the need case requirements.

Grid expansion is the only option that fully resolves the structural bottlenecks and secures long-term supply for the Zeeland region. It is the preferred option in all retrieved assessments.

2.2 AC versus DC

Regarding the choice of AC versus DC technology for expanding the grid, a comparison table for AC and DC reflecting specific requirements and policies of the Dutch system is provided below in Table 1.

Table 1 – Generic comparison table for AC vs DC

Criterion	AC	DC
Fit with existing grid architecture	The EHV / HV grid is almost entirely AC-based; a new 380 kV AC connection integrates directly into the existing meshed grid with no fundamental system modifications.	Requires DC/AC converter stations at each end to interface with the AC grid, adding interfaces and changing system behaviour.
Primary use-case suitability	Very efficient and reliable for meshed grids over relatively short distances.	Well-suited to long-distance transmission, submarine crossings, and interconnection between non-synchronous grids; less aligned with this short, internal reinforcement use-case.
System complexity & operational risk	Uses well-known AC equipment and protection concepts; no additional critical system components beyond standard substations and OHL/UGC segments.	HVDC is technically proven but complex, requiring specialized management and maintenance; converters form additional critical components, making the system more sensitive and less robust than a conventional AC system.
Reactive power behaviour	AC behaves conventionally; reactive power management is well understood within existing TenneT policies.	HVDC does not transport reactive power, but the converter interfaces and control add their own requirements; overall, it is not presented as a solution to the key reactive power challenges (which primarily arise from long AC UGC sections, not from the backbone choice).
Policy alignment	Aligned with national policy that new 380 kV connections are to be realised with AC OHLs, with undergrounding only in special cases.	Conflicts with the basic policy preference for AC OHL; would require additional justification, policy deviations and new operational experience.

Environmental & visual impact (system level)	Visual impact similar to existing 380 kV lines and substations; mixed OHL/UGC crossing can minimize impact while staying within AC technology.	Very large converter platforms concentrate visual and environmental impact at multiple sites, plus larger industrial-scale structures and increased local impacts due to construction and operation.
Scalability within Dutch system	Uses standard AC concepts; future extensions and reinforcements can follow the same approach across the national 380 kV grid.	Introduces a non-standard “HVDC island” within an otherwise AC grid; additional HVDC schemes would further increase coordination complexity and operational interdependencies.
Overall conclusion in documents	Identified as the preferred solution: provides robust reinforcement of the Zeeland 380 kV grid with acceptable technical risks, footprint, and timing.	Considered technically feasible but not proportionate: much higher cost, larger footprint, more complexity, and substantial delay without commensurate benefit in grid performance for this case.

The Dutch transmission system is built on a meshed AC-based 380 kV network, making AC expansion the natural and preferred extension method. AC provides direct compatibility, high availability, and avoids the need for complex converter infrastructure.

For Zeeuws-Vlaanderen, the preferred design is therefore an AC ring structure involving BSL, Rilland (RLL), and a new 380 kV substation at Terneuzen (TNZ). The design consists of four 380 kV circuits (two BSL–TNZ and two TNZ–RLL), each ~14 km long and crossing the Western Scheldt (~7 km). Each circuit can transmit 2635 MVA. The advantages of this method include:

- provision of the required transport capacity to accommodate >700 MW new load in TNZ and upcoming electrolyser connections,
- ensures regional security of supply, which alternative options cannot guarantee,
- supports the national energy transition, including offshore HVDC injections (IJVER Alpha, Nederwiek 1).
- technically proven with fewer system complexities compared to HVDC options,

Considering the AC solution as the base, a comparison of a DC solution is provided for the specific Zeeus-Vlaanderen project under consideration in Table 2.

