CL-Windcon

Closed Loop Wind Farm Control

CL-Windcon, a control project approach

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CENER

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

Wind Energy Science Conference 2019
17 - 20 June, Cork

MOTIVATION

- **Holistic approach**
  - Treat the wind farm control as a whole, instead of isolated wind turbine problems
  - Collect as much information as is available for wind farm operation improvements
  - Bridge the gap between simple models and CFD tools
- A **Control problem/solution approach**, by creating the necessary knowledge
  - Multi-fidelity modeling approach
  - Establish common cases/scenarios for developing
    - Models: development, comparison & validation
    - Control: development, comparison & validation
- **Cooperative endeavour**
- **Following H2020 philosophy " As open as possible"**

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PROJECT AT A GLANCE

- CL-Windcon (Closed- loop Wind Farm Control)
- H2020-LCE-2016-RES-CCS-RIA ⇒ LCE-07-2016-2017- Developing the next generation technologies of renewable electricity and heating/cooling
- Duration: 36 months (2016/11/01 – 2019/10/31)
- Funding: 4.9 MEUR
- 15 partners from 6 countries
- Coordinator: CENER

❖ Multi-fidelity dynamic modelling

❖ Open and closed-loop advanced control algorithms at farm level

❖ Treating the entire wind farm as a comprehensive optimization problem

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THE PROJECT

TECHNICAL GENERAL OVERVIEW

WP1 – Wind farm control-oriented model development

- Reference wind turbine, farms and scenarios
- Farm models development
- Pre-/post-processing
- Models classification

WP2 – Wind farm flow technologies and algorithms

- Closed-loop & open-loop control
- Induction & wake redirection control
- Supporting wind farm control technologies
- Integrated wind farm control

WP3 – Demonstration and validation of prototypes

- By simulation
- By wind tunnel testing
- By full-scale testing

WP4 – Feasibility

- Technology at wind turbine/farm level
- Technology by redesign
- O&M and reliability
- Economics & environment
- Standards

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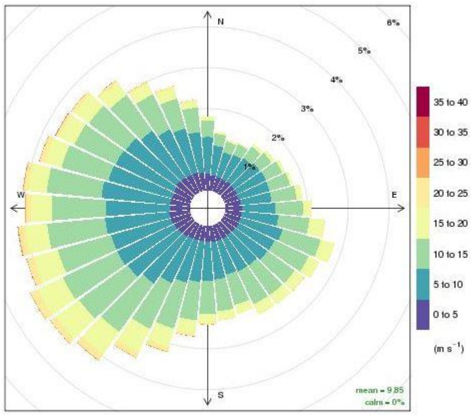
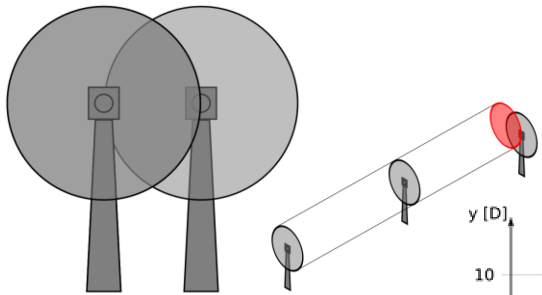
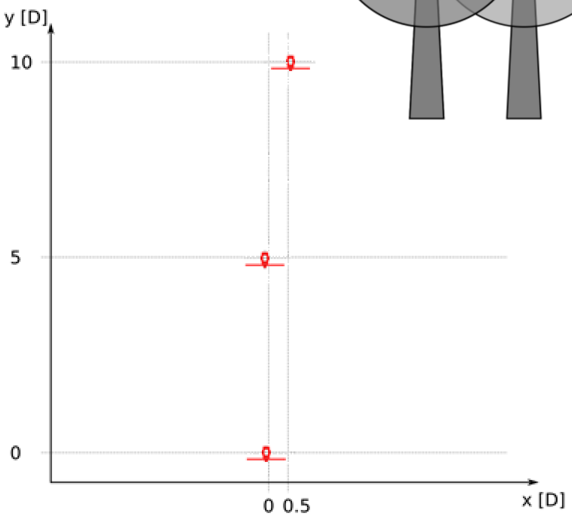
WP1 – WIND FARM CONTROL-ORIENTED MODEL DEVELOPMENT

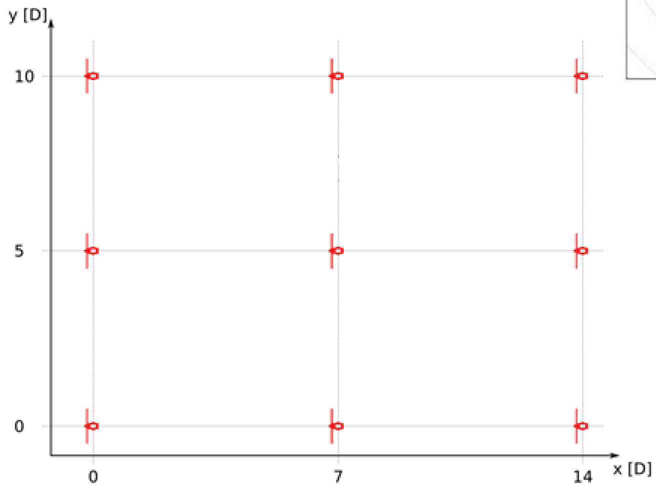
D1.1 - DEFINITIONS

- **Definition of 4 reference wind farms**, from simple topologies to more complicated layouts, focusing on the effects under study
- **Reference wind turbine**: 10 MW INNWIND.EU wind turbine









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WP1 – WIND FARM CONTROL-ORIENTED MODEL DEVELOPMENT

D1.1 - DEFINITIONS

- **Definition of simulation scenarios and use cases (7),** following Verification & Validation (V&V) practices, with the aim of:
  - Model validation
  - Control verification

Use cases
Axial induction control
Yaw control
Wake mitigation techniques
Combined control (axial induction & yaw)
Annual energy production
Component loading
Redesigned turbines

Described by
Aim of the use case
Wind farm layout
Ambient conditions
Required fidelity and time for the simulations
Control inputs (if applicable)
Evaluation metrics

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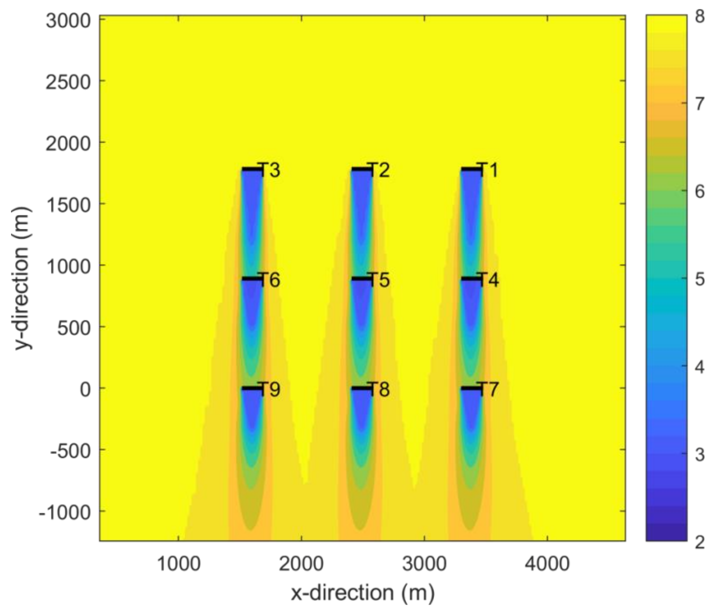
WP1 – WIND FARM CONTROL-ORIENTED MODEL DEVELOPMENT

D1.2 - DESCRIPTION OF REFERENCE & CONTROL-ORIENTED WIND FARM MODELS

- Steady-state models
  - Low complexity & computational cost
  - High number of tuning parameters
  - Time-averaged dynamics (minutes-scale)



