Ref. Ares(2017)2159130 - 26/04/2017

CL-Windcon

Closed Loop Wind Farm Control

# DELIVERABLE REPORT

# Definition of reference wind farms and simulation scenarios

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|---|---|---|---|---|---|
| Deliverable No. | D1.1 | Work Package No. | WP1 | Task/s No. | Task 1.1 |
| Work Package Title | | Wind farm control-oriented model development | | | |
| Linked Task/s Title | | Definitions | | | |
| Status | | Draft Final | (Draft/Draft Final/Final) | | |
| Dissemination level | | PU | (PU-Public, PP, RE-Restricted, CO-Confidential) (https://www.iprhelpdesk.eu/kb/522-which-are-different-levels-confidentiality) | | |
| Due date deliverable | | 2017-04-30 | Submission date | 2017-04-26 | |
| Deliverable version | | CL-Windcon-D1.1-DraftFinal-Definitions | | | |

**This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727477**

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# DOCUMENT HISTORY

| Version | Date | Comment |
|---|---|---|
| 0.0 | 2017-03-24 | First draft for partners review issued by CENER |
| 0.1 | 2017-03-31 | Second draft for partners review issued by CENER |
| 0.2 | 2017-04-11 | Third draft issued by CENER for internal quality review |
| Draft Final | 2017-04-26 | Draft Final |

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# LIST OF ABBREVIATIONS

| Abbreviation | Description |
|---|---|
| AAIA | American Institute of Aeronautics and Astronautics |
| ABL | Atmospheric Boundary Layer |
| a.s.l | Above sea level |
| ASME | American Society of Mechanical Engineers |
| CFD | Computational Fluids Dynamic |
| D | Rotor Diameter |
| DoE | Department of Energy |
| DTU | Danmarks Tekniske Universitet |
| ENEL | Ente nazionale per l'energia elettrica |
| FAST | Fatigue Aerodynamics Structures and Turbulence |
| GE | General Electric |
| IEC | International Electrotechnical Commission |
| IPC | Individual pitch control |
| LCoE | Levelized Cost of Energy |
| NASA | National Aeronautics and Space Administration |
| NEWA | New European Wind Atlas |
| NORCOWE | Norwegian Centre for Offshore Wind Energy |
| O&M | Operation and maintenance |
| RCN | Research Council of Norway |
| RWF | Reference Wind Farm |
| SOWFA | Simulator fOr Wind Farm Applications |
| TI | Turbulence Intensity |
| TSR | Tip Speed Ratio |

# 1 EXECUTIVE SUMMARY

This report describes the theoretical base for the reference wind farm and simulation scenarios definition for CL-Windcon project. Definitions have been made in the light of the requirements of the applications of WP2 (Wind Farm Flow control technologies and algorithms) and WP3 (Demonstration and Validation of Prototypes) in order to facilitate comparisons between the different technologies within the project.

This reports deals with the definition of four different reference wind farms. From simple topologies with one or two arrays with three turbines, to more complicated layouts with eighty turbines in four rows in the offshore case (Norcowe RFW) and an existing wind farm (Sedini WF). The aim of the simple layouts (three turbine case and nine turbine case) is to allow faster detailed simulations within SOWFA, being able to simulate different scenarios without excessive computational cost. These simple layouts will also allow analysing strengths and weaknesses of current models and algorithms and assessing the sensitivity of the parameters. The offshore layout, with more wind turbines, focuses on physical phenomena and effects which only emerge inside large wind farms with multiple overlapping wakes. The fourth layout corresponds to a real wind farm, Enel Green Power´s Sedini wind farm, where experiments are going to be performed giving all the partners the possibility to work together on common datasets and validate the models, as well as demonstrate the control algorithms developed within the project in a real-world application.

The turbine selected for the minimal layouts and the offshore wind farm is the reference turbine from the EU project INNWIND (DTU 10 MW), since this turbine is described in detail in public literature and reflects the current state of the art for wind turbine technology. For Sedini wind farm, GE 1.5 MW installed turbines are the reference turbines.

Furthermore, a set of simulation scenarios have been defined following a formal verification and validation (V&V) framework originally developed by Sandia National Laboratory and a decision tree. The definition of the simulation scenarios will provide the framework guidelines that will enable reference cases to be defined by inputs/outputs, variables and evaluation metrics, for a common analysis and accurate comparisons between the different models and control strategies.

# 2 INTRODUCTION

Wind farm control is an active field of research that aims at improving the performance of the wind plant as a whole, through coordinated control of the operation of individual turbines within the wind farm. Wind farm control has the possibility to improve the overall performance of the farm as a whole, instead of just the performance of each individual turbine, in terms of annual energy production, life, and O&M cost, aimed at minimizing levelized cost of energy (LCoE) of wind.

Advances in technology and innovations in the field of wind energy have been possible through the introduction of advanced computing methods that allow the modelling of the wind field, of the wind turbine aerodynamics and their interaction. The simulation of the wind energy conversion process for both single wind turbines and wind farms requires complex mathematical models whose fidelity needs to be validated and parameters must be calibrated to maximize their accuracy.

Scaled testing driven in a wind tunnel does not replace simulation nor real field testing on a wind farm, but works in synergy with both towards the goal of delivering validated and calibrated simulation models and advanced control algorithms.

The definition of several reference wind farms, from very simple layouts to a large complex one, including a real wind farm, sets up a common framework for the validation, comparison and parameterization of all the models and control strategies.

Furthermore, different simulation environments or scenarios covering the requirements for successful verification of the models and the control concepts have been defined. This brings the opportunity to compare the expected results from the different engineering and higher-fidelity models, against highly detailed CFD simulations by SOWFA, wind tunnel test data and wind farm field test data.

# 3 DEFINITION OF THE REFERENCE WIND FARMS

## 3.1 Methodology followed for the definition

Any control development or its related design model needs to demonstrate its performance. The validation of the wind farm models is based on three levels: high-fidelity CFD simulations conducted with SOWFA, experiments in the wind tunnel, and experiments using the Sedini wind farm. The performance of the control methods developed in WP2 (Wind farm flow control technologies and algorithms), will be demonstrated in increasing levels of practical complexity in CL-Windcon.

In the reference wind farm definition process, a questionnaire was used in order to provide an overview of possible layouts and desired layouts of the different partners, taking into account the aim of using each layout, whether it is hypothetical or represents an existing wind farm, as well as information like the turbine type, availability of the data, existence of a reference wind turbine controller and the type of terrain. Further discussion on the survey results was done through multiple meetings among partners. The definition of the reference wind farms is essential to ensure a high degree of comparability between the different models, control technologies and algorithms to optimize the performance of wind farms.

Two minimal layouts have been defined, with three turbines and nine turbines respectively. The aim of these layouts with few wind turbines is to allow faster detailed simulations with SOWFA, being able to simulate different scenarios without excessive computational effort. These simple layouts will also allow analysing strengths and weaknesses of current models and algorithms and assessing the sensitivity of the parameters. The offshore layout, with more wind turbines, focuses on physical phenomena and effects which only emerge inside large wind farms with multiple overlapping wakes. It also allows assessing the scalability of the control algorithms, and gives a practical quantification of the potential gains in existing large-scale wind farms. Due to the size and complexity of the layout of this windfarm, only the most promising of the simulation scenarios will be chosen for this case.

Wind tunnel testing cannot exactly reproduce full-scale conditions and is no substitute for field-testing, but experiments in the wind tunnel nevertheless play an important role in the validation and tuning of the models and control strategies as they offer the possibility to control the boundary conditions as well as the inflow.

Although study of existing commercial wind farms is often difficult for researchers due to data confidentiality, during this project, experiments are going to be performed in Sedini wind farm giving all the partners the possibility to work together on common datasets.

## 3.2 Three turbine case

### 3.2.1 Turbines

It is interesting to study wind farms at scales likely to be common when the technologies developed by CL-Windcon are available and mature. It is also important that all turbine data is publicly available, in order to allow for replication of results, and further development on their basis. These criteria are met by the DTU 10 MW reference turbine, which was developed within the FP7 Project INNWIND. Its basic parameters are summarised by Table 1. A detailed description is given by Bak et al [1] and Deliverable 1.21 of FP7 Project INNWIND [2], and aeroelastic models are available at http://dtu-10mw-rwt.vindenergi.dtu.dk/.

**Table 1: Basic parameters of DTU 10 MW reference turbine**

| | |
|---|---|
| Wind regime | IEC Class 1A [3] |
| Rotor orientation | Clockwise, upwind |
| Control | Variable speed, collective pitch |
| Rated wind speed | 11.4 m/s |
| Rated power | 10 MW |
| Number of blades | 3 |
| Rotor diameter | 178.3 m |
| Hub height | 119 m |
| Maximum tip speed | 90 m/s |

Given the multi-fidelity modelling planned within WP1, the turbine characteristics will be adapted to the needs of the different modelling techniques, based on the reference characteristics given in [1] and [2]. Similarly, the turbine controllers will be modelled or implemented by partners to suit each specific turbine model. However, the following preliminary considerations are made here:

1. High-fidelity farm models using simplified turbine models will similarly use simplified turbine controller models, and will communicate directly with the farm controllers developed in WP2.

2. Farm models using aeroelastic turbine models based on FAST will share turbine model data with the farm model via the turbine controllers. Said controllers will communicate with FAST via the standard FAST interfaces, or similar *ad hoc* ones.

A publicly available basic turbine controller by DTU exists for the DTU 10 MW reference turbine, which is described by Deliverable 1.21 of FP7 Project INNWIND [4]. Said controller can be used in conjunction with aeroelastic models of the DTU 10 MW reference turbine. However, it neither provides the services needed for closed-loop farm control, nor is directly applicable to simplified turbine models. This makes the basic DTU controller difficult to use directly in the context of CL-Windcon.

Turbine-controller-level algorithms will be developed in WP2, the aim of which will be to provide the necessary means for the farm-level controllers also developed in WP2 to derate individual turbines, misalign their yaw angle, activate/deactivate their IPC or use their operational data for farm control. This may require a considerable departure from the basic DTU controller and adaptations thereof. Therefore, reference turbine controllers compatible with WP2 developments and WP3 simulation implementations will be used.

### 3.2.2 Coordinates

The farm coordinate system shall be oriented so that the x axis is perpendicular to the row direction, the z axis points upwards and the y axis coincides with the row direction.

The position of each turbine is given by the position of the origin of its tower coordinate system, as specified by DNVGL-ST-0437. [5]

The origin of the farm coordinate system is located so as to coincide with the origin of the tower coordinate system of the turbine located at the smallest farm coordinate x. If more than one location complies with this criterion, that turbine with the smallest farm coordinate y shall be chosen amongst them. Coordinates are shown in APPENDIX A: LAYOUT COORDINATES, Table 6.