Table 2 – Generic comparison table for AC vs DC

Criterion	AC	DC
Transmission capacity & topology	Planned AC solution: four 380 kV circuits in a ring between BSL, RLL and TNZ; each circuit ~14 km and rated ~2635 MVA, directly	To match the AC design, four HVDC links would be needed; using TenneT’s standard 2000 MW design requires four links with two converters per link (eight converter stations in total) and at least 12 cables.

	strengthening the 380 kV backbone.	
Spatial footprint (land use)	Uses standard EHV substations and line corridors; no large extra converter complexes are required beyond the normal AC ring.	Each 2000 MW converter requires ~5.5 ha; including buildings, roads, etc., ~24 ha is needed per site. With four links, this implies four converter stations on each side, i.e. ~33.6 football fields of area at each end.
Capital cost	Conventional technology with no need for high-power converter stations; no specific extra cost drivers are identified beyond normal AC grid expansion.	A single 2000 MW converter is ~€750M; for multiple links, cost escalation results in about €5,000M of additional investment without demonstrable improvement of grid performance relative to the AC solution.
Project lead time / deliverability	Follows established AC design and permitting practice; no additional technology development or complex integration is required.	Requires extensive additional studies, system integration work, specification, and permitting of converters; estimated to delay the in-service date by ~4–8 years.

It should be mentioned that the comparison in Table 2 considers the standard 2000 MW TenneT design developed for offshore link and that this does not match the AC design fully. In order to get an exact match, more DC cables and a larger converter station will be required.

Taking the whole argument of AC versus DC, AC has been the selection with the following key discussion and justification points.

Infrastructure Requirements and Spatial Impact

AC remains the default policy for the 380 kV network in the Netherlands. The circuit capacity required for the circuits between BSL, TNZ and RLL, each at 2635 MVA capacity, can be achieved with conventional OHL towers and substations.

In order for DC to match this capacity, four HVDC links would be needed, each requiring two converter stations (eight converters in total). Each converter station requires 5.5 ha each, with the total site including access roads and buildings accounting for about 24 ha.

System integration and compatibility

The EHV grid in the Netherlands is AC-based, making AC the natural first choice for new 380 kV connections. It integrates directly with the national mesh without requiring major system modifications. DC requires multiple converter stations at every interface with the AC grid. These converters are large, expensive, and introduce additional system complexity. This extra investment does not bring any demonstrable improvement in grid performance.

Technical Complexity and Operational Behaviour

AC has a very high reliability and high transmission capacity in meshed networks with short to medium distances, and its behaviour is very well understood and consistent with existing grid policies. DC is more technically complex and requires specialized operation and maintenance and adds an additional critical component layer to the system which may reduce overall system robustness.

Cost

The costs associated with AC are substantially lower as the standard technology is well established and there is no need for conversion equipment. Conversely, each 2000 MW converter station would cost around €750M, with an estimated cost of around €5,000M for the total project (assuming 20% cost efficiency across the eight converter stations). However, this does not account for additional planning / legal costs that may be incurred over that time.

Project Schedule and Delivery

AC projects can be delivered using established engineering pathways, permitting processes and construction methods. DC is relatively niche and requires more analysis and integration studies, introducing up to 4-8 years in delays.

2.3 Circuit Technology

It is stated in the guidance document on the construction of 220/380 kV high-voltage connections that the Dutch policy is "above ground, unless", indicating that this is the default option for new 220 kV and 380 kV connections is an OHL. Six exceptions to this rule are noted in Section 2.2 of the document, where around a total of 23 km of underground circuits are installed in the 380 kV. These include two underwater circuits from Maasvlakte-Westerlee (2.1 km) and the Beverwijk-Vijfhuizen circuit crossing the North Sea Canal (1 km). The other circuits are located underground for other reasons such as:

- Located near Schiphol's runway,
- Along residential areas near Delft and Hoofdorp,
- Near / through special natural areas in Midden-Delfland.

It is also noted in the report that these projects were carried out as pilot projects, and extensive research has been conducted into the effects in the electricity grid on stability, the susceptibility to disturbances, and maintenance aspects, and it was concluded by TenneT that the networks that are constructed underground have a lower reliability compared to networks that are above ground, mainly due to longer recovery and downtimes after a cable failure.

