



ADVANCING WIND PLANT PERFORMANCE AND LOAD PREDICTION

A TOOL CHAIN TO DESIGN, OPERATE AND MAINTAIN
SURFACE AND AIRBORNE WIND PLANTS

INNOVATION HANDBOOK - SEPTEMBER 2026



Funded by
the European Union

Table of Contents

EXECUTIVE SUMMARY	3
INTRODUCTION	
WHY WE NEED TO IMPROVE WIND PLANTS	5
THE MERIDIONAL INNOVATION FRAMEWORK	
A DATA, KNOWLEDGE AND TOOL CHAIN	7
BUILDING THE KNOWLEDGE, DATA AND TOOL CHAIN	
THE WINDLAB KNOWLEDGE AND DATA HUB	10
WIND FIELD MODELLING AND INFLOW GENERATION	12
MODEL VALIDATION AND PERFORMANCE ASSESSMENT	14
PERFORMANCE, LOADING AND OPERATIONAL APPLICATIONS	15
TOPDESIGN TOOL CHAIN	17
ADVANCED VISUALISATION AND USER INTERACTION	18
APPLICATIONS AND IMPACTS	
TEST CASES	20
BENEFITS FOR THE WIND ENERGY COMMUNITY	22
LESSONS LEARNT AND FUTURE PROSPECTS	
KEY LESSONS FROM MERIDIONAL	24
BEYOND THE PROJECT	26
CONCLUSIONS	28
LIST OF ONLINE RESOURCES	29

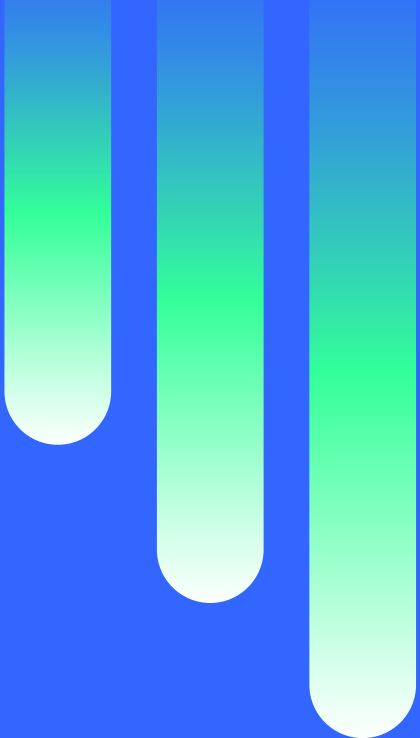
The **MERIDIONAL** project has developed an integrated knowledge and data hub and a validated, **open-source tool chain** to assess the performance and structural loads of onshore, offshore and airborne wind plants.

Built around **inflow generation, validation, performance/loading and test-case demonstration**, the tool-chain – including the WindLab data hub, TopDesign integration platform and Vistle visualisation software – was validated on five test cases spanning onshore, offshore and airborne wind energy at scales from 100 kW to 30 MW.

The project delivered open-source tools, data and guidelines that reduce uncertainty and increase **confidence in wind plant design, supporting industry, researchers and policymakers** towards leaner, more reliable and cost-effective wind energy.

This handbook is intended for two main audiences: the **research community**, for whom it offers a foundation to build further research on MERIDIONAL's models, data and tools; and **industry**, for direct application in the design, operation and optimisation of wind plants.

MERIDIONAL was funded by the EU's Horizon Research and Innovation programme under GA n°101084216 and has a budget of roughly €6m. Running from October 2022 to September 2026, the project enabled the efficient and accurate assessment of the performance and loads experienced by onshore, offshore, and airborne wind energy systems.



1

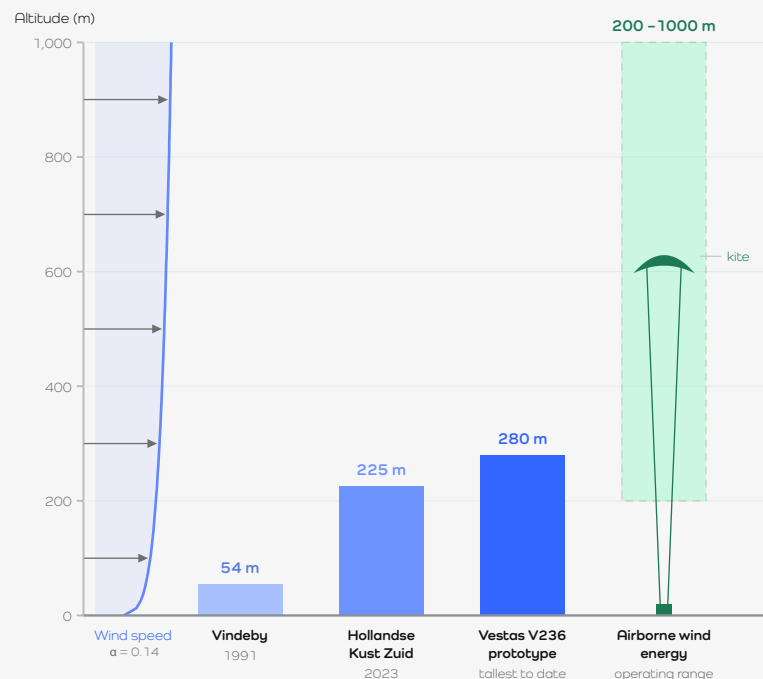
INTRODUCTION

WHY WE NEED TO IMPROVE WIND PLANTS

As the sector deploys ever-larger turbines and pioneers airborne wind energy devices to harvest stronger winds at higher altitudes, it faces **critical challenges: understanding complex inflow conditions and loads on wind farms and airborne systems, reducing uncertainty in performance predictions, and combining measurements and models** of different fidelities to accurately and efficiently forecast loads and performance.

