CL-Windcon

Closed Loop Wind Farm Control

CL-Windcon, a control project approach

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CENER

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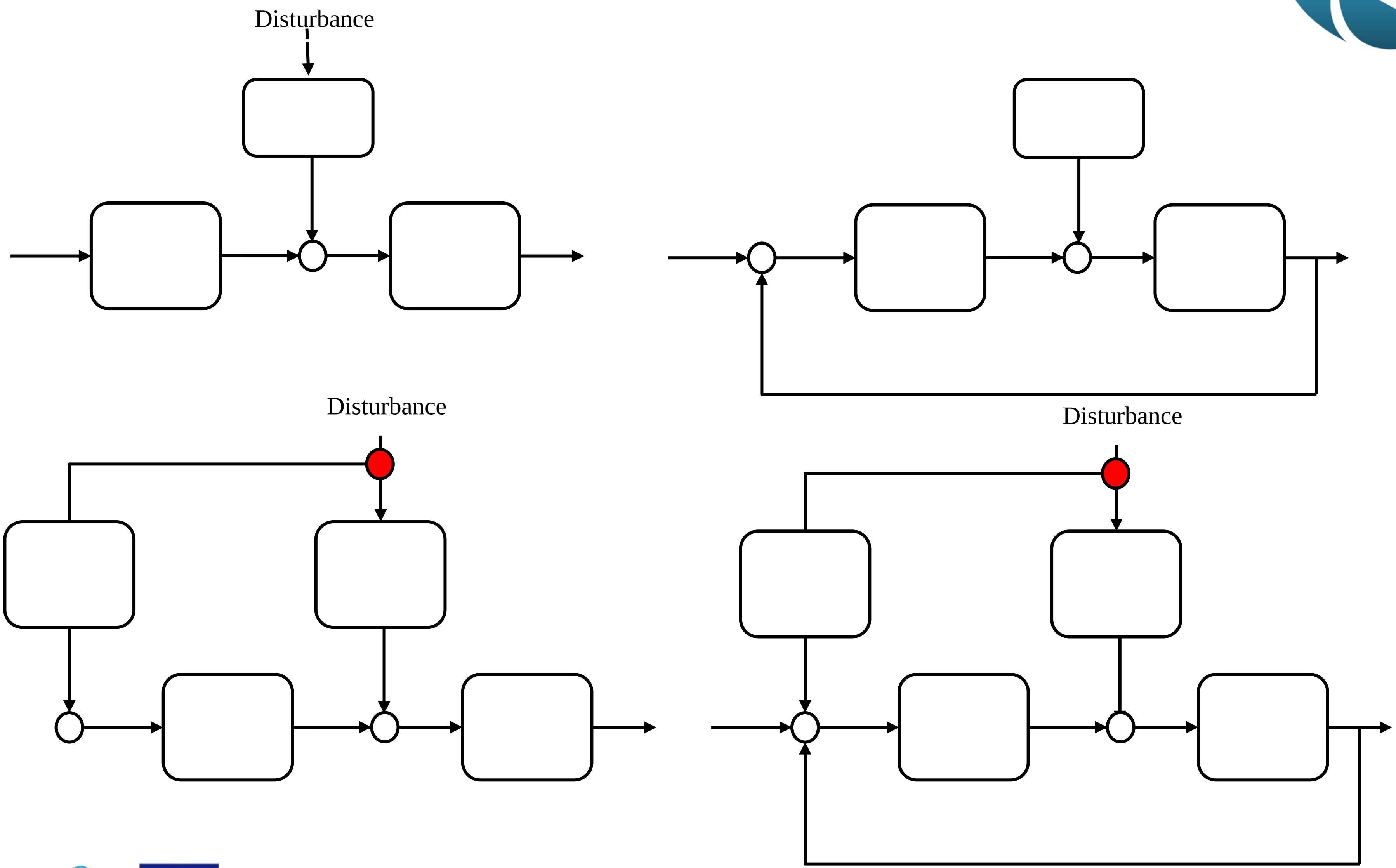
A CONTROL PROJECT APPROACH



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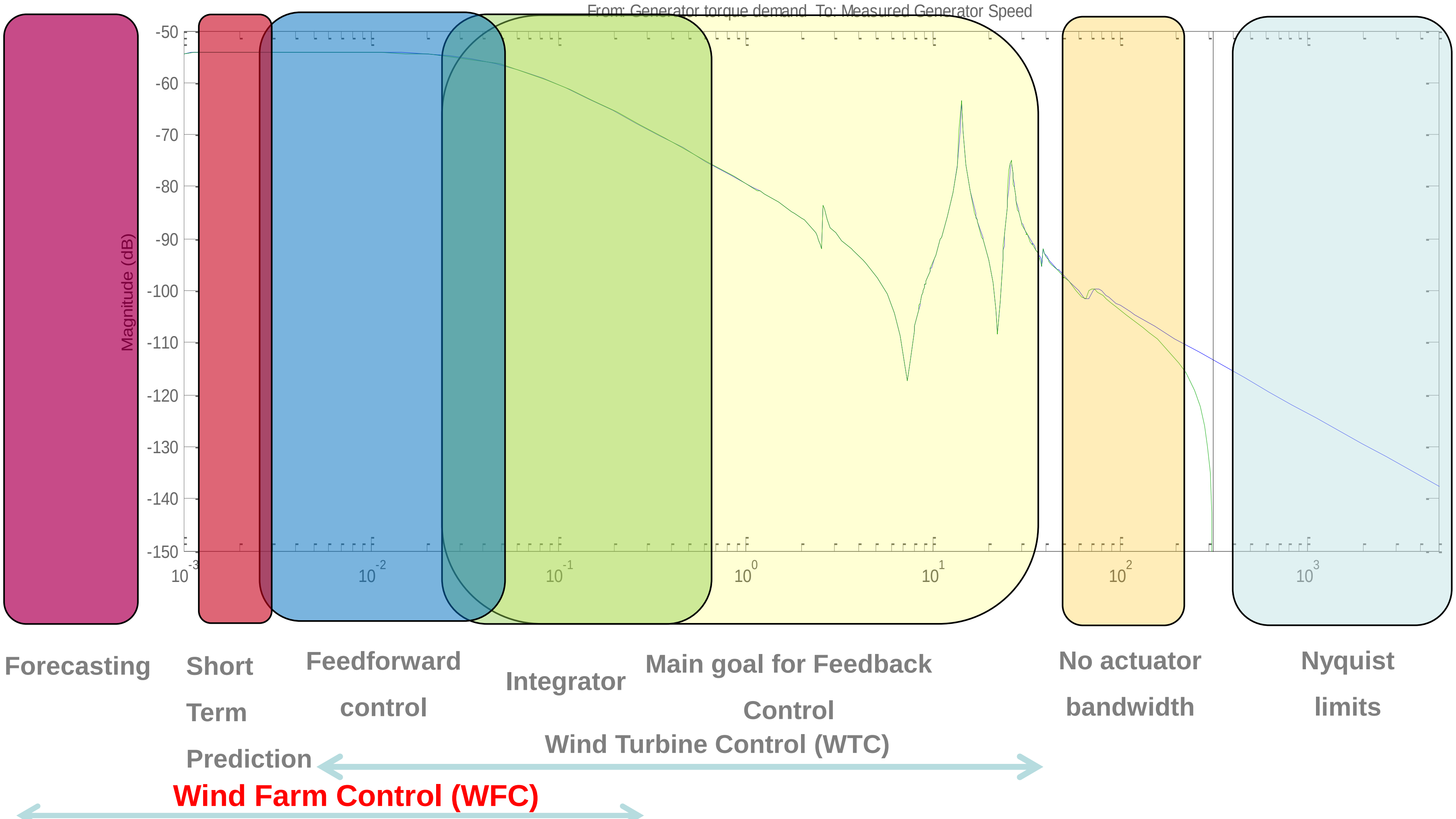