Other concerns regarding the use of UGCs mentioned in the guidance document include:

- Environmental impact of UGCs include the temporary and permanent effects of excavating / drilling to install the cables in trenches,
- Although the visible impact of OHL is more readily apparent than that of UGCs, the impact of UGCs above ground is not zero; the user possibilities of the ground above UGCs when installed are limited, as no buildings or deep-rooted trees are allowed to be planted above them,
- Take off points, where UGCs are brought back above ground, must be constructed (along with compensation resources such as filters and reactors to mitigate the challenges associated with high capacitance cables).

Utilizing OHLs to cross the Westerschelde is technically possible with very high towers, but these must not obstruct the important shipping lanes in this waterway. The most prudent approach would be to utilize OHLs onshore, and use UGCs or a similar alternative such as a gas-insulated line (GIL) (see typical GIL construction details in Figure 3) in a tunnel underneath the waterway to:

- Minimize any risk to shipping,
- Reduce the visual impact from the OHLs, and
- Avoid the difficulty in maintenance of OHLs over water.

Figure 3 Gas insulated line construction details

UGC are proven technology but generate excessive reactive power that can be compensated using shunt reactors. A GIL has similar electrical properties to an OHL by insulating the conductors with gases (the most applied being SF_6 – a strong green gas but alternatives are being developed) under pressure but have only been implemented over very short distances with no quantification on reliability for long distances. GIL vendors indicate challenges for such an approach regarding installation, reliability and maintainability. Due to Westerschelde crossing, a tunnel would the most sensible option. Considering all these, even the 7 km Westerschelde crossing could be deemed a step too far and therefore an UGC is considered to be the most appropriate option to cross Westerschelde in a mixed circuit with OHLs.

UGCs physical construction is different from that of an OHL (solid insulation and the distance between two metallic components) and therefore it has different electrical properties (see Figure 4). The key difference is a much higher capacitance than OHLs. A 380 kV, 2500 mm^2 UGC has a capacitance of 0.232 uF/km generating 10.52 Mvar/km reactive power. A typical capacitance for OHL would be around 0.015 uF/km.

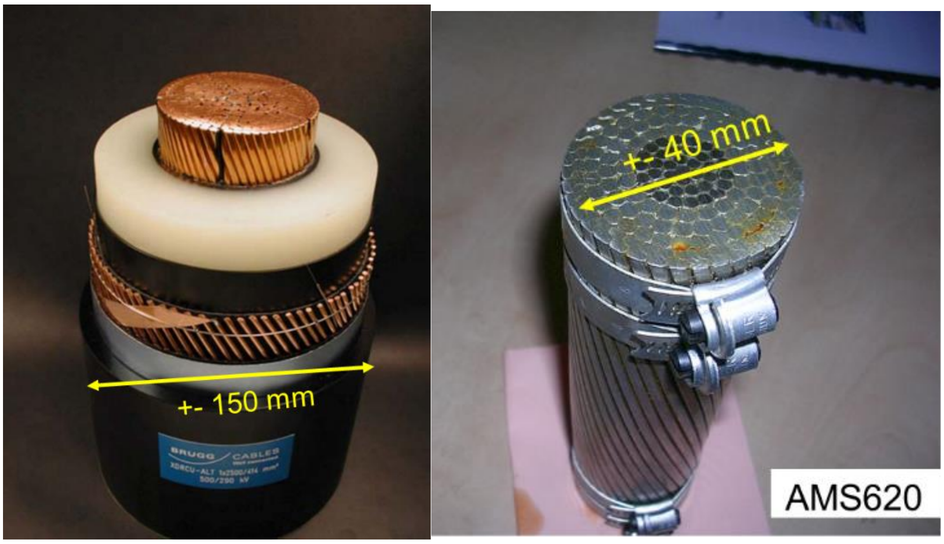

Figure 4 – UGC (with the relevant insulation level) versus and OHL

Heat dissipation in UGC is much slower due to surrounding ground and hence to establish a transmission capacity matching that of the 380 kV OHL, 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.