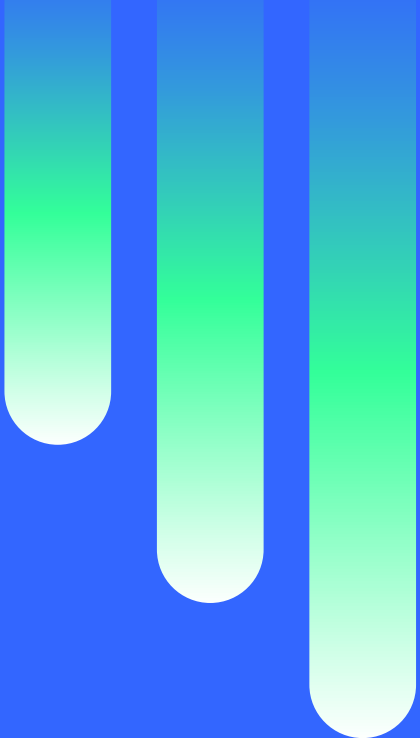
MERIDIONAL aimed to respond to these challenges with an integrated knowledge and data hub and a validated tool chain, built on an open-source platform that supports the **design, operation and maintenance of wind power plants**. By combining advanced modelling, diverse data sources and innovative visualisation, the project enabled industry, researchers and policymakers to assess wind plant performance and structural loading more accurately – contributing to leaner designs, optimised plants and a decarbonised energy system.

HARVESTING STRONGER WIND AT GREATER HEIGHTS



Maximum height reached by wind energy technologies, from the first offshore turbines to airborne systems operating between 200 and 1000 m.

Sources: Vindeby (1991), Bonus B35/450, 54 m total height, Danish Energy Agency decommissioning plan; Hollandse Kust Zuid (2023), 125 m hub height and 200 m rotor; Vestas V236-15.0 MW prototype at Østerild, 280 m total height (Vestas). Wind speed profile shown as a power law and is illustrative, not site-specific.



2

THE MERIDIONAL INNOVATION FRAMEWORK

A DATA, KNOWLEDGE, AND TOOL CHAIN

MERIDIONAL's innovation lies in an **integrated approach that connects data, models and tools into a single, coherent tool-chain for assessing the performance and loads of onshore, offshore and airborne wind energy systems**. Rather than treating inflow characterisation, validation and performance assessment as separate exercises, the project links them through a shared knowledge and data hub, ensuring that information flows consistently from raw measurements to design-ready outputs.

At the core of the framework is a **knowledge and data hub which collects, catalogues and standardises heterogeneous data sources** – wind atlases (ERA5, MERRA2), atmospheric re-analyses, site-specific measurements, high fidelity simulations and remote sensing observations – **making them accessible for upload, extraction and reuse across the toolchain**. The hub also connects to open-access code repositories, built on an existing suitable platform to support transparency and long-term uptake by the wind energy community.

Around this hub, **the data, knowledge and tool chain integrates four interlinked building blocks:**

01

Inflow generation

Producing the heterogeneous wind conditions (speed, turbulence intensity, direction, up-flow) required to characterise real sites, drawing on low- and high-fidelity models.

02

Validation and tuning

Combining model simulations, wind-tunnel scaled tests and full-scale field datasets to reduce and quantify uncertainty.

03

Performance and loading

Assessing farm performance, structural loads, fatigue damage and power forecasting through tuned farm-flow, wake and aeroservoelastic models.