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A CONTROL PROJECT APPROACH

WP1- Modelling

WP 1.1
Framework definition

WP 1.2
Multi-fidelity modelling

WP 1.3
Evaluation and Classification of wind farm models

WP2 - Wind Farm Flow Control technologies

WP 2.1 – Induction based control

WP 2.2 – Wake redirection control

WP 2.3 – WT technologies for Wind Farm Control

WP 2.4 – Integrated Wind Farm Control

WP3 -Demonstration and Validation

WP 3.1 – Demonstration by simulation

WP 3.2 – Demonstration by wind Tunnel Tests

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WP4: Feasibility analysis

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WP 4.5 – Economics of advanced integrated controls (LCOE)
WP4.6 –Impact on STANDARDS

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A CONTROL PROJECT APPROACH

- **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

- **Following H2020 philosophy " As open as possible"**

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A CONTROL PROJECT APPROACH

- CL-Windcon (Closed- loop Wind Farm Control)
  - Duration: 36 months (2016/11/01 – 2019/10/31)
  - Funding: 4.9 MEUR
  - Generated Budget: 5M€ in a super computer centre
  - 15 partners from 6 countries
  - Coordinator: CENER

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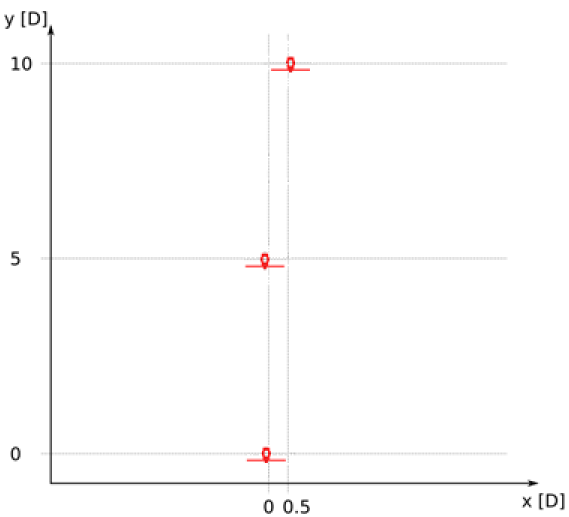
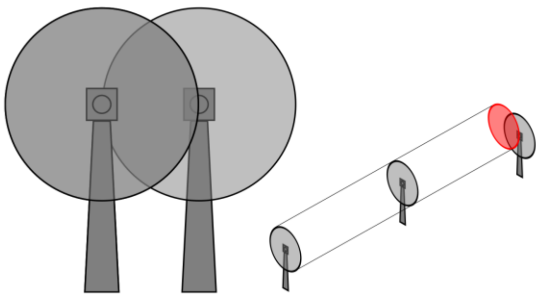
A CONTROL PROJECT APPROACH

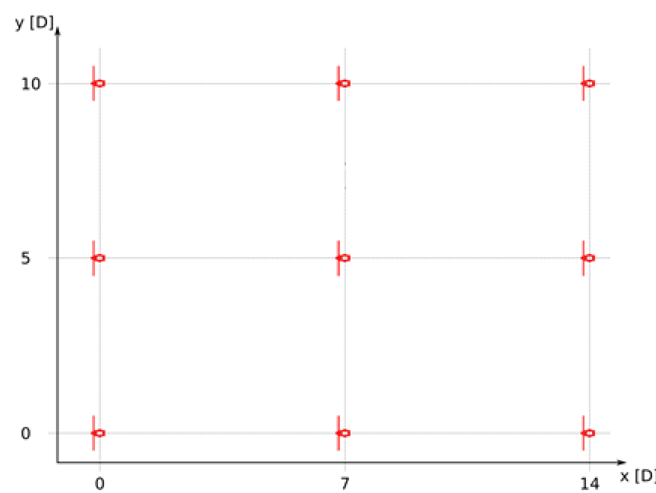
OUTCOMES

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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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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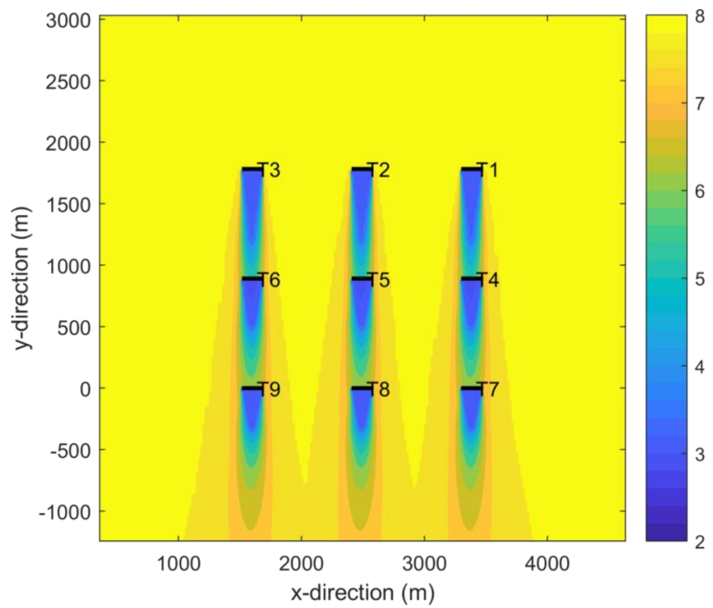
OUTCOMES