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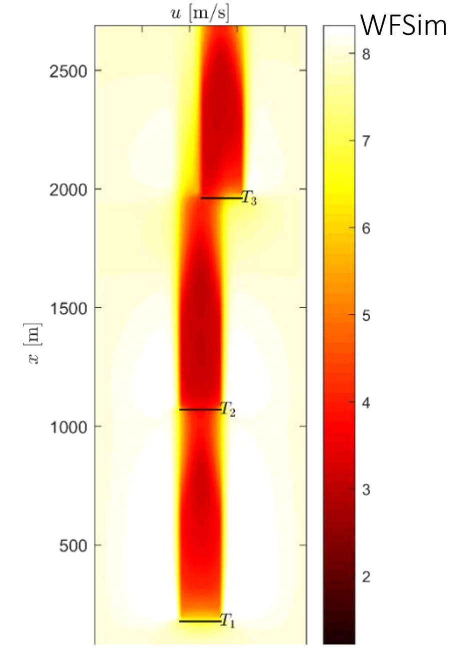
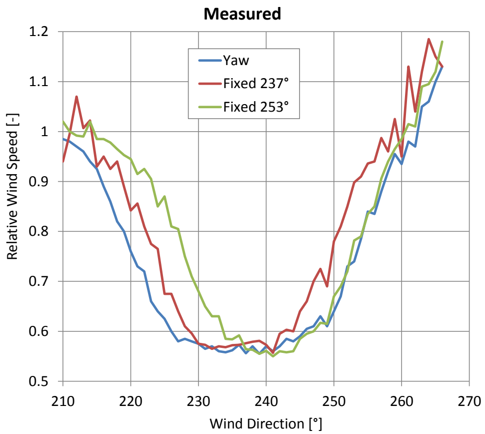
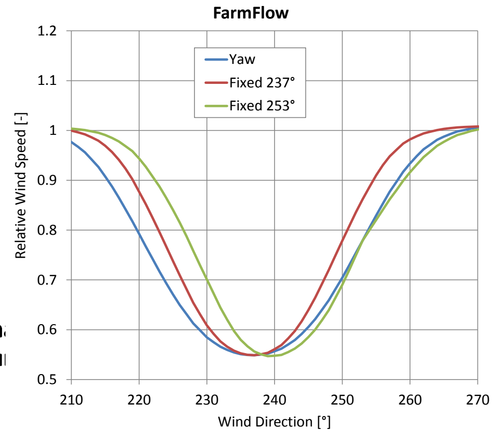
WP1 – WIND FARM CONTROL-ORIENTED MODEL DEVELOPMENT

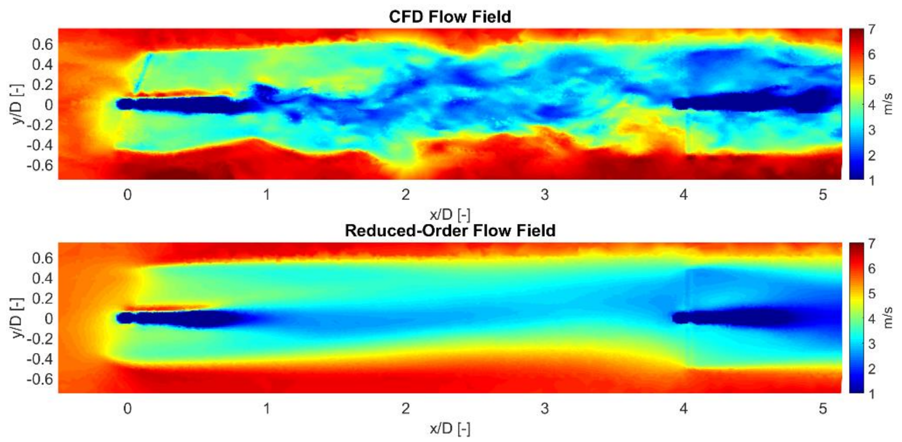
D1.2 - DESCRIPTION OF REFERENCE & CONTROL-ORIENTED WIND FARM MODELS

- **Steady-state models**
  - Low complexity & computational cost
  - High number of tuning parameters
  - Time-averaged dynamics (minutes-scale)
- **Control-oriented dynamical models**
  - Increase in complexity & computational cost
  - Often derived from Navier-Stokes equations
    - $\Rightarrow$ fewer tuning parameters
  - Dynamics on a second-to-second scale





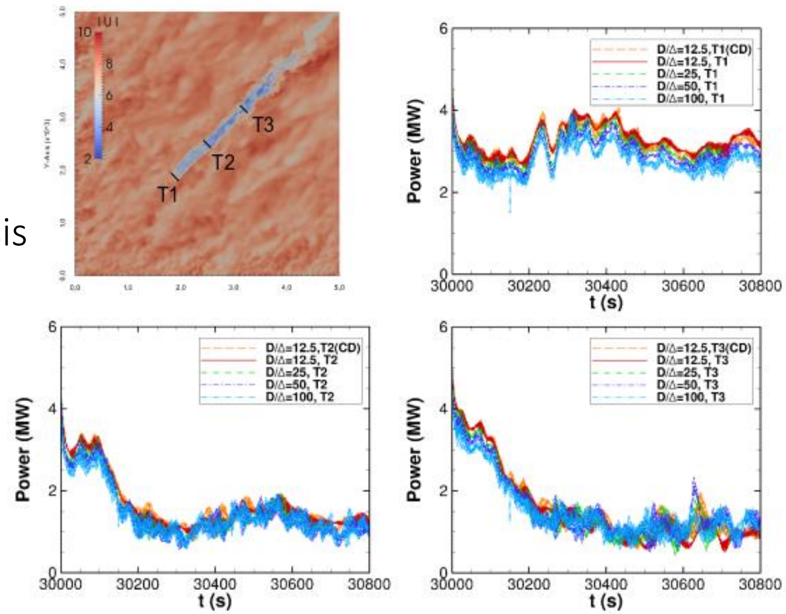


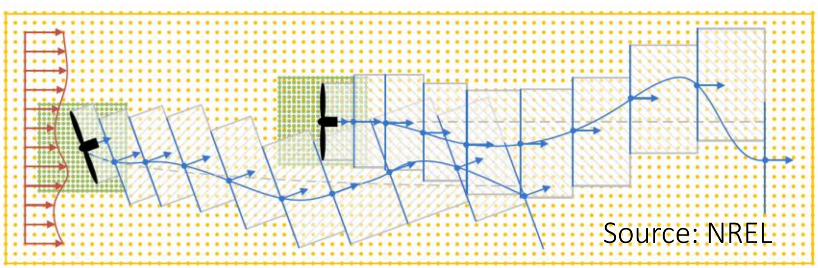


WP1 – WIND FARM CONTROL-ORIENTED MODEL DEVELOPMENT

D1.2 - DESCRIPTION OF REFERENCE & CONTROL-ORIENTED WIND FARM MODELS

- **Medium-fidelity simulation models**
  - Not used for controller synthesis (computational cost & complexity)
  - Reasonable accuracy for controller testing running on desktop/small cluster
- **High-fidelity simulation models**
  - Typically large-eddy simulations
  - High spatial and temporal resolution
  - Very high computational cost (HPC clusters)
  - Exclusively for controller testing and wind analysis





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WP1 – WIND FARM CONTROL-ORIENTED MODEL DEVELOPMENT

D1.2 - DESCRIPTION OF REFERENCE & CONTROL-ORIENTED WIND FARM MODELS

Steady-state

FLORIS

- FarmFlow
- Wake dissipation model for wake tracking

Control-oriented dynamical

- LongSim
- WindFarmSimulator (WFSim)
- Reduced-order model from high-fidelity simulation data

Wind farm controller synthesis

Wind farm controller testing

Medium-fidelity

- FAST.Farm
- SimWindFarm

High-fidelity

SOWFA

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WP1 – WIND FARM CONTROL-ORIENTED MODEL DEVELOPMENT

D1.3 - CLASSIFICATION OF MODELS FOR WIND FARM CONTROL APPLICATIONS

- Software toolbox for pre-/post-processing of wind farm simulations (multi-tool)
- In collaboration with IEA Task 37
- Reference structure format (wind turbine / farm)
- Common data structure format: YAML

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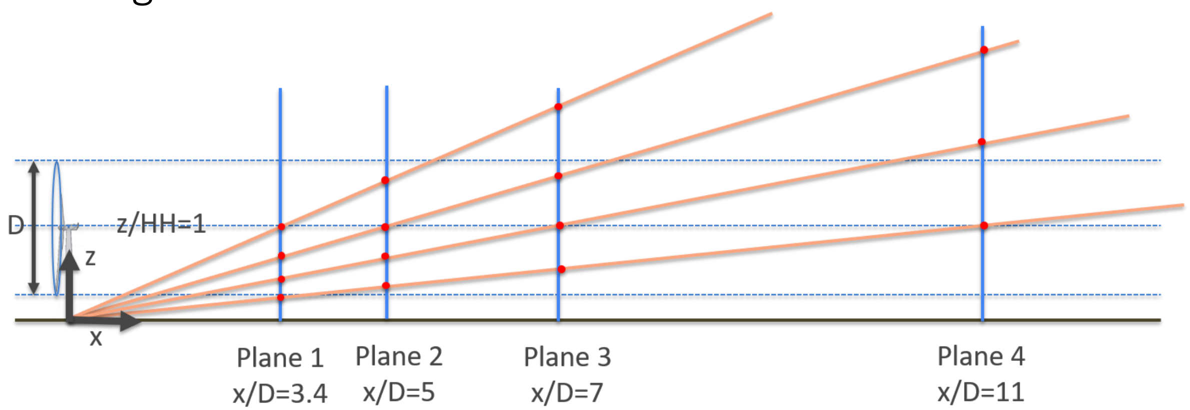
WP1 – WIND FARM CONTROL-ORIENTED MODEL DEVELOPMENT

