TotalControl

Advanced integrated supervisory and wind turbine control for optimal operation of large Wind Power Plants

Reference Wind Power Plant
D1.03

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Sebastian Sanchez Perez-Moreno (TU Delft) contributed preliminary layouts for the IEA Wind Task 37 Offshore Reference Wind Power Plant.
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1 INTRODUCTION

From a scientific perspective, the ideal benchmark case for wind power plant control would be an operational wind power plant, on which the different control algorithms could be implemented, and measurements collected. In practice, this is not possible: the design data of the wind turbine and plant components is proprietary, and there are restrictions on the control algorithms that can be implemented, prior to their certification, on a commercial plant. The solution is to break the process into two steps, separating the validation of models, which may involve the use of proprietary data, from the benchmark studies on control algorithms. The latter may then be documented to the extent that the work is reproducible, and published in the open scientific literature.

TotalControl defines two reference wind power plants (RWPs) that are recommended for benchmark studies on wind power plant control. These RWPs are intended to provide a controlled environment for the comparison of different algorithms and analyses. One of the plants, the TotalControl Reference Wind Power Plant (TC RWP), is a densely-spaced array of 32 turbines. Its layout is tailored to high-resolution simulations of the atmospheric flow, and it will be used to study how plant control algorithms can improve the performance of high-density layouts, for better utilization of concession areas. The other plant is the IEA Wind Task 37 Offshore Reference Wind Power Plant (IEA RWP), which is to the extent possible a realistic design for the Borssele III and IV (Blauwwind) zones in the Dutch North Sea.

The RWPs have been defined over the course of a series of meetings between the authors. It became clear during the discussions that to standardize on a single configuration would compromise the quality of research. In particular, the tasks involving high-fidelity flow analyses are pushing the limits of the available computational resources; thus it is of primary importance to be able to exploit symmetry in the RWP layout to reduce the number of simulations required. The computational requirements are also a function of the domain size, and hence the number of turbines and their spacing. This, and the fact that the Lillgrund wind farm ($s/D = 3.3D$ to $4.3D$) is the subject of measurement campaigns in TotalControl WP1, suggest a dense spacing. At the same time, a dense spacing will tend to bias the results obtained with a given plant control algorithm. There is a need to evaluate how a proposed control algorithm will perform at the type of large wind power plants presently being constructed in the North Sea; hence the definition of two RWPs.

2 A SURVEY OF CANDIDATE REFERENCE WIND POWER PLANTS

There is at present no single, broadly accepted reference wind power plant. Examples can be found scattered throughout the literature, although these have typically been developed in the context of a particular academic field, such as flow analysis, layout optimization algorithms, or electrical grid design; for instance, Munters and Meyers (2016), Chowdhury *et al.* (2013), and Akhmatov *et al*. (2003).

Layouts of existing wind power plants can be obtained from various sources on the Internet (Fig. 1). Of particular mention is the Horns Rev wind farm, at which a large amount of data has been collected since its commissioning in 2002. In particular, data on the wakes and power deficits during operation are available in the open literature (Barthlemie *et al.* 2009). That said, the Vestas V80 2 MW wind turbines are not representative of the latest generation of offshore wind turbines. In common with all commercial wind power plants, the turbines' aeroelastic design is proprietary, which is problematic for a reference case.