### 3.2.3 Layout

A reasonable layout for a three turbine wind farm is on a line perpendicular to the predominant wind direction. This minimises wake interactions. When wind directions perpendicular to the predominant one are unlikely, it is also reasonable to install turbines as close together as possible, with a spacing of 1 rotor diameter (D) the absolute lower limit, and one of 2 to 5 D more typical, as shown by Figure 1. Said spacing is larger as wind direction variability increases. Since we are here interested in wake interactions, we will consider the wind direction to be rather variable. Therefore, a spacing of 5 D seems most typical.

Wake interactions occur in our three turbine farm when wind direction is close to the turbine line, i.e. perpendicular to the predominant wind direction. The probability of this is site-dependent, and we have chosen turbine spacing in accordance with a site in which said probability is large. Indeed, it is in such winds that we are interested in analysing our farm's dynamic behaviour. However, all three turbines lying on the same straight line results, when wind flows along said line, in perfect wake overlap, In order to be able to simulate and test wider range of wake overlaps with a moderate number of scenarios and with reasonably simple engineering models, our three turbine farm is laid out as shown by Figure 2, i.e. with one of the turbines 0.5 D out of line with the other two. This means that within a single scenario in which wind direction is perpendicular to the predominant one, the wake of the first turbine overlaps the rotor of the second, while both their wakes overlap only half of the rotor of the third turbine, as shown by Figure 3.

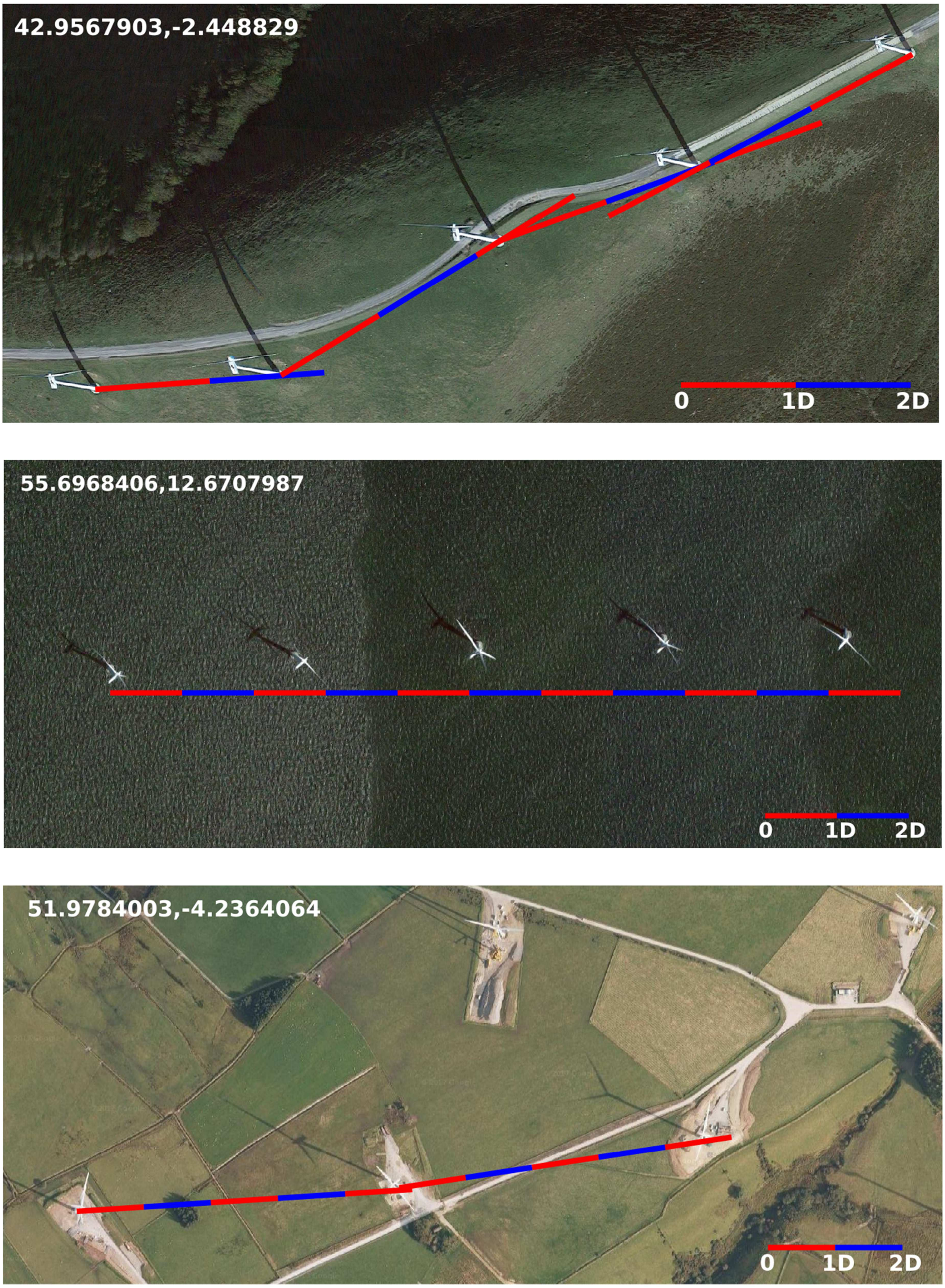

**Figure 1: Wind turbine spacing at three different European wind farms.**

**Geographical coordinates given at the upper left corner.**

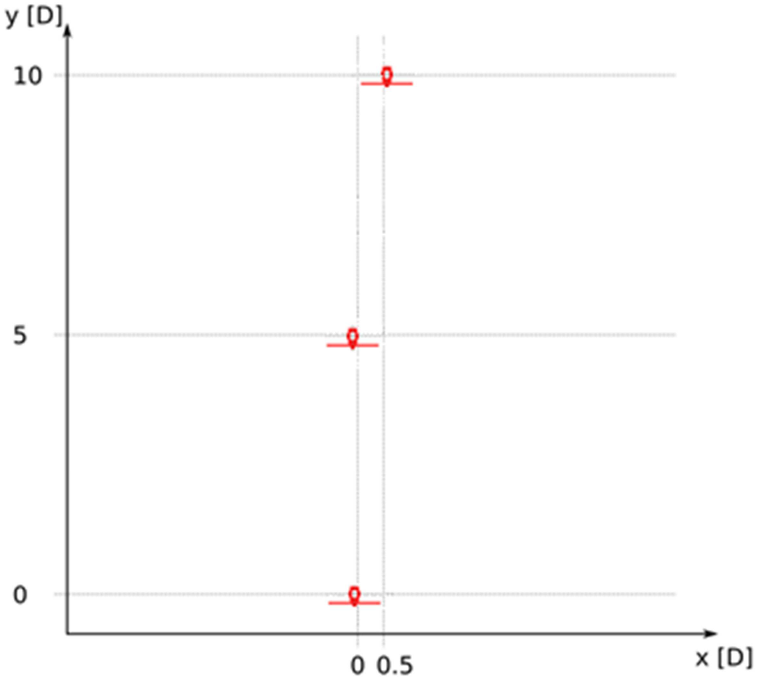

**Figure 2: Three turbine farm layout.**

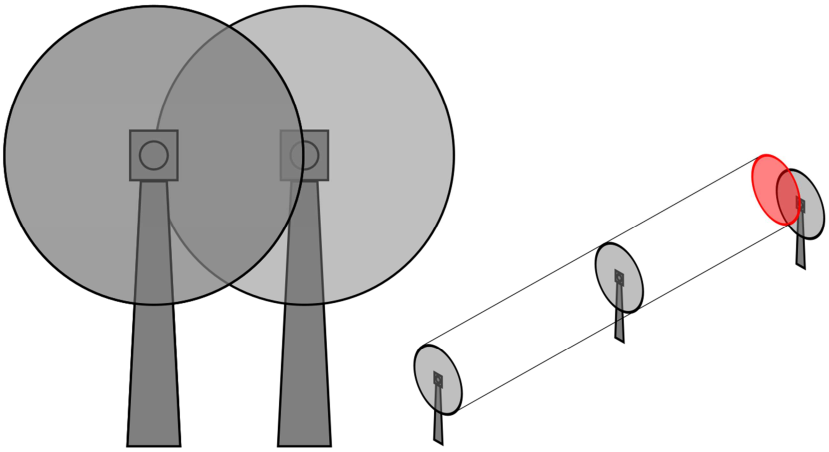

**Figure 3: Wake overlap at three turbine farm when wind direction coincides with the row direction.**

## 3.3 Nine turbine case

### 3.3.1 Turbines

Refer to section 3.2.1.

### 3.3.2 Coordinates

Refer to section 3.2.2.

Coordinates shown in APPENDIX A: LAYOUT COORDINATES, Table 7.

### 3.3.3 Layout

A line perpendicular to the predominant wind direction is as reasonable a layout for a nine turbine farm as for a three turbine one. However, we are interested in stacked rows of turbines, which are common on flat terrain and offshore farms. Figure 4 shows four turbines at one such farm.

Therefore, our nine turbine farm layout is as shown by Figure 5. Turbines are arranged in three lines of three turbines each, perpendicular to the predominant wind direction. Within each of said lines, turbines are separated by 5 D, whereas the distance between rows is 7D.

With this farm layout, wake interactions are already relevant in winds flowing in the predominant direction, since wake overlap occurs on each of the three rows, as shown by Figure 6. Partial overlap occurs as wind deviates from its predominant direction.

**Figure 4: Wind turbine layout and spacing at a European wind farm. Geographical coordinates given at the upper left corner.**

