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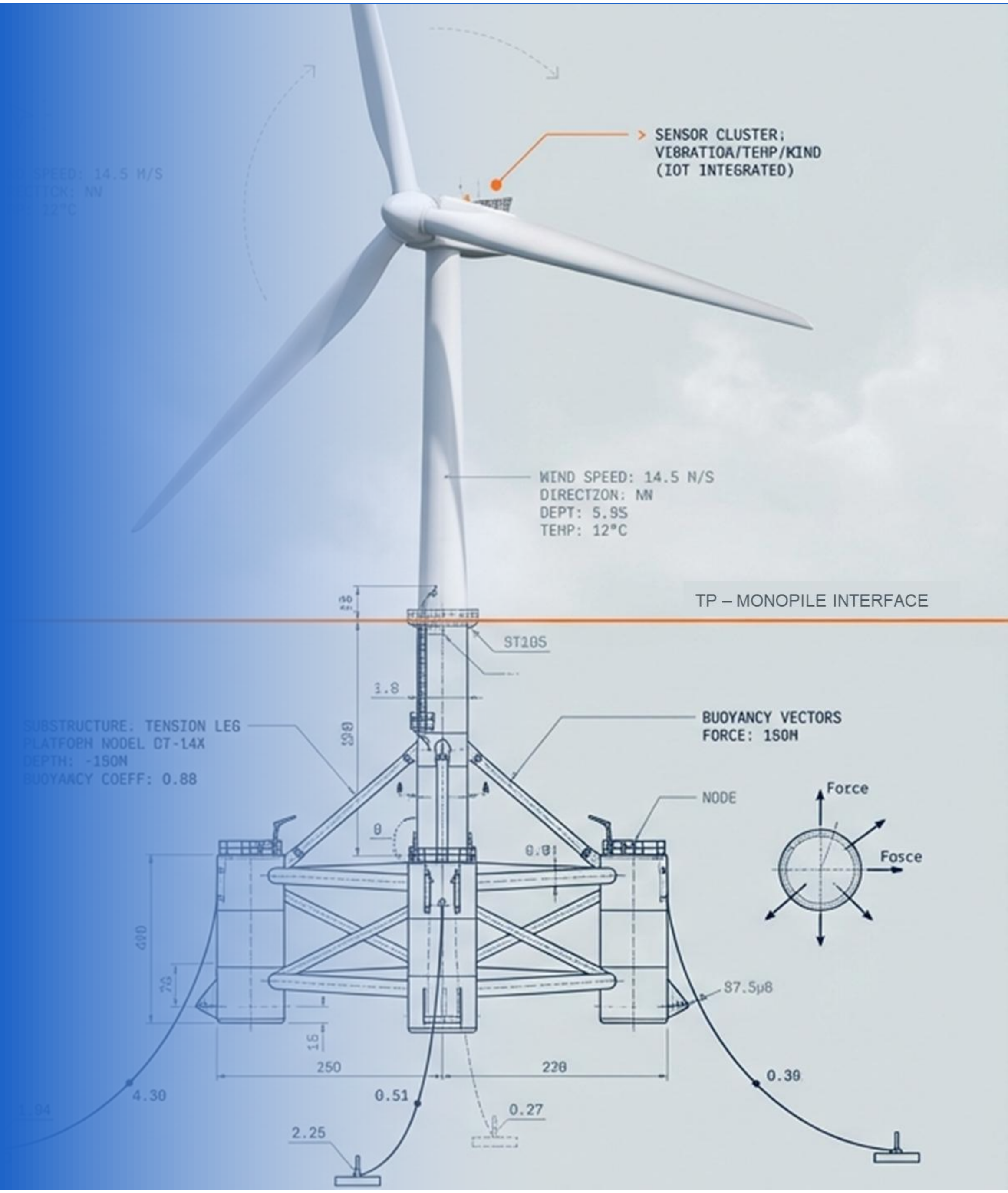
AND ARCHITECTURE

DEPARTMENT ELECTROMECHANICAL, SYSTEMS AND METALS ENGINEERING
RESEARCH GROUP LABORATORY SOETE

Advancements in digital twin frameworks for offshore wind: ongoing research and future directions