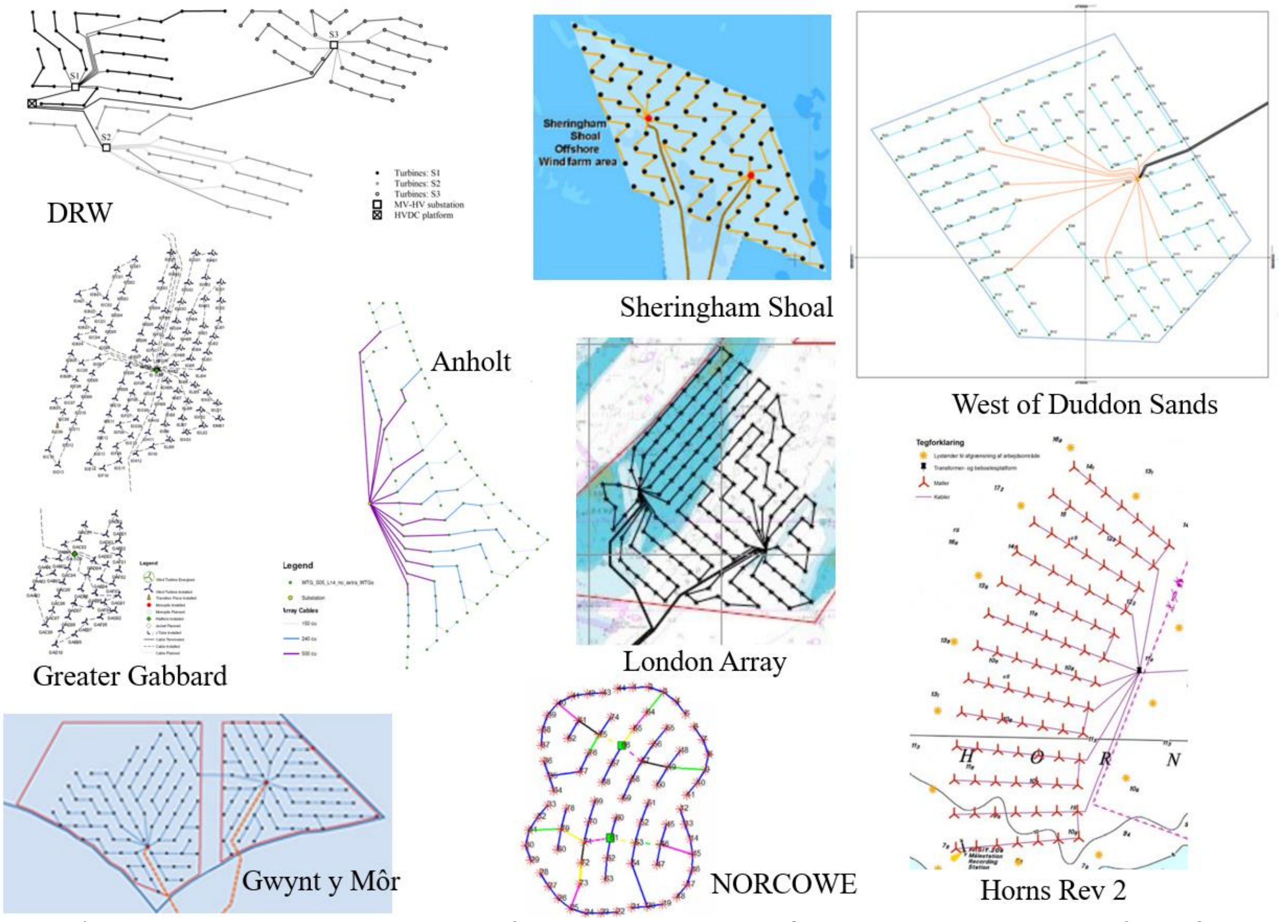

Figure 1: Wind power plant layouts, obtained from public websites via Google Pictures. The DRW (NOWITECH) and NORCOWE plants are fictitious designs, and the others are commercial plants.

Two offshore reference wind power plants have been developed respectively by the NORCOWE and NOWITECH research centers (Bak *et al*. 2017, Kirkeby and Merz 2018). These are both large plants – 800 MW and 1.2 GW – with irregular layouts, which can be found in Fig. 1. An additional reference plant is presently being developed under the IEA Wind Task 37 on Wind Energy Systems Engineering (Perez-Moreno *et al*. 2018).

The IEA RWP is one of the cases selected for use in the TotalControl project, and is described in Section 5. The IEA RWP was preferred over the alternatives, since, being developed in the context of the IEA, it is more likely to be adopted as an internationally standard reference case.

Figure 2 characterizes existing commercial offshore wind power plants in terms of the specific rating, which is the rated power of the plant divided by the surface area occupied; roughly the outer boundary of the turbine arrays pictured in Fig. 1. The TotalControl RWP and Borssele III and IV sites are also shown.