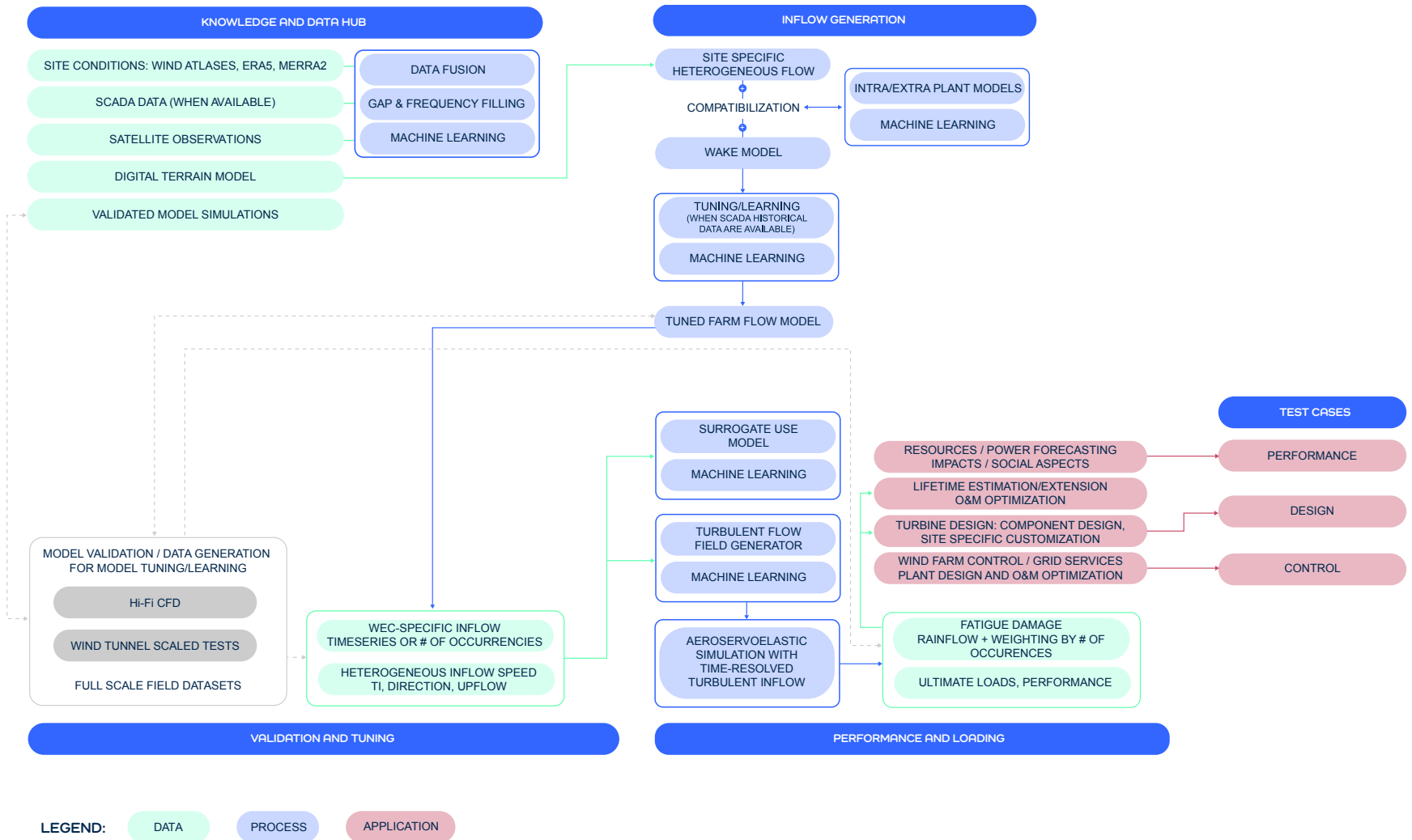
04

Test cases

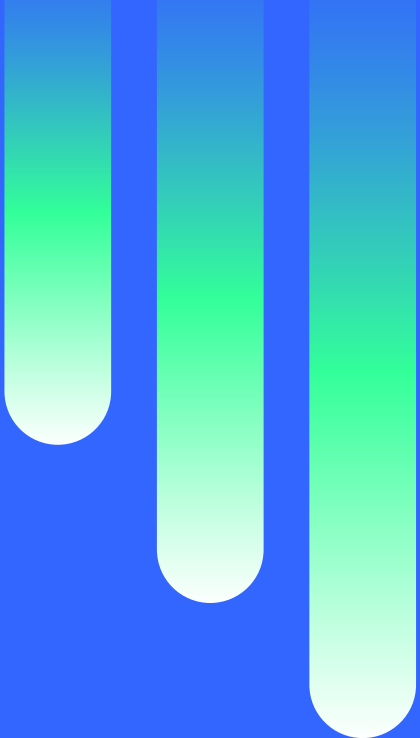
Demonstrating the toolchain on onshore, offshore and airborne applications to support design, control and O&M decisions.

By combining data fusion, machine learning and physics-based modelling, **MERIDIONAL turns fragmented sources of information into a validated, reusable knowledge base.**

THE MERIDIONAL INNOVATION FRAMEWORK



A flowchart describing how the data, knowledge and tool chain works for performance and loads assesement of on-shore, off-shore and airborne wind energy systems.



3

**BUILDING THE KNOWLEDGE,
DATA AND TOOL CHAIN**

THE WINDLAB KNOWLEDGE AND DATA HUB

The **WindLab knowledge and data hub** is the open platform underpinning MERIDIONAL's tool chain, developed specifically for wind energy research data. Created in collaboration with AIRE and FLOW projects, it supports **data management, sharing and reuse**. WindLab gives academic researchers, wind farm and turbine modellers, tool developers and industry collaborators a central access point to store, document and access datasets on wind inflow, wake turbulence, wind farms and turbines in a structured way.

Deployed on HLRS's HPC infrastructure using CKAN, WindLab applies structured, **domain-specific metadata templates** to keep datasets consistent, discoverable and reusable over time.

Within the hub, users share data and provide information needed for re-use and interpretation by using **established taxonomies and vocabularies** from the wind energy research domain.



WindLab Knowledge & Data Hub

AN OPEN TOOL BUILT FOR:



Academic researchers and scientists in wind energy



Engineers working on wind farm and turbine modelling



Developers of simulation, optimisation and analysis tools



Collaborators across research and industry

THE WINDLAB KNOWLEDGE AND DATA HUB OPEN
PLATFORM WAS DEVELOPED IN COLLABORATION WITH:



Discover the platform at <https://windlab.hlr.de/>



Learn more through our dedicated infopack





The dataset resources (files), if already published, can remain in the designated storage. The WindLab record can produce a link to the resources and domain specific metadata. In addition, it provides **interfaces for displaying metadata in machine readable formats** (DCAT, OAI-PMH) to support data discoverability.

Metadata organisation is based on a simplified FAIR compliant metadata template. It combines core elements from DataCite alongside domain-specific vocabularies for the following contexts: **wind energy research topic, dataset variables and external conditions**. Access to data is arranged through a web interface or a customised API.

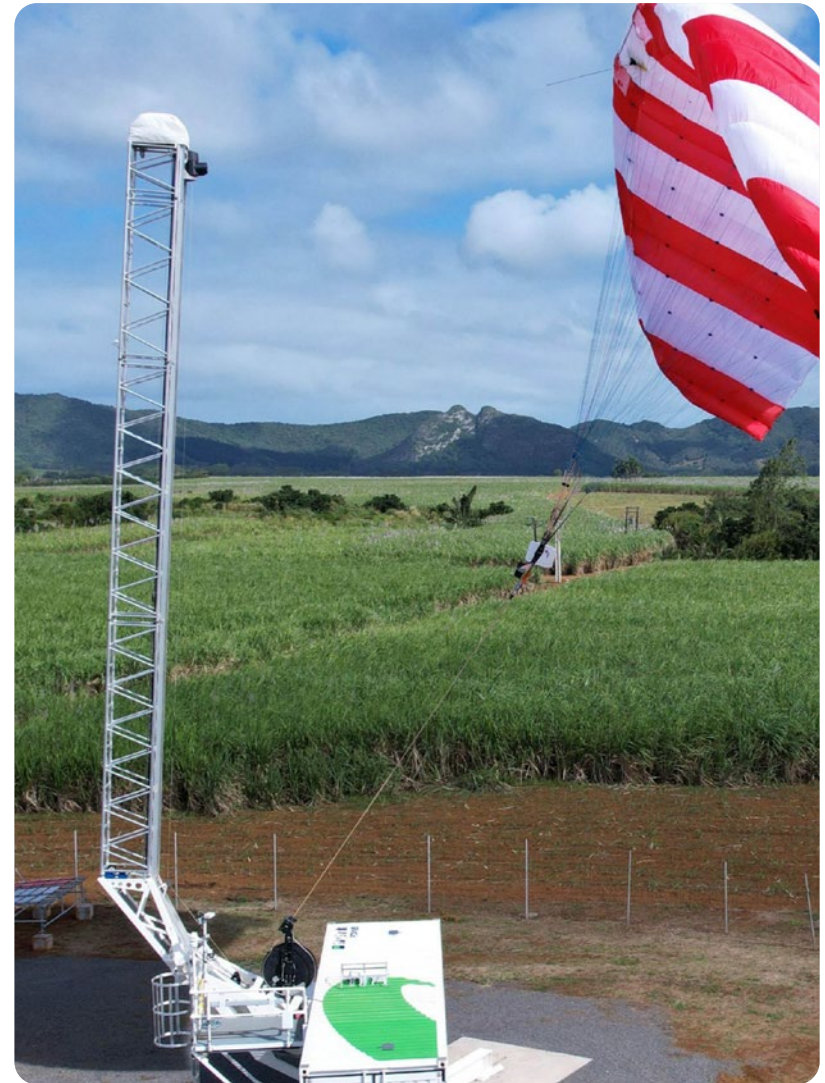
Being built around the FAIR data principles – making data findable, accessible, interoperable and reusable – WindLab lowers the barriers to data access and reuse. **This supports reproducibility, transparency and knowledge transfer** across the wind energy research ecosystem, ensuring heterogeneous data sources feed consistently into the models and tools of the MERIDIONAL toolchain.