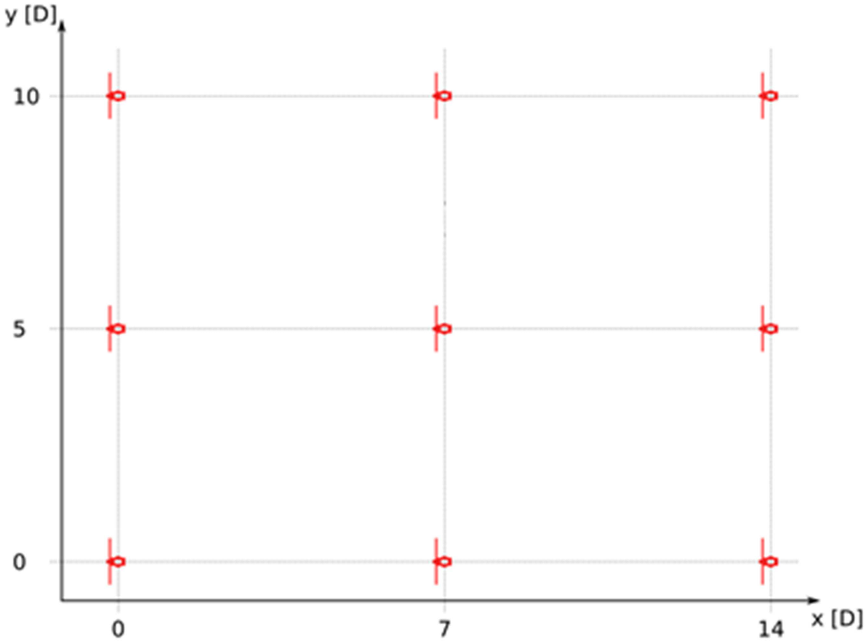

Figure 5: Nine turbine farm layout

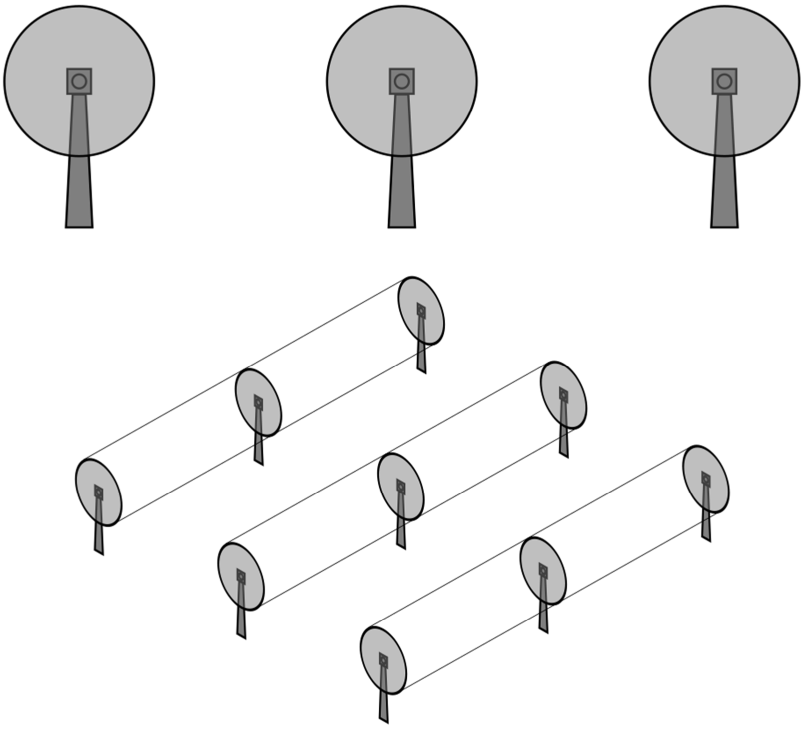

Figure 6: Wake overlap at nine turbine farm in wind in predominant direction

## 3.4 Offshore case

A fictitious, but realistic reference wind farm, has been selected for the offshore case: the Norcowe offshore reference wind farm (RWF), developed in the Norwegian project Norcowe (http://norcowe.no/) funded by Norwegian Centre for Offshore Wind Energy (NORCOWE) under grant 193821/S60 from Research Council of Norway (RCN). NORCOWE is a consortium with partners from industry and science, among them CL-Windcon partner AAU (Aalborg University), hosted by Christian Michelsen Research. The wind farm has a webpage of its own https://rwf.computing.uni.no/.

Norcowe RWF is sited in the vicinity of Fino 3 met mast , some eighty kilometres west of the island of Sylt in Schleswig-Holstein, Germany, near the Danish-German border. Norcowe RWF definition is aligned with IEA Wind Task 37 Wind Energy Systems Engineering: Integrated RD&D (https://www.ieawind.org/), where reference wind farms are a very important topic as they will allow researchers and industry to collaborate to improve and benchmark wind plant design tools. [6]

### 3.4.1 Turbines

Refer to section 3.2.1.

### 3.4.2 Coordinates

The position of each turbine is given by the position of the origin of its tower coordinate system, as specified by DNVGL-ST-0437.

The origin of the farm coordinate system is located so as to coincide with the farm centroid, between turbine 39 and turbine 44.

Coordinates of the locations of the turbines and the substations are shown in APPENDIX A: LAYOUT COORDINATES, Table 8: Norcowe RWF baseline rectilinear layout installation locations.

### 3.4.3 Layout

The wind farm layout comprises a set of eighty wind turbines and a grid connection involving two substations (locations 26 and 61 in Figure 8) and two HVAC links to shore. Mean water depth at the site is 23 m, and the substrate is sand with some gravel and silt constituents. Turbine foundations are monopiles.

Turbines are set in five rows: one row with 12 turbines, one row with 14 turbines and three rows with 18 turbines. Distance between rows is 8 rotor diameters (D) and between turbines it is 7 rotor diameters (D).

Fino 3 met mast was installed in 2009, so met-ocean measurements are available over a number of years with which to validate and calibrate model climatology.

The layout geometry has been derived from the Fino 3 wind rose shown below, but information on the variation of mean water depth and substrate in the vicinity of the met station is deliberately ignored in the layout design to avoid it dominating the design.

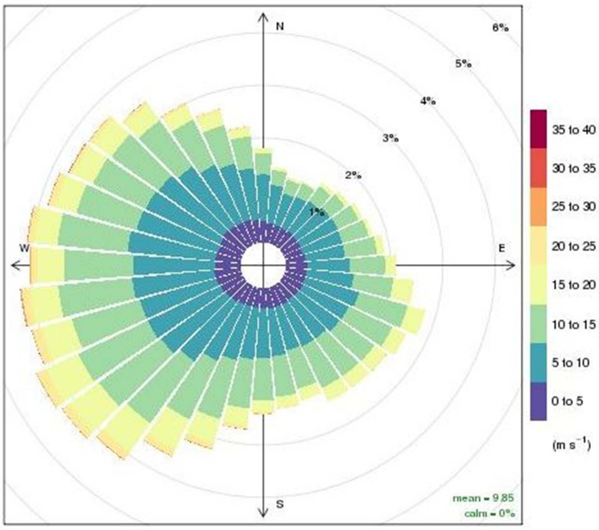

**Figure 7: Fino 3 wind rose**

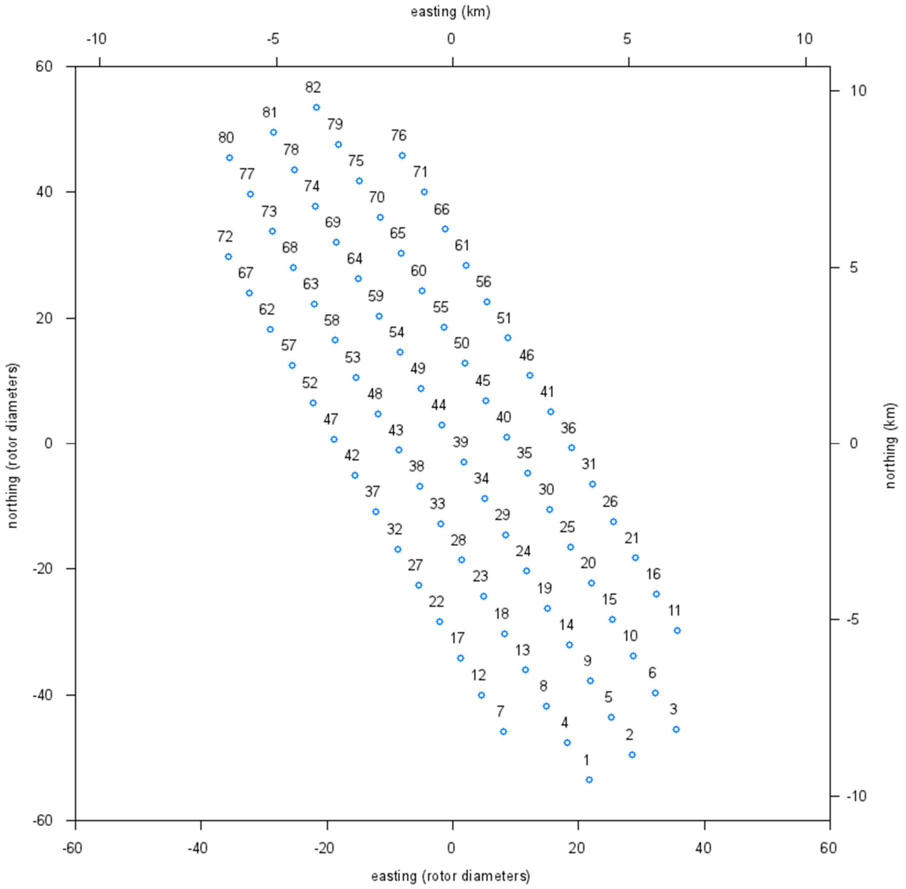

**Figure 8: Norcowe RWF rectilinear layout**

## 3.5 Sedini windfarm case

During the second and third year of the project, full-scale wake experiments will be performed at an existing wind farm on configurations of several wind turbines.

The experiment will obtain loads and farm inflow measurements at high resolution spatially and temporally, to characterize and validate dynamic open-loop wake-deficit and wake-deflection models. The software orchestrating the experiment will command changes in turbine set-points in response to measured flow conditions, so that wake propagation within the cluster can be actively modified. The range of set-points will be predefined and varied as a function of wind speed and wind direction, in the form of lookup tables, to cover the necessary modelling space with adequate number of occurrences. A wind farm control trial is also considered.

The candidate site for the field experiment is Enel Green Power´s Sedini wind farm located in the island of Sardinia, Italy.

The wind farm was developed in two phases. First phase is constituted by 36 GE 1.5s wind turbines with a rotor diameter of 70.5 metres and 1.5MW. Second phase is constituted by 7 GE 1.5sle wind turbines with a rotor diameter of 77 metres and 1.5MW.

A selected sub-cluster of several wind turbines manufactured by General Electric, with nominal power of 1.5MW will be used.

### 3.5.1 Turbines

The GE 1.5 MW has been for years one of the world's most widely used wind turbines in its class.

The 1.5 MW machine is active yaw and pitch regulated with power/torque control capability and an asynchronous generator.

With different hub heights and rotor diameters, the 1.5 MW wind turbine is both versatile and adaptable, and has proven itself in a wide variety of wind energy sites around the world.

1.5 MW turbine features efficient and reliable variable speed control. This feature enables the turbines’ control system to continually adjust the rotor rpm level for optimum thrust at each wind speed – allowing the wind turbine to continually operate at its highest level of aerodynamic efficiency.

**Table 2: Basic parameters GE1.5 s and GE 1.5 sle wind turbines**

| **Technical specifications** | **1.5s** | **1.5sle** |
|---|---|---|
| Rated capacity: | 1,500 kW | 1,500 kW |
| Cut-in wind speed: | 4 m/s | 3.5 m/s |
| Rated wind speed: | 13 m/s | 12 m/s |
| Number of rotor blades: | 3 | 3 |

| Technical specifications | 1.5s | 1.5sle |
|---|---|---|
| Rotor diameter: | 70.5 m | 77 m |
| Swept area: | 3,904 m2 | 4,657 m2 |
| Hub height (m): | 64.7 | 80 |
| Power control: | Active blade pitch control | Active blade pitch control |

### 3.5.2 Site overview

Sedini site is located in the island of Sardinia, Italy. The mistral from the northwest is the dominant wind on and off throughout the year, though it is most prevalent in winter and spring.