Prof. dr. ing. Kris Hectors

25/03/2026



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Goals of offshore renewable generation in 2050

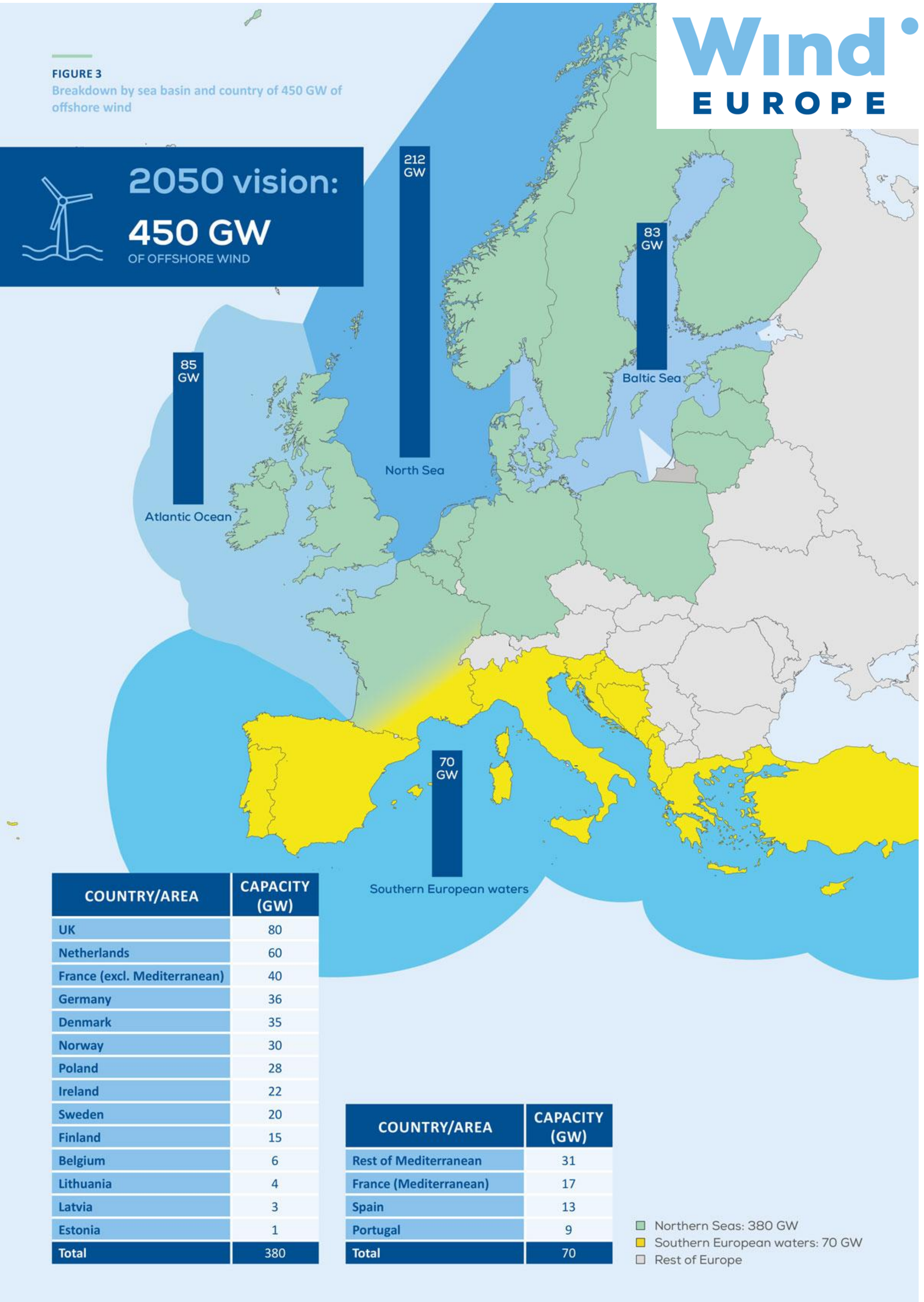