WIND FIELD MODELLING AND INFLOW GENERATION

The project has produced several tools for the generation of inflow and the modelling of wind flow for both surface and airborne wind energy systems.

Examples include:

- **The use of data assimilation for high fidelity simulations** of transient wind fields due to unsteady phenomena including the diurnal cycle and gravity waves;
- **Using a 'kite as a sensor' to help predict** airborne wind energy system (AWES) inflow profiles through kite sensor data;
- **Dynamic reconstruction of full 2D inflow** based on sparse measurement data;
- **Clustering of tall wind profiles (up to 600m) for the rapid assessment** of AWES energy yield;



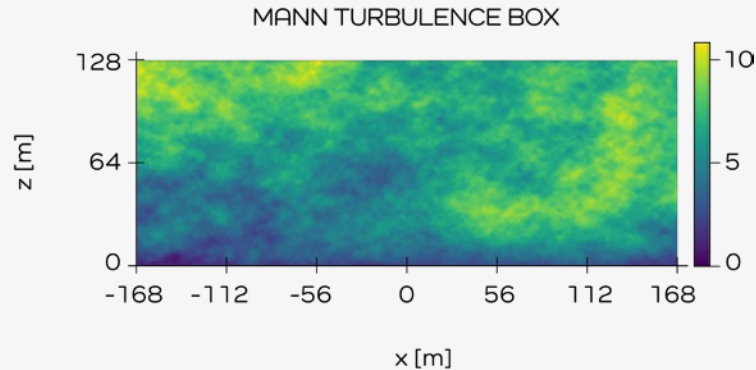


Figure 1: A turbulent wind field generated using the well-known Mann model injected at the mid-point plane of the FLOWer CFD model.

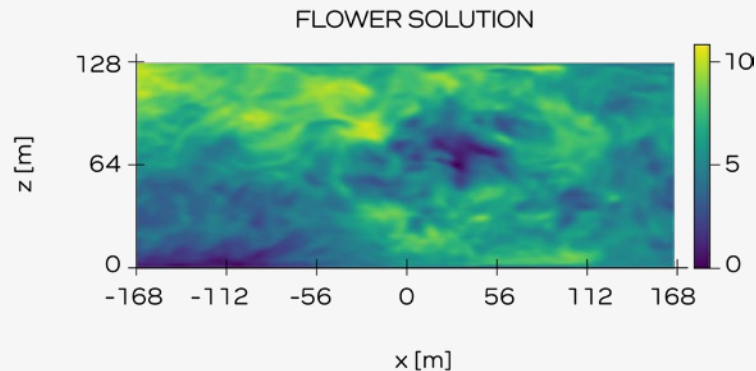


Figure 2: The corresponding FLOWer solution showing how turbulent structures are generally preserved in the first half of the domain and start to break down in the second half of the domain due to an energy cascade to smaller scales.

- **Data-driven reduced order modelling** using techniques such as spectral proper orthogonal decomposition for simulating inflow under transient conditions;
- **Rapid inflow generation** based on RANS modelling based on the use of 1D columns;
- **Mesoscale model-driven fast LES modelling** using ASPIRE of wind fields validated in moderate and complex terrain;
- **The application of machine learning (diffusion models)** to reconstruct 3D fields based on LES simulations to produce observation constrained 3D inflow for input to high fidelity CFD codes;
- **Data-driven and hybrid modelling of wind fields/turbine wakes** based on turbine SCADA data including the use of the 'wind farm as a sensor';
- **Improved turbulent inflow generation** using the FLOWer RANS/DDES code (see figures 1 and 2).

MODEL VALIDATION AND PERFORMANCE ASSESSMENT

The models developed and used in the project have been validated using data from several onshore and offshore sites to demonstrate that **a variety of unique terrain, wind farm and atmospheric phenomena can be captured.**

Onshore wind farms used for validation include the **King Plains wind farm (USA)** as part of the IEA Wind TCP Task 57 AWAKEN Benchmark, **Sedini wind farm (Italy)**, and the **Karaburun wind farm (Turkey)**. Validation efforts with offshore wind farms include **Anholt (Denmark)**, the Belgian/Dutch offshore cluster and the **N4 Heligoland Cluster (Germany)**.

The airborne wind energy tools have been validated using extensive lidar campaigns at two airborne wind energy test sites in Ireland and Germany.



PERFORMANCE, LOADING AND OPERATIONAL APPLICATIONS

MERIDIONAL has developed a range of tools and model approaches to take the inflow generated in the first part of the project and convert this into wind plant performance and loading.

