POSITION
PAPER

STAKEHOLDER CONSULTATION PROCESS OFFSHORE GRID NL	
Type:	Position paper
Work Stream:	Technical
Topic:	T16 - Cable laying configurations
Filename:	ONL TTB-05579
Version:	V3.0
Pages:	12 pages

QUALITY CONTROL	
Prepared:	AMO
Reviewed	AMO / NLO-OD / BLIX
Approved:	Consultation Board
Release:	BLIX

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1. Background material

LITERATURE USED:

- CIGRE TB379, "update of service experience of HV underground and submarine cable systems" (2009).
- ENTSOE-EUROPACABLE "Recommendations to improve HVDC cable systems reliability" (2019).

2. Scope and considerations

For the roadmap offshore wind 2030 (routekaart windenergie op zee 2030) TenneT is tasked with the connection of several offshore wind farms up to 2030. The wind farm zones 'Hollandse kust West' and 'Ten Noorden van de Waddeneilanden' will be connected with TenneT's previously established and consulted standardized 700 MW grid connection concept. Due to its size and distance to shore, a new grid connection concept has been established for the wind farm zone IJmuiden Ver. The figure below shows a schematic cross-section of this new grid connection concept. Wind turbines are connected through 66 kV “inter-array” cables (in orange) to an offshore (HVDC) converter station. Using 2 GW high voltage (525 kV) export cables (in green) the electricity is transported to shore. TenneT will be responsible for the offshore grid, from the onshore substation up to and including, the offshore substation. TenneT intends to create a new standard HVDC grid connection concept for both connections to IJmuiden Ver and potential future far shore wind farms.

The DC cable system can be laid in a bundled or an unbundled system configuration. Each with pros and cons.

This position paper describes the position of TenneT regarding the laying configuration of the 525 kV DC cables from onshore towards the 2 GW platform.

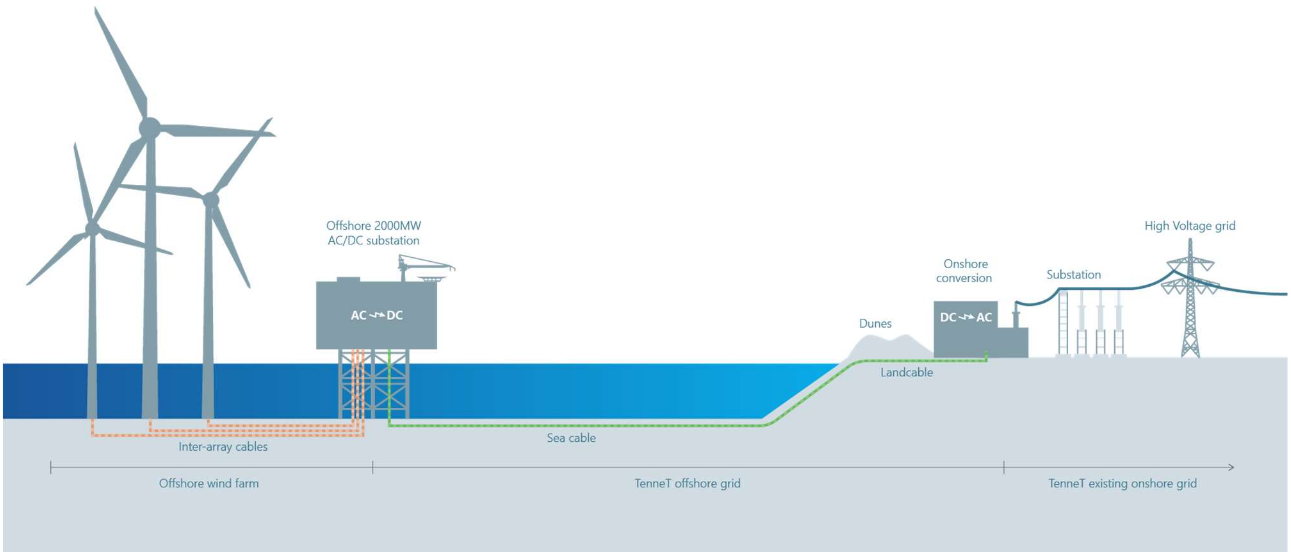


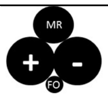
Figure 1: HVDC grid connection concept

This position paper contains elaboration on the following topics

- Possible cable laying configurations
- Static magnetic fields
- Failure frequency, failure types and impact
- Results from the market consultation with cable installers
- Cable availability calculations
- LCOE calculations
- Overview and evaluation of different laying configurations
- Position of TenneT