As per the TenneT policy, two cores UGC per phase will be required to match the 2635 MVA capacity of the OHL, so the reactive power generated per km is 21.04 Mvar.

2.4 Routing Options

The routing of the new 380 kV connection between Zuid-Beveland and the new 380/150 kV substation at TNZ is shaped by both spatial planning and technical feasibility studies. The proposed routing options fall into three groups:

- Land routes on Zuid-Beveland (L-routes)
- Crossing options for the Westerschelde (K-routes)
- Routing from tunnel outlet to TNZ (OHL)

These are defined in detail in EPN-2026-008.

Routing on Land at Zuid-Beveland

The Environmental Impact Assessment (EIA) identifies four land-based routing alternatives—L1, L2, L3, and L4. These were further refined to their UGC variants:

- L1O – 1.5 km UGC,
- L2O – 3 km UGC,
- L3O – 6 km UGC, and
- L4 – considered initially but dropped as an underground alternative later in the study process.

These land segments define the northern part of the cable routing before crossing the Westerschelde as shown in Figure 5.

Crossing of the Westerschelde

For the ~7 km wide Westerschelde, the EIA identifies four corridor options, each with its own tunnel (T) variant:

- K1T – 6.5 km tunnel,
- K2T – 8 km tunnel,
- K3T – 8 km tunnel, and
- K4T – 7 km tunnel.

Each K-route represents a different spatial corridor across the river, and the tunnel variant is the preferred construction method, given:

- OHL crossing is technically possible but complex and visually intrusive, and
- UGC crossing is feasible for ~7 km without additional compensation measures.

These crossing options form the central section of each routing configuration and a schematic for the routing options is shown in Figure 5.

Figure 5 – Routing options schematic

Combined Routing Options

The total UGC length per circuit is computed by combining an L-route with a K-route, as summarised below in Table 3.

Table 3 – Routing options

Combined Option	Land (L) [km]	Tunnel (K) [km]	**Total** [km]
L1O + K1T	1.5	6.5	8
L1O + K2T	1.5	8	9.5
L2O + K3T	3	8	11
L3O + K4T	6	7	13
Other variants (e.g., L4 + K4T) were considered early but dropped from scope.			

With the combinations given, the electrical study considers three options overall that cater for a range of UGC lengths, and these options are given in Table 4.

Table 4 – UGC options studied in electrical models

UGC Options	Length (km)	Comment
Option 1	7	Covers an UGC length in each circuit from 6.5 to 8 km
Option 2	10	Covers an UGC length in each circuit from 9.5 to 11 km
Option 3	14	Covers an UGC length in each circuit from 13 to 13.5 km

Routing to the New TNZ Substation

Regardless of which L+K combination is chosen, the final section from the tunnel exit to the new 380 kV TNZ substation is likely to be constructed as an OHL unless the substation is built right beside the cable tunnel exit in which case the cables will presumably be routed directly to the substation.

This is due to:

- The need to integrate into a standard 380 kV station layout.
- Spatial and thermal constraints that make full undergrounding unsuitable at the substation interface.

2.5 Reactive Power Compensation

Reactive power compensation is a critical design constraint for the 380 kV Zeeuws-Vlaanderen project due to the generation of significantly more reactive power by the UGCs compared to OHLs.

As mentioned earlier in the report, with two cores per phase (matching the thermal capacity of the OHLs), the reactive power generated per km of UGC is 21.04 Mvar.

