MEMORANDUM

TO: Windfarm developers
DATE: November 02, 2018
REFERENCE: ONL-TTB-04761v2
FROM: TenneT TSO

SUBJECT: Overplanting - version: Hollandse Kust (zuid) v2

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1 Scope and considerations

The Figure 1 below shows a schematic cross section of the connection of an offshore wind farm to the onshore electricity grid. Wind turbines are connected through “inter-array” cables (in orange) to the offshore Connection Point (CP) at the offshore substation, from which electricity is transported to shore. TenneT is responsible for the grid connection up to, and including, the offshore substation and will take care for the supply and installation.

The wind park, including the wind turbines and the array cables, up to the offshore CP at the switchgear installation on the offshore substation of TenneT, is to be supplied and installed by the owner of the Power Park Module (PPM).

TenneT intends to standardise the offshore substations as much as possible for all five wind areas to be realised in the coming years in line with the Energy Agreement.

Figure 1 - Schematic of the offshore electrical grid. Source: TenneT
Overplanting

An important aspect in the design of an offshore wind farm, is to optimise the offshore wind farm capacity (type and number of wind turbine generators) to the fixed electrical infrastructure export capacity. This principle is also referred to as overplanting or overbooking since it usually leads to installing a (small) number of extra wind turbine generators compared to the grid connection capacity limit\(^1\). The "overplanted" power from these extra turbines will result in higher energy yield at lower wind speeds but will lead to a curtailed power at higher wind speeds as depicted in Figure 2. Of course, the extra turbines will result in higher CAPEX, which should be balanced by extra revenues from the extra energy yield.

![Curtained Power](image)

*Figure 2 - Principal of Capacity Optimisation. Source: Global Offshore Wind Conference 2014.*

To be able to further optimise the PPM lay-out (location, type and number of wind turbine generators), it is necessary for the PPM owner not only to know to what extent the grid connection may be continuously loaded (e.g. the grid capacity limit) but also to what extent the grid connection may be (temporary) loaded above this capacity limit. In this way, the curtailed power is reduced and the energy yield is increased further.

This paper describes the position of TenneT with respect to the extent to which the offshore grid specific for Hollandse Kust (zuid) may be loaded more than the rated power at CP and under which conditions. As the limiting factor in the offshore grid are both a) the 220 kV export cables from the offshore substation up to and including the beach landing and b) the 380 kV export cables from the 220kV/380kV landstation to the existing 380 kV grid, this paper will focus on both of these cable systems.

\(^1\) Money does grow on turbines – Overplanting Offshore Windfarms, Andrew Henderson a.o., Global Offshore Wind Conference 2014
2 Active power transfer through the TenneT offshore grid

The offshore grid design will be based on the parameters as listed in Table 1.

Table 1 - TenneT NL offshore grid parameters

<table>
<thead>
<tr>
<th>Grid parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid capacity per PPM at offshore CP:</td>
<td>350 MW</td>
</tr>
<tr>
<td>Number of PPM per offshore platform:</td>
<td>2</td>
</tr>
<tr>
<td>Reactive power exchange at CP under normal conditions:</td>
<td>Max +/- 0.1 p.u. (+/- 35 Mvar)</td>
</tr>
<tr>
<td>Nominal voltage level (220 kV part) onshore / offshore:</td>
<td>225 / 230kV +/- 1%</td>
</tr>
<tr>
<td>Nominal voltage level (380 kV part) onshore</td>
<td>380 – 400 kV</td>
</tr>
</tbody>
</table>

To determine if more than 700 MW (2 * 350 MW) of active power (P) can be transferred through the offshore grid, TenneT makes an assessment of the capability of the 220 kV export cables (paragraph 2.2) and 380 kV export cables (2.3) based on the parameters shown above. If there is additional capacity found in the design which allows the 220 kV / 380 kV export cables to transfer more than 700 MW of active power, TenneT will assure that other grid components will also be capable to transfer this extra power. The absolute maximum of transferred active power will in all cases be limited to 760 MW (2 * 380 MW).

With respect to the overloading of the grid connection system, the 380 MW shall be seen as an absolute maximum as other grid components such as the main transformers have much shorter thermal time constants.