3. Possible cable laying configurations

Laying configurations can be bundled or unbundled and in case of unbundled laying configuration either one or two metallic returns can be applied. This leads to four laying options in total (see table below). Moreover, one or two fibre optic (FO) cables can be applied in unbundled systems. FO´s are not considered further in this paper.

 Option 1	 Option 2	 Option 3	 Option 4
Bundled	Unbundled with two metallic returns	Unbundled with one metallic return (one pole separated from other pole and DMR)	Unbundled with one metallic return (DMR separated from plus and minus)

4. Static magnetic fields

DC cables produce DC magnetic fields which are static, like the earth magnetic field. The bundled and unbundled configurations each have a different magnetic field strength, as for bundled configuration the magnetic field of the plus and minus poles cancel each other out significantly, resulting in a lower magnetic field than in unbundled configuration.

The effect of DC magnetic fields on marine mammals or fish is largely unknown[1].
DC magnetic fields may affect compass deviation and can be calculated. In Netherlands and Germany, up to now, DC cable systems are laid in bundled configuration. One of the reasons is to reduce magnetic field strengths. In Denmark and Norway however, unbundled cable laying configurations are accepted even though they have higher magnetic field strengths. Legislation or policy for offshore magnetic fields is missing and acceptable static magnetic field levels are still subject of discussion with the authorities.

[1] Study "Potential effects of electromagnetic fields in the Dutch North Sea Phase 1 – Desk Study (Bureau Waardenburg, Oct 2016)

To gain more insight in the different field strengths, the magnetic fields of bundled and unbundled configurations have been calculated at a vertical distance of 1.5 m above the cable (at seabed for 1.5 m soil cover). The results of these preliminary calculations by TenneT AMO[2] are presented below.