TenneT Policy on Reactive Power Compensation

The policies relating to reactive power compensation are set out by TenneT:

- For a single 380 kV busbar the possibilities of reactive shunt compensation are:
    - One 380 kV reactor (total 150 Mvar),
    - One 380 kV reactor and one transformer with a reactor at the tertiary winding (total 250 Mvar),
    - Two transformers with a reactor at the tertiary winding (total 200 Mvar).
- At a 380 kV substation, with three busbars, a maximum amount of 750 Mvar of reactive power compensation capacity can be connected.
- At a 380 kV substation, maximum four power transformers of 380/150/50 kV will be installed. A power transformer has a standard rating of 500 MVA.
- At a 380/150/50 kV transformer (standard rating 500 MVA) only one reactor with a maximum rating of 100 Mvar can be connected. This value is the result of an economical and technical optimization of the power transformer design.
- The standard rating of a 380 kV reactor is 150 Mvar.
- A reactor connected to the tertiary winding of a power transformer is in general approximately 50% effective for the 380 kV grid and 50% effective for the 150 kV grid.
- The installation of additional power transformers at a substation (while respecting the maximum number of four) will always take priority over the installation of reactive power compensation.

Substation Capacity for Reactive Power Compensation

It is common practice in the Netherlands to locate reactors on the tertiary winding of a transformer; this provides compensation of 50% of the rated MVA at the primary winding (i.e., a 100 Mvar reactor connected to the tertiary winding of a 380/150/50 kV transformer can provide 50 Mvar to the HV side). The 50% figure is quoted as a reasonable rule of thumb from analysis of EMS data. The other 50% is effective at the MV voltage level. Standard reactor sizes used by TenneT are:

- 150 Mvar @ 380 kV (connected to the busbar substation),
- 100 Mvar @ 50 kV (connected to the tertiary winding of a transformer),
- 75 Mvar @ 50 kV (connected to the tertiary winding of a transformer).

For the Zeeland system:

- UGC generates 21.04 Mvar/km per circuit (due to high capacitance and the need for two cable cores per phase), hence with four circuits, the cables generate 84.16 Mvar/km,
- There is always a need for further compensation considering various system planning and operational constraints to keep the voltages within statutory limits, and
- Compensation must be absorbed at the substations BSL, TNZ, RLL, and HVL within each station's available shunt reactor capacity.

The available margins at each substation are as follows:

- BSL: 150 Mvar
- TNZ: 350 Mvar
- RLL: 300 Mvar
- HVL: 300 Mvar

Full details of the level available compared to theoretical capacity and the existing or planned utilization along with physical capacity are provided in Table 5.

Table 5 – Substation capacity for reactive power compensation

	BSL	TNZ	RLL	HVL
Busbars	4	3	3	3
Theoretical capacity (Mvar)	1000	750	750	750
Physical capacity to install and connect reactors (Mvar)	550	700	700	700
Actual capacity effective at 380 kV (Mvar)	300	500	300	300
Already allocated (Mvar)	150	150	0	0
Available capacity (Mvar)	150	350	300	300

2.6 Suitability of UGC Options

The feasibility of each UGC option and the routing each represent depends on whether its total reactive power generation along with what else is required by the system fits within these margins.

Steady-state studies looking at the overall reactive power requirements at each of the four substations taking into account statutory voltage limits and rapid voltage change (RVC) level show the required reactive power levels as given in Table 6.

It should be noted that for the 380 kV system voltage should be within 361 kV to 418 kV band and the RVC level must be less than 3%.

Table 6 – Reactive power compensation requirements at each substation (all in Mvar)

	BSL	TNZ	RLL	HVL
Option 1 (7 km)	150	200	300	300
Option 2 (10 km)	405	479	463	341
Option 3 (14 km)	523	631	497	375

UGC Option 1 (covering route L1O + K1T)

For UGC Option 1, which is the shortest of the options at 7km (covering 6.5 km – 8 km):

- BSL: 150 Mvar required vs 150 Mvar available → 0 Mvar deficit
- TNZ: 200 Mvar required vs 350 Mvar available → 150 Mvar surplus
- RLL: 300 Mvar required vs 300 Mvar available → 0 Mvar deficit
- HVL: 300 Mvar required vs 300 Mvar available → 0 Mvar deficit

Option 1 fits within available compensation capacity at all substations. No expansion of substation compensation capability is required.