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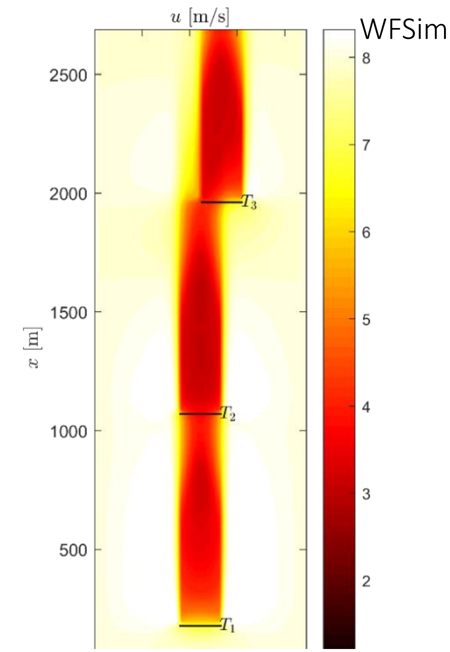
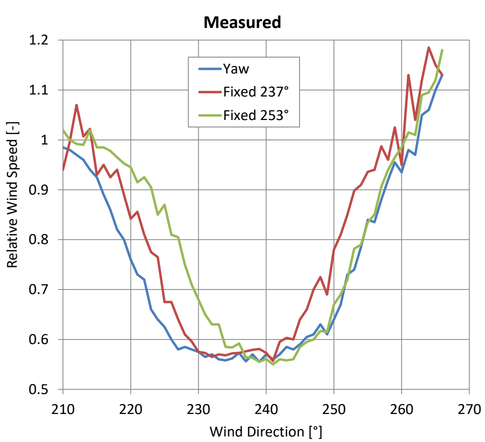
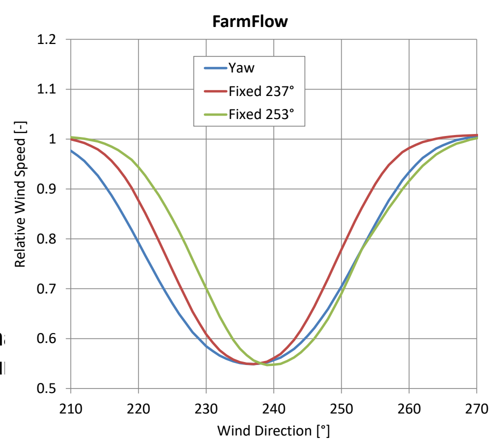
D1.2 - DESCRIPTION OF REFERENCE & CONTROL-ORIENTED WIND FARM MODELS

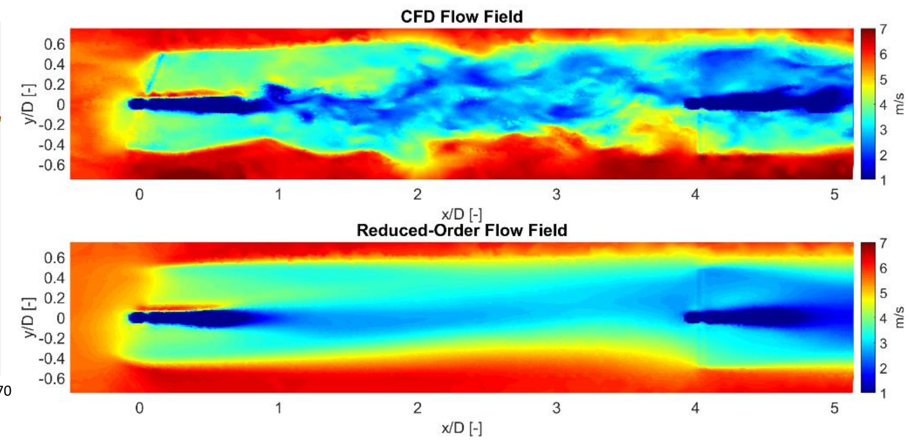
- **Steady-state models**
  - Low complexity & computational cost
  - High number of tuning parameters
  - Time-averaged dynamics (minutes-scale)
- **Control-oriented dynamical models**
  - Increase in complexity & computational cost
  - Often derived from Navier-Stokes equations

    $\Rightarrow$ fewer tuning parameters
  - Dynamics on a second-to-second scale









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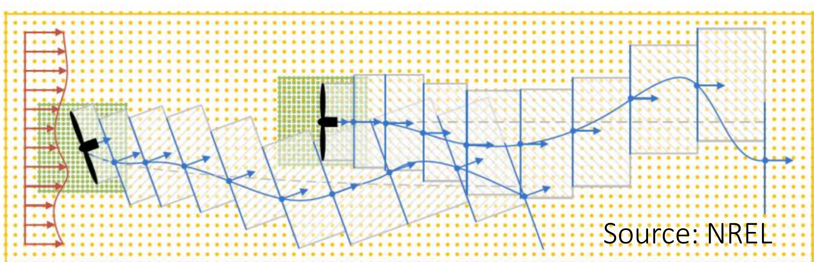
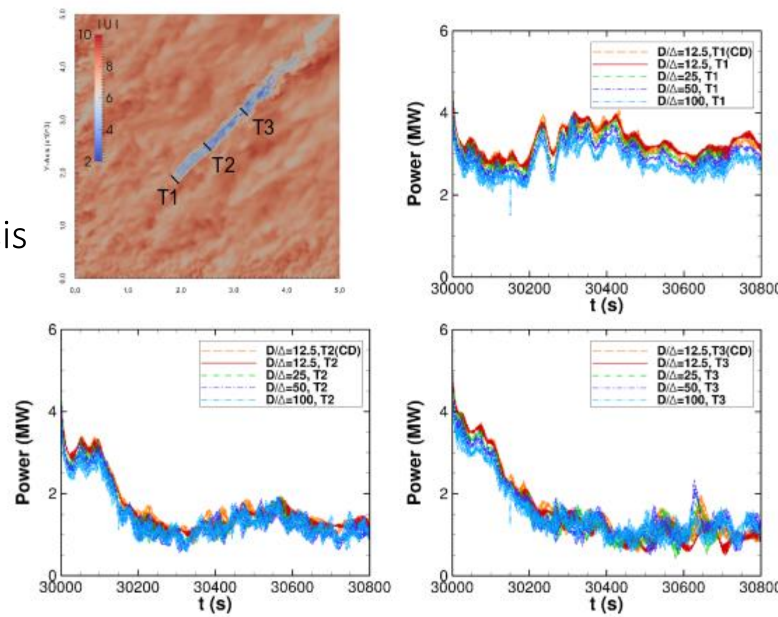
OUTCOMES

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





Source: NREL

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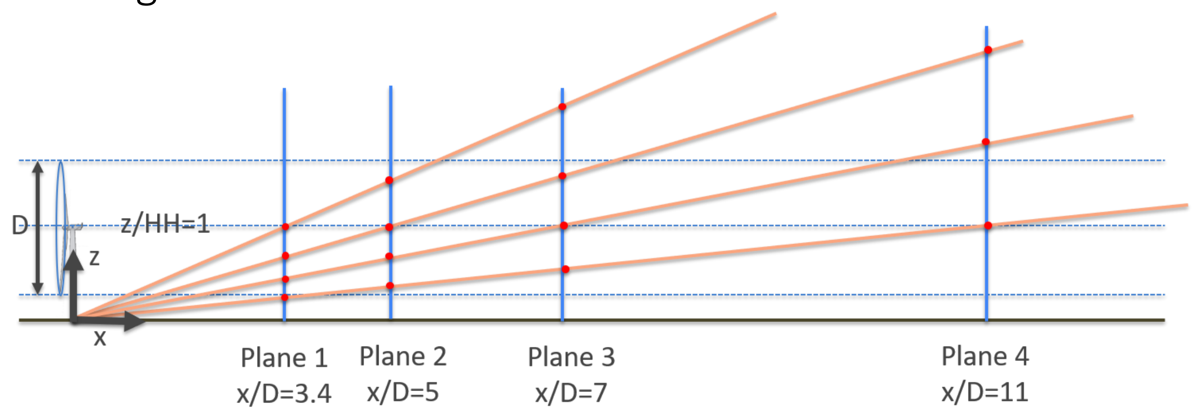
OUTCOMES