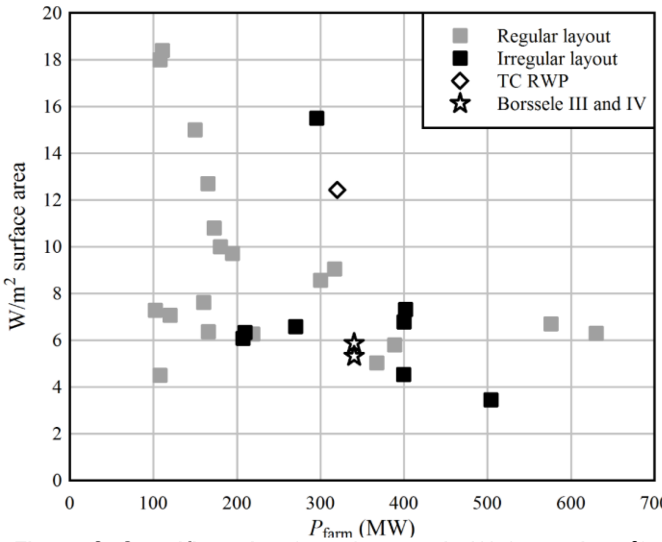

Figure 2: Specific rating (rated power in W / area in m²) as a function of rated power for a number of offshore wind power plants. One of the targets of plant control is to make higher specific ratings practical for large plants.

3 WIND TURBINES

TotalControl supports two wind turbines: the Samsung 7 MW Levenmouth prototype, and the IEA/DTU 10 MW Reference Wind Turbine (RWT). The Samsung turbine is supported in order to link to the measurement campaigns of WP3. Its design data is strictly proprietary, so for scientific work intended for open publication, the IEA/DTU 10 MW Reference Wind Turbine (RWT) is used.

The RWP layouts, rated power, electrical components, and so forth are specified based on the IEA/DTU 10 MW RWT.

> *When the Samsung turbine is used, the length scale of the RWP layouts should be scaled according to the turbine diameter, such that the s/D (spacing to diameter) ratios are constant. The rated power of the plant is also scaled by 7/10.*

3.1 SAMSUNG 7MW LEVENMOUTH PROTOTYPE

The Samsung 7 MW Levenmouth prototype is a proprietary commercial turbine, on which measurement campaigns are conducted as part of WP3. Table 1 summarizes some public-domain specifications for this turbine.

Table 1. Some public-domain specifications for the Samsung Turbine (source: www.wind-turbine-models.com)

Wind class	IEC Class IA
Control	Variable speed, pitch
Cut in wind speed	3 m/s
Cut out wind speed	25 m/s
Rated wind speed	11.5 m/s
Rated electrical power	7 MW
Number of blades	3
Rotor diameter	171.2 m
Hub height	110 m
Drivetrain	Planetary gear, 400 rpm

3.2 IEA/DTU 10 MW Offshore Reference Wind Turbine

The IEA/DTU 10 MW RWT is a redesign of the DTU 10 MW RWT (Bak *et al*. 2013). The primary motivation for the redesign was to increase the rotor diameter, and hence the energy production at below-rated windspeeds, such that the P_r/A (rated power to swept area) ratio is representative of the latest generation of commercial wind turbines. The updated design is complete, but is not yet published; some important specifications are summarized in Table 2.

Table 2: Specifications of the IEA/DTU 10 MW RWT.

		Change with respect to original DTU 10 MW RWT
Wind class	IEC Class IA	
Rotor orientation	Clockwise rotation - upwind	
Control	Variable speed, collective pitch	
Cut in wind speed	4 m/s	
Cut out wind speed	25 m/s	
Rated wind speed	11 m/s	Optimized
Rated electrical power	10 MW	
Number of blades	3	
Rotor diameter	198 m	Increased from 178.3 m
Airfoil series	FFA-W3	
Hub diameter	4.6 m	Reduced from 5.4 m
Hub height	119 m	
Drivetrain	Direct drive	Originally a medium-speed, multiple-stage gearbox
Minimum rotor speed	6 rpm	
Maximum rotor speed	8.68 rpm	Constrained by maximum tip speed
Maximum tip speed	90 m/s	
Hub overhang	7.1 m	
Shaft tilt angle	6 deg	Increased from 5 deg
Rotor precone angle	-4 deg	Increased from -2.5 deg
Blade prebend	6.2 m	Increased from 3.2 m
Rotor mass	47,700 kg	12% increase
Nacelle mass	446,036 kg	
Tower mass	628,442 kg	

It is expected that a full description of the IEA/DTU 10 MW RWT will be published as an IEA report in the near future. In the event that publication is delayed to the point that this would impact the TotalControl project, then the original DTU 10 MW RWT (Bak *et al*. 2013) will be used.