1 Neural network for load predictions

To **enable load predictions** in engineering tools that typically lack that capability (FLORIS and PyWake), **a methodology was developed for training an artificial neural network**. This takes velocity and turbulence intensity information at the wind turbine rotor disk as inputs and maps these onto estimated damage-equivalent loads. The method is location agnostic, meaning **the results are applicable to a turbine located anywhere** within a wind farm. As it is **designed to couple to engineering tools like FLORIS and PyWake**, which are typically used for design and optimisation routines, the load surrogate model enables **wind farm control optimisation for extended wind farm lifetime** and load-aware wind farm design. In this project, the methodology was applied to develop a load surrogate model of the IEA 3.4-MW wind turbine, which is designed for onshore wind farms.



FLOWer SIMULATION VISUALISATION

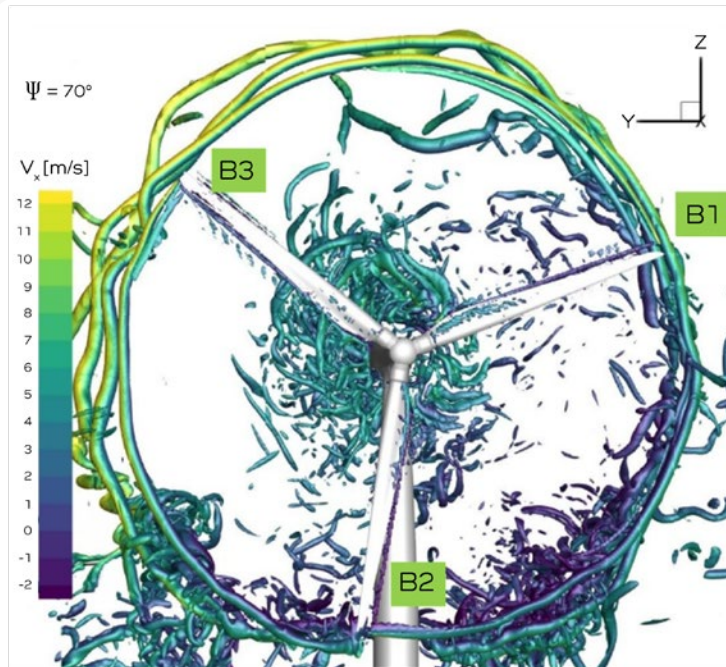


Figure 3: FLOWer simulated flow visualization of a turbine rotor operating in unsteady flow showing asymmetric blade wakes (purple) and helical tip vortices (yellow) resulting from an 8.70° misalignment.

2 Improved turbulent inflow generator

Dynamic blade loads on wind turbines operating in complex terrain arise from the superposition of deterministic and stochastic forcing mechanisms. On the one hand, the **deterministic component** is governed by **rotor-scale phenomena** such as atmospheric boundary layer wind shear, yaw misalignment and tower shadow effects, which impose periodic load variations, the three-per-revolution (3P) harmonic. On the other hand, the **stochastic component** originates from **atmospheric turbulence**, whose spatial and temporal structure is shaped not only by synoptic-scale meteorological conditions but also (in complex terrain) by topographically induced flow distortions, forest canopy effects, and thermal stratification.

The interaction between these two components yields complex load distributions that are difficult to capture with simplified engineering models. **High-fidelity CFD approaches** are therefore required to resolve the instantaneous aerodynamic phenomena driving unsteady blade loads under realistic inflow conditions. In the project, the **FLOWer DDES solver is used to investigate loads** on a 750-kW wind turbine at the WINSSENT test site using the **improved turbulent inflow generator**. The turbine operates under complex-terrain-affected inflow conditions resulting in unsteady blade loads. The results showed good agreement with measurements and highlighted the requirement to resolve turbulent structures to accurately predict blade loads especially when the terrain is complex (see figure 3).

TOPDESIGN TOOL CHAIN

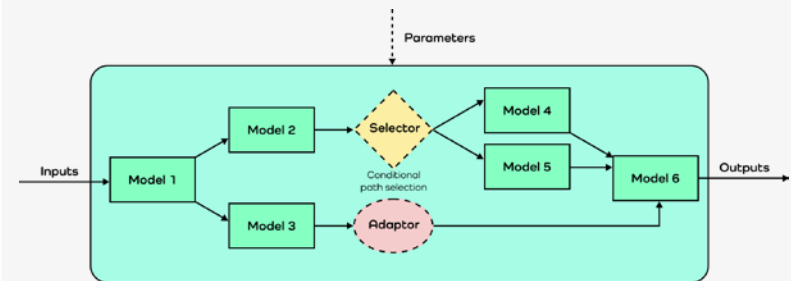
TopDesign is MERIDIONAL's tool chain **integration platform for multi-disciplinary analysis and optimisation (MDAO) in wind energy**. It responds to three challenges:

- the difficulty of combining different tools and models for wind turbine and farm design;
- the complexity of existing MDAO platforms (e.g. DAKOTA, OpenMDAO);
- the lack of a platform tailored to the wind energy sector.

Built in Python, TopDesign **wraps custom models – regardless of language or format – into Python objects that can be coupled into a system** via a directed graph, enabling smooth integration of open-source, commercial, in-house or third-party tools. It integrates three established wind farm modelling tools: PyWake (flow fields, power production, AEP), FLORIS (controls-focused wake modelling) and TopFarm (onshore/offshore optimiser), supporting layout optimisation to improve energy yield and reduce costs. It includes popular optimizers, like GA, PSO and RS (Random Search) and can also use other third-party optimisers, for various optimisation applications in wind energy.

Released under an open-source MIT licence and available via PyPI and GitLab, **TopDesign is designed for long-term use, reuse and extension by academia and industry** beyond MERIDIONAL.