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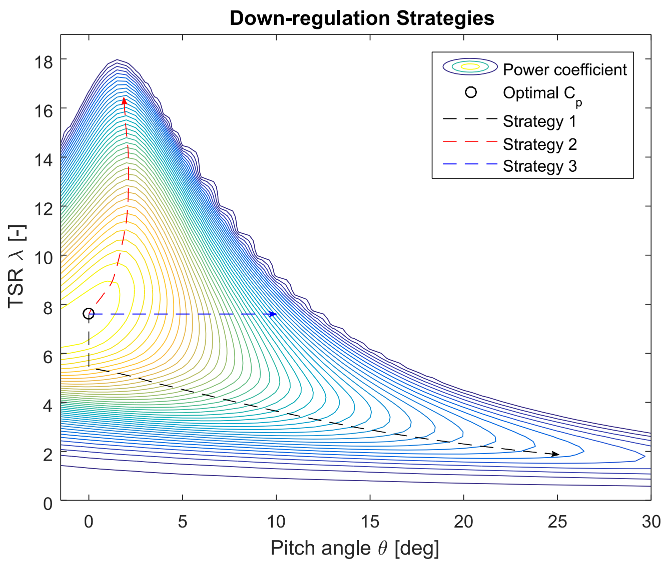
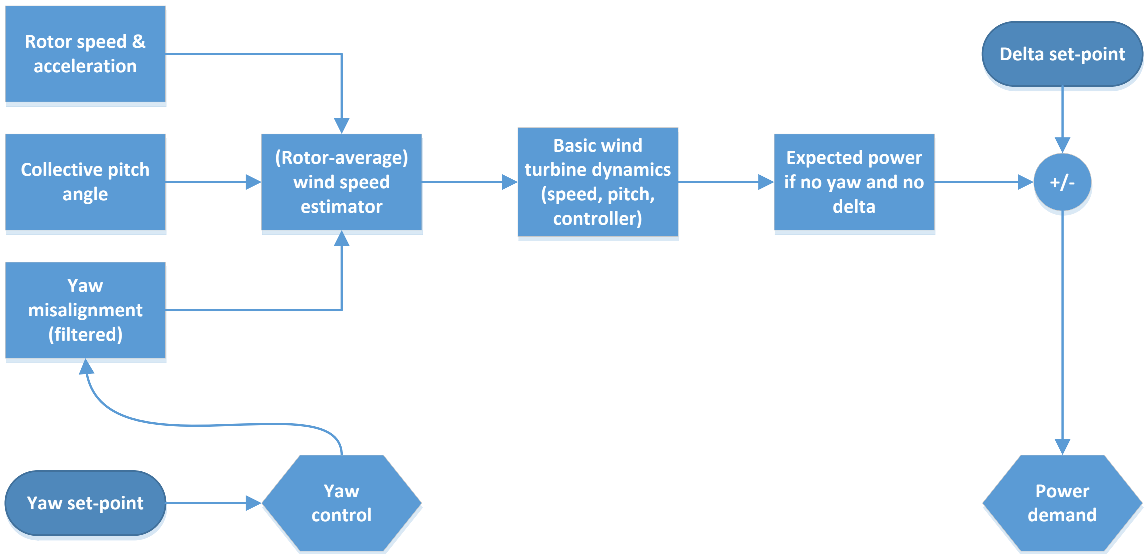
D2.1 – MINIMAL LOADING WT DERATING AND ACTIVE YAW CONTROLLERS

- 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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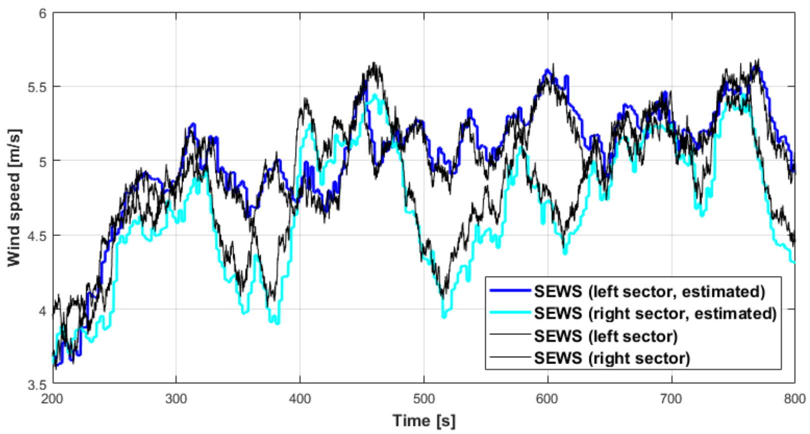
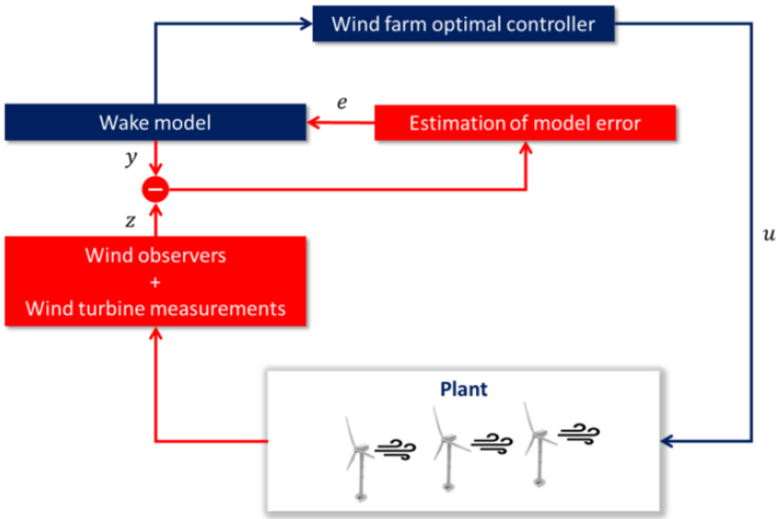
D2.2 – METHODOLOGY FOR ACTIVE LOAD CONTROL

- 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
  - Wake detection
  - Wake position and deficit estimation by online model update





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OUTCOMES

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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OUTCOMES

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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OUTCOMES