UGC Option 2 (covering routes L1O + K2T or L2O + K3T)

For UGC Option 2, which is the second shortest of the options at 10km (covering 9.5 km – 11 km):

- BSL: 405 Mvar required vs 150 Mvar available → 255 Mvar deficit
- TNZ: 479 Mvar required vs 350 Mvar available → 129 Mvar deficit
- RLL: 463 Mvar required vs 300 Mvar available → 163 Mvar deficit
- HVL: 341 Mvar required vs 300 Mvar available → 41 Mvar deficit

Option 2 pushes the system significantly beyond existing substation compensation limits. The deficits range from 41 Mvar at HVL to 255 Mvar at BSL, which cannot be accommodated with current infrastructure.

UGC Option 3 (covering route L30 + K4T)

For UGC option 3, the longest of the options at 14km (covering 13 km -13.5 km):

- BSL: 523 Mvar required vs 150 Mvar available → 373 Mvar deficit
- TNZ: 631 Mvar required vs 350 Mvar available → 281 Mvar deficit
- RLL: 497 Mvar required vs 300 Mvar available → 197 Mvar deficit
- HVL: 375 Mvar required vs 300 Mvar available → 75 Mvar deficit

Option 3 generates very large deficits at all substations, in the case of BSL, exceeding available compensation by a factor of 3.5.

2.7 Accommodating Other UGC Options

The next stage of the investigation covers the possibility of fulfilling Option 2 and Option 3 reactive power requirements as there is no physical space to accommodate the levels established by the studies.

Three possible approaches have been examined:

- New grid design or technology solutions
- Non-technical solutions
- Other measures

The next sections provide information on each of these investigations in their ability to increase the level of shunt compensation that can be accommodated.

2.7.1 New Grid Design or Technology Solutions

Within this category the following options have been investigated:

Dynamic reactive power compensation (e.g., STATCOM)

Implementing a fast-acting compensation plant such as a STATCOM would provide reactive power support to the system, although these are not typically used for compensation of cable systems. They are a well-proven technology but at present there are no installations in the TenneT system.

Regarding land use, a typical 300 Mvar STATCOM installation (along with associated transformer and cooling units) would require 2000 m^2. Furthermore, multiple STATCOMs would be required, which makes this option commercially unviable.

Direct connection of shunt reactors at cable termination

The locations where the UGCs come back above ground could be used as locations for reactors (and any auxiliary equipment). Extra land would be required, along with spatial planning agreements. Furthermore, both switchable and non-switchable reactors can be used, with switchable reactors requiring further space for circuit breakers.

Expansion of 380 kV system with new substations

Expanding the number of 380 kV nodes in the region would provide further options for locating reactors. The constraints on adding reactive power compensation are provided in Section 2.5, and one way to increase the available substation capacity without breaching TenneT's policy is to increase the number of 380 kV substations.

Adjustment to existing substation design

It is also an option to change existing substation designs from the triple busbar arrangement to a higher number of busbars; however, along with changing substation design policy, this would require further land acquisition.

2.7.2 Non-Technical Solutions

Aside from technical solutions, there are also non-technical solutions available also.

Reactive power procurement

This method would involve purchasing reactive power from third parties close to the new development. This could involve existing installation or new commercial suppliers with additional reactive power. Currently no generator units are available and installation of new units just for this purpose would be very unlikely.

Accept voltage violations

Another potential option would be to accept that these nodes would be in violation of the voltage limits set out in the grid code requirements. This is not allowed as it will jeopardize security of supply for the whole network. Allowing any exception could set a precedent that could be irreversible. Adherence to the grid code requirements is critical for the integrity of the system and the opposite will have consequences that could prove costly.

2.7.3 Other Measures

Change of reactor size

Connecting smaller shunt reactors would allow for a finer regulation of the voltage and would provide an opportunity to better match the actual need of the system. However, it will not help overall with the large need for additional compensation.

Use of variable shunt reactors (VSRs)

Implementing VSRs in the network would provide more controllability in terms of the level of Mvar introduced in one go with the possibility to avoid some of the technical performance issues. It is a proven technology, but TenneT has no experience of VSRs in their system.