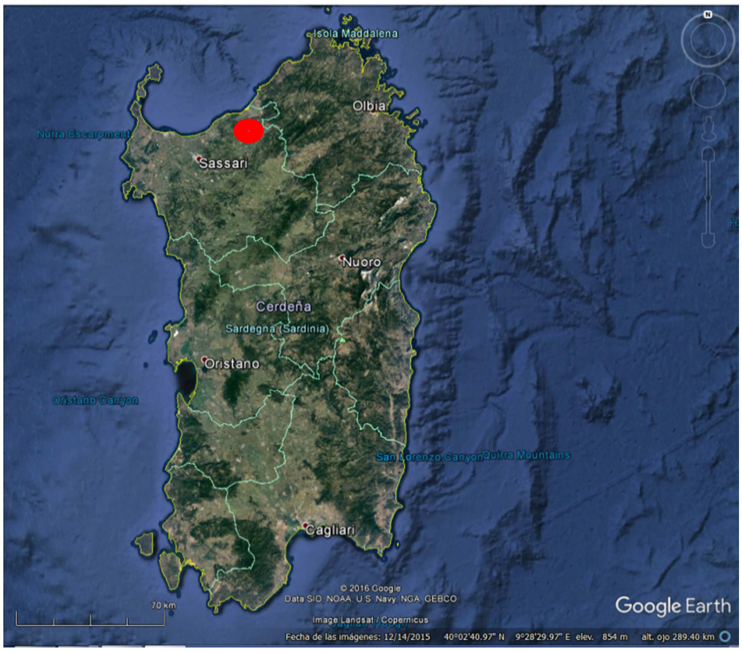

Figure 9: General location of Sedini windfarm in the island of Sardinia

The wind farm area is located 4 km west from Sedini.

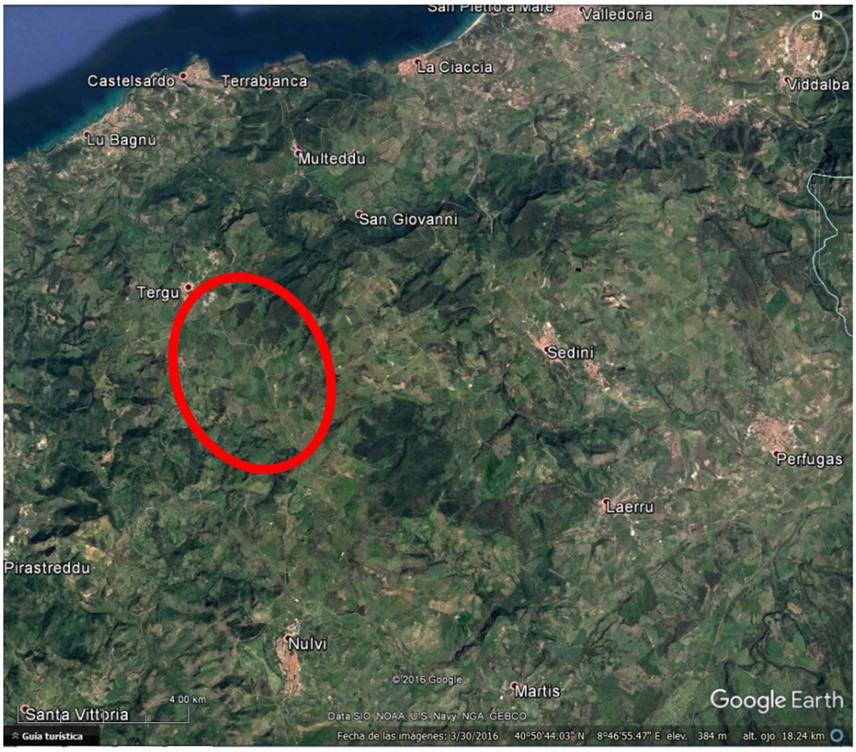

**Figure 10: Location of Sedini windfarm**

Sedini wind farm is located in a relatively flat area with an average elevation between 360 and 400 m above sea level (a.s.l.) surrounded by several hills (between 400 and 450m a.s.l.). The site vegetation consists of scrub and clear areas.

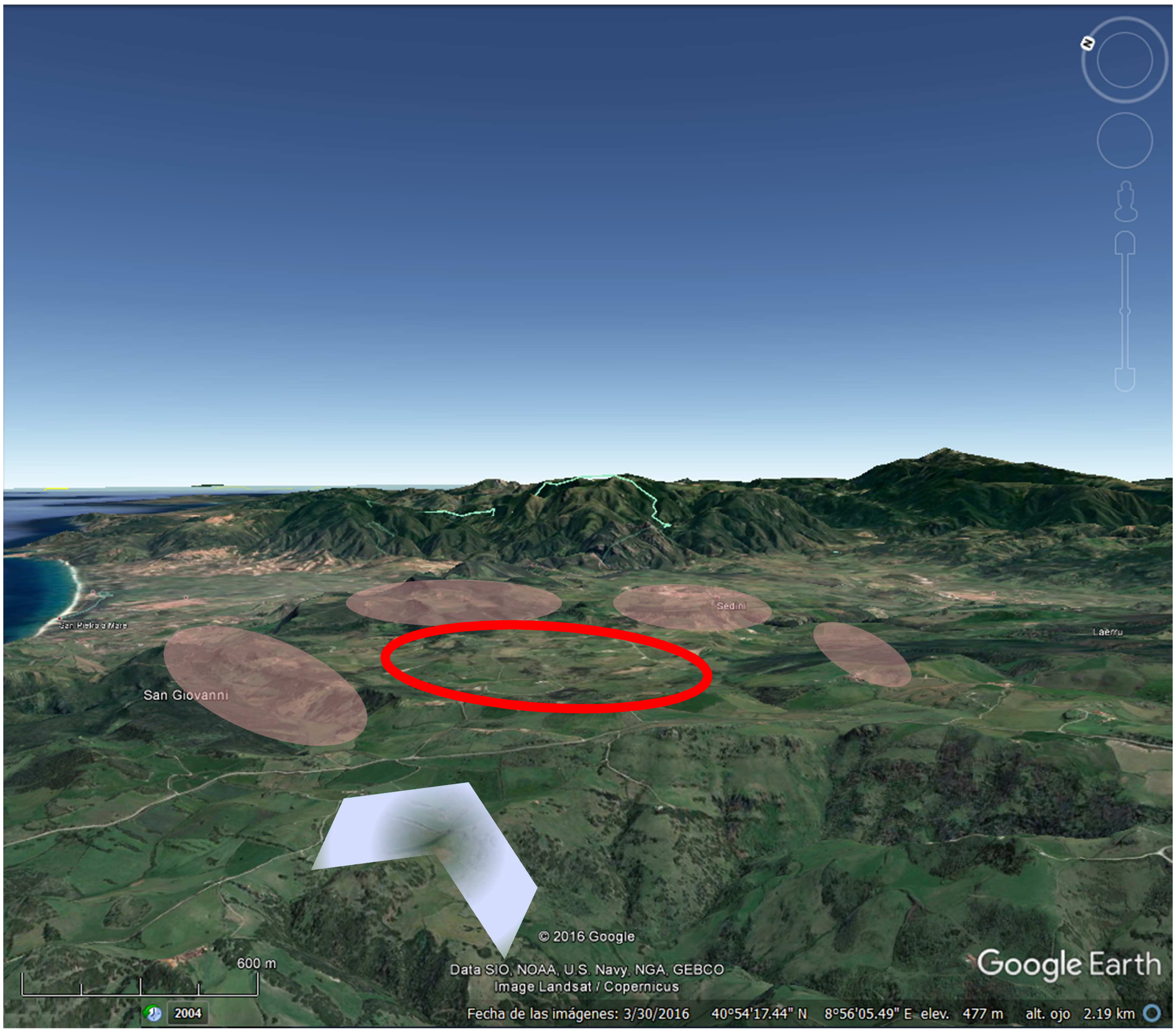

**Figure 11: Sedini windfarm, surrounding hills and predominant wind**

### 3.5.3 Layout

The 43 GE 1.5 wind turbines are not aligned in regular rows. They are placed in an area keeping an irregular distance between turbines. This layout offers many different scenarios to study the turbines in different sub-clusters of several wind turbines depending on the proposed test.

Figure 12: Sedini windfarm. Photo credit: Enel Green Power

## 3.6 Wind tunnel

The Polimi wind tunnel, shown in Figure 13, or GVPM (*Galleria del Vento* of *Politecnico di Milano*) is a special closed-circuit wind tunnel, arranged in a vertical layout with two test rooms located on the opposite sides of the loop. The first one is located in the lower part of the loop and is suitable for Low Turbulence tests. The second one, bigger, is located in the upper part of the loop and is intended for civil engineering testing (the Boundary Layer Test Section). Due to this unique feature, GVPM offers the widest possible range of test arrangements. The facility is powered by a flow generator array of 14 1.8m diameter, 100kW fans, for a total power of 1.4 MW. The fans are organized in two rows of seven 2x2m independent cells. Independent inverters drive the fans allowing for continuous control of the rotation speed of each fan to obtain the desired wind speed in the test section.

After the fans two corners fitted with vanes conducts the flow to the upper level of the facility in the opposite direction. The flow is cooled by a heat exchanger that is placed just downstream of bend number 2 and, after a grid, enters the boundary layer test section. A second set of two corners fitted with vanes conducts the flow back to the lower level where, after 2 meters long settling chamber, it passes a honeycomb screen and a set of three wire nets with different porosity to reduce axial and lateral turbulence and to promote a more uniform axial flow. A two-dimensional contraction cone with area ratio 3.46:1 reduces the duct section to fit the low turbulence test section size. Finally, a short diffuser expands the duct section back to the fans array size. Table 1 summarizes the GVPM main characteristics.