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**

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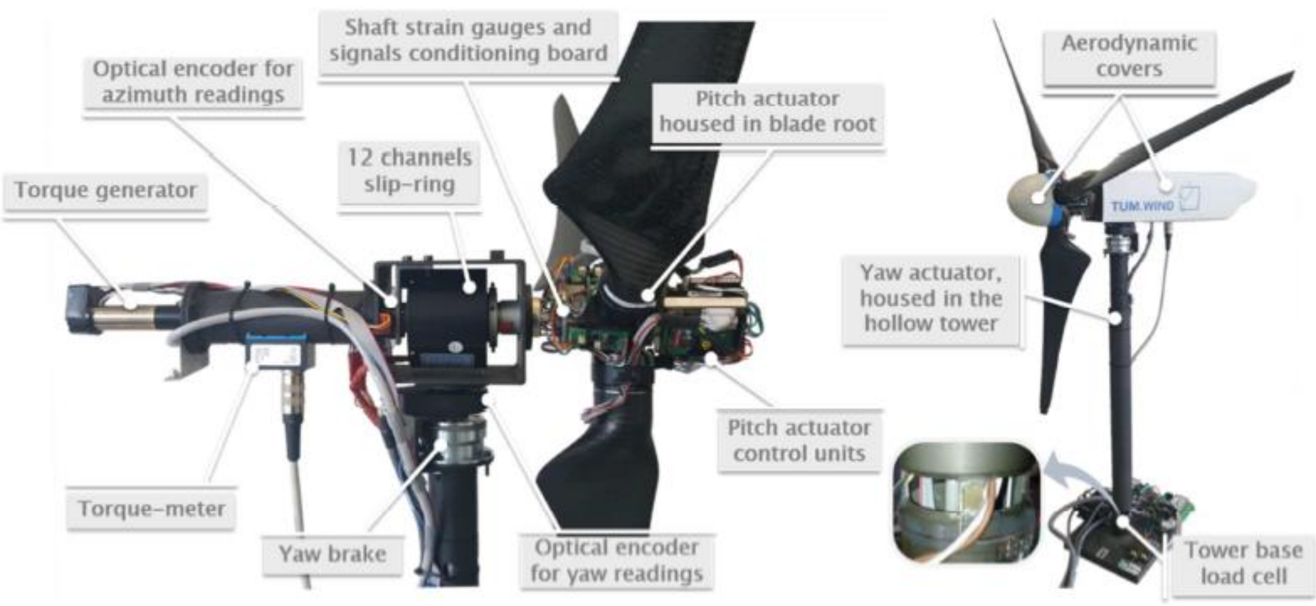
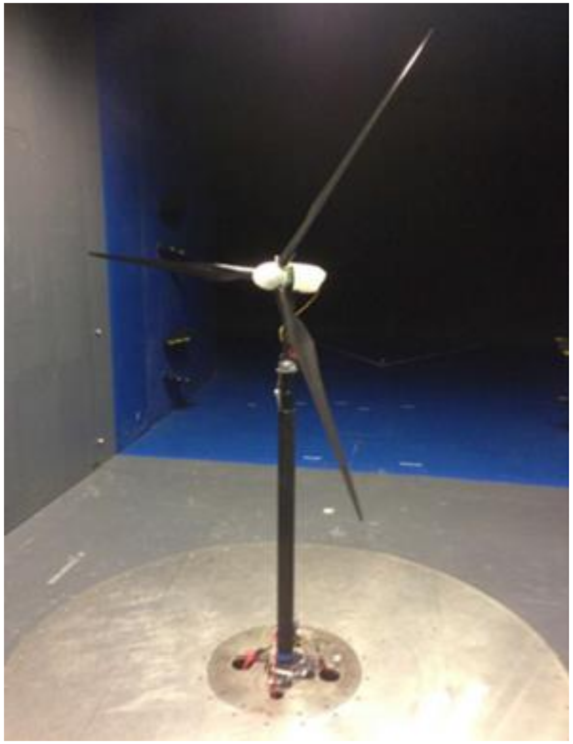
OUTCOMES

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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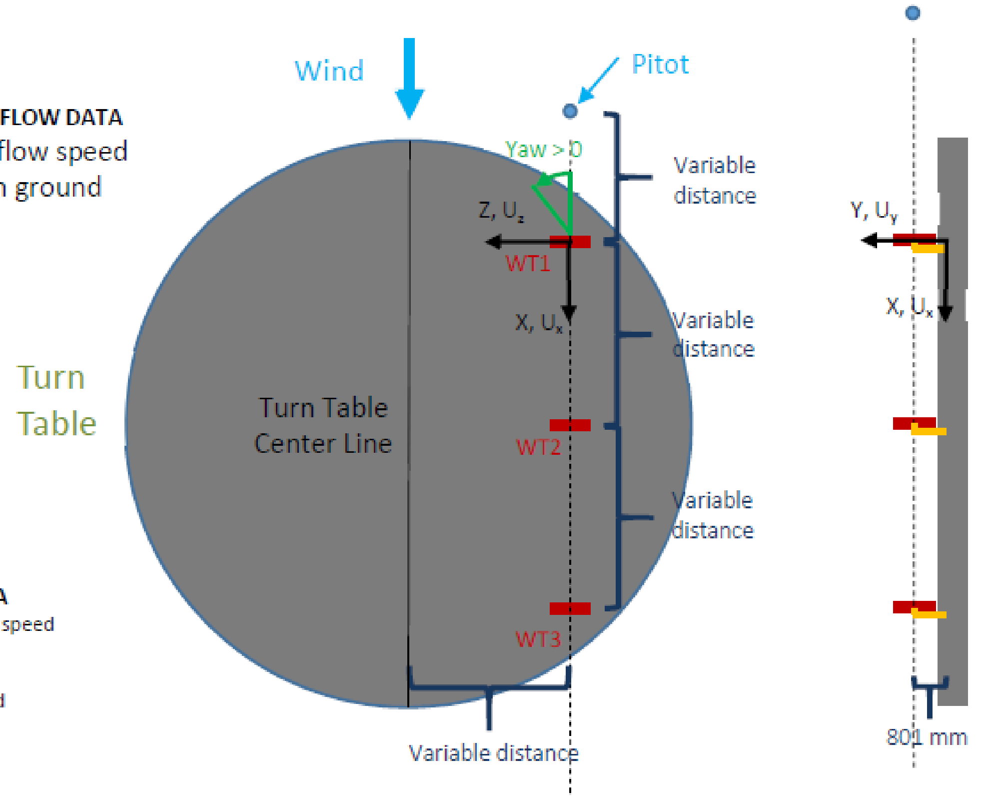
D3.1 – DEFINITION OF WIND TUNNEL TESTING CONDITIONS

- Definition of **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

REF. FRAME FOR FLOW DATA
x: Aligned with flow speed
y: Distance from ground
z: Lateral



FLOW DATA
U_x : Longitudinal flow speed
U_y : Upflow speed
U_z : Lateral flow speed

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OUTCOMES

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

- 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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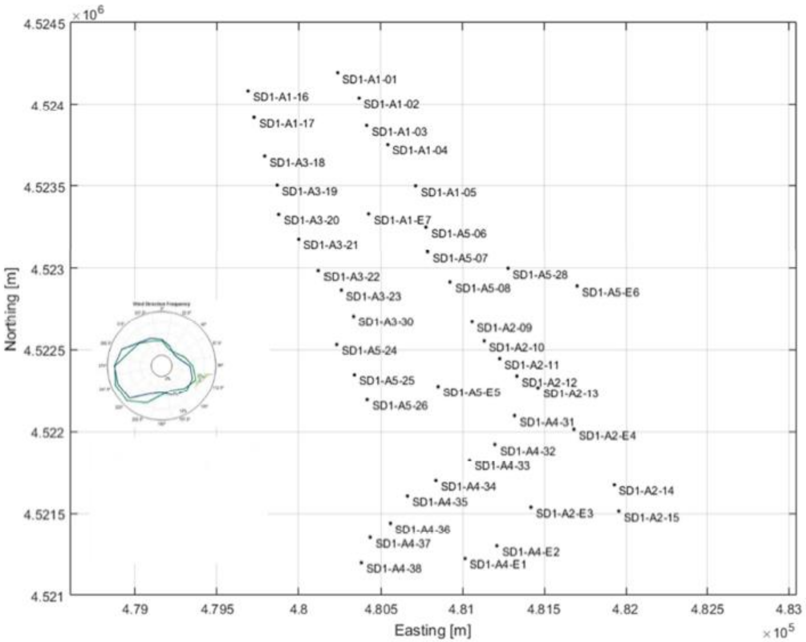
OUTCOMES