D1.4 - CLASSIFICATION OF MODELS FOR WIND FARM CONTROL APPLICATIONS

- With respect to:
  - State of development & validation
  - Model nature
  - Fidelity
  - Modelling effort
  - Controllability
  - Computational effort
  - Limitations for real-world application
  - Application areas
  - Expected evolution

- Blind test in a single wake benchmark with field measurement data



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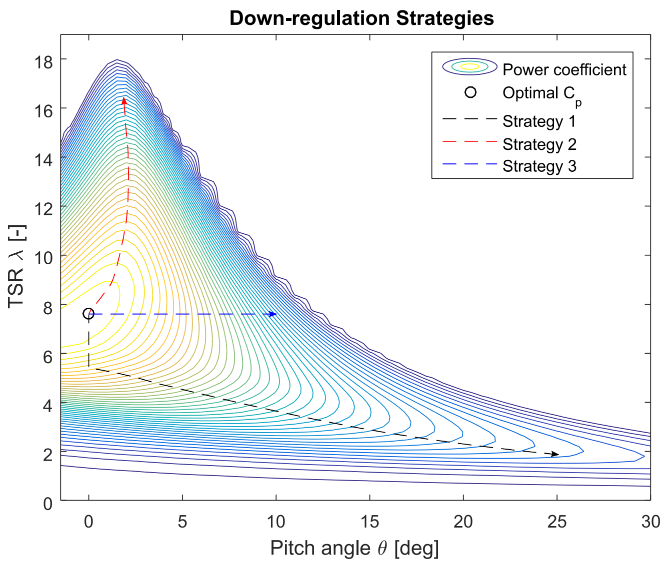
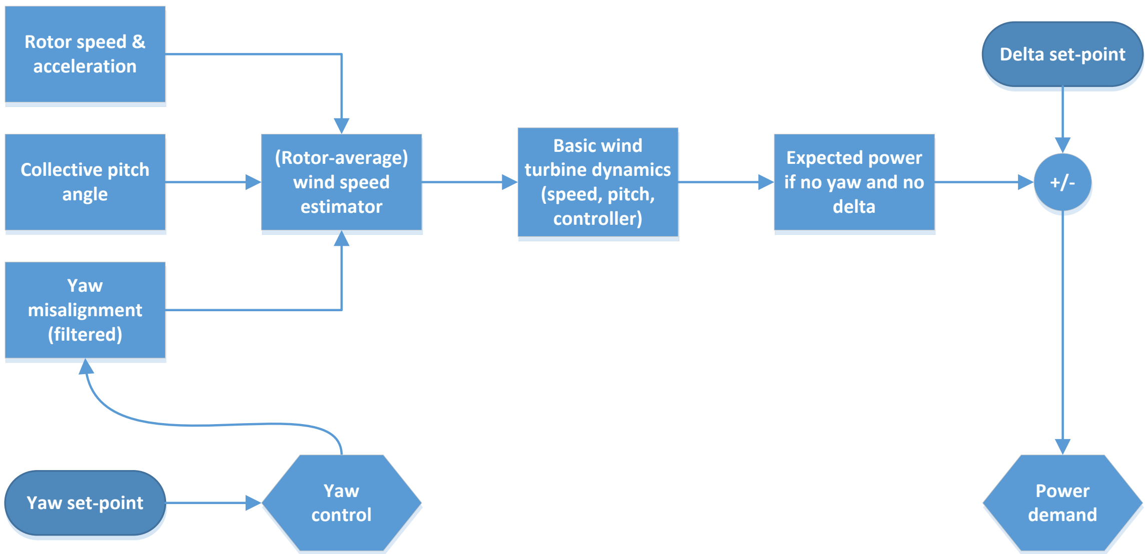
WP2 – WIND FARM FLOW CONTROL TECHNOLOGIES AND ALGORITHMS

D2.1 – MINIMAL LOADING WT DERATING AND ACTIVE YAW CONTROLLERS

- Explore different strategies at WT level from the fatigue perspective
  - Down-regulation
  - Active yaw control
  - Combination of both
- Implementation in a common baseline WT controller structure (**open-source code available at GitHub**)





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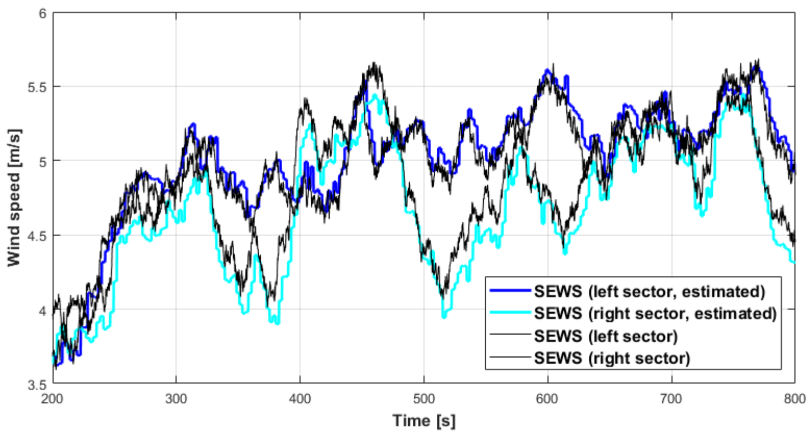
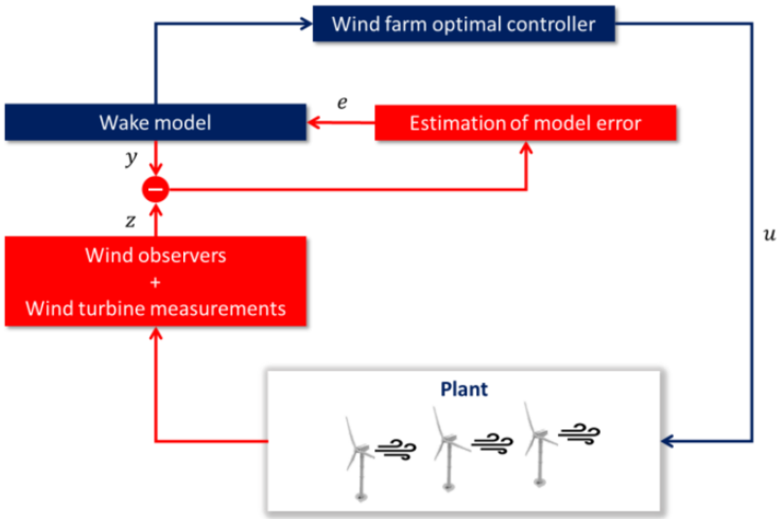
WP2 – WIND FARM FLOW CONTROL TECHNOLOGIES AND ALGORITHMS

D2.2 – METHODOLOGY FOR ACTIVE LOAD CONTROL

- Specific **control mechanisms for the reduction of loads caused by a wind turbine being a part of a farm**
- Estimators for partial wake overlap detection, which may be used for triggering
  - Sector effective wind speed estimation (through blade root bending moments)
  - Wake detection
  - Wake position and deficit estimation by online model update





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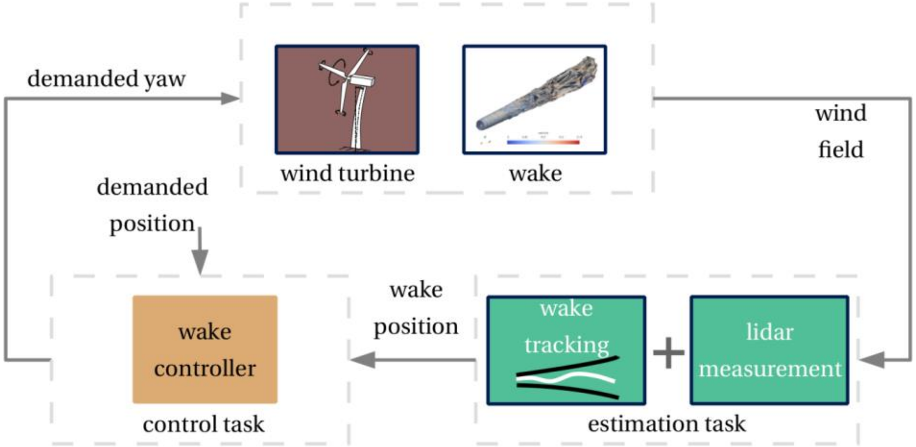
WP2 – WIND FARM FLOW CONTROL TECHNOLOGIES AND ALGORITHMS