According to RfG, PPMs will be required to contribute to the primary voltage regulation with more reactive power than shown in Table 1. It is assumed that these circumstances (Q > 35 Mvar or Q < -35 Mvar) will be limited in time and therefore will not significantly influence the thermal loading of the cables.
2.1 Simulation method

The duration in hours that a load of 760 MW can be transferred through one of the export cables systems (two 220 kV circuits with 380 MW per circuit or one 380 kV circuit with the full 760 MW) before curtailing of output power of the wind park will take place (referred to in this paper as dynamic ampacity) is dependent on the following factors:

1. Temperature of the cable before the 760 MW limit is reached. This temperature is again dependent on the loading history of the cable the previous hours or even days. This again is directly related to the wind speed;
2. The method of curtailing\(^2\);
3. Final soil resistivity values over the complete cable route;
4. Final design of the cable system;
5. Voltage level of the system.

A clear and binding answer on the question of duration before curtailing will occur can't be given due to e.g. soil resistivity which will only be determined on a limited set of samples and the power output of the wind farms. Only when a wind farm is in operation, the actual temperature response will be known by the actual cable conductor temperature measurements (see chapter 2.4).

After a) soil resistivity measurement results along the export cable route of HKZ (which are part of the geotechnical survey) are available to TenneT and b) a preliminary cable design has been made based on the survey results, dynamic ampacity calculations are made for the worst case location(s) on the cable route (hot spot) as further explained in the paragraphs below based on one preloading conditions and a full load condition of 380 MW per PPM.

The chosen preloading condition of 67% reflects an average loading of the cable which may be expected over a long time with a wind farm loading profile. For this condition, a preloading time of ten years has been used to assure a starting temperature which is nearby the steady state conductor temperature when calculated according the IEC 60267. The dynamic calculations for this update have been made according to the IEC 60853.

These simulation results (which are still estimates) can be used in the business case calculations of the offshore wind park developers.

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\(^2\) See section 2.4 of this document.
2.2 220kV export cables

2.2.1 Analysis of soil data of the geotechnical survey

In July 2017 the final reports of the offshore geotechnical survey have been received by TenneT. One report consists of the results of the offshore (trenched) route and one report consists of the analysis of the two landfall HDD options. The relevant parts of these final reports (ref: Appendix C1 to P902534_HKZ_Route-Survey-Report_Vol2a and Appendix C to Vol2b) are available for wind developers preparing for the offshore wind tender on request via netopzee@tennet.eu. In this survey about 70 locations were investigated including soil sample analysis and various measurements of the thermal conductivity.

The raw data of this final survey report has been processed where for each borehole the effective thermal resistivity value (G) has been determined on the target depth of burial (DOB) using the conformal mapping methodology as stipulated in [Cigré ELECTRA nr 98, The calculation of the effective external thermal resistance of cables laid in materials having different thermal resistivities, 1985]. These effective thermal resistivity (G) values are included in Annex A. The target DOB per route section (which can also be found in the table of Annex A) has preliminary been determined by TenneT based on expected permit requirements and preliminary results of the morphological study and may change during the ongoing route engineering works.

Based on the data of the final survey report and Annex A, the areas with the highest thermal resistivity values have been listed in Table 2, where also a short description is included per area.

Table 2 – Areas with highest thermal resistivity values along the Borssele cable route

<table>
<thead>
<tr>
<th>Location</th>
<th>Soil coverage [m]</th>
<th>Effective G [K.m/W]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landstation</td>
<td>1,2</td>
<td>1,2 / 2,9</td>
<td>Thermal resistivity with partial / full soil dehydration taken into account.</td>
</tr>
<tr>
<td>HDD</td>
<td>28</td>
<td>0,7</td>
<td>Deepest point of HDD in a significant layer of clay</td>
</tr>
<tr>
<td>HDD</td>
<td>55</td>
<td>0,4</td>
<td>Deepest point of long HDD</td>
</tr>
<tr>
<td>Sand dump area</td>
<td>5,5</td>
<td>0,83</td>
<td>Cable in layer of clay, soil coverage after burial</td>
</tr>
<tr>
<td>Sand dump area</td>
<td>14,5</td>
<td>0,65</td>
<td>Cable in layer of clay including dumped sand (future soil condition)</td>
</tr>
<tr>
<td>Offshore part</td>
<td>3,5</td>
<td>0,6</td>
<td>Cable in worst case sand type with additional cover due to limited sand wave activity</td>
</tr>
<tr>
<td>Offshore part</td>
<td>7,0</td>
<td>0,55</td>
<td>Cable below full sandwave (future soil condition)</td>
</tr>
</tbody>
</table>