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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OUTCOMES

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)

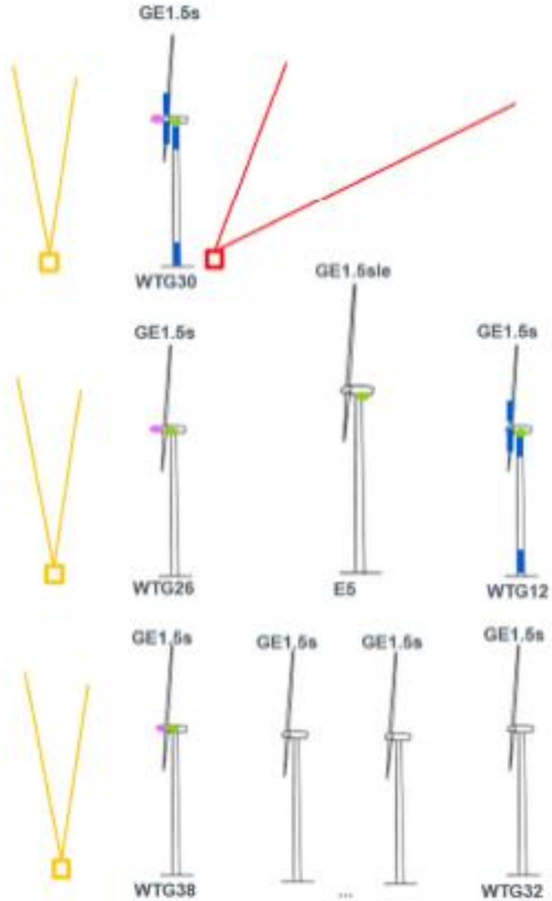
- vertical lidar and iSpin (TBD) for free stream measurement
- Blade & tower loads instrumentation
- scanning lidar for wake characterization
- yaw sensor
- optional: electrical power measurement
- optional: nacelle accelerometer box

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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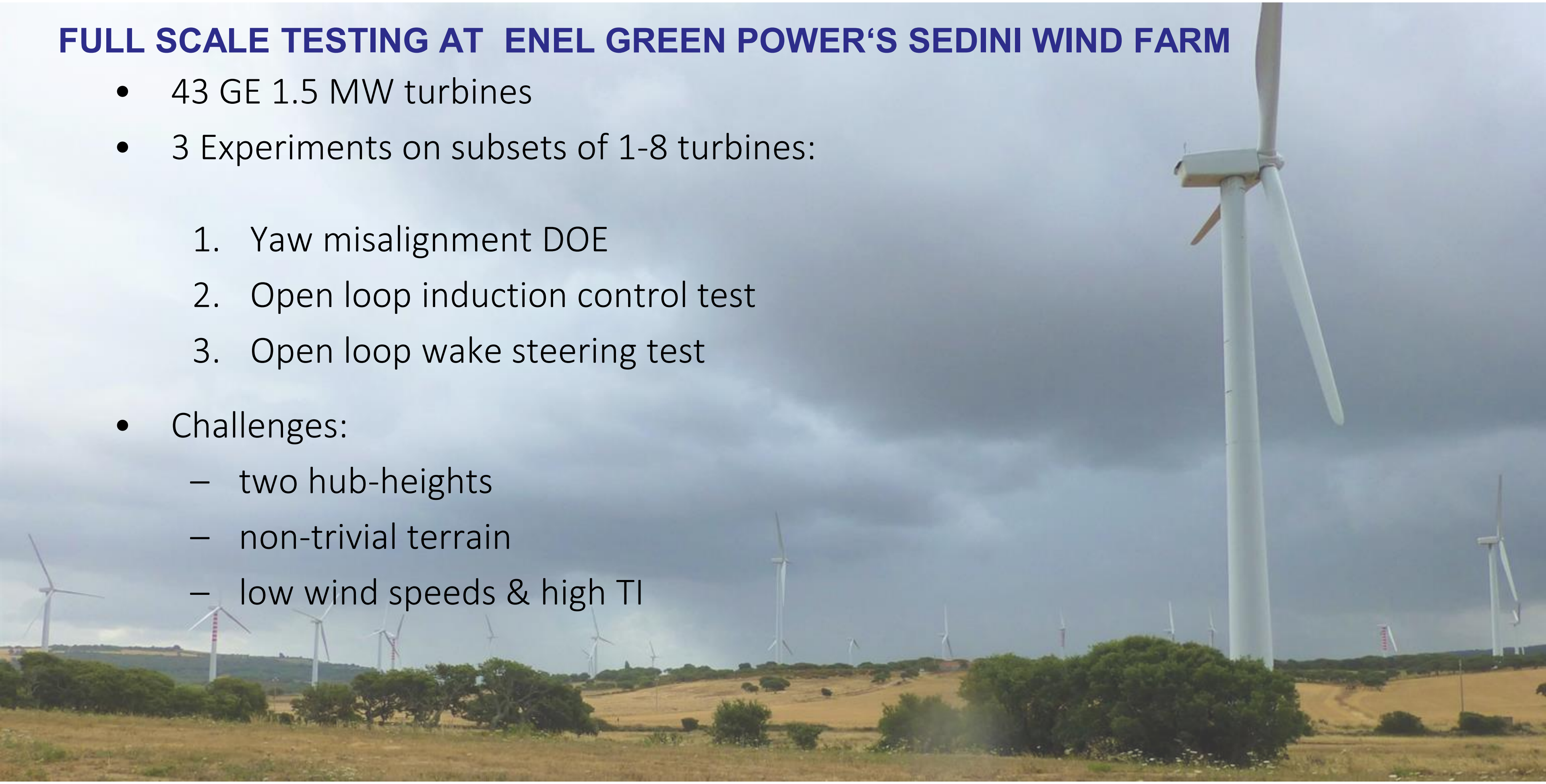

FULL SCALE TESTING AT ENEL GREEN POWER‘S SEDINI WIND FARM

- 43 GE 1.5 MW turbines
- 3 Experiments on subsets of 1-8 turbines:

  1. Yaw misalignment DOE
  2. Open loop induction control test
  3. Open loop wake steering test

- Challenges:
  – two hub-heights
  – non-trivial terrain
  – low wind speeds & high TI