A SYSTEM COUPLING MULTIPLE MODELS WITH
A DIRECTED GRAPH DEFINING THE FLOW



Discover TopDesign on GitLab



Learn more through our dedicated infopack

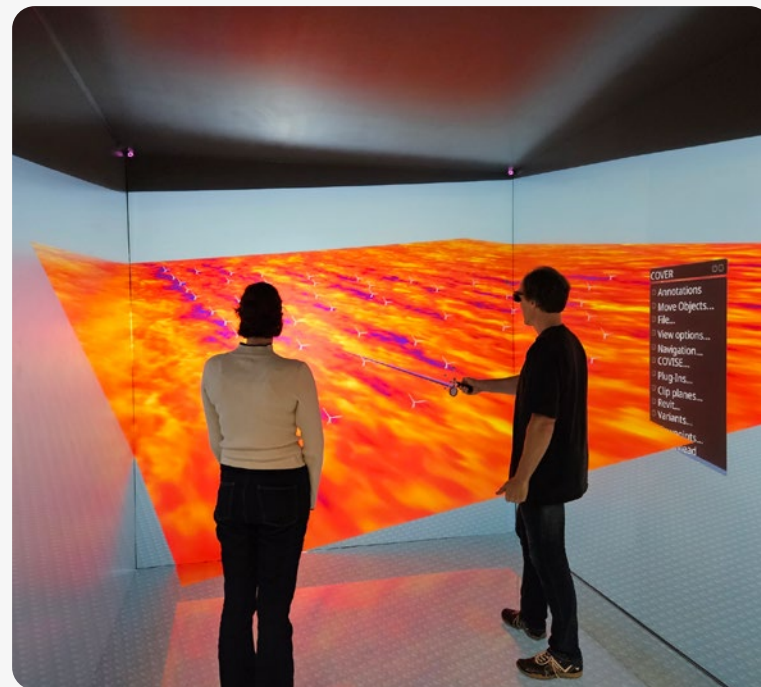


ADVANCED VISUALISATION AND USER INTERACTION

Vistle is an open-source scientific **visualisation platform for immersive, interactive analysis of large-scale simulation datasets** in HPC environments, supporting real-time exploration of CFD simulations and 3D infrastructure across desktop, AR and VR systems. Within MERIDIONAL, it **powers a collaborative digital twin combining airflow simulations, terrain models and wind farm infrastructure in a single navigable environment**, using Level-of-Detail rendering to manage large territorial datasets.

The project delivered a **functional prototype for remote, immersive visualisation of offshore wind farms**, including digital twins of the He Dreiht offshore wind farm and the WINSSENT test site (integrating lidar and UAV data), **turbulence visualisation around wind blades** and KitePower trajectory datasets, with compatibility across multiple simulation formats and display systems.

Beyond MERIDIONAL, Vistle's open-source, interoperable architecture supports further digital-twin and simulation-visualisation applications across research, industry and sustainable innovation.



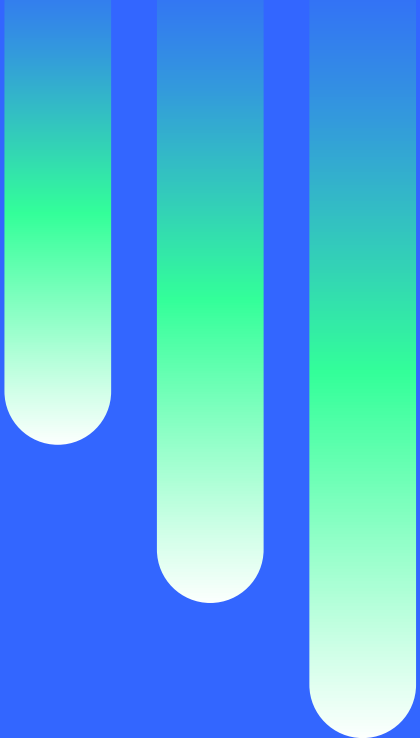
Vistle 3D Visualization in the CAVE, a walkable room combined with six projected plexiglasses that combined with 3D shutter glasses creates a 3D experience.

Discover Vistle Visualisation Software on GitHub



Learn more through our dedicated infopack





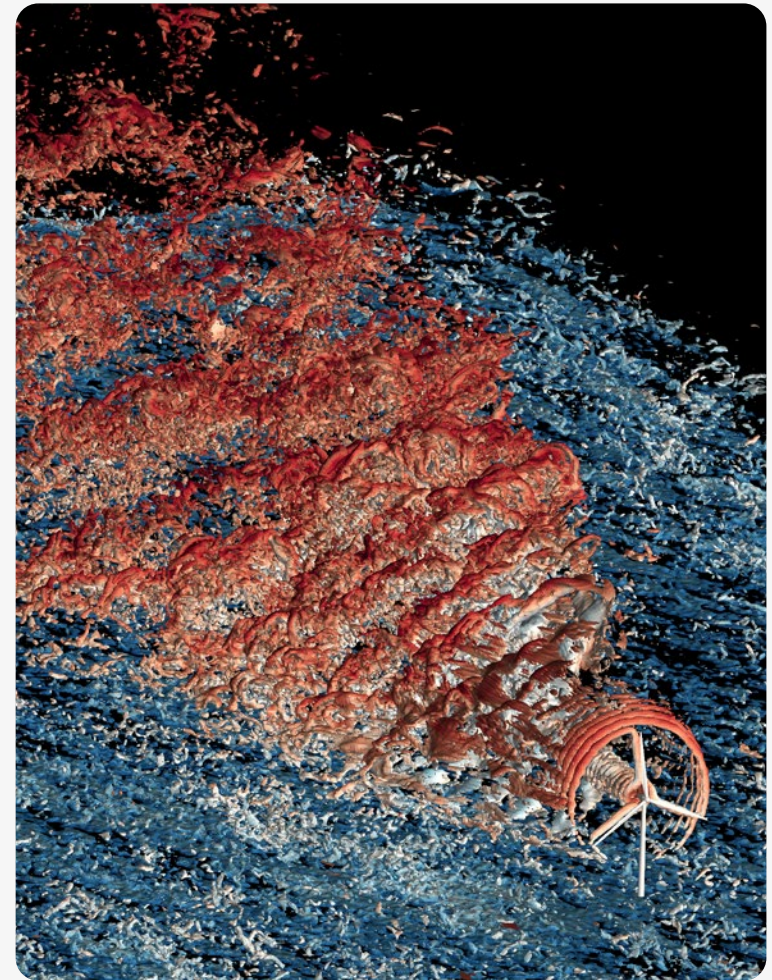
4

APPLICATIONS AND IMPACTS

TEST CASES

MERIDIONAL validated its knowledge, data and tool chain through **five demonstration test cases spanning onshore, offshore and airborne wind energy**, chosen to cover a broad range of technologies, scales and environmental conditions.