D2.2 – METHODOLOGY FOR ACTIVE LOAD CONTROL

- Externally triggerable IPC

- Closed-loop wake steering



- Reliability enhancing technologies
  - Redundancy of generator speed monitoring, by using measurements from 3 sensors (generator speed, rotor speed and azimuth)
  - Management of sensor failure

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WP2 – WIND FARM FLOW CONTROL TECHNOLOGIES AND ALGORITHMS

D2.3 – FARM CONTROL METHODOLOGY: INDUCTION BASED & WAKE REDIRECTION

- Feedback & feedforward induction control
  - Data-driven Economic Model Predictive Controller (EMPC) feedback control
  - Feedforward induction control for power and loads (partial wake loads)
  - Closed-loop induction control
- Fast wake recovery techniques
- Feedback and feedforward wake steering
  - Dynamic wake steering and its impact on power and loads
  - Wind direction measurement bias estimation
  - Wake-redirection by yawing with model augmentation
  - LIDAR-assisted closed-loop wake redirection control
  - Closed-loop model-based wake redirection control using a steady-state surrogate model

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WP2 – WIND FARM FLOW CONTROL TECHNOLOGIES AND ALGORITHMS

D2.4 – MINIMAL LOADING POWER CURTAILMENT CONTROL TECHNIQUES

- Novel **load-balancing wind farm power curtailment control strategy**
  - Time-varying active power setpoint for the whole wind farm
  - Different types of power curtailment strategies
    - Absolute power limitation
    - Balance control
    - Power rate limitation
    - Delta control
  - Optimal distribution among the wind turbines to ensure:
    - Tracking of total power production
    - Achieve minimal load increase over the whole farm
    - Balance accumulated fatigue loading over the wind farm

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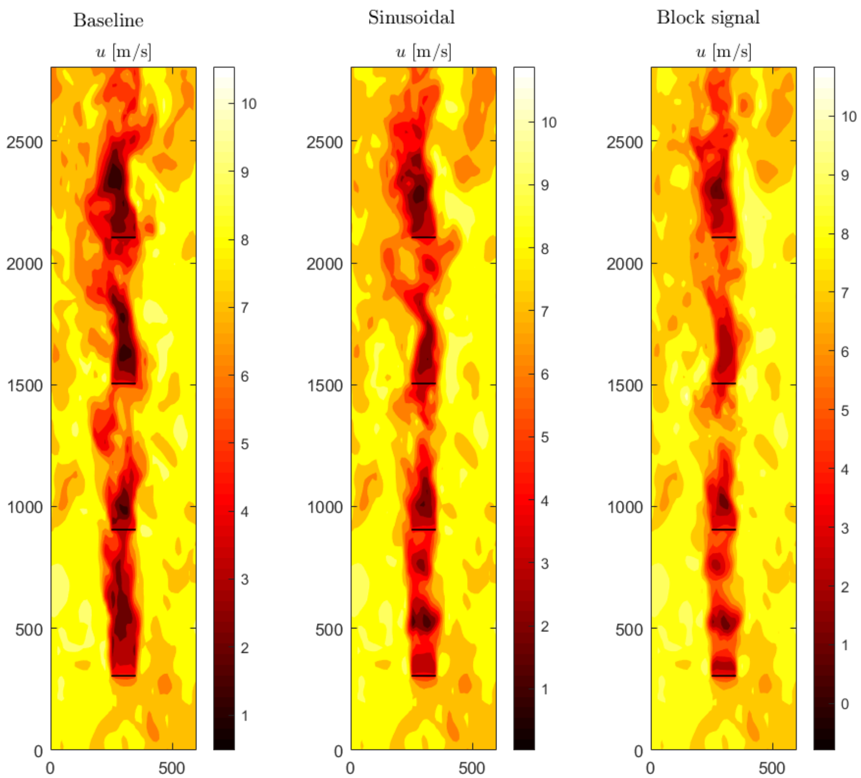
WP3 – DEMONSTRATION & VALIDATION OF PROTOTYPES

D3.3 – DEMONSTRATION OF WT CONTROLLERS & SUPPORTING TECHNOLOGIES BY SIMULATIONS

- Simulation & analysis at turbine level, by using the developed:
  - CL-Windcon baseline controller
  - Power derating & CL wake steering
  - Wake mixing strategy
  - Supplementary control strategies
  - Wind state and wake observers

Wake mixing



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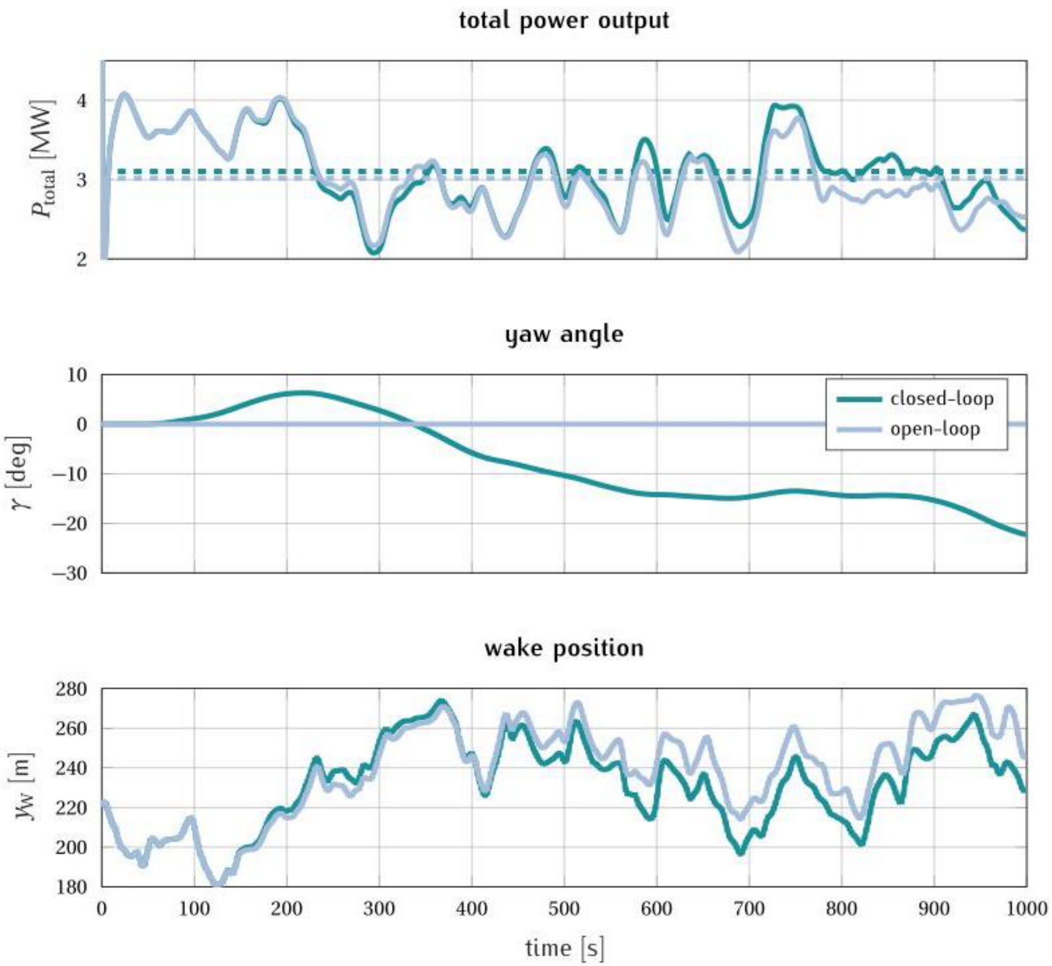
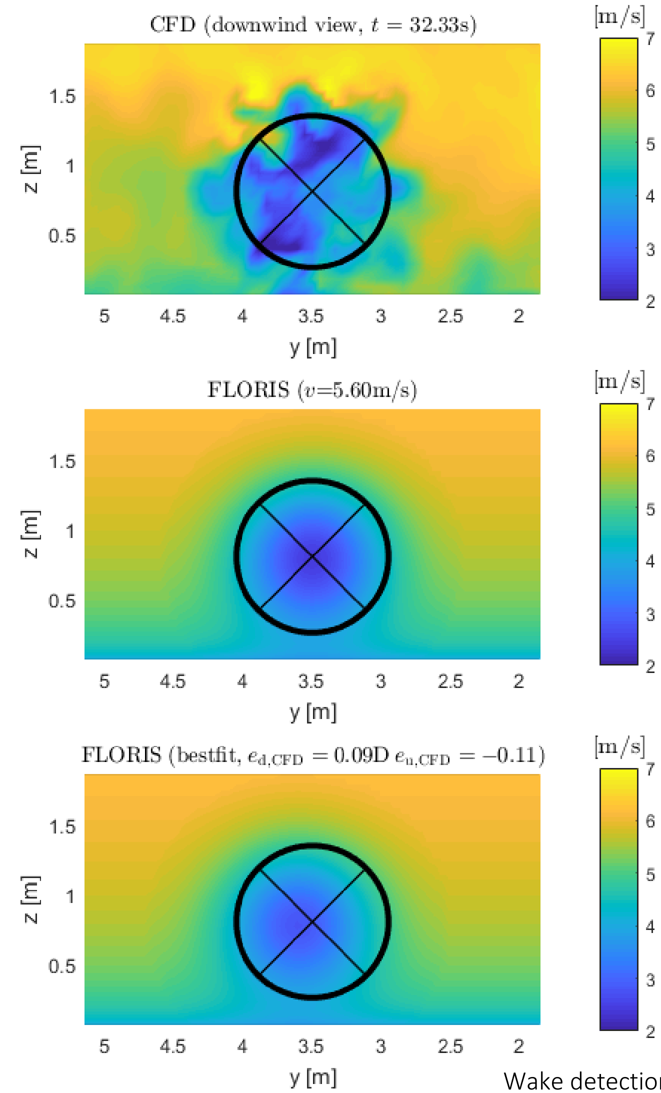
WP3 – DEMONSTRATION & VALIDATION OF PROTOTYPES