The areas of Table 2 are shown on a map in Figure 3.
220 kV / 380 kV Land station area: As soil dehydration can't be neglected, backfill must be considered for the onshore part. Backfill is a mitigating measure where thermal resistivity is improved by embedding the cable in sand with a better thermal resistivity value than the original soil. For the current situation, the assumption has been made that with the backfill the thermal resistivity is lowered such that the cable designs (used in the case example below) just reaches a static (continuous) ampacity corresponding to 350 MW per cable circuit. In the experience of TenneT with Borssele, this will lead to the worst case 380 MW dynamic ampacity for the whole 220 kV route.

To achieve the static (continuous) ampacity corresponding to 350 MW per cable circuit, estimates were used for the thermal resistivity of the backfill. For the cable type 1 (STS, see 2.2.2), the soil resistivity was lowered to 1,0 K.m/W and for the cable type 2 (GS) the soil resistivity was lowered to 0,8 K.m/W.
**HDD** (horizontal directional drilling): The values in *Table 2* of the effective thermal resistivity of the specific parts of the HDD have been given which reflects the expected points in the HDD which will be the leading points for cable design. As the soil coverage of these points are large, the 380 MW dynamic ampacity will be relatively high in the HDD.

**Sanddump area**: As the soil coverage in this area is also large (5.5 m and 14.5 m, see *Table 2*) the 380 MW dynamic ampacity will be relatively high.

**Offshore part**: For the offshore part, cable design will be based on the given soil coverage of 3.5 m and 7.0 m. Although parts of the cables will be buried at around 1.5 m, it is expected that this route part will not be leading for the worst case dynamic ampacity. The reasons for this is that the 3.5 m and 7.0 m soil coverage are leading for cable design resulting in additional ampacity for the cable when only covered by 1.5 m of soil.

### 2.2.2 Cable design

#### Load Flow

For cable properties which have an impact on the load flow, following values have been assumed for the dynamic ampacity calculations of this position paper:

- Capacitance of cable: 0.22 µF / km (mean value)
- Length of cable: ~43 km (HKZ Alpha, longest route)

This results in a full load current (350 MW) at the land station side of 940 A and an overload current (380 MW) of 1010 A. Also, an additional preloading condition of 67% (of 380 MW) has been taken into account of 750 A.

Variance of capacitance will lead to a variance of full load current. The chosen capacitance used in this paper is a conservative estimate resulting in the largest full load current. Also for cable length the worst case has been selected (longest route, HKZ Alpha). For HKZ Beta with a route which is 7 km less, the full load current will be lower.

The reactive power compensation scheme foresees on shunt reactors at onshore side only which results in an estimate full load compensation distribution of 75%/25% onshore and offshore. At lower loads this will shift towards 100%/0%.

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3 This current is higher than 67% * 1010 A as at lower currents, the compensation scheme is shifting towards a higher current at land station side. This higher current in the loadflow has been used here.
Losses

In this position paper, two different 1600mm² AL cable designs are used for the simulations of which the results are presented below (paragraph 2.2.3).

For these designs, on other cable properties which have an impact on the losses (apart from conductor design), following assumptions have been used:

- Cable type 1: Armour design: stainless steel (STS) wires with $\lambda_2$ factor of 0 (zero), $\lambda_1$ factor of 0,28;
- Cable type 2: Armour design: galvanized steel (GS) wires with $\lambda_1+\lambda_2$ factor of 0,65

J-tube

As the time constants for temperature rise in the J-tube are low, the steady state rated ampacity requirement in the J-tube used by TenneT is increased to 380 MW. Therefore, the cable inside the J-tube is no limiting factor with respect to the dynamic ampacity.