4 THE TOTALCONTROL REFERENCE WIND POWER PLANT

The TC RWP is a virtual test bed for wind power plant control. It is designed with symmetry in order to facilitate high-resolution numerical flow simulations. It has a compact spacing representative of the more densely-packed offshore wind power plants (Fig. 2). This will tend to emphasize the efficacy of plant control actions, and will serve to demonstrate how plant control can improve the performance of high-density layouts.

4.1 LAYOUT

The TC RWP consists of 32 turbines in a staggered pattern, Fig. 3. The separation between rows and columns is $5D$. The choice of a staggered pattern is somewhat arbitrary; but it makes sense to arrange the turbines in this manner if the prevailing wind direction were from the left.

The number of turbines results from a compromise between limiting the computational cost of high-resolution flow simulations and having an array that is large enough to be relevant as an offshore wind power plant. More specifically the main driver for the computational cost of such high-resolution simulations is the total amount of gridpoints, resulting from the grid resolution that is required to adequately resolve turbulent flow features in the main regions of interest on the one hand, and the dimensions of the total domain including buffer regions to avoid blockage effects and spurious influence of boundary conditions on the other hand.

The high-resolution simulations in the TotalControl project will be performed using the KU Leuven SP-Wind and the DTU EllipSys3D solver. SP-Wind employs a high order pseudo-spectral discretization, which allows the flow to be simulated accurately at relatively low resolution, but implies that this resolution is fixed throughout the entire domain. This includes the abovementioned buffer regions, whose size is proportional to the extent of the wind farm itself. The converse is true for EllipSys3D: the finite volume discretization requires an increased resolution in the wind farm, but allows the grid to be coarsened significantly in the surrounding buffer regions of the simulation domain. In practice, for both solvers this entails that the simulation cost is directly connected to the surface area of the wind farm or, for a given layout and turbine spacing, to the number of turbines. A total amount of 32 turbines was found to be feasible for both KU Leuven and DTU.

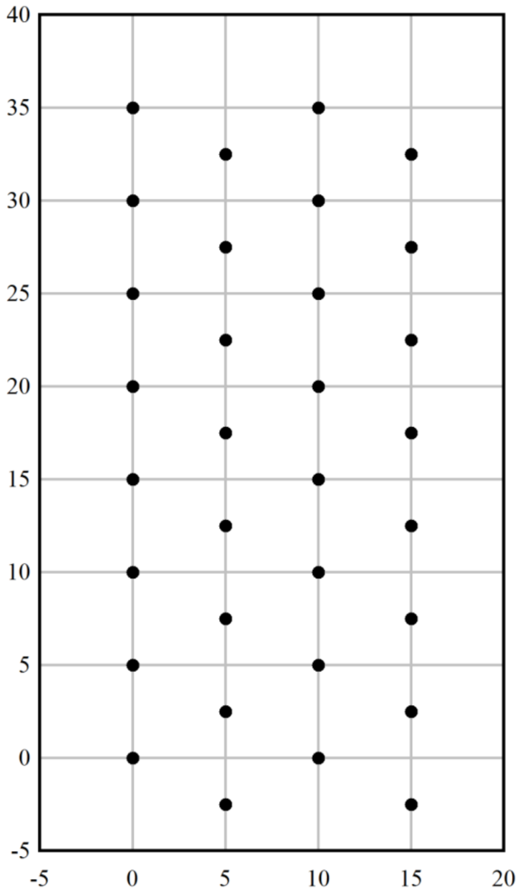

Figure 3: Layout of the TotalControl Reference Wind Power Plant. Axes have units of s/D, that is, length in terms of the number of rotor diameters, where D = 198 m.