D3.3 – DEMONSTRATION OF WT CONTROLLERS & SUPPORTING TECHNOLOGIES BY SIMULATIONS





Wake detection

WP3 – DEMONSTRATION & VALIDATION OF PROTOTYPES

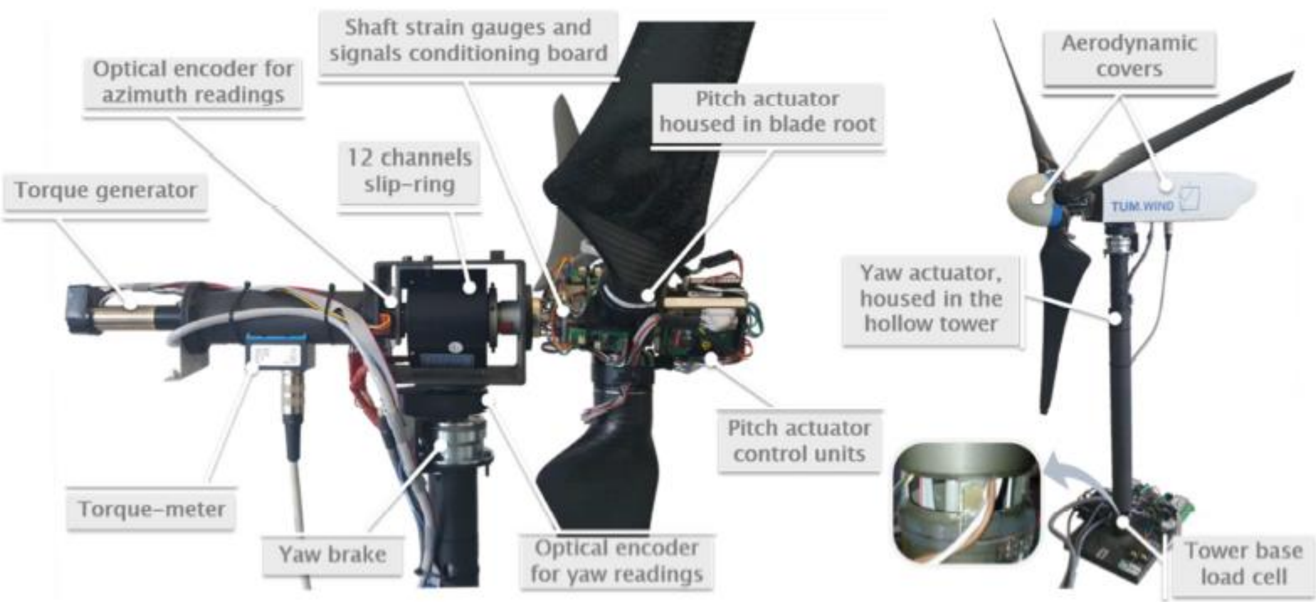
D3.1 – DEFINITION OF WIND TUNNEL TESTING CONDITIONS

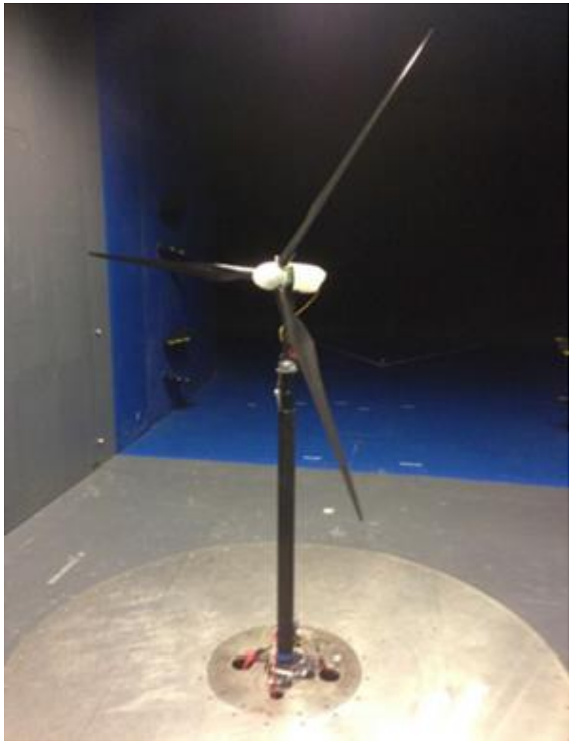
- Wind tunnel testing as a validation pillar within CL-Windcon
- Experiments performed in the **wind tunnel facility of Politecnico di Milano**

WP3 – DEMONSTRATION & VALIDATION OF PROTOTYPES

D3.1 – DEFINITION OF WIND TUNNEL TESTING CONDITIONS

- Wind tunnel testing as a validation pillar within CL-Windcon
- Experiments performed in the wind tunnel facility of POLIMI
- With **2 different types of scaled wind turbine models from TUM (G1 & G2)**





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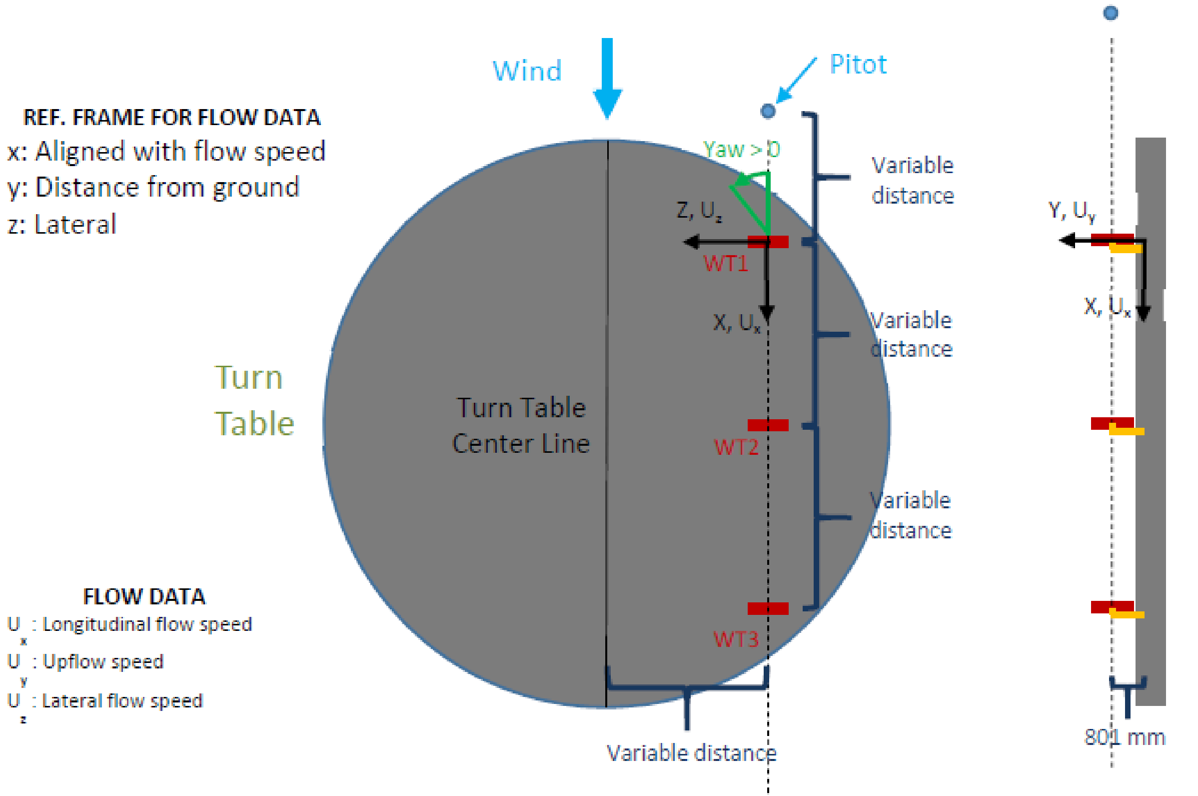
WP3 – DEMONSTRATION & VALIDATION OF PROTOTYPES