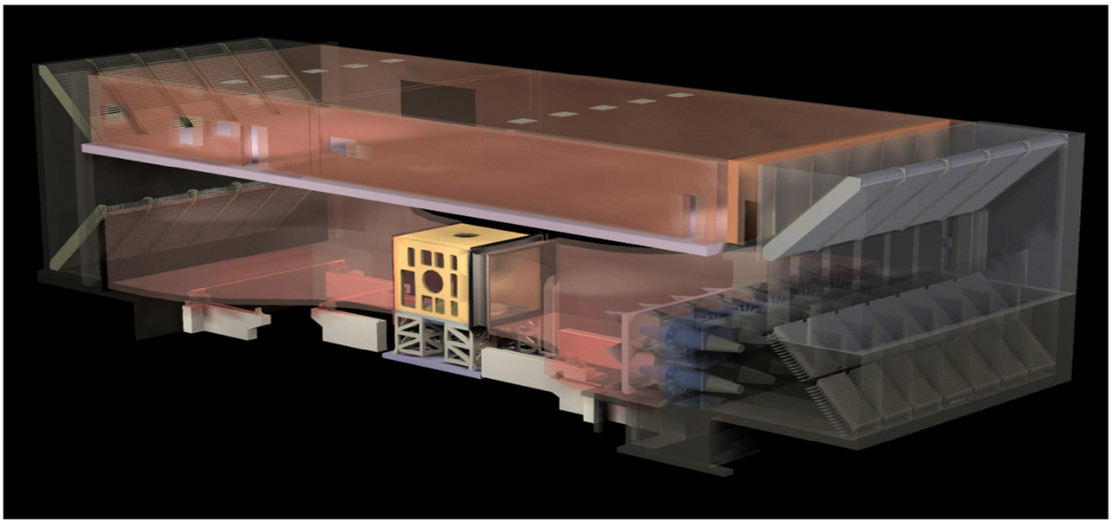

Figure 13: Overview of the flow circuit

Table 3: Plant characteristics

| **Politecnico di Milano Wind Tunnel**<br>**Tunnel Overall Dimensions: 50x15x15 (m)**<br>**Maximum Power (Fans only): 1.5 (MW)** | | | | |
|---|---|---|---|---|
| **Test Section** | **Size (m)** | **Max Speed (m/s)** | **ΔU/U (%)** | **Turb. Int. Iu (%)** |
| Boundary Layer | 14x4 | 16 | < ±3 | <2<br>Up to 35 % for ABL condition |
| Low Turbulence | 4x4 | 55 | < ±0.2 | <0.1 |

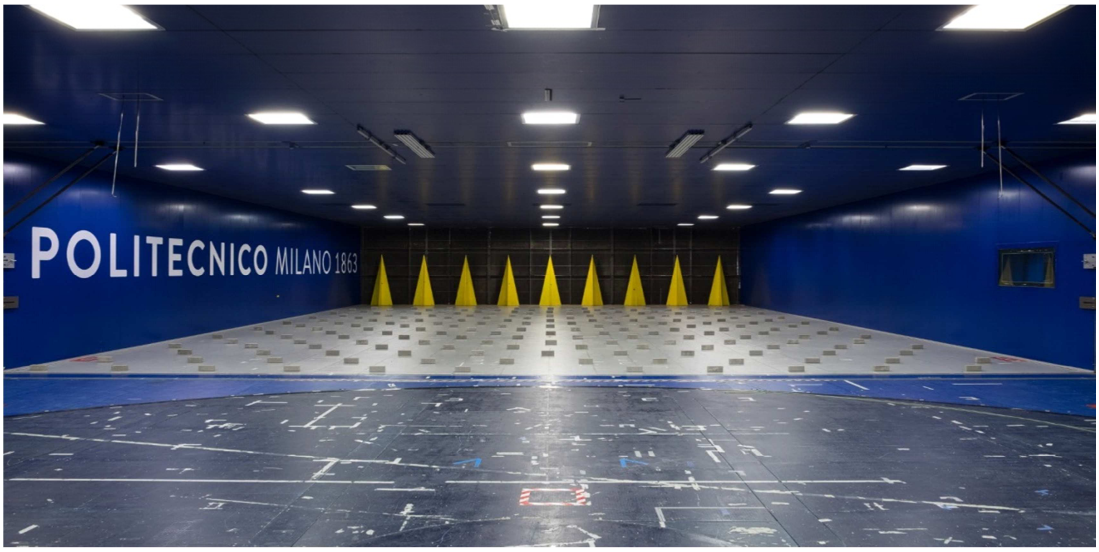

**Figure 14: The boundary layer low-speed test section used for civil and environmental applications. View of the large turntable (diameter 13.5m).**

The CL-Windcon wind tunnel tests are going to be performed in the upper leg of the wind tunnel loop that hosts the large Boundary Layer Test Section. The 35m long, constant section test chamber enables the setting up of passive turbulence generators to simulate the atmospheric boundary layer. Several layouts of spires and floor roughness elements makes possible to reproduce different terrain roughness length categories in a wide range of geometric length model scales. Figure 14 shows an example of a possible arrangement which employs both spires and bricks in order to recreate specific boundary layer characteristics. The model, together with the related environment, is generally set up on a 13m diameter turntable, included in the wind tunnel floor, allowing an easy wind misalignment angle change. A floating floor allows for a clean model set-up, leaving all the instrumentation cable connections out of the flow.

The different typologies of the flow which can be obtained in the wind tunnel, along with the measurement instrumentation connected with the facility itself, are fully and extensively described in the CL-Windcon Deliverable D3.1 - Definition of wind tunnel testing conditions.

# 4 DEFINITION OF THE SIMULATION SCENARIOS

## 4.1 Methodology

The definition of the simulation scenarios will provide the framework guidelines that will enable reference cases to be defined by input/outputs, variables and evaluation metrics, for a common analysis and accurate comparisons among the different models and control strategies.

The purpose of the definition of the simulation scenarios is to provide guidance on the development and execution of a highly integrated modelling and experimental research activity based on well-established verification and validation (V&V) [7] practices adapted to the development of tools for wind farm dynamic modelling and control.

The formal V&V framework adopted here comes from Sandia National Laboratories. A recent review (Hills et al. [8]) has been published in the frame of the Atmosphere to Electrons (A2e) wind energy research program, based on existing V&V methodologies developed by various American organizations including DoE, NASA, AIAA and ASME (AIAA [9]; ASME [10]; Oberkampf et al. [11]; Pitch et al. [12]; Trucano et al. [13]). The framework is also adopted in the frame of the IEA Task 31 WAKEBENCH: Benchmarking Wind Farm Flow Models (http://windbench.net/wakebench2; https://www.ieawind.org/) to establish a model evaluation protocol for wind farm flow models (Sanz Rodrigo and Moriarty, 2015 [14]) and also applied to the New European Wind Atlas (NEWA) ERA-NET plus project (http://euwindatlas.eu/).

Given the different nature of modelling tools and control strategies, they are addressed separately in the following sections.

## 4.2 Model validation

**Verification** is defined in DoD (1996) [15] and modified slightly in AAIA (1998) as the process of determining that the model implementation accurately represents the developer's conceptual description of the model and the solution of the model. Here accuracy is measured with respect to high-fidelity CFD simulations conducted with SOWFA.

In contrast, the AIAA (1998) defines **validation** as the process of determining the degree to which the model is an accurate representation of the real world from the perspective of the intended uses of the model. Here accuracy is measured first with respect to experiments conducted in the wind tunnel and later to observational data from the experimental wind farm, with the objective of providing evidence of the model suitability.

The planning process shown in the top panel of Figure 15, extracted from Hills et al. (2015) is composed of four steps:

1. Define the objective or objectives of the model in precise terms in order to know what is expected from the model and which the predicted quantities of interest from the perspective of the intended use (application) are.
2. Identify the physics and non-physics based phenomena that are important to represent the model and prioritize them according to the capability of the model to represent such phenomena.
3. Define a validation hierarchy that will allow assessing the model performance for the prioritized phenomena.
4. Plan model validation experiments to generate experimental datasets for the validation hierarchy based on how the limited resources can be used most effectively to assess predictability for those issues that are of concern.

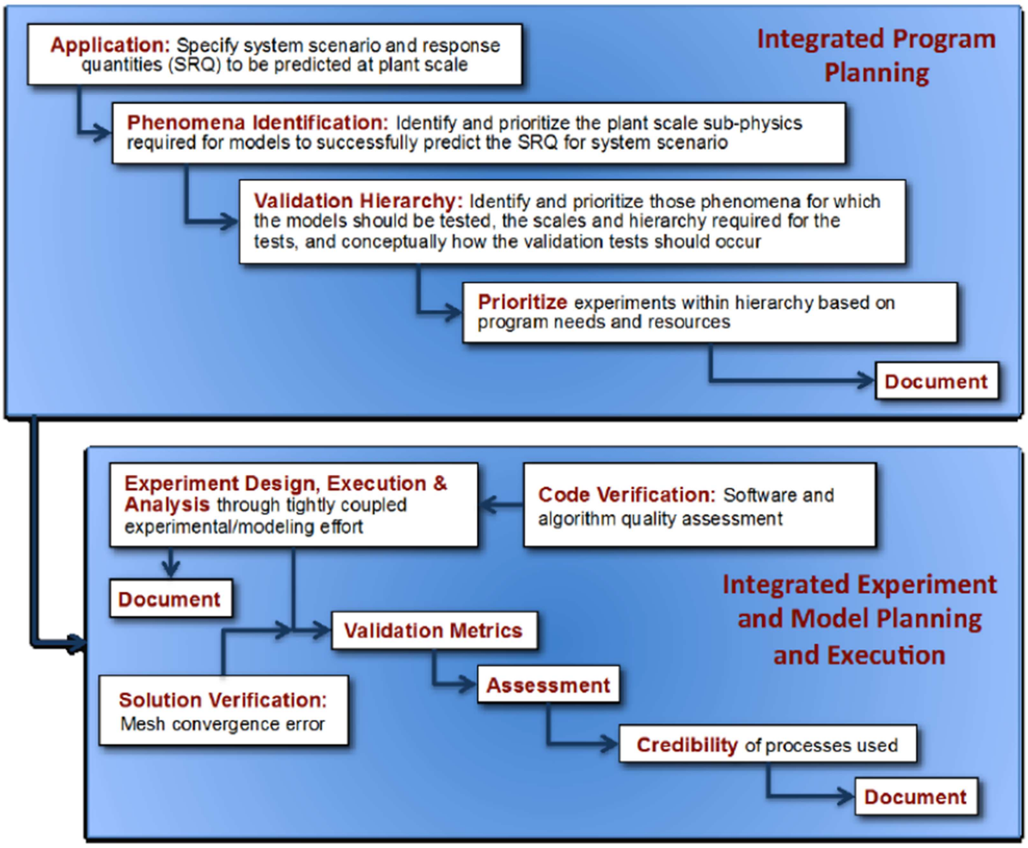

**Figure 15: Validated directed program planning and execution (Hills et al.2015)**

The planning resulting from this analysis are the simulation cases. The planning should be revised during the project and adapted to include the outcome of each experiment in the wind tunnel and the experimental wind farm.

The lower panel of Figure 15 shows the process of experiment design, execution and validation activities that lead to the model assessment and demonstration and validation of prototypes by wind tunnel testing and full scale testing. Measured data from the wind tunnel and from Sedini wind farm is needed for the validation of the basic flow modelling. The detailed approach for such experiments is addressed in-depth in the corresponding deliverables within WP3- Demonstration and Validation of Prototypes: D3.1- Definition of wind tunnel testing conditions, and D3.2- Definition of field-testing conditions.

## 4.3 Control verification

Control verification deals with analysing the performance and impact of a control strategy. In the same way as in model validation, different steps are necessary for a controller verification.

1. Define the objective or objectives of the controller in precise terms in order to know what is expected from the controller and which quantities the controller intends to manipulate.
2. Define an objective hierarchy that will allow assessing the controller performance for the prioritized specifications.
3. Plan and perform idealized controller verification experiments to generate experimental datasets for the verification hierarchy based on how the limited resources can be used most effectively to assess predictability for those issues that are of concern. The experiments should be designed in a way to isolate the performance of the controller on the objective(s).
4. Based on the results of the idealized performance analysis, plan and perform realistic controller verification experiments to generate experimental datasets for the verification hierarchy based on how the limited resources can be used most effectively to assess predictability for those issues that are of concern.