The columns of eight turbines (vertical in Fig 3) provide a "long" direction where the turbine-to-turbine wake effects can approach their asymptotic values. Furthermore, given a top-down wind direction a typical aligned layout is achieved, for which wake redirection was found to be a very efficient wind-farm control strategy (Munters and Meyers 2018). In the perpendicular "short" direction (horizontal in Fig 3) only two turbines are directly aligned. For a left-right wind direction, a standard staggered configuration is achieved, for which wake induction control strategies have been found to be more suitable. In this way, both the redirection and induction approach to wind-farm control can be investigated without a priori favoring one over the other based on wind-farm layout.

4.2 Environmental specifications

The TC RWP is not located at a specific site. If a set of met-ocean conditions is required for certain studies, it is recommended to use the UPWIND Design Basis (Fischer *et al*. 2010), K13 shallow water site.

4.3 Electrical specifications

The electrical layout, shown in Fig. 4, has been conducted according to the EERA DTOC inter-array design procedure (Endegnanew *et al*. 2013). It consists of two strings of 7 turbines, and 3 strings of 6 turbines. Branching reduces the overall length of the thickest (500 mm^2) cable.

The inter-array grid voltage is 66 kV, which is foreseen as the standard for the next generation of offshore wind power plants, with turbines approaching a 10 MW rating. The electrical substation contains two 66/220 kV transformers rated at 180 MVA each. The AC system frequency is 50 Hz.

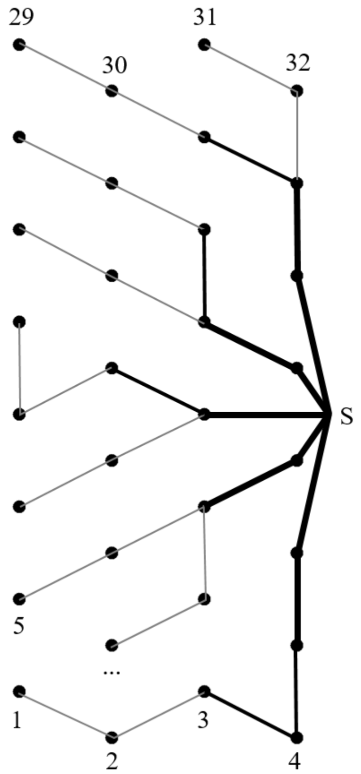

Figure 4: The electrical layout of the TC RWP. Thin gray lines: area 95 mm², ampacity[1] 300 A. Thin black lines: 150 mm², 375 A. Thick black lines: 500 mm², 655 A. Turbine identification numbers are shown, and S indicates the location of the electrical substation.

5 THE IEA WIND TASK 37 OFFSHORE REFERENCE WIND POWER PLANT

The IEA RWP is developed as a showcase for multidisciplinary analysis and optimization, with the aim of applying such methods on a realistic North Sea wind power plant. It is selected as a case in the TotalControl project in order to provide a link with international work in the field of wind power plant design, dynamics, and control.

5.1 LAYOUT

The IEA RWP is based on the Borssele III and IV zones (now being developed by Blauwwind) in the Dutch North Sea. An initial set of candidate layouts is given by Perez-Moreno *et al*. (2018), based on constrained numerical optimizations. Based on these candidate layouts, a semi-regular layout has been defined, and this is shown in Fig. 5. Note that this is not the final IEA RWP; but a description is provided here to serve as a default for the TotalControl project.

[1] Areas and corresponding ampacities are taken from ABB, *XLPE Submarine Cable Systems, Attachment to XLPE Land Cable Systems – User's Guide*, Rev 5. The rating factor is assumed to be 1.0, with an increased rating due to low water temperature offsetting possible reductions due to other influences.

The official publication of the IEA RWP may supercede the design shown in this section.

In the event that publication of the IEA RWP is delayed to the point that this would impact the TotalControl project, then the present design will be used.

The semi-regular layout obeys the actual constraints on turbine placement at the Borssele site, which includes several "no-go" corridors for pipelines and telecommunication cables. The turbines in the central area have been placed in gently curving rows and columns, akin to the Horns Rev 2 and Anholt layouts (Fig. 1). This curvature has the benefit of reducing the sensitivity to wind direction of the plant power output. As a consequence, the case where the wind is precisely aligned with a long, straight row of wind turbines – often studied in the literature – loses its relevance. Rather, the development of the atmospheric boundary layer across the wind power plant plays a more significant role than the local wakes.