D3.1 – DEFINITION OF WIND TUNNEL TESTING CONDITIONS

- Definition of **10 experiments along 45 testing days**:
  - characterization of the single / multiple wind turbine wake
  - performance of an array of wind turbines (axial induction & yaw redirection)
  - test of different wind farm control algorithms



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WP3 – DEMONSTRATION & VALIDATION OF PROTOTYPES

D3.4 – TESTING IN THE WIND TUNNEL OF WIND TURBINES CONTROLLERS

- Tests accomplished in 27 days of experimentation
- Accurate **mapping of the inflow upwind** within the wind tunnel, for:
  - Reproduction of wind tunnel conditions for simulation
  - Post-process of experimental wake data
- **Single and multiple wake characterization (1 & 2 turbines)**
  - Under a range of conditions (ambient, operational)
  - Effects of yawing and derating on wake recovery, deficit and deflection
  - For validation of wake models
- **Individual pitch control** effects on loads and wake shed by a **misaligned turbine**
- Effectiveness of the **state update method** : compensate wake model mismatches
- Verification of techniques for **fast wake recovery**
- Validation of a **wind state observer**, able to estimate wind states: yaw misalignment, upflow angle, vertical and horizontal shear layers

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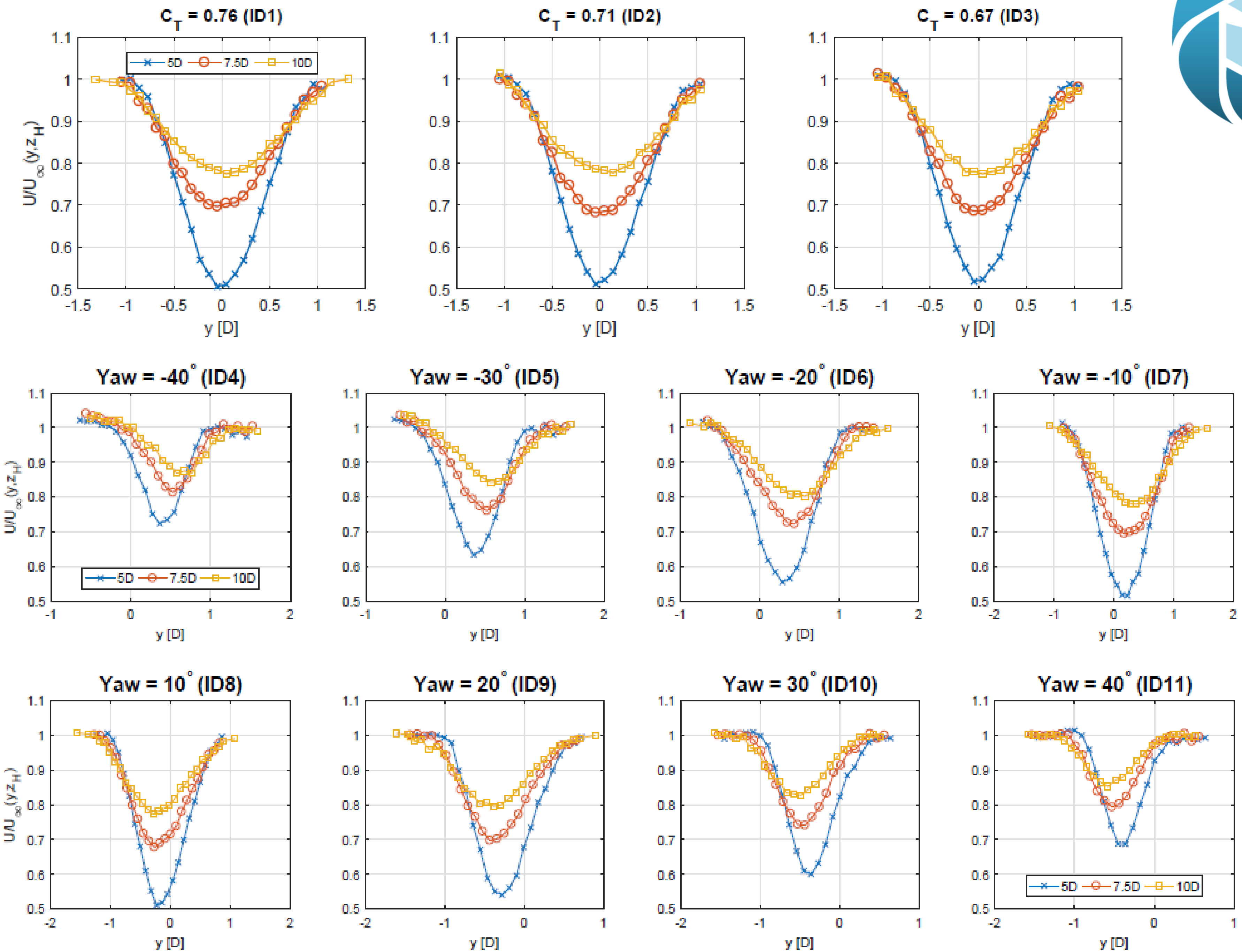
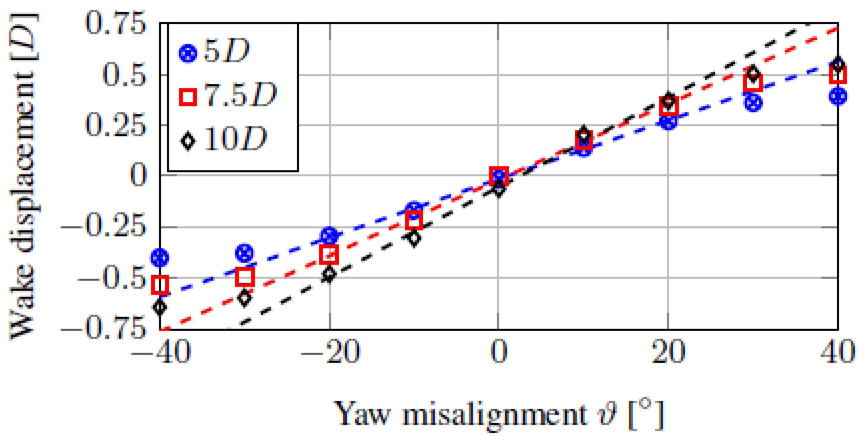


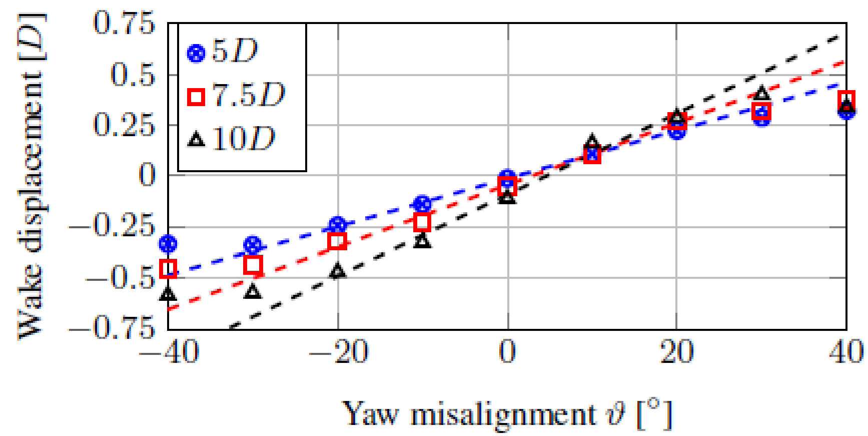
C_T = 0.76 (ID1)
C_T = 0.71 (ID2)
C_T = 0.67 (ID3)
Yaw = -40° (ID4)
Yaw = -30° (ID5)
Yaw = -20° (ID6)
Yaw = -10° (ID7)
Yaw = 10° (ID8)
Yaw = 20° (ID9)
Yaw = 30° (ID10)
Yaw = 40° (ID11)
5D
7.5D
10D
U/U_∞(y,z_H)
y [D]

WP3 – DEMONSTRATION & VALIDATION OF PROTOTYPES

D3.4 – TESTING IN THE WIND TUNNEL OF WIND TURBINES CONTROLLERS



(a) Mod-TI inflow conditions.



(b) High-TI inflow conditions.