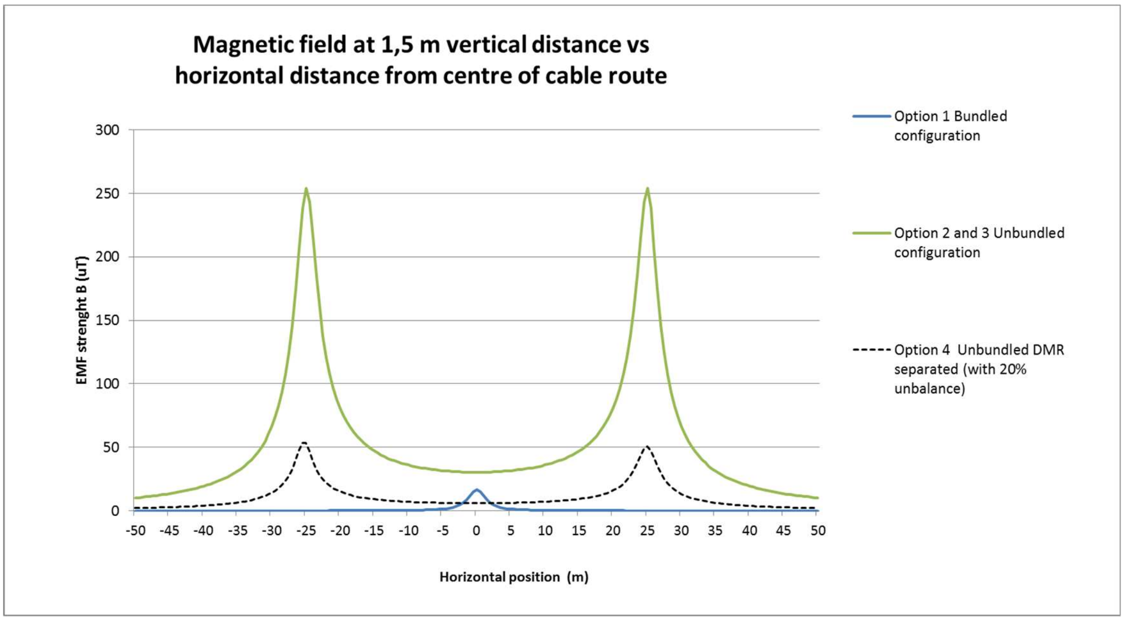


Figure 2: Magnetic field of different cable laying configurations

The blue line in Figure 1 represents a bundled configuration (option 1) and has the lowest magnetic field (<20 µT). The green line represents the unbundled systems (option 2 and 3) with the highest magnetic field (255 µT). The black dotted line indicates the magnetic field of unbundled systems with the poles close together and DMR separated (option 4) during 20% unbalanced operations showing a magnetic field of is maximum 55 µT. During fully balanced operations the magnetic field of option 4 is equal to option 1. During mono-pole operation the magnetic field of option 4 will be equal to unbundled systems option 2 and 3 (the green line).

5. Probability and impact of cable failures

5.1 Failure probability for HVDC submarine cable

TenneT assessed the failure data for HVDC submarine cable systems from the following sources:

- **CIGRE TB379**, "update of service experience of HV underground and submarine cable systems" (2009). This technical brochure contains quite old data. Also a lot of external failures occurred on

[2] This preliminary calculation does not take into account local earth magnetic field, soil properties and large metal structures and other power cables in the vicinity. The separation distance for unbundled configuration is still to be assed and may be more. Further increase of separation distance magnetic will not increase the magnetic field strength.

unprotected cable systems while installation and maintenance strategy has improved a lot over the last 10 years.

- **ENTSOE-EUROPACABLE** "Recommendations to improve HVDC cable systems reliability" (2019).This paper is based on quite new information but describes failure probability for both offshore and onshore cable systems as a whole.
- **TenneT** internal failure data for offshore cable systems. This data is quite detailed but represents a smaller population.

Based on all sources TenneT has estimated a failure probability of 0.0007 /km.year for DC submarine cable circuits (per bundle).

5.2 Type of failures and failure impact

A cable failure can occur due to internal or external causes. It is TenneT's experience that, out of all offshore cable failures, 50% are internal and 50% are external related, leading to an internal failure probability of 0.00035 /km.year and an external failure probability of 0.00035 /km.year. For unbundled laying configurations the cable system is more exposed to external threats compared to bundled systems, leading to a two times higher probability of external damage.

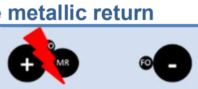
For some failure and configuration scenario's the cable system can still operate on half capacity by using the healthy cores. This means that during the time the power output of the WTGs stays below 1000 MW there is no loss of MWh.

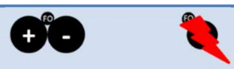
A failure in the DMR is most likely caused by external threats. The electrical stresses in the DMR insulation are low. An (external) failure in the DMR only influences balancing capabilities. Without a DMR, unbalance up to 10% can still be managed by voltage control. More than 10% unbalance without DMR will lead to power curtailment, however, this scenario is considered to be very unlikely.

5.2.1 External failures

External failures are caused by unexpected events from the surroundings, like sinking vessels, dropping or hooking anchors, dropping containers, severe movement of the cable (e.g. free spans) etc. It is assumed that in case of an external failure, all cables in the specific bundle are damaged and all cores in the damaged bundle will be out of operation during the complete repair time (MTTR).

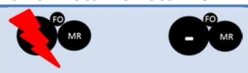
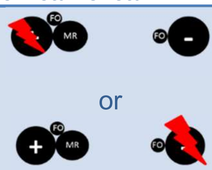
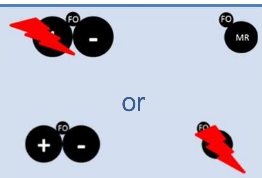
TenneT uses a Risk Based Burial Depth study combined with a seabed mobility study to determine the sections with higher risk for external damage and to mitigate risks by increasing burial depth to provide sufficient protection for the cable and minimizes reburial actions during operational life time.