2.2.3 Case study results

The results of the calculations for the 220 kV / 380 kV land station are given in Table 3 where the time until the conductor reaches 90 °C is stated in hours. For this scenario an ambient temperature of 15 °C has been used and effective thermal resistivity values of the soil as described in paragraph 2.2.1. The graph of this scenario is depicted in Figure 4.

Table 3 - Time (in hours) for conductor to reach 90 °C for 220 kV / 380 kV land station scenario

<table>
<thead>
<tr>
<th>Preloading</th>
<th>Overloading</th>
<th>Time to reach 90°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td># of days</td>
<td>[A] / [MW]</td>
</tr>
<tr>
<td>67%</td>
<td>3650</td>
<td>750 / 1010 / 380</td>
</tr>
</tbody>
</table>

Figure 4 – Development of temperature of conductor with overload of 1010 A (380 MW) and preload of 750 A

Note (02-11-2018): calculations on the scenario’s based on the actual winning 220 kV tender design and updated 380 kV ampacity calculations are provided in §2.4. Results in table 3 and figure 4 are superseded.
2.3 380kV export cables

2.3.1 Cable route and soil survey
As part of the net op zee Hollandse Kust (zuid), 380 kV export cables will connect the 220 kV / 380 kV land station to the onshore 380 kV grid at existing substation Maasvlakte 380. This cable system consists of two cable circuits of each 700 MW and is about 3.5 km in length. The cable route consists of two major parts: a HDD part (horizontal directional drilling) below the Yangtze kanaal and a part where cables will be installed into an excavated trench. The route is shown in Figure 5 and a geotechnical survey has been performed along the route. The final report (ref: VN-65003-1 R50294) is available for wind developers preparing for the offshore wind tender on request via netopzee@tennet.eu.

2.3.2 Cable design
Although calculations on dynamic ampacity are ongoing, TenneT concluded that with the currently foreseen cable design, the cables directly buried in soil (blue part of route in Figure 5) will have a better dynamic ampacity behaviour as the land station scenario described in paragraph 2.2.3.

Note (02-11-2018): calculations on the scenario’s based on the actual winning 220 kV tender design and updated 380 kV ampacity calculations are provided in §2.4.

Figure 5 – 380 kV cable route (yellow: HDD, blue: installation in open excavation)
2.4 Update 01 - 02-11-2018 - based on winning 220 kV tender design and updated 380 kV ampacity calculations (V2)

2.4.1 220 kV tender design

In the winning tender design the cable system is optimized compared to the cable types presented in §2.2.2. The identified critical route sections do not only consist of the 220 kV / 380 kV land station area but also the HDD at the identified layers of clay (at 28 m, see table 2 and at 12.2 m).

The calculation with the lowest time to reach 90°C made by the winning tenderer is presented in table 4. In this table also the calculation preconditions are shown.

<table>
<thead>
<tr>
<th>Preloading %</th>
<th># of days</th>
<th>Preload I [A]</th>
<th>Overloading [A] / [MW]</th>
<th>Time to reach 90°C [hours]</th>
</tr>
</thead>
<tbody>
<tr>
<td>67%</td>
<td>3650</td>
<td>720</td>
<td>1000 / 380</td>
<td>Winning tender design</td>
</tr>
</tbody>
</table>

Based on the tender calculations, with a preload of 67% over 3650 days, an overloading of 380 MW (1000 A in this route section) can be maintained for about 300 hours before the conductor temperature reaches 90 °C. No graph is available for this condition.

2.4.2 updated 380 kV ampacity calculations

For the 380 kV cable route TenneT specified that the conductor cross section shall be at least 2500 mm² with an aluminium conductor type. The procurement process for the 380 kV cable is still ongoing and also other conductors (type and cross section) may be offered as long as the AC resistance at 90 °C is equal or better than for the 2500 mm² aluminium conductor type.