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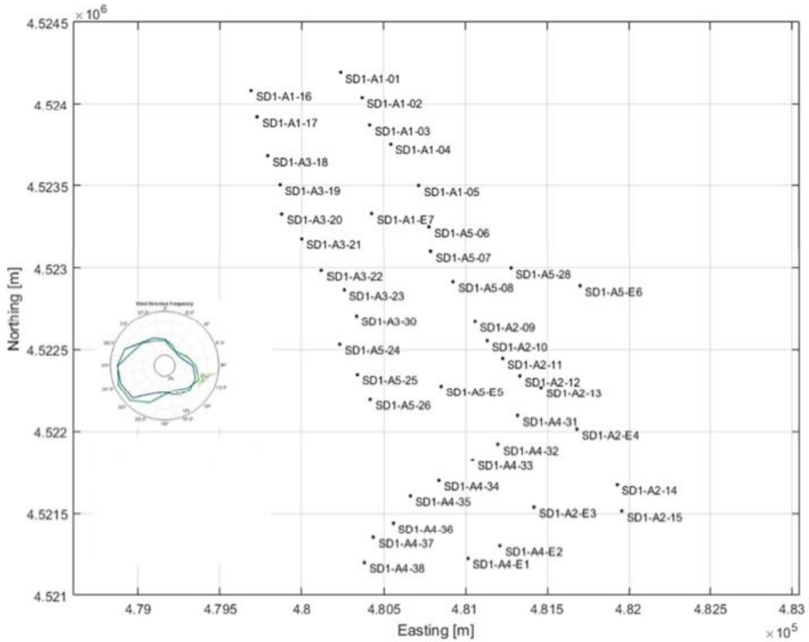
WP3 – DEMONSTRATION & VALIDATION OF PROTOTYPES

D3.2 – DEFINITION OF FIELD-TESTING CONDITIONS

- Wind farm in Sedini (Italy), property of ENEL Green Power, GE turbines (1.5 MW)
- Detailed study of interactions and design of experiments
- Objectives
  - Single turbine performance and wake characterization:
    - thrust reduced operation
    - yaw misalignment
  - Demonstration of farm control algorithms



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WP3 – DEMONSTRATION & VALIDATION OF PROTOTYPES

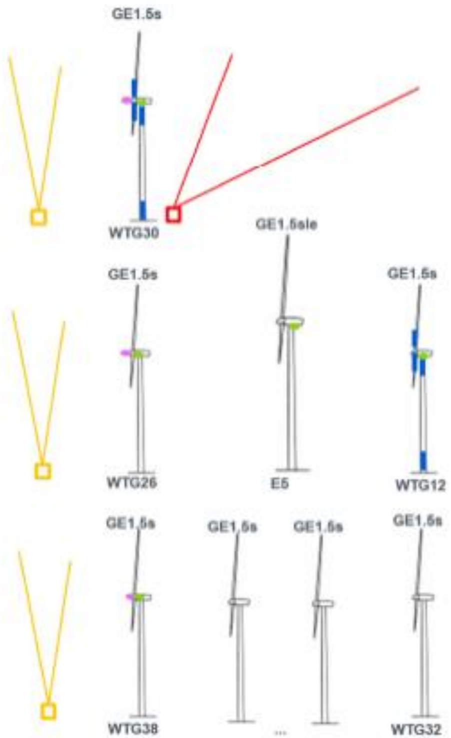
D3.2 – DEFINITION OF FIELD-TESTING CONDITIONS

Met mast
- temperature, wind speed and direction at different altitudes

Instrumentation of single free-stream turbine (WTG 30)
- vertical lidar and iSpin (TBD) for free stream measurement
- Blade & tower loads instrumentation
- scanning lidar for wake characterization
- yaw sensor
- optional: electrical power measurement
- optional: nacelle accelerometer box

Instrumentation of row of three turbines (WTG 26, E5, WTG12)
- vertical lidar and/or iSpin for free stream measurement (TBD)
- Blade & tower loads instrumentation on WTG12
- yaw sensor (WTG26,E5,WTG12)
- optional: nacelle accelerometer box (E5)

Partial instrumentation of row of seven turbines (WTG 32 to WTG 38)
- vertical lidar and/or iSpin for free stream measurement (TBD)
- yaw sensor (WTG38)
- optional: nacelle accelerometer box on downstream unit



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ON-GOING WORK

- WP2
  - Integrated wind farm control (D2.5)
- WP3
  - Demonstration of combined turbine/farm level controls by simulations (D3.5)
  - Documentation of test campaigns (D3.6)
  - Final validation report (D3.7)
- WP4
  - Assessment of controller key performance indicators & Guidelines on controller application for the management of existing wind farms (D4.1)
  - Optimized farm layout (D4.3)
  - Feasibility by re-design (D4.4)
  - Operation and maintenance cost modelling (D4.5)
  - Cost-benefit analysis (D4.6)
  - Review on standards and guidelines (D4.7)

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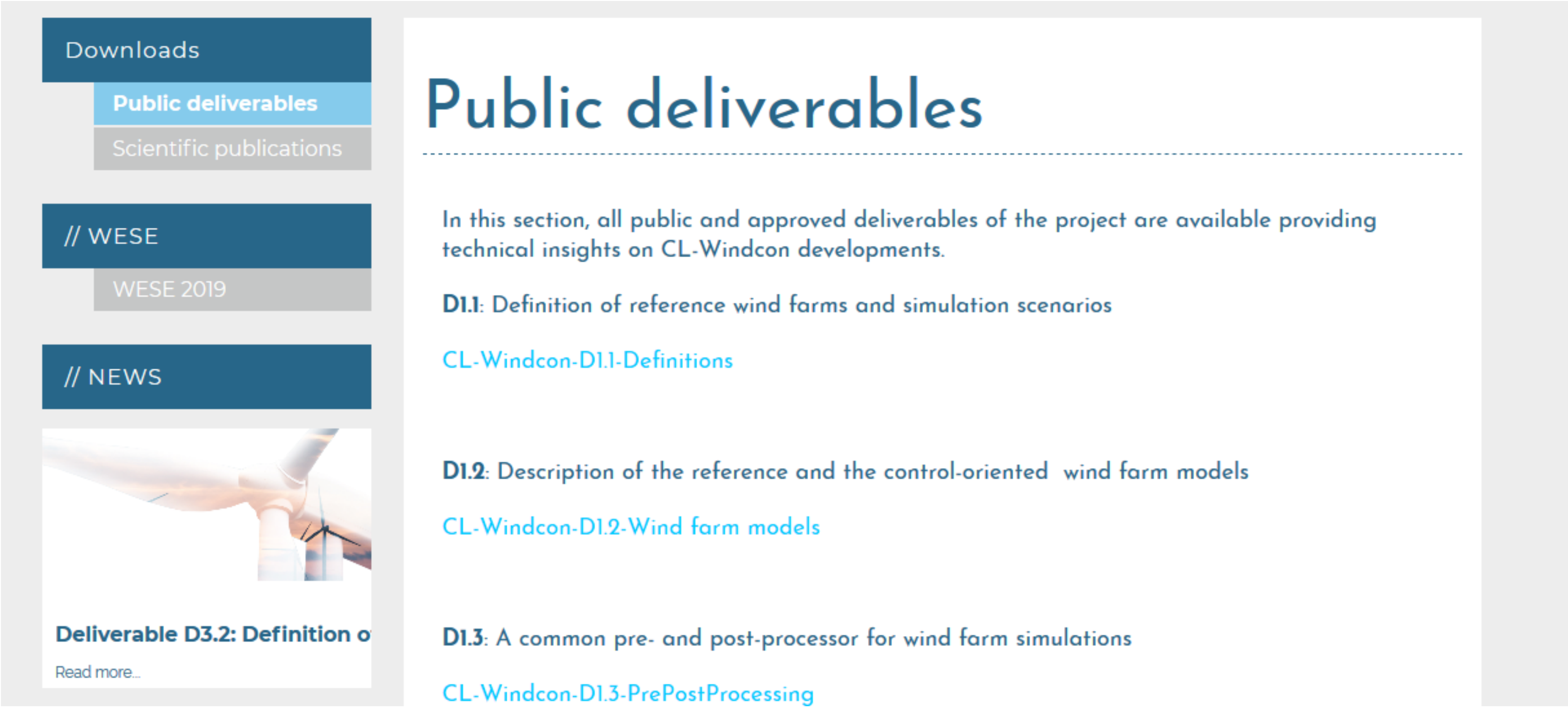
AVAILABLE MATERIALS