The **onshore case examined the AWAKEN benchmark at the King Plains wind farm (Oklahoma, USA)**, assessing energy production and load verification for a newly installed turbine on a highly instrumented site. The offshore case draws on multiple **North Sea wind farms** to quantify and predict energy yield under inflow phenomena such as blockage, atmospheric stability and inter-farm wakes, using modelling tools.



DOE AWAKEN Project. Illustration by Matt Churchfield, NREL.



Three airborne wind energy (AWE) test cases progressively scale up the technology: a 100-kW isolated inland system (Ireland/Italy) assessing feasibility and microgrid integration; a 1 MW inland farm of ten airborne wind energy devices at Maasvlakte 2, evaluating farm layout and wake losses; and a 30 MW offshore farm within the N4 Heligoland cluster, testing large-scale deployment and scalability.

Together, these five cases demonstrate how **the MERIDIONAL tool-chain supports design, performance assessment and optimisation** across the full spectrum of wind energy applications.

[Learn more on the on-shore test case](#)



[Learn more on the off-shore test case](#)



[Learn more on the airborne wind energy test case](#)



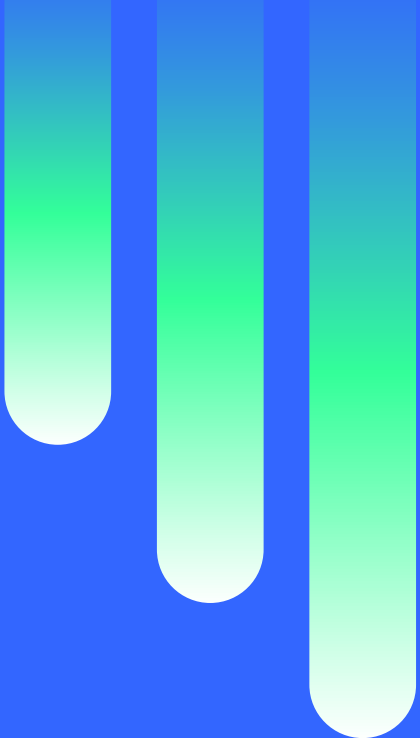
BENEFITS FOR THE WIND ENERGY COMMUNITY

The MERIDIONAL data, model and tool chain guarantees a set of benefits for the full wind energy research and industrial community.

They include:

- **Effective and efficient tools** for planning and designing wind farms and airborne wind energy systems;
- **A knowledge and data hub** which can support the use of existing and new tools for predicting performance and loads;
- **A validated tool chain** that can simplify modelling requirements, reduce uncertainty and increase confidence in predicting wind plant performance;
- **Guidelines** for the application of modelling tools for performance and load assessment;
- **Insights** into what model fidelity is required for what situation.





5

LESSONS LEARNT AND FUTURE PROSPECTS

KEY LESSONS FROM MERIDIONAL

Credible wind energy decisions depend on credible modelling.

As turbines grow, sites become more complex and new technologies (e.g. airborne wind) approach the demonstration phase, model choice increasingly shapes expectations on production, loads, wakes and risk.

Model choice changes the decision: a model suited to average energy production may not be reliable for fatigue loads, extreme events or wake interactions between farms.

Inflow matters from the start: turbulence, shear, stability, low-level jets and gravity waves affect loads and performance. Higher-fidelity simulations capture more physics at greater cost.

Wakes are a system issue: wake-aware planning is increasingly important as offshore build-out grows.

Complex terrain and large projects need stronger evidence: simplified assumptions may be inadequate unless calibrated or checked against benchmark cases and open or protected data.

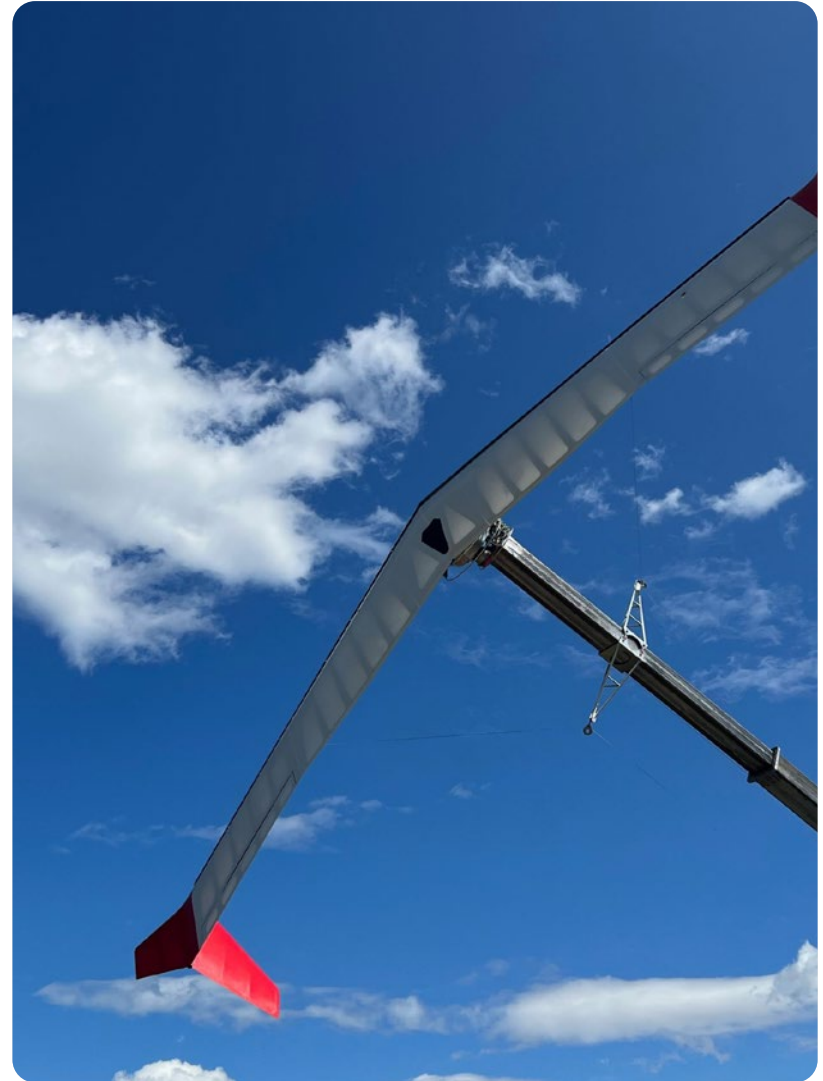
Data-driven models need guardrails: surrogate and machine-learning tools accelerate uptake, but only when training data, validation range and extrapolation limits are documented.