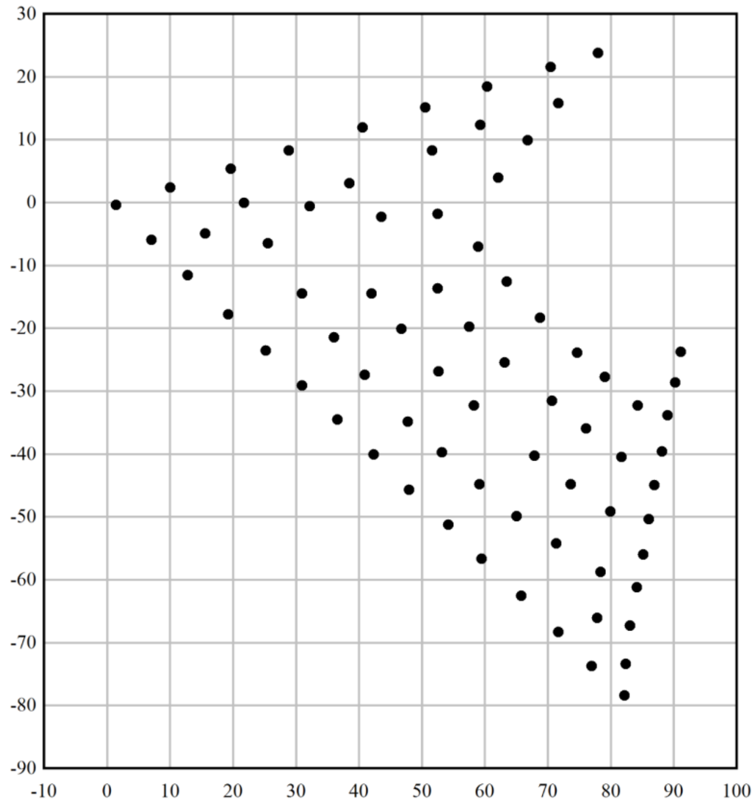

Figure 5: A preliminary layout for the Borssele RWP. This is a semi-regular, perimeter-weighted pattern, and obeys the actual Borssele zone constraints on turbine placement. Axes have units of s/D, where D = 198 m.

Figure 6 shows the turbine identification numbers, the substation location, and parcel boundaries. Telecommunications cables or pipelines run through the channels between parcels, and no turbines can be placed such that the rotor blades extend beyond the parcel boundaries.

Figure 7 compares the TC RWP and Borssele layouts. It is clear that the atmospheric flow will develop, and respond to turbine control actions, differently over these two plants.