3 CONCLUDING REMARKS

This report provided a summary of the observations relating to the use of UGCs following a comprehensive review of several reports, notes and memoranda associated with the Zeeland 380 kV grid expansion project.

The following key observations are offered as concluding remarks:

- The need case for the power system developments in Zeeland region is defined clearly taking into account the development of electric power system in Netherlands from 2030 to 2050.
- The study and analysis show that two further alternatives (interconnection to Belgium and introduction of local generation) to grid expansion have been investigated and discounted on various engineering, commercial and strategic grounds.
- As the Dutch transmission system is based on a meshed 380 kV AC network, the default and preferred expansion choice is based on AC. This provides direct compatibility, high availability, and avoids the need for complex converter infrastructure.
- A comparison is provided looking at a similar capacity DC option. This has been discounted on four key criteria:
    - spatial design – HVDC bringing in significant footprint,
    - cost and social benefits – HVDC requiring high investment without demonstrable improvement in grid performance,
    - complexity and operational risks – HVDC being a proven technology but technically complex with specialized management and maintenance needs, and
    - time and feasibility - HVDC needing additional engineering, permitting, integration, and construction lead time bringing in 4-8 years delay.
- In terms of AC circuit technology, OHLs is given as the default choice. However, crossing of Westerschelde has been considered and to avoid any obstruction to shipping lanes and any difficulties in maintenance, undergrounding is deemed suitable.
- Both UGC and GIL options were checked and GIL is discounted on the basis of required length (minimum of 7 km length to cross the waterway), lack of quantification on reliability for long distances and indications of challenges from vendors regarding installation, reliability and maintainability.
- Mixed OHL and UGC was therefore chosen as the preferred circuit technology to the 380 kV Zeeuws-Vlaanderen grid expansion project.
- Each OHL circuit can transmit 2635 MVA. Hence the UGC part must at least match that to avoid any thermal constraints. This implies two cores per phase match for the UGC with a corresponding reactive power generation of 21.04 Mvar/km.

- The project then identified a number of routes taking into account the EIA and the routes have been classified into three distinct UGC lengths to be used as part of the electrical studies:
    - Option 1 → 7 km
    - Option 2 → 10 km
    - Option 3 → 14 km
- The level of available capacity in each of the four substations have been established considering TenneT compensation policy, individual shunt reactor sizes, physical space availability in each substation and the level of compensation that is already under development plans:
    - BSL: 150 Mvar
    - TNZ: 350 Mvar
    - RLL: 300 Mvar
    - HVL: 300 Mvar
- Using statutory voltage and RVC limits, required level of reactive power compensation is worked out for the four substations for the three UGC length options:
    - For BSL, the requirements are - Option 1: 150, Option 2: 405 and Option 3: 523 (all in Mvar)
    - For TNZ, the requirements are - Option 1: 200, Option 2: 479 and Option 3: 631 (all in Mvar)
    - For RLL, the requirements are - Option 1: 300, Option 2: 463 and Option 3: 497 (all in Mvar)
    - For HVL, the requirements are - Option 1: 300, Option 2: 341 and Option 3: 375 (all in Mvar)
- Required level of compensation is within the available capacity for Option 1. However, for Option 2 and Option 3, the level of reactive compensation exceeds the available capacity.
- Alternative approaches to accommodate the extra reactive compensation where there is no capacity have been investigated at a high level. These have been categorized based on technical and non-technical and other possible solutions. All alternatives that were looked suggested major issues in going forward.
- Based on the results of required reactive power compensation, Option 1 is a possible alternative that can be taken forward.
- Option 2 and Option 3 will need further investigation and work before either of it can be deemed suitable for taking it further.

TenneT's processes in analysing the various alternatives at each stage of the project appears to be in line with the normal expectations as well as approaches in other jurisdiction in similar project settings:

- All foreseeable options have been considered at various stages of the project.
- All practically reasonable steps have been taken into account in analysing the various alternatives.