Option 1 Bundled systems	Option 2 Unbundled system with two metallic returns	Option 3 Unbundled system with one metallic return	Option 4 Unbundled system with one metallic return
		 or	 or

			
System out of service during the total MTTR.	System operates at half capacity during the total MTTR.	Failure in the left bundle: System out of service during the total MTTR. Failure in the right bundle: System operates on half capacity during the total MTTR.	Failure in the left bundle: System out of service during the total MTTR. Failure in the right bundle: Negligible impact.

5.2.2 Internal failures

Internal failures are caused by design, production or assembly errors. It is TenneT's experience with DC offshore cables that an internal failure in one core will NOT affect other cores. Therefore, the cable can still operate on half capacity (1 GW) for a limited time (time is depending on the laying configuration).

Option 1 **Bundled systems**	**Option 2** **Unbundled system with two metallic returns**	**Option 3** **Unbundled system with one metallic return**	**Option 4** **Unbundled system with one metallic return**
			
System out of service for 50% of MTTR[3] and operates on half capacity for other 50% of MTTR.	For both bundles: System operates at half capacity during the total MTTR.	Failure in the left bundle: System out of service for 50% of MTTR (only during cutting and repair) and operates on half capacity for other 50% of MTTR. Failure in the right bundle: System operates on half capacity during the total MTTR.	Failure in the left bundle: System out of service for 50% of MTTR and operates on half capacity for other 50% of MTTR. Failure in the right bundle: Negligible impact.

6. Market consultation results

Recently TenneT held a market consultation with cable suppliers and cable installers to gain insight in the expected repair times and costs for installation. This input is used for the availability and LCOE calculations.

Most important outcomes of the market consultation are stated below:

[3] It is assumed that cutting and repair takes 50% of the MTTR

- The installation costs for unbundled systems are expected to be higher than for bundled systems;
- A few suppliers expect a longer repair time for bundled systems. They see possibilities to reduce repair times by optimising the bundled laying configuration and repair procedures. This has to be worked out during detailed engineering. The average repair time for offshore cable failures is normally set at 60 days for unbundled systems. Based on the market consultation, the repair time for 3-core bundled systems is set at 70 days (30 days for preparation, 40 days for cut and repair). For the LCoE calculations these repair times are incorporated in the availability numbers of the different bundled and unbundled configurations.

7. Cable availability

7.1 Basic assumptions

The basic assumptions for availability calculations are stated in Annex 1.

7.2 Availability score

The table below shows the availability of the cable system only, for both IJmuiden Ver alpha and beta. Converter and other systems are not considered here.

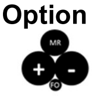
		Option 1  **Base case**	**Option 2** 	**Option 3** 	**Option 4** 
alpha	Failure probability total cable system	0.1225 failures/year	0.1838 failures/year	0.1838 failures/year	0.1838 failures/year
	Availability delta compared to bundled systems (base case)	-	+0.98% 88,767 MWh/a	-0.14% - 12,681 MWh/a	0.25% 22,645 MWh/a
beta	Failure probability total cable system	0.1085 failures/year	0.16275 failures/year	0.16275 failures/year	0.16275 failures/year
	Availability delta compared to bundled systems (base case)	-	+0.86% 77,897 MWh/a	-0.12% -10,869 MWh/a	0.21% 19,021 MWh/a

Table 1 – Failure probabilities and the availability deltas of the unbundled options compared to Option 1

8. Impact on costs

8.1 Basic cost assumptions

Based on the availability calculations, the market consultation and TenneT project information the cost assumptions for CAPEX and OPEX for the three unbundled configurations are set. The relative assumptions compared to the CAPEX and OPEX of the bundled option 1 are presented in Table 2.