Based on the ampacity calculations performed by TenneT, with a preload of 67% over 3650 days, an overloading of 770 MW (1136 A for one circuit) can be maintained for about 250 hours before the conductor temperature reaches 90 °C as presented in Table 5. No graph is available for this condition. As the cables are installed in a designated route for piping and cabling, the cables must be installed in trefoil configuration and in HDPE ducts for additional mechanical protection. Also the cables will be subject to thermal influence of other cable systems nearby. The time presented in Table 5 is based on the worst case location of the route including thermal influence of other existing and future planned cable systems.

<table>
<thead>
<tr>
<th>Preloading %</th>
<th># of days</th>
<th>Preload I [A]</th>
<th>Overloading [A] / [MW]</th>
<th>Time to reach 90°C [hours]</th>
</tr>
</thead>
<tbody>
<tr>
<td>67%</td>
<td>3650</td>
<td>703</td>
<td>1136 / 770</td>
<td>2500 mm² AL type</td>
</tr>
</tbody>
</table>

The calculation of the overloading capacity of the export cables (both 220 kV and 380 kV) is an estimation based on assumptions by TenneT, as clearly described in chapter 2.1.
3 Export cable load management

In general, TenneT identifies three levels in the export cable load management process:

1. Alignment of the wind park owner's (WPO) generation forecasts to dynamic cable loading capabilities;
2. Actual curtailment of the power output of the wind park by the WPO;
3. Actual curtailment of the power output of the wind park by TenneT.

This process will be further agreed upon in the Annex 3 to the offshore Connection and Transmission Agreement with the offshore wind farm.

Ad 1
It is the responsibility of the WPO to align its forecasts to possible curtailment of the wind park power output due to the temperature limit of the export cables (only if wind park power output is higher than the guaranteed 350 MW). To facilitate this alignment process, TenneT will provide:

a) calculation results as described above (updated on the as-built situation);
b) the actual cable conductor temperature measurements (data format and frequency to be defined in a later stage).

Ad 2
If the conductor temperature will increase above a certain threshold value (value to be determined per project), WPO will receive a warning signal from TenneT. WPO shall start at that moment (at the latest) with the curtailment of the wind park power output, down to 350 MW. If this curtailment is not started or is not sufficient and conductor temperature will increase above a second threshold value (close to but below 90 degrees Celsius, to be determined per project), WPO will receive a second and final warning signal from TenneT. Immediately after this second signal has been released, TenneT has the right to proceed to the third level as described below.

The warning signals are considered to be the official legally binding information provided by TenneT to the WPO. The cable conductor temperature measurements as described under level 1 are provided by TenneT as an extra service and will be for information only.

Ad 3
When the second warning signal has been released, WPO shall immediately reduce the power output to a maximum of 350 MW. TenneT will at that time monitor conductor temperature and power output continuously. If the reduction of power by the WPO is not sufficient, TenneT will have the right to curtail under 350 MW by switching off one of the strings of the wind park without any further notice.

With the three levels described above, an export cable load management process has been introduced that enables the WPO to manage its generation forecasts and actual power output curtailment while at the other hand it is assured that the export cable conductor temperature will never increase above 90 degrees Celsius.
4 Position of TenneT

Above considerations lead TenneT to the following position:

TenneT allows the PPMs to transmit up to 30 MW above their rated power (350 MW), with the requirement for PPM's to curtail their produced power, in case the 220 kV and / or 380 kV export cables reach their maximum allowable temperature limits. Details on curtailment of the PPMs will be addressed to in the 'Connection and Transmission Agreement (CTA)'.

The results of paragraph 2.2, 2.3 and 2.4 are only valid for Hollandse Kust (zuid). For this Hollandse Kust (zuid) case, an overloading of 380 MW can be maintained for about 250 hours (before conductor temperature reaches 90 °C) based on a preload of 67% over 3650 days, at the 380 kV onshore cable route.

For the Hollandse Kust (Noord) tender, TenneT will give an update in due time based on specific Hollandse Kust (Noord) soil data.

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4 Operational limits of sea and land cables will be monitored continuously by temperature sensing systems.
5  Annex A: Soil resistivity analysis - Offshore cable route from landfall to Hollandse Kust (zuid) Alpha and Beta platforms

Table with effective soil resistivity values. Revision 2.