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FULL SCALE TESTING AT ENEL GREEN POWER'S SEDINI WIND FARM

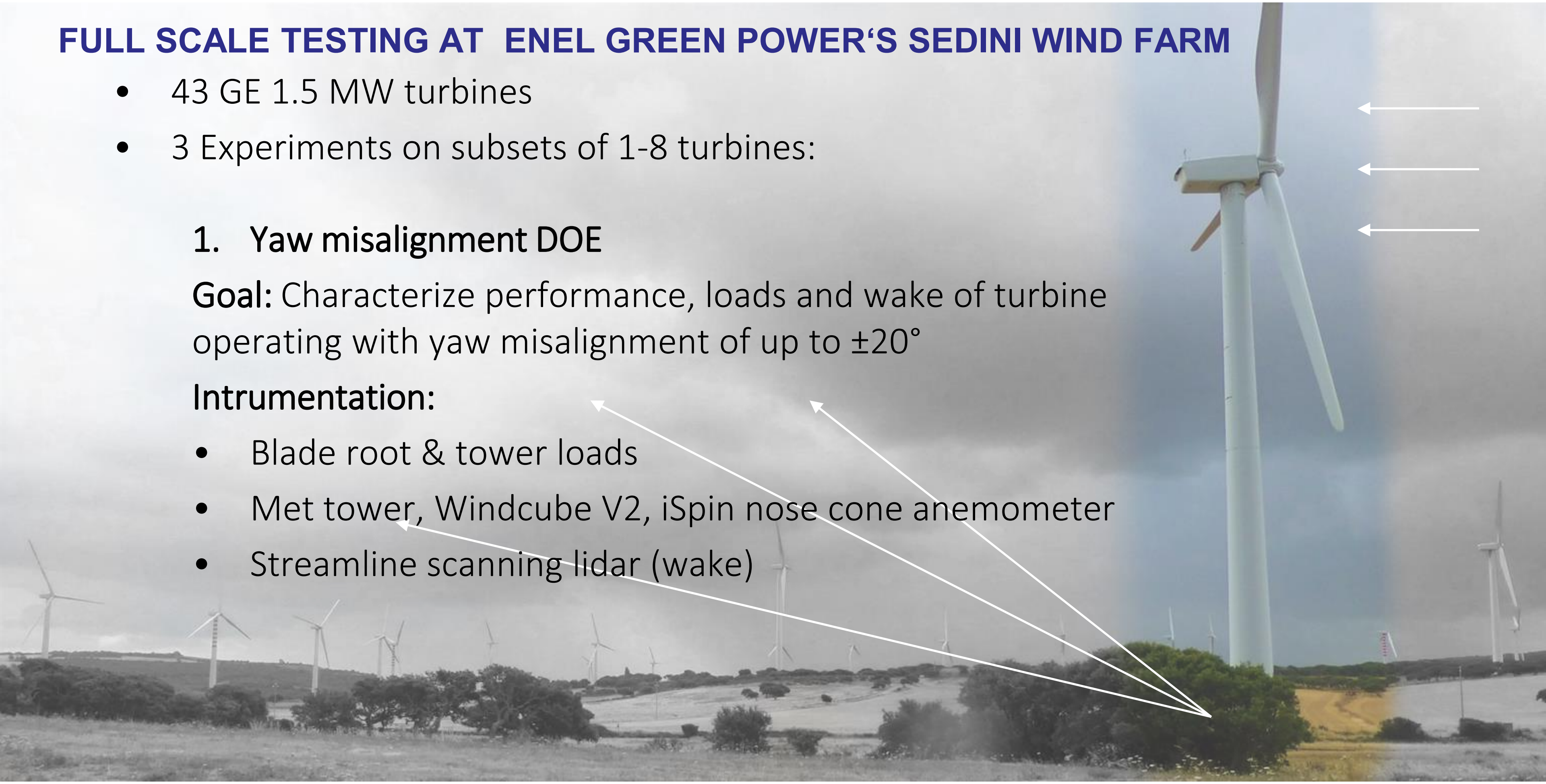
- 43 GE 1.5 MW turbines
- 3 Experiments on subsets of 1-8 turbines:

1. Yaw misalignment DOE

Goal: Characterize performance, loads and wake of turbine operating with yaw misalignment of up to ±20°

Intrumentation:

- Blade root & tower loads
- Met tower, Windcube V2, iSpin nose cone anemometer
- Streamline scanning lidar (wake)



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FULL SCALE TESTING AT ENEL GREEN POWER'S SEDINI WIND FARM

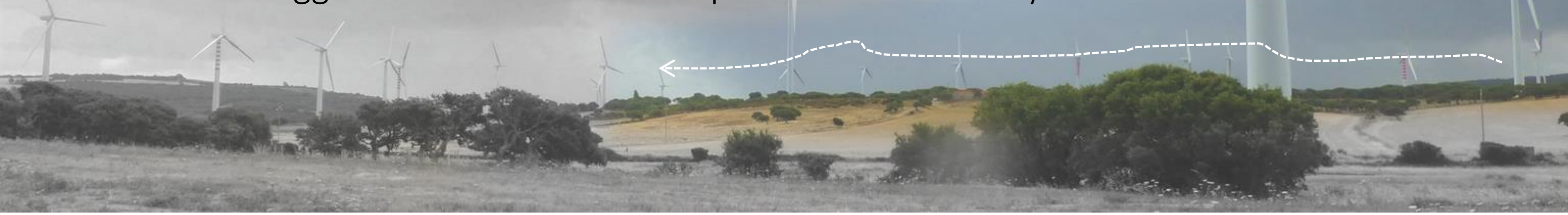
- 43 GE 1.5 MW turbines
- 3 Experiments on subsets of 1-8 turbines:

2. **Open loop induction control test**

Goal: Demonstrate induction control on group of 7 turbines

Approach:

- Look-up-tables of optimized setpoints for each turbine as function of wind speed, direction and TI
- Most upstream turbine unchanged as reference
- Toggle between baseline & optimized mode every 35 min