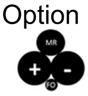
	Option 1  Base case	Option 2 	Option 3 	Option 4 
Cost:				
Cable manufacturing	-	+26%	-	-
Cable installation	-	+ 50%	+ 50%	+ 50%
Cable maintenance	-	+39%	+39%	+39%
Cable repairs	-	+50%	+50%	+50%

Table 2 – Cost assumptions, relative increase/decrease compared to bundled Option 1

8.2 Results

The LCoE impact analysis results for the different options are shown below.

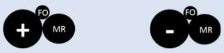
		Option 1	Option 2	Option 3	Option 4
LCoE impact	Developer	-	-1,0%	-0,1%	-0,3%
LCoE impact	TenneT	-	3,6%	1,9%	1,7%
Total LCoE impact	Societal	-	0,3%	0,4%	0,3%

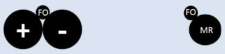
Table 3 – LCoE impact analysis results of unbundled options compared to bundled Option 1

As can be seen, the bundled option 1 gives a better overall (societal) LCoE result than the other unbundled options.

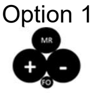
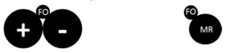
9. Overview and evaluation of each configuration

An overview of the pros and cons of each laying configuration is given in the table below:

	Pros	Cons
Option 1 	Best LCOE Lowest environmental impact Lowest magnetic field Smallest spatial footprint	Complex installation method MI not feasible as backup solution
Option 2 	Highest availability (MWh) Standard installation method	Highest magnetic fields Highest CAPEX Higher probability of external failures (OPEX)

		More maintenance (OPEX)
Option 3 	Standard installation method	Lowest LCOE Highest magnetic fields Higher CAPEX Higher probability of external failures (OPEX) More maintenance (OPEX)
Option 4 	During balanced operation the magnetic field is equal to option 1 Standard installation method	During mono-pole operation a high magnetic field (equal to option 2 and 3) Higher CAPEX Higher probability of external failures (OPEX) More maintenance (OPEX) MI not feasible as backup solution

The table below shows how the laying configurations relatively score against each other. The base case (bundled configuration) is set to a neutral score.

	Option 1  Base case	Option 2 	Option 3 	Option 4 
LCOE	.	-	-	-
Environmental impact	.	-	-	-
Magnetic field	.	-	-	./- [4]
Spatial footprint	.	-	-	-
MI back-up solution	.	+	+	.
Complexity of cable installation	.	+	+	+

[4] During mono pole operation the magnetic field scores negative compared to the base case

10. Position of TenneT

TenneT will install a bundled cable laying configuration (option 1), if technically feasible[5]. A bundled laying configuration has the best LCoE, the smallest spatial footprint and the lowest static magnetic field.

Unbundled laying configuration with plus and minus bundled together and a separate metallic return (option 4) is seen as the best alternative for option 1. This option scores average on LCoE and has a lower static magnetic field.

TenneT is in the opinion that a higher availability should be achieved by decreasing the cable failure rate (using the risk based burial depth philosophy) instead of unbundle the cable system and adding a second metallic return.

[5] A PQ and type test certified XLPE cable with 525 kV DC extruded insulation material and 3-core bundle installation

Annex 1

Basic assumptions for availability calculations

	Quantity	Source:
Cable route length	175 km Alpha 155 km Beta	IJVER team
Voltage class	525 kV DC	IJVER team
Total installed capacity	2000 MW Alpha 2000 MW Beta	IJVER team
Transport capacity (ampacity) per cable system	2000 MW = 3810 A over 2 cores 1000 MW = 1905 A per core	IJVER team
Failure probability	0.0007 /km.year **Bundled:** Internal: 0.00035 /km.year External: 0.00035 /km.year **Unbundled:** Internal: 0.00035 /km.year External: 2 x 0.00035 /km.year	TenneT conclusion based on Cigré TB379, ENTSOE and internal failure data
Outage time – MTTR	70 days – 1680 hrs for bundled 60 days – 1440 hrs for undbundled	TenneT conclusion based on Cigré TB379, internal and ENTSOE data, Market Consultation
Load factor	0,517 (without overplanting)	Position paper T10
Load duration curve		BLIX