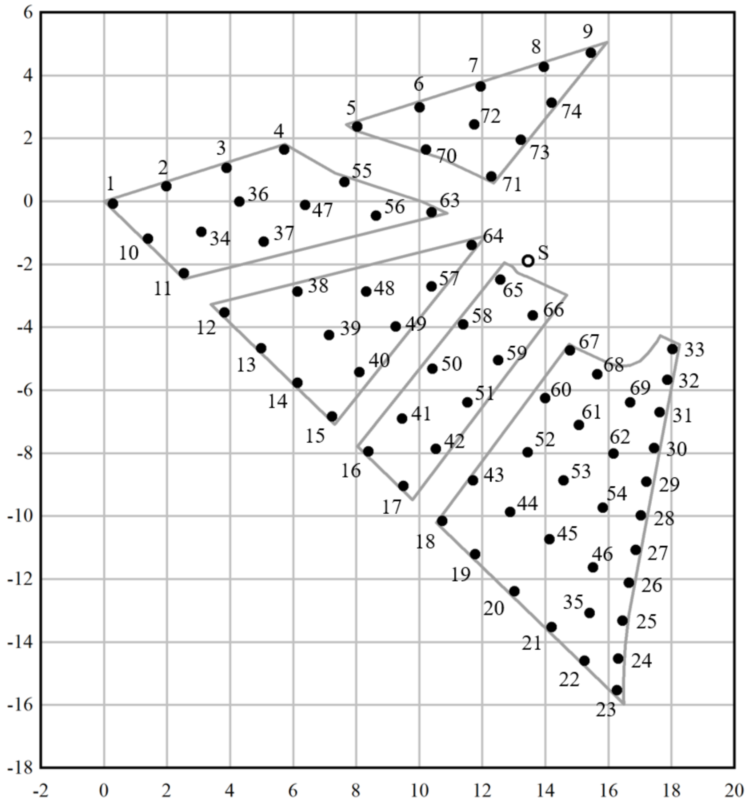

Figure 6: Turbine identification numbers and parcel boundaries. The axes are shown here in units of km.

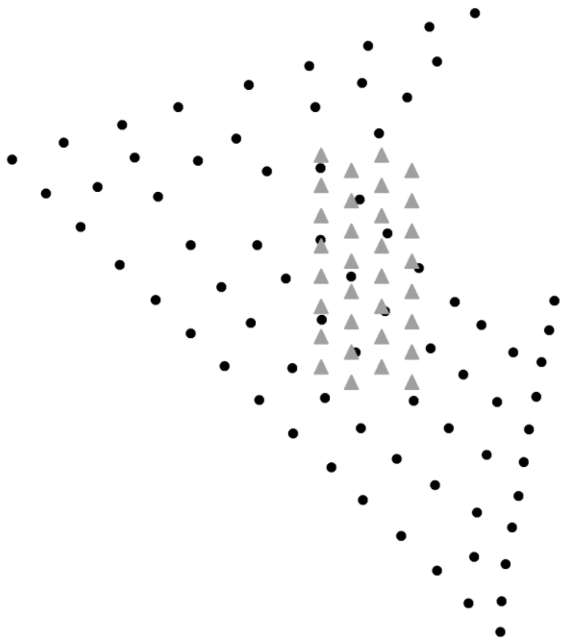

Figure 7: A comparison to scale of the TC RWP and Borssele layouts.

5.2 Environmental specifications

Figure 8 shows the bathymetry at the Borssele site. The data was obtained from NEA (2016). Should the plant control algorithms consider foundation fatigue in some cost metric, then the water depth will influence the fatigue loads.

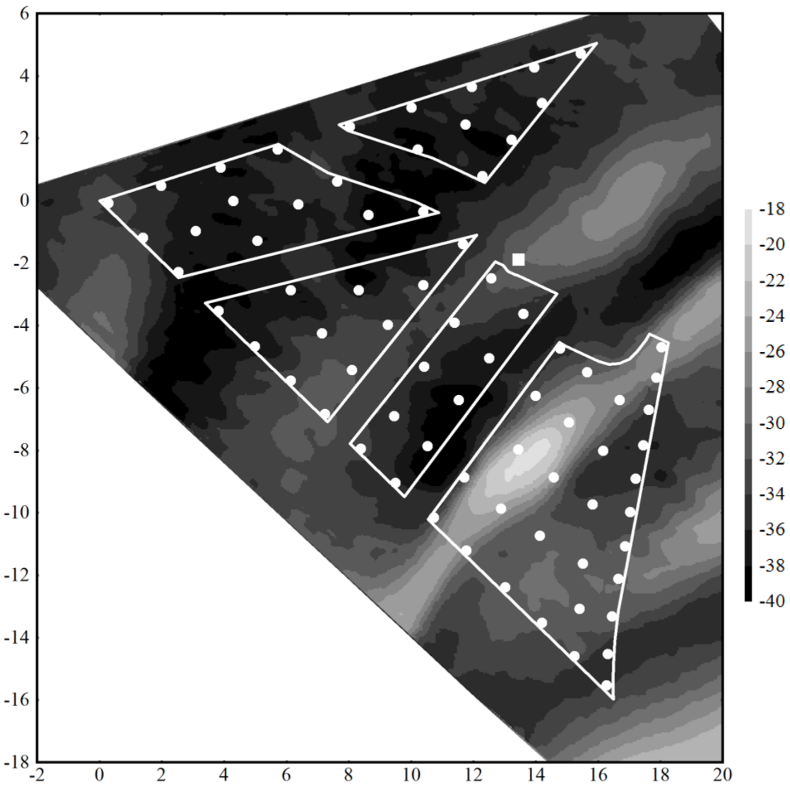

Figure 8: Bathymetry at the Borssele site. The legend shows depths in meters; the x and y axes are in units of km.