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FULL SCALE TESTING AT ENEL GREEN POWER'S SEDINI WIND FARM

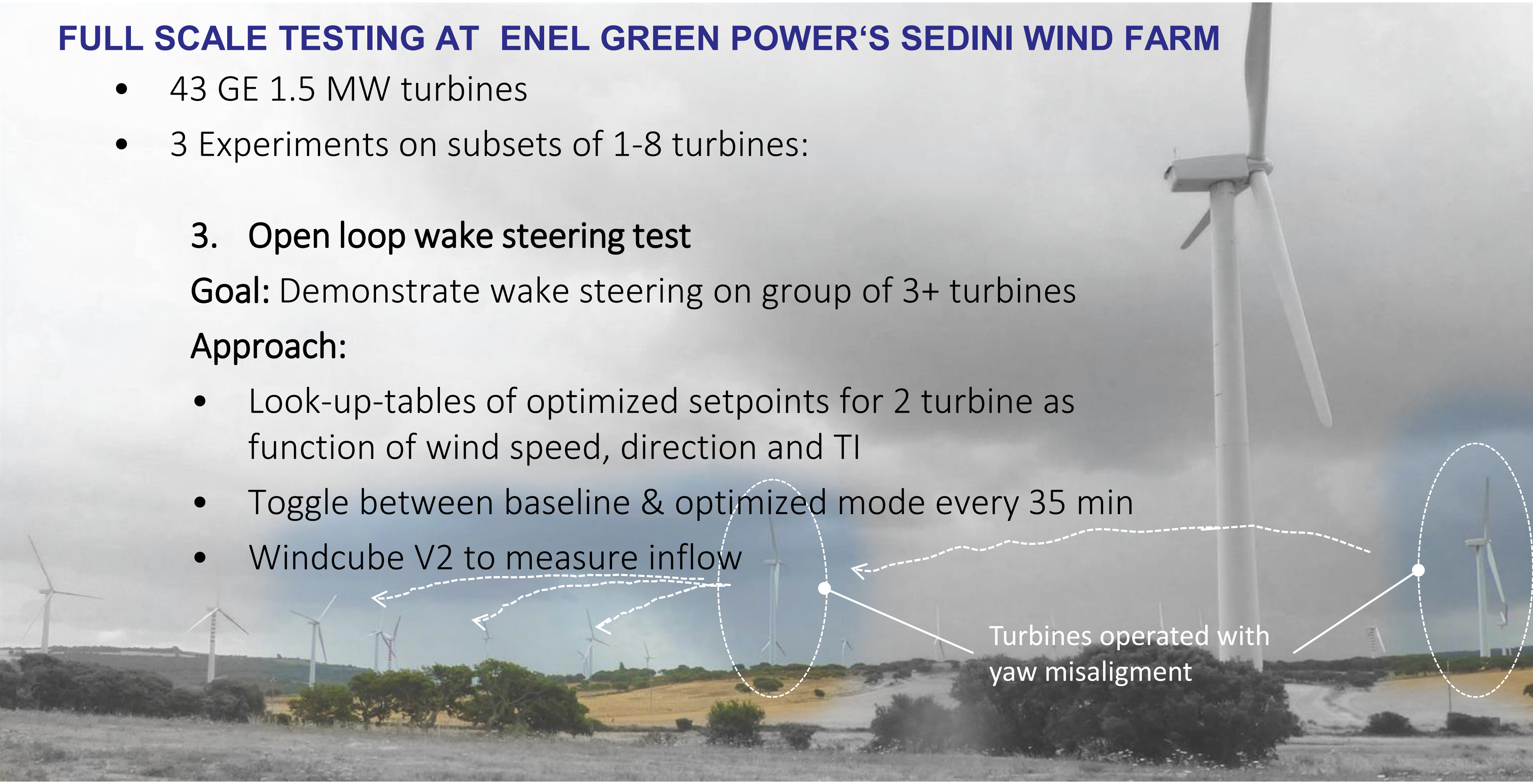
- 43 GE 1.5 MW turbines
- 3 Experiments on subsets of 1-8 turbines:

3. Open loop wake steering test

Goal: Demonstrate wake steering on group of 3+ turbines

Approach:

- Look-up-tables of optimized setpoints for 2 turbine as function of wind speed, direction and TI
- Toggle between baseline & optimized mode every 35 min
- Windcube V2 to measure inflow



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OUTCOMES

FULL SCALE TESTING AT ENEL GREEN POWER'S SEDINI WIND FARM

STATUS AND PRELIMINARY RESULTS

Data capture for all 3 experiments still ongoing

1. **Yaw misalignment DOE**
   Capturing data since mid **May 2019**
   Data so far used to assess & calibrate **yaw deviation demand vs achieved offset & TI estimation**
2. **Open loop induction control test**
   Capturing data since mid **July 2019**
   Data count from right wind speed & direction range **still low**
   Results not yet statistically significant, but showing **encouraging trends**
3. **Open loop wake steering test**
   Capturing data since mid **August 2019**
   Data count from right wind speed & direction range **still low** for meaningful analysis

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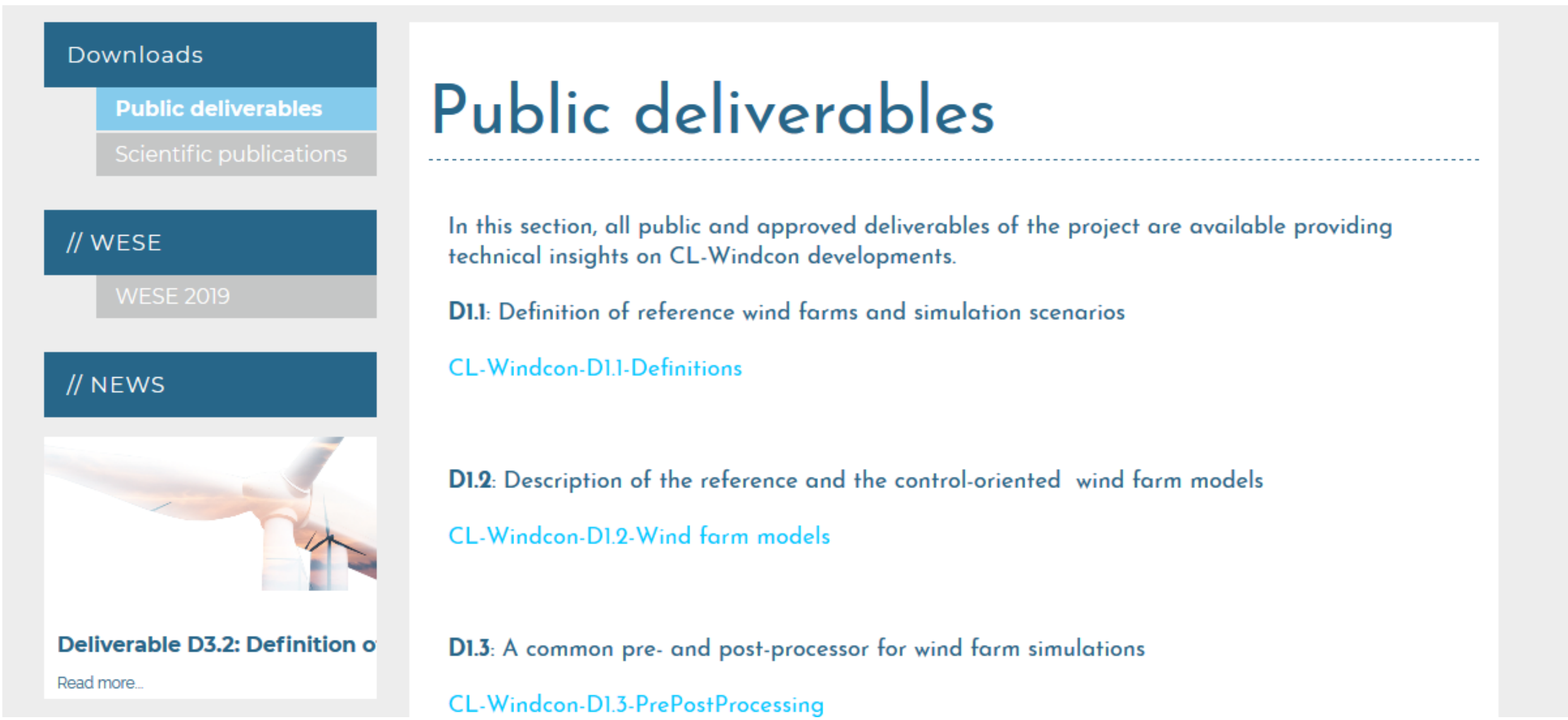
PUBLIC DELIVERABLES & SCIENTIFIC PUBLICATIONS

- You can consult CL-Windcon public deliverables

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



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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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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 campaign at Sedini

- Available upon request: clwindconftp@cener.com

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AND ALL THIS HAS BEING POSSIBLE THANKS TO...

... AMONG OTHERS

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CENER | CENTRO NACIONAL DE ENERGÍAS RENOVABLES

ADItech

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THANK YOU!

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