The different control fields in CL-Windcon are separated in use cases. They basically define the framework in which the controller verification is performed. In section 4.4, a set of use cases is presented. They give assistance in planning the experiments in terms of stating the main influence of the controller and its main goal. A decision tree is used to find the relevant conditions and use best the limited resources for step 3 and for the controller verification.

### 4.3.1 Exemplary process of a controller verification: closed-loop wake redirection

Wake redirection is one of the key wind farm control methods which will be investigated in CL-Windcon. The idea is to minimize or avoid wake impingement on downwind wind turbines by redirecting the wake of a wind turbine using the yaw actuator. The method has shown success in increasing the total power output of a simulated wind farm by applying optimized yaw angles in a feedforward controller, which were precomputed beforehand with an engineering wake model.

Although the method has performed well, there are disadvantages in the approach since the method does not cover model uncertainties and cannot react to disturbances. Therefore, closed-loop wake redirection is suggested in which a feedback of the wake position is used in a feedback controller to redirect the wake to the desired position. In the following, the process of controller verification and performance evaluation of such a control approach is described according to the general description of section 4.3.

1. Objectives of the controller: the controller is redirecting the wake in a closed-loop approach to a desired position.
2. Measure of control performance: The measure of the controller is the bandwidth and performance in terms of disturbance attenuation.
3. Plan and perform idealized controller verification experiments:
    a. Step responses in reduced order simulation models (e.g. 2D flow model) with different constant inflow wind speed conditions (see Figure 16)
    b. Frequency assessment of the performance measures of the controller (sensitivity, complementary sensitivity and controller sensitivity)
4. Based on the results of the idealized performance analysis, plan and perform realistic controller verification experiments:
    a. Step responses in realistic simulation model with different constant inflow wind speed conditions
    b. Step responses in realistic simulation model with different mean wind speeds and different atmospheric conditions

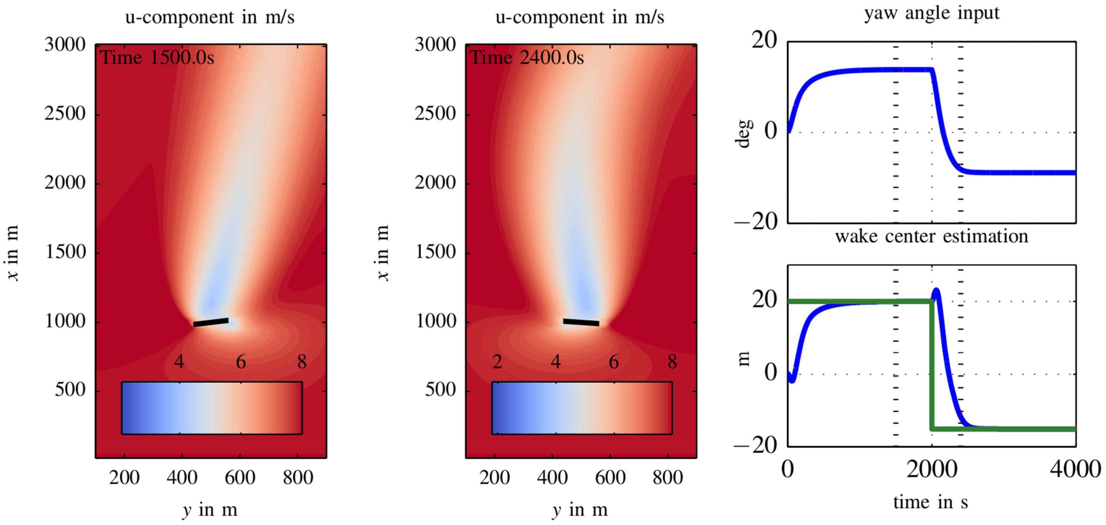

**Figure 16: Simulation results of the closed-loop simulations in a reduced order 2D flow model.**

**The flow snapshots are from 1500s and from 2400s, which is also indicated in the time series results (dotted lines). The time series shows the yaw angle and the estimated wake centre. The desired wake centre set points are shown in green.**

## 4.4 Use cases

Due to the inherent complexity to define the simulation scenarios for use cases, only model validation and control verification are at this point defined. For the comparison of models to wind tunnel, wind tunnel setup/model will drive definition of the corresponding simulations and is fully and extensively described in the corresponding deliverable within WP3- Demonstration and Validation of Prototypes: D3.1- Definition of wind tunnel testing conditions. For the comparison of models versus field data, the approach for the experiments is addressed in the corresponding deliverable within WP3- Demonstration and Validation of Prototypes, namely D3.2- Definition of field-testing conditions.

Conducting a complete full-system model validation and control verification is really challenging due to the large variety of models, control approaches, and objectives in CL-Windcon.

For the model validation and control verification, a set of validation or use cases should be defined in order to test the phenomena for the application of interest.

In order to define the simulation scenarios all participants were asked to provide a description of the use cases with the following format:

1. **Aim of the use case:** The main goal of the use case drives its definition and adoption, setting the objective to be verified, validated or analysed.
2. **Wind farm layouts:** From the set of defined wind farm layouts in section 3, those of application in correspondence to the use case aim are selected.
3. **Ambient conditions:** Depending on the objective pursued by the use case, different ambient conditions are chosen, focusing on those having higher expected effects. These ambient conditions cover the range of wind speeds, wind directions, turbulence intensity or atmospheric stability.
4. **Required fidelity and time for the simulation:** Depending on the objective of the use case, different levels of fidelity may be required so that the main phenomena are sufficiently represented and also making the best use of resources as explain in sections 4.1 to 4.3.
5. **Control inputs (if applicable):** In the case of control verification use cases, one important aspect is the set of control inputs necessary to depict the controller performance.
6. **Evaluation metrics:** According to the use case aim, different sets of variables will be measured and analysed.

After a first round of responses from CL-Windcon participants, results were homogenized to come up with a first draft of the most important aspects to cover. This process will be iterative as far as research advances and is expected to lead to a reasonable level of consensus across the project. Therefore, although definition of the most important aspects must be ensured, they are open to future changes according to the research results.

For model validation we are looking mostly at cases to compare lower fidelity models against each other and to SOWFA, and for control verification, the model fidelity should be chosen according to the aspects of the control strategy to be verified and thus somewhat depends on the results of the model validation. In both cases, the following aspects would be taken into account.

- Wind farm layouts: the three turbine case and the nine turbine case are simple layouts where, in terms of control, the flow corresponding to the farm will be the simplest to model and also increases the chance of successful control/optimization. While the first two layouts are theoretical (idealized) topologies used for development, Norcowe RWF is used to really show the power of the control method on a large-scale wind farm. These simulations will show the scalability of the control algorithm. Sedini wind farm is chosen for a priori analysis of potential difficulties in the real-life wind farm control tests and will allow verifying the ability to work with noisy measurements of the environment, delays and transients in wind conditions and speeds.
- Wind speed: it is important to assess its potential over a wide range. From lower end of variable rotor speed, middle of variable rotor speed until close to the rated power. In some cases like yaw redirection control, even above-rated speed is an interesting ambient condition since it can be used both for power optimization and/or load minimization.
- Range of atmospheric conditions (stable, neutral and unstable) with corresponding typical wind shear and turbulence intensity. According to recent studies [16], some control strategies have the best chance of succeeding under low TI and a neutral ABL, but different stabilities and turbulence intensities will be studied.
- Range of wind direction from the worst case scenario, were as many wakes are overlapping as possible, to positive and negative variance (less critical situations). Uncertainty in wind direction will have a large impact on the results of control strategies like yaw control, which is very sensitive to the ambient wind direction, especially its effect on loads.
- Validation of the change of wake characteristics and turbine performance and rotor thrust as function of turbine operation (rotor induction set point, TSR, positive and negative yaw offset).
- The evaluation metrics to use depend on the model and the control strategy, some of them being ambient wind direction and speed, turbulence intensity, current turbine settings (TSR, blade pitch angles, yaw, generator torque, power set-point, true generated power), magnitude,

shape, position and decay of wake velocity deficits, turbine power output and rotor thrust/loads, etc.

On the basis of the gathered information, the following aggregated uses cases have been defined.

- **Use case #1 - Axial induction control**: generator torque and/or collective blade pitch is altered to optimize wake velocities. Some of the turbines within a farm will lower their energy capture by increasing their blade pitch angle or, equivalently, power de-rating. Reducing the axial induction upstream is expected to increase the wind velocity and reduce the turbulence downstream. This should increase the available energy while reducing mechanical loads.
- **Use case #2 - Yaw control**: yaw offsets redirect the wakes and steer them away from downstream turbines. Some of the turbines within a wind farm will redirect their wakes, by active yawing or harmonic pitching, to reduce the wake effects on other turbines further downstream.
- **Use case #3 - Wake mitigation techniques**: through small-amplitude high-frequency variations on the blade pitch angles, more turbulent structures are introduced by a turbine on the flow than in regular operation. These turbulent structures promote wake recovery, effectively reducing wake effects further downstream, without deteriorating performance for the operated turbine. Similar to axial induction control, this means a higher wind velocity in the wake, from which more power can be generated by downstream turbines than in the baseline scenario.
- **Use case #4 - Combination of axial induction control and yaw control**: since both methods work through different principles and on different control variables, the combination of the two should supersede the individual control methods.

In order to assess the benefits of the new control technology when applied on an industrial scale and to provide guidance on the implementation rationales, and taking into account the same aspects as in model validation and control performance verification, three more use cases have been defined:

- **Use case #5 - Energy production on turbine level**: expected energy production of each turbine in an array, in dependence of wind direction and wind speed (and, potentially turbulence intensity and atmospheric stability).
- **Use case #6 - Component loading**: expected loading of main components on each turbine in an array, in dependence of wind direction and wind speed (and, potentially turbulence intensity and atmospheric stability).
- **Use case #7 - Re-designed turbines**: expected energy production and expected loading of main components on each turbine in an array, for the redesigned turbines.

This use cases roadmap is subject to change throughout the project as more evidence is acquired from the model development and validation and verification activities.

Detailed information per use case is shown in subsequent Table 4 and Table 5.