For studies in which the lifetime exposure to wind and wave loads is considered, it is recommended to use the UPWIND Design Basis (Fischer *et al*. 2010), K13 shallow water site. This reference contains a full set of wind-wave scatter diagrams for a location in the Dutch sector of the North Sea. It is not expected that the K13 environmental conditions correspond exactly to the true conditions at Borssele; but they should be close, and having a full set of wind-wave scatter diagrams will be useful for research on the influence of plant control algorithms on lifetime loads.

5.3 Electrical specifications

Figure 9 shows the electrical layout of the Borssele RWP. The parcels are shaded grey, as is a cable corridor leading from selected parcels to the substation. To the extent practical, the inter-array cables are bundled before crossing the existing telecommunications cables and pipelines.

The inter-array grid voltage is 66 kV, which is required by NEA (2016). The electrical substation contains two 66/220 kV transformers rated at 400 MVA each; the extra capacity is used to handle reactive power. The AC system frequency is 50 Hz.

There are two 220 kV export cables for transmission from the substation to shore. Each cable is rated at 400 MVA. The cable length between the substation and onshore grid connection is approximately 68 km.

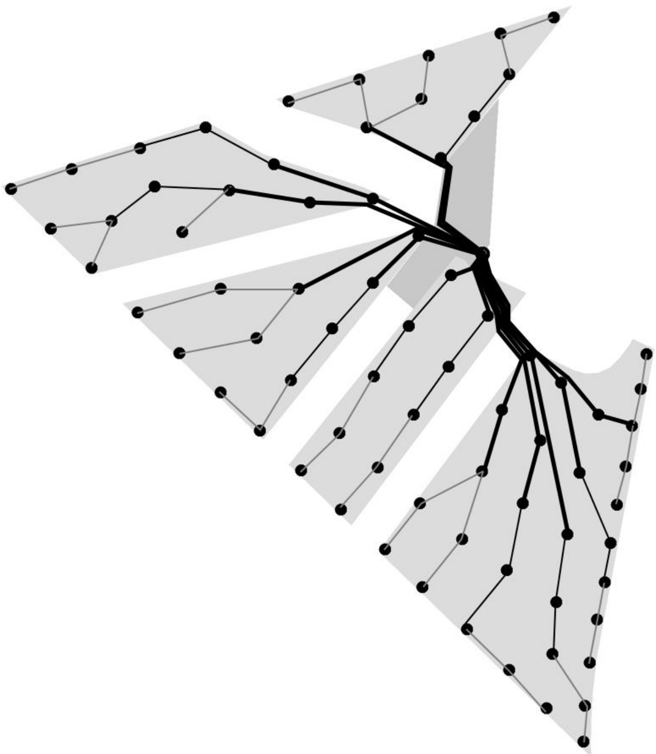

Figure 9: The electrical layout of the Borssele RWP. Thin gray lines: area 95 mm^2, ampacity 300 A. Thin black lines: 150 mm^2, 375 A. Thick black lines: 500 mm^2, 655 A.

6 Conclusions

Two reference wind power plants are defined for use in the TotalControl project. The TotalControl Reference Wind Power Plant (TC RWP) is an idealized, regular layout with a dense spacing. It is intended for studies involving high-fidelity flow analyses, and investigating how plant control can make possible denser layouts, with better utilization of concession areas. The Borssele Reference Wind Power Plant is intended to be a realistic design at an actual North Sea site. It covers a much larger area than the TC RWP, and the majority of the turbines are not arranged in straight rows – thus atmospheric boundary layer effects will be more significant than local turbine-to-turbine wakes. The present Borssele design is a preliminary version of the IEA Wind Task 37 Reference Wind Power Plant, and may be superceded upon official publication of the IEA RWP.

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APPENDIX: DATA FILES

Files are made available on the TotalControl SharePoint site, which contain the numerical data associated with the layouts shown in this report.