PUBLIC DELIVERABLES & SCIENTIFIC PUBLICATIONS

- You can consult CL-Windcon public deliverables (up to 15 deliverables so far)

  http://www.clwindcon.eu/public-deliverables/



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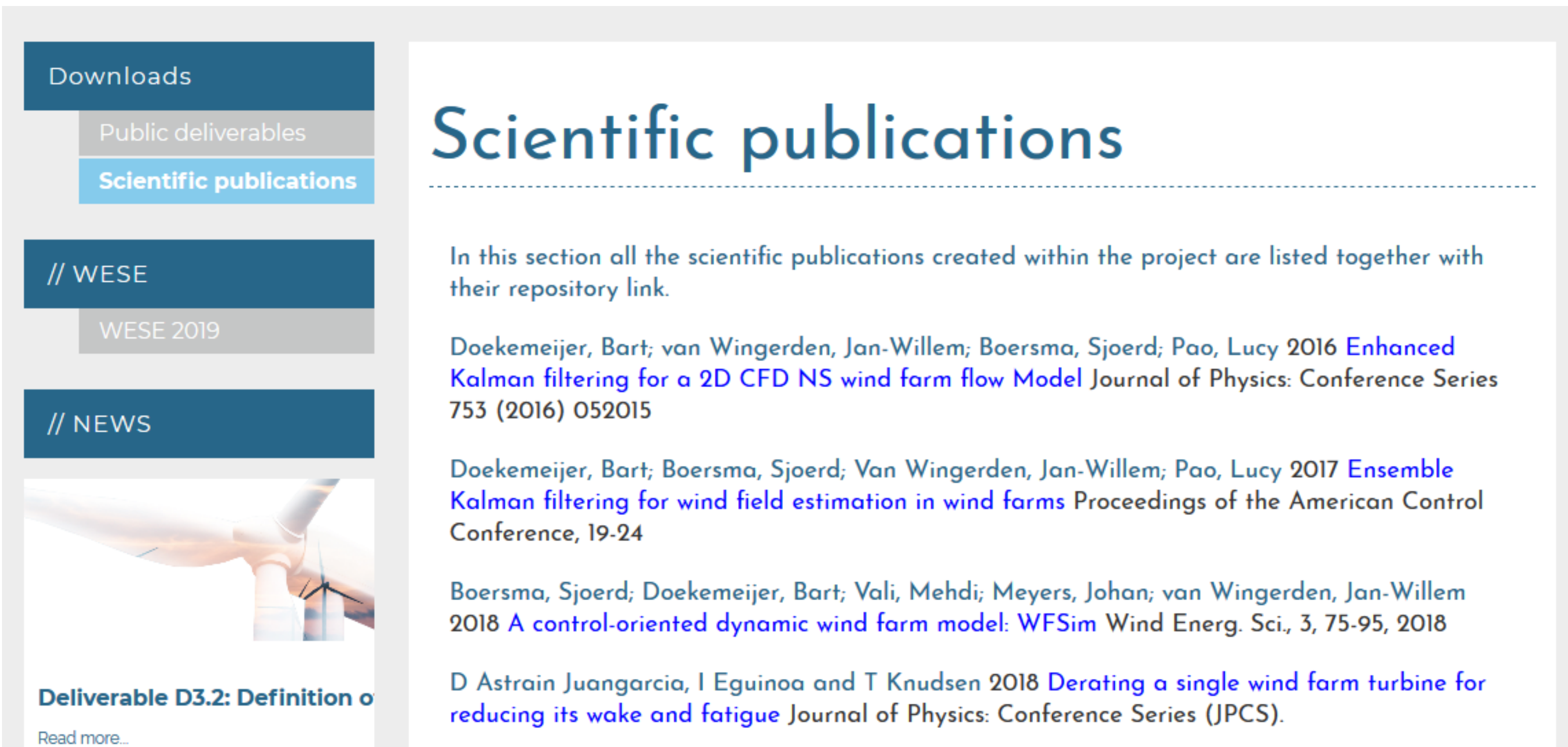
AVAILABLE MATERIALS

PUBLIC DELIVERABLES & SCIENTIFIC PUBLICATIONS

- You can also download the project open access scientific publications

http://www.clwindcon.eu/publications/


Downloads

Public deliverables

Scientific publications

// WESE

WESE 2019

// NEWS

Deliverable D3.2: Definition o

Read more...

Scientific publications

In this section all the scientific publications created within the project are listed together with their repository link.

Doekemeijer, Bart; van Wingerden, Jan-Willem; Boersma, Sjoerd; Pao, Lucy 2016 Enhanced Kalman filtering for a 2D CFD NS wind farm flow Model Journal of Physics: Conference Series 753 (2016) 052015

Doekemeijer, Bart; Boersma, Sjoerd; Van Wingerden, Jan-Willem; Pao, Lucy 2017 Ensemble Kalman filtering for wind field estimation in wind farms Proceedings of the American Control Conference, 19-24

Boersma, Sjoerd; Doekemeijer, Bart; Vali, Mehdi; Meyers, Johan; van Wingerden, Jan-Willem 2018 A control-oriented dynamic wind farm model: WFSim Wind Energ. Sci., 3, 75-95, 2018

D Astrain Juangarcia, I Eguinoa and T Knudsen 2018 Derating a single wind farm turbine for reducing its wake and fatigue Journal of Physics: Conference Series (JPCS).

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AVAILABLE MATERIALS

OPEN SCIENCE

- Some **tools** developed (models, wind turbine controller), available on **GitHub**

- Different **research data** will be provided in **Open Access** to the community:
  - High-fidelity simulations
  - Wind tunnel testing measurements
  - Results from the field testing

- For the **high fidelity simulation databases publicly available**:
  - Precursors & documented simulations
  - Available upon request: clwindconftp@cener.com
  - Subject: "Cl-Windcon FTP data access request"

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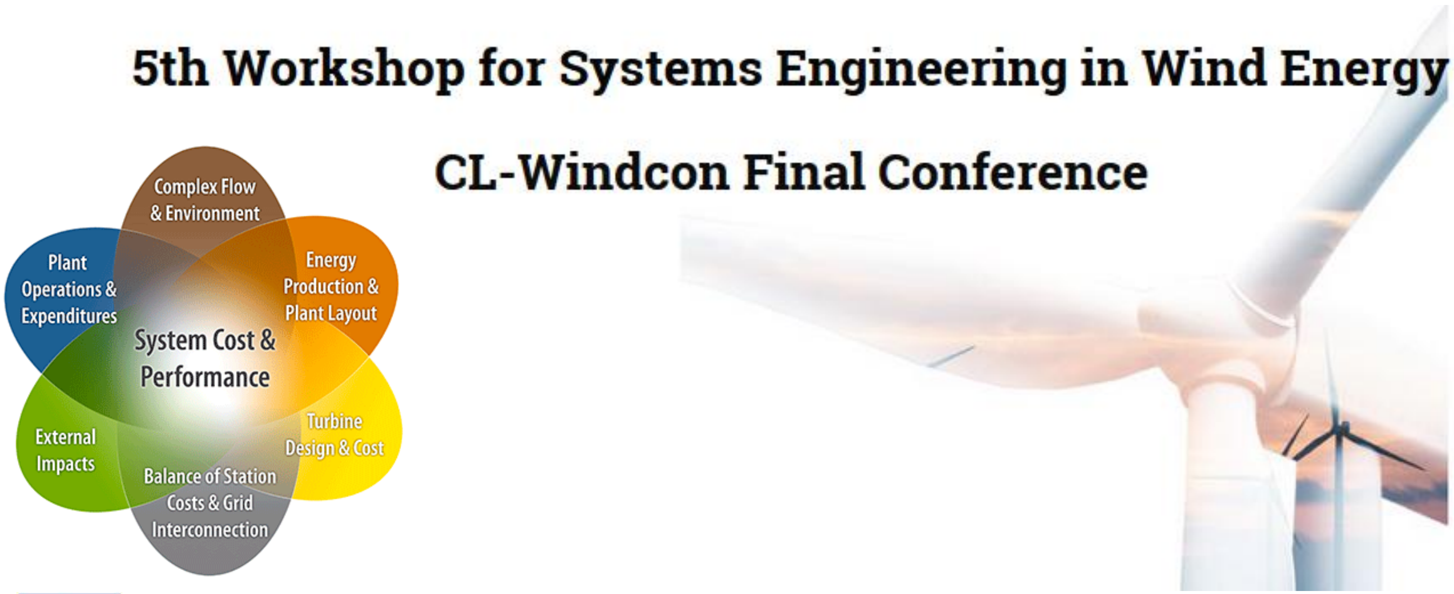
CL-WINDCON FINAL CONFERENCE

- Jointly held with the **5th Workshop for Systems Engineering in Wind Energy**
- **2nd – 4th October 2019, Pamplona (Spain)**
- Co-hosted by partnering of CENER, NREL & DTU Wind Energy
- Attendance free of charge and by invitation only in the early registration stage (until 15th July), after which promotion to a wider audience will be performed.
- Contact: wese2019@cener.com

http://www.clwindcon.eu/wese2019/



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AND ALL THIS IS BEING POSSIBLE THANKS TO...

the great commitment and collaboration of CL-Windcon partners

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THANK YOU!

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