Table 4: Use cases and simulation scenarios for controller performance verification

| USE CASE #1 – AXIAL INDUCTION CONTROL | |
|---|---|
| **Aim of the use case** | To assess the capabilities of one of the two major control methodologies currently considered for wind farm control, namely axial induction control. So far, literature has not been one-sided on the feasibility of axial induction control, so it will be essential to investigate whether and in what scenarios it can increase overall power production and/or reduce loads, and for which scenarios it cannot. |
| **Wind farm layouts** | • 3-turbine WF<br>This is a fairly simple layout, in which we can look at the individual turbine interactions in the farm. In terms of control, the flow corresponding to this farm will be the simplest to model, which also increases the chance of successful control/optimization. Recent insights have suggested that the benefits of axial induction control may only show 3-4 turbines down in the array; hence a 3-turbine array is the minimum size for this control method.<br>• 9-turbine WF<br>This is a step up from the single-array, three-turbine wind farm. By adding two rows of turbines, the modelling and control of the flow becomes more complicated. Namely, for varying wind directions, different turbines interact with each other, which is not the case for the 3-turbine case. Thus, this layout will allow in-depth performance assessment and give insights into the strong and weak points of the designed axial induction control strategies.<br>For the most promising strategies from above:<br>• Offshore WF<br>While the first two scenarios are theoretical (idealized) topologies used for development, this layout is used to really show the power of the control method on a large-scale wind farm. These simulations will show the scalability of the control algorithm. If successful, the results from these simulations will be really a selling point of the project.<br>• Sedini WF<br>This layout is chosen for a priori analysis of potential difficulties in the real-life wind farm control tests at Sedini like uncertainties in the wind flow , combination of atmospheric boundary layer with wakes and variations in flow characteristics under different conditions, and furthermore to allow forming a hypothesis on the expected results. The hypothesis may also be an upper performance limit to what can be truly achieved beyond simulations with idealized conditions and measurements without noise or delays. |

| USE CASE #1 – AXIAL INDUCTION CONTROL | | |
|---|---|---|
| | | |
| **Ambient conditions** | **Wind speeds** | ⇨ 3 wind speeds<br>Since it is still unclear in the scientific community under which conditions axial induction control is fully successful, it will be important to look at a range of ambient conditions, among which is wind speed. Three different values will be chosen. The initial hypothesis is that above-rated conditions are less interesting for axial induction control since turbines are already power-limited. Specific focus on loads performance can be brought in any case as it is interesting for optimisation of curtailment strategies to manage loading acroos the farm. |
| | **Wind directions** | ⇨ Range of different wind directions<br>The rationale behind the final choice can comply with the following:<br>The most closely examined wind direction should be such that as many wakes are overlapping as possible (the worst case scenario), since the largest improvements can be expected then. These wind directions initially should have little fluctuations so that an "optimal control" scenario can be defined. In a subsequent step, uncertain wind directions can be studied (e.g. with +- 5 degrees), to assess the robustness of the algorithms. Finally, a roll in wind direction, or a different wind direction altogether, may be interesting to explore in order to assess the potential gains of the control algorithms in less critical situations. |
| | **TI** | According to a recent papers [16], axial induction control has the best chance of succeeding under low TI and a neutral ABL, hence this will be a first hypothesis. However, conclusive high-fidelity simulation results are still needed to support this assumption. Depending on these simulations, study of higher TI values may be required. |
| | **Atmospheric stability** | ⇨ 2 different stabilities<br>Although stable conditions give rise to the lowest turbulence intensities, they will be avoided. Namely, a number of CFD studies show that, in a stable atmosphere, the wake will skew laterally. By contrast, and according to Gebraad P.M.O [17] , in an unstable atmosphere, vertical mixing makes wind direction shear nearly nonexistent, so this wake skewing effect is not present. Thus, the initial focus will be on neutral and unstable ABL stabilities. Subsequently, and as a check of the original assumption, stable ABL could be potentially examined too, but not for all the scenario combinations (wind speeds, directions, topologies). Rather, we just want to assess whether the lateral wake skewing deteriorates the control performance. |
| **Required fidelity and** | | Axial induction control heavily depends on the amount of wake recovery in the flow, and its relation to the uprating or |

| USE CASE #1 – AXIAL INDUCTION CONTROL | |
|---|---|
| **simulation time** | derating of the turbine. Hence, to model the smaller-scale turbulent structures, a high-fidelity rotor model should be employed, such as the Actuator Line Model (ALM) although lower-fidelity rotor models could be used to check if they give reasonable results in any situation. |
| **Control inputs (if applicable)** | The turbine should be de-rated, either through generator torque, blade pitch angles, or by setting a different power set-point. Finding the optimal method of de-rating is the objective of next deliverable D2.1- Minimal loading wind turbine de-rating strategy and active yaw controllers. |
| **Evaluation metrics** | Variables for control, depending on the model: ambient wind direction and speed, TI, flow density, generated power, current turbine settings (TSR, blade pitch angles, yaw, generator torque, power set-point, true generated power), flow measurements at assigned locations in the field, etc.<br>Variables for performance analysis: generated power, turbine loads, flow fields (in wakes). |

| USE CASE #2 – YAW CONTROL | |
|---|---|
| **Aim of the use case** | To assess the capabilities of the second of the two major current control methodologies in wind farm control, namely wake redirection control through yaw. So far, literature has indicated that this might be the more effective method of the two for farm control. Thus, investigation will be directed to determine whether, how much and in which scenarios it can increase power production and/or reduce loads. |
| **Wind farm layouts** | • 3-turbine WF<br>(See also explanation for use case #1). Although simple turbine to turbine interactions can be achieved with a 2-turbine wind farm, with high-fidelity results available in the literature, the additional turbine in this layout will improve the understanding of overlapping wakes. Besides, by using the same topology as for use case #1, comparison between the two control methods can be performed.<br>• 9-turbine WF<br>(See also explanation for use case #1). As for the 3-turbine wind farm, the application of the same layout as that used in axial induction control will allow comparison between both control technologies. Additionally, the consideration of 9 turbines will provide better comprehension of multiple wake overlaps when using wake |

| USE CASE #2 – YAW CONTROL | | |
|---|---|---|
| | | redirection control and in-depth performance assessment.<br>For the most promising strategies from above:<br>• Offshore WF<br>(See also explanation for use case #1). More realistic results are expected with this farm layout with the increasing complexity and scale.<br>• Sedini WF<br>(See also explanation for use case #1). This layout will allow consideration of real limitations in contrast with idealized conditions. |
| **Ambient conditions** | **Wind speeds** | ⇨ 3 wind speeds<br>A priori, yaw control is interesting over all wind speeds, both below- and above-rated, since it can be used both for power optimization and/or load minimization. |
| | **Wind directions** | ⇨ Range of different wind directions<br>(See also explanation for use case #1). Furthermore, for yaw control the uncertainty in wind direction is of primary importance, since this technique is very sensitive to the ambient wind direction, especially its effect on loads. |
| | **TI** | Successful SOWFA simulations for wake redirection control have already been performed under a low TI (6%) [18]. These conditions can be representative for offshore wind farms. Additionally, it is also interesting to look at higher TI values, to assess the strengths and limitations of the current approach and be able to extend the results to onshore wind farms. |
| | **Atmospheric stability** | ⇨ 2 different stabilities<br>See explanation for use case #1 |
| **Required fidelity and simulation time** | | Wake redirection control appears to be less sensitive to the turbine-induced turbulent structures in the flow, and hence using an ADM as rotor model might suffice. However, for more reliable results, ALM may still be used if the computational cost can be afforded. |
| **Control inputs (if applicable)** | | The turbine should be misaligned with the flow by controlling the yaw angle. |
| **Evaluation metrics** | | See explanation for use case #1 |

| USE CASE #3 – WAKE MITIGATION TECHNIQUES | | |
|---|---|---|
| **Aim of the use case** | | In this use case, new wake mitigation concepts will be tested in simulation to determine if they have potential to induce wake recovery, which has a benefit similar to axial induction control. That is, the higher wake recovery, the faster it achieves free-stream conditions and the less affected downstream turbines are. However, potential deteriorations in power and loads of the respective turbines would have to be outweighed by the gains of such a concept. |
| **Wind farm layouts** | | 3-turbine WF<br>The only layout investigated is a 3-turbine array. Indeed, this concept only requires focusing on a small number of turbines and their wakes, in order to investigate if such a control method results in increased wake recovery. Although theoretically a single turbine and its wake could just be examined, the 3-turbines farm allows early detection of the effects on the downstream turbines in terms of loads and power. |
| **Ambient conditions** | **Wind speeds** | Since this is a very new concept, it will be interesting to assess its potential over a wide range of wind speeds. |
| | **Wind directions** | The wind direction should be aligned with the turbines, such that there is maximal wake overlap. Since there is no wind farm control, one wind direction could be sufficient. |
| | **TI** | Since this is a very new concept, it will be interesting to assess its potential over a wide range of TI. |
| | **Atmospheric stability** | Since this is a very new concept, it will be interesting to assess its potential over a wide range of atmospheric stability. |
| **Required fidelity and simulation time** | | Since it is crucial to this use case to model the turbine-induced turbulent structures in the flow accurately, ALM must be used and the spatial resolution must be fine. |
| **Control inputs (if applicable)** | | Given the novelty of this technique, further study within WP2 needs to be performed. |
| **Evaluation metrics** | | Flow speeds and TI at several locations downstream (1D, 2D, 3D, …, 10D) each controlled turbine, power capture of both controlled and downstream turbines, loads on both controlled and downstream turbines. |

| USE CASE #4 – COMBINED CONTROL (AXIAL INDUCTION & YAW) | | |
|---|---|---|
| **Aim of the use case** | | In this use case, we will assess the capabilities of the combination of the two major control methodologies in wind farm control, currently: namely axial induction control and wake redirection control through yaw. Since both methods work through different principles and on different control variables, the combination of the two should out-perform the individual control methods. However, as it is a challenging concept and to reduce the computational cost, only the most successful scenarios in previous simulations will be tested. |
| **Wind farm layouts** | | For the same reasons described in use cases #1 and #2, the topologies tested range from a simple 3-turbine-case that allows in-depth analysis of the flow dynamics and control algorithms, to a demonstration of the control concept on a large-scale wind farm (layout 3 – offshore wind farm). |
| **Ambient conditions** | **Wind speeds** | The ambient conditions will be based on the simulation results of use cases #1 and #2. Namely, the most successful simulation scenarios will be used to test this combined controller, since it is a challenging control concept and furthermore it will reduce the computational cost making better use of resources. Thus, the particular ambient conditions will be decided accordingly. |
| | **Wind directions** | |
| | **TI** | |
| | **Atmospheric stability** | |
| **Required fidelity and simulation time** | | Since this is a combination of use cases #1 and #2, the finest resolution of the two is expected to be chosen, that is, simulations with ALM and a fine grid. However the choice will depend on the findings from those earlier use cases. |
| **Control inputs (if applicable)** | | The combination of use cases #1 and #2. |
| **Evaluation metrics** | | See explanation for use case #1. |

Table 5: Use cases and simulation scenarios for feasibility validation

| USE CASE #5 – ANNUAL ENERGY PRODUCTION | | |
|---|---|---|
| **Aim of the use case** | | The use case shall provide the expected annual energy production of each turbine in an array, in dependence of wind direction and wind speed (and, potentially turbulence intensity and atmospheric stability), in order to perform financial analyses. The study is performed at wind farm / turbine level with different control strategies implemented. |
| **Wind farm layouts** | | It would be profitable to get this information for all setups in order to be able to compare effects in different scenarios, that is:<br>• 3-turbine wind farm<br>• 9-turbine wind farm<br>• Offshore wind farm<br>• Sedini wind farm |
| **Ambient conditions** | **Wind speeds** | The set of ambient conditions needs to represent the majority of operating states expected for the different setups.<br>All expected in 1 m/s bins. |
| | **Wind directions** | All / initially in 15° bins. |
| | **TI** | Initial +-20 % (may be revised) |
| | **Atmospheric stability** | Low, medium and high (may be revised) |
| **Required fidelity and simulation time** | | The simulation should be capable of capturing the expected energy production at distinct points in time – initially 10 min mean values will be used. |
| **Control inputs (if applicable)** | | As appropriate to the control strategies which are implemented. |
| **Evaluation metrics** | | Expected annual energy production. |