Innovation needs staged confidence: early modelling supports screening, while stronger experimental and high-fidelity evidence is required for loads, control and safety-critical claims.

Practical recommendations

- **Match model complexity to decision risk** and require every modelling submission to state the decision it supports and its limitations.
- **Ask for sensitivity to inputs/uncertainty** bounds, not just single numbers.
- **Treat validation data and benchmark cases as shared infrastructure**, supported by protected data-sharing routes for sensitive commercial data.

Overall, fit-for-purpose modelling, transparent uncertainty and shared validation helped MERIDIONAL's results transfer across regions, technologies and institutions.



BEYOND THE PROJECT

MERIDIONAL's tools and data are designed for use well beyond the project itself.

The **WindLab knowledge and data hub** and **TopDesign integration platform** are open-source – built on FAIR principles, hosted on GitHub/GitLab and PyPI – letting researchers, developers and industry reuse and extend them after the project ends. **Vistle's** open, interoperable visualisation architecture likewise supports further digital-twin applications in research and industry.

The test cases point to a clear **scale-up pathway**: methodologies validated on the King Plains onshore site and North Sea offshore farms **apply to any comparable site**, while airborne wind energy systems progress in a staged way from a 100-kW single unit to 1 MW and 30 MW farm configurations, opening **opportunities for off-grid, microgrid and hybrid deployments** alongside conventional turbines.

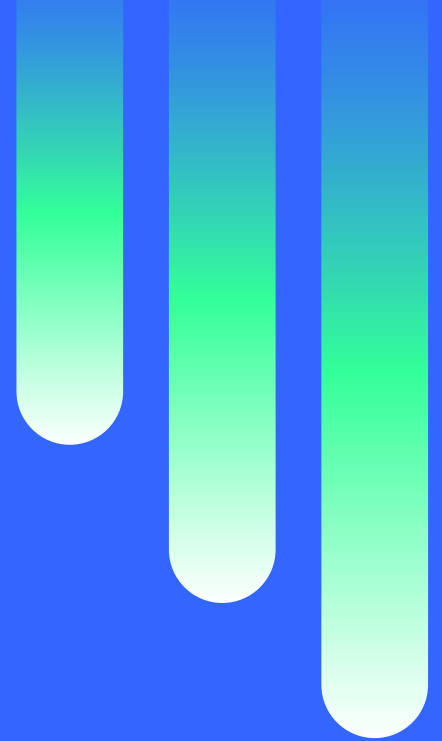
Wider adoption depends on **turning these results into reusable guidance**: fit-for-purpose modelling, transparent uncertainty and protected data-sharing as standard practice, so outcomes can travel across regions, technologies and institutions and support faster wind energy deployment.

Lastly, a **commercial uptake** of the project's research was the establishment of the [Ventoplani](#) start-up, funded by Politecnico di Milano. The start-up is **exploring small-scale airborne wind energy systems for direct local use**. It aims to combine a novel windplane design with advanced flight control to harness higher-altitude winds for a more resilient and sustainable energy future.



6

CONCLUSIONS



Over four years, MERIDIONAL has **turned a fragmented landscape of wind energy data and models into a connected, validated tool chain** – open to researchers, industry and policymakers alike. From the WindLab knowledge and data hub to TopDesign and Vistle, and from onshore benchmarks to airborne wind energy farms, the project shows that fit-for-purpose modelling, transparent uncertainty and shared validation data are the foundation for confident, better-informed decisions on wind plant design and operation.

These **results do not end with the project**: the tools, data and lessons are built for further testing and development, and the emergence of Ventoplani shows how MERIDIONAL's research can translate into new market opportunities. The project team invites the wind energy community to explore, adopt and build on this toolchain to accelerate a leaner, more reliable and cost-effective low-carbon energy future with wind energy at the core.



List of online resources

Platforms and software

WindLab Knowledge and Data Hub – <https://windlab.hlr.de/>

TopDesign (GitLab) – <https://gitlab.windenergy.dtu.dk/TOPFARM/basic-plugins/topdesign>

VISTLE Visualisation Software (GitHub) – <https://github.com/vistle/vistle>

Infopacks

WindLab Knowledge and Data Hub – <https://zenodo.org/records/20085064>

TopDesign Toolchain – <https://zenodo.org/records/20085119>

VISTLE: Wind farm visualisation software – <https://zenodo.org/records/20831849>

AWAKEN Benchmark: Onshore test case – <https://zenodo.org/records/21641614>

North Sea wind farms: Offshore test cases – <https://zenodo.org/records/22691213>

Airborne wind energy test cases – <https://zenodo.org/records/21098823>



Find us on    **MERIDIONAL EU**

 meridional.eu

 info@meridional.eu

This Innovation Handbook was produced by ICONS in September 2026.

Authors

Federica Fusco – ICONS

Desirae Major – Technical University of Munich

Simon Watson – Delft University of Technology

Contributors

Rosina Baumann – High-Performance Computing Center Stuttgart (HLRS)

Niccolò Belluati – ICONS

Ju Feng – Technical University of Denmark

Miroslav Puskaric – High-Performance Computing Center Stuttgart (HLRS)

Roland Schmehl – Delft University of Technology

Jens Nørkær Sørensen – Technical University of Denmark

Dominik von Terzi – Delft University of Technology

Graphic design and layout

Orazio Di Maria – ICONS



Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