<table>
<tr><th colspan="3">USE CASE #6 – COMPONENT LOADING</th></tr>
<tr><td colspan="2"><b>Aim of the use case</b></td><td>The use case shall provide the expected loading of main components on each turbine in an array, in dependence of wind direction and wind speed (and, potentially turbulence intensity and atmospheric stability). That is, the aim is to calculate the loading on defined components for reliability and lifetime estimates (degradation functions).</td></tr>
<tr><td colspan="2"><b>Wind farm layouts</b></td><td>It would be profitable to get this information for all setups in order to be able to compare effects in different scenarios.</td></tr>
<tr><td rowspan="4"><b>Ambient conditions</b></td><td><b>Wind speeds</b></td><td>The set of ambient conditions needs to represent the majority of operating states expected for the different setups.<br>All expected in 1 m/s bins.</td></tr>
<tr><td><b>Wind directions</b></td><td>All / initially in 15° bins.</td></tr>
<tr><td><b>TI</b></td><td>Initial +-20 % (may be revised)</td></tr>
<tr><td><b>Atmospheric stability</b></td><td>Low, medium and high (may be revised)</td></tr>
<tr><td colspan="2"><b>Required fidelity and simulation time</b></td><td>The simulation should be capable of representing location specific load levels for each turbine and main component under the conditions specified. The format and exact requirements are to be defined as per WP4 developments.</td></tr>
<tr><td colspan="2"><b>Control inputs (if applicable)</b></td><td>As appropriate to the control strategies which are implemented.</td></tr>
<tr><td colspan="2"><b>Evaluation metrics</b></td><td>Component loading</td></tr>
</table>

| **USE CASE #7 – REDESIGNED TURBINES** | | |
|---|---|---|
| **Aim of the use case** | | The use case shall provide outputs as per use case #5 and #6 for the re-designed turbines. |
| **Wind farm layouts** | | The exact setup is to be selected. |
| **Ambient conditions** | **Wind speeds** | A reduced setup of simulation cases may be feasible. |
| | **Wind directions** | |
| | **TI** | |
| | **Atmospheric stability** | |
| **Required fidelity and simulation time** | | The simulation should be capable of capturing the expected energy production and component loading. |
| **Control inputs (if applicable)** | | As appropriate to the control strategies which are implemented. |
| **Evaluation metrics** | | Expected annual energy production and component loading. |

As seen above, the final number of use cases and their corresponding mix of variables reach a high number of combinations. Given the computational load of high-fidelity simulations with SOWFA, a direct execution of all those simulations would become economically and technically unfeasible. Consequently, further work on simulation cases will be performed so that a reasonable plan of simulations under validated medium-fidelity and high-fidelity models is carried out.

# 5 CONCLUSION

Four different reference wind farms have been defined: three fictitious cases ranging from simple topologies with three or nine turbines to a more complicated layout with eighty turbines in four rows in the offshore case (Norcowe RFW), and one existing onshore wind farm (Sedini WF) with 43 turbines. Simple layouts (three turbine case and nine turbine case) have been defined in order to allow faster detailed simulations within SOWFA, while the offshore layout and Sedini WF, with more wind turbines, focus on physical phenomena and effects which only emerge inside large wind farms with multiple overlapping wakes.

The turbine selected for the minimal layouts and the offshore wind farm is the reference turbine from the EU project INNWIND (DTU 10 MW), since this turbine is described in detail in public literature and reflects the current state of the art wind turbine technology. For Sedini wind farm, GE 1.5 MW installed turbines are the reference turbines.

A set of simulation scenarios have been defined to provide the framework guidelines that will enable reference cases to be defined by input/outputs, variables and evaluation metrics, for a common analysis and accurate comparisons between the different models and control strategies. Further work will be performed to establish a detailed simulation plan so that high-fidelity SOWFA simulations are leveraged by making use as well of validated medium-fidelity models.

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# 7 APPENDIX A: LAYOUT COORDINATES

**Table 6: Three turbines layout installation locations.**

**Easting and northing in rotor diameters (D) and meters as defined**

| Turbine Number | X (D) | Y (D) | X | Y |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |
| 2 | 0 | 5 | 0 | 892 |
| 3 | 0.5 | 10 | 89 | 1783 |

**Table 7: Nine turbines layout installation locations.**

**Easting and northing in rotor diameters (D) and meters as defined**

| Turbine Number | X (D) | Y (D) | X | Y |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 |
| 4 | 7 | 5 | 1248 | 892 |
| 5 | 7 | 5 | 1248 | 892 |
| 6 | 7 | 5 | 1248 | 892 |
| 7 | 14 | 10 | 2496 | 1783 |
| 8 | 14 | 10 | 2496 | 1783 |
| 9 | 14 | 10 | 2496 | 1783 |

**Table 8: Norcowe RWF baseline rectilinear layout installation locations.**

**Easting and northing in rotor diameters (D) and meters from farm centroid**

| Turbine Number | X (D) | Y (D) | X | Y |
|---|---|---|---|---|
| 1 | 21.618 | -53.444 | 3852 | -9524 |
| 2 | 28.546 | -49.444 | 5087 | -8811 |
| 3 | 35.475 | -45.444 | 6322 | -8098 |
| 4 | 18.26 | -47.627 | 3254 | -8487 |
| 5 | 25.188 | -43.627 | 4488 | -7774 |
| 6 | 32.116 | -39.627 | 5723 | -7062 |
| 7 | 7.973 | -45.81 | 1421 | -8163 |
| 8 | 14.901 | -41.81 | 2655 | -7451 |
| 9 | 21.83 | -37.81 | 3890 | -6738 |
| 10 | 28.758 | -33.81 | 5125 | -6025 |
| 11 | 35.686 | -29.81 | 6359 | -5312 |

| Turbine Number | X (D) | Y (D) | X | Y |
|---|---|---|---|---|
| 12 | 4.615 | -39.993 | 822 | -7127 |
| 13 | 11.543 | -35.993 | 2057 | -6414 |
| 14 | 18.471 | -31.993 | 3292 | -5701 |
| 15 | 25.399 | -27.993 | 4526 | -4988 |
| 16 | 32.328 | -23.993 | 5761 | -4276 |
| 17 | 1.256 | -34.176 | 224 | -6090 |
| 18 | 8.185 | -30.176 | 1458 | -5377 |
| 19 | 15.113 | -26.176 | 2693 | -4665 |
| 20 | 22.041 | -22.176 | 3928 | -3952 |
| 21 | 28.969 | -18.176 | 5162 | -3239 |
| 22 | -2.102 | -28.359 | -375 | -5054 |
| 23 | 4.826 | -24.359 | 860 | -4341 |
| 24 | 11.754 | -20.359 | 2095 | -3628 |
| 25 | 18.683 | -16.359 | 3329 | -2915 |
| 26 * | 25.611 | -12.359 | 4564 | -2202 |
| 27 | -5.46 | -22.542 | -973 | -4017 |
| 28 | 1.468 | -18.542 | 262 | -3304 |
| 29 | 8.396 | -14.542 | 1496 | -2591 |
| 30 | 15.324 | -10.542 | 2731 | -1879 |
| 31 | 22.252 | -6.542 | 3965 | -1166 |
| 32 | -8.819 | -16.725 | -1572 | -2980 |
| 33 | -1.891 | -12.725 | -337 | -2268 |
| 34 | 5.038 | -8.725 | 898 | -1555 |
| 35 | 11.966 | -4.725 | 2132 | -842 |
| 36 | 18.894 | -0.725 | 3367 | -129 |
| 37 | -12.177 | -10.908 | -2170 | -1944 |
| 38 | -5.249 | -6.908 | -935 | -1231 |
| 39 | 1.679 | -2.908 | 299 | -518 |
| 40 | 8.607 | 1.092 | 1534 | 195 |
| 41 | 15.536 | 5.092 | 2768 | 907 |
| 42 | -15.536 | -5.092 | -2768 | -907 |
| 43 | -8.607 | -1.092 | -1534 | -195 |
| 44 | -1.679 | 2.908 | -299 | 518 |
| 45 | 5.249 | 6.908 | 935 | 1231 |
| 46 | 12.177 | 10.908 | 2170 | 1944 |
| 47 | -18.894 | 0.725 | -3367 | 129 |
| 48 | -11.966 | 4.725 | -2132 | 842 |
| 49 | -5.038 | 8.725 | -898 | 1555 |
| 50 | 1.891 | 12.725 | 337 | 2268 |
| 51 | 8.819 | 16.725 | 1572 | 2980 |

| Turbine Number | X (D) | Y (D) | X | Y |
|---|---|---|---|---|
| 52 | -22.252 | 6.542 | -3965 | 1166 |
| 53 | -15.324 | 10.542 | -2731 | 1879 |
| 54 | -8.396 | 14.542 | -1496 | 2591 |
| 55 | -1.468 | 18.542 | -262 | 3304 |
| 56 | 5.46 | 22.542 | 973 | 4017 |
| 57 | -25.611 | 12.359 | -4564 | 2202 |
| 58 | -18.683 | 16.359 | -3329 | 2915 |
| 59 | -11.754 | 20.359 | -2095 | 3628 |
| 60 | -4.826 | 24.359 | -860 | 4341 |
| 61 * | 2.102 | 28.359 | 375 | 5054 |
| 62 | -28.969 | 18.176 | -5162 | 3239 |
| 63 | -22.041 | 22.176 | -3928 | 3952 |
| 64 | -15.113 | 26.176 | -2693 | 4665 |
| 65 | -8.185 | 30.176 | -1458 | 5377 |
| 66 | -1.256 | 34.176 | -224 | 6090 |
| 67 | -32.328 | 23.993 | -5761 | 4276 |
| 68 | -25.399 | 27.993 | -4526 | 4988 |
| 69 | -18.471 | 31.993 | -3292 | 5701 |
| 70 | -11.543 | 35.993 | -2057 | 6414 |
| 71 | -4.615 | 39.993 | -822 | 7127 |
| 72 | -35.686 | 29.81 | -6359 | 5312 |
| 73 | -28.758 | 33.81 | -5125 | 6025 |
| 74 | -21.83 | 37.81 | -3890 | 6738 |
| 75 | -14.901 | 41.81 | -2655 | 7451 |
| 76 | -7.973 | 45.81 | -1421 | 8163 |
| 77 | -32.116 | 39.627 | -5723 | 7062 |
| 78 | -25.188 | 43.627 | -4488 | 7774 |
| 79 | -18.26 | 47.627 | -3254 | 8487 |
| 80 | -35.475 | 45.444 | -6322 | 8098 |
| 81 | -28.546 | 49.444 | -5087 | 8811 |
| 82 | -21.618 | 53.444 | -3852 | 9524 |

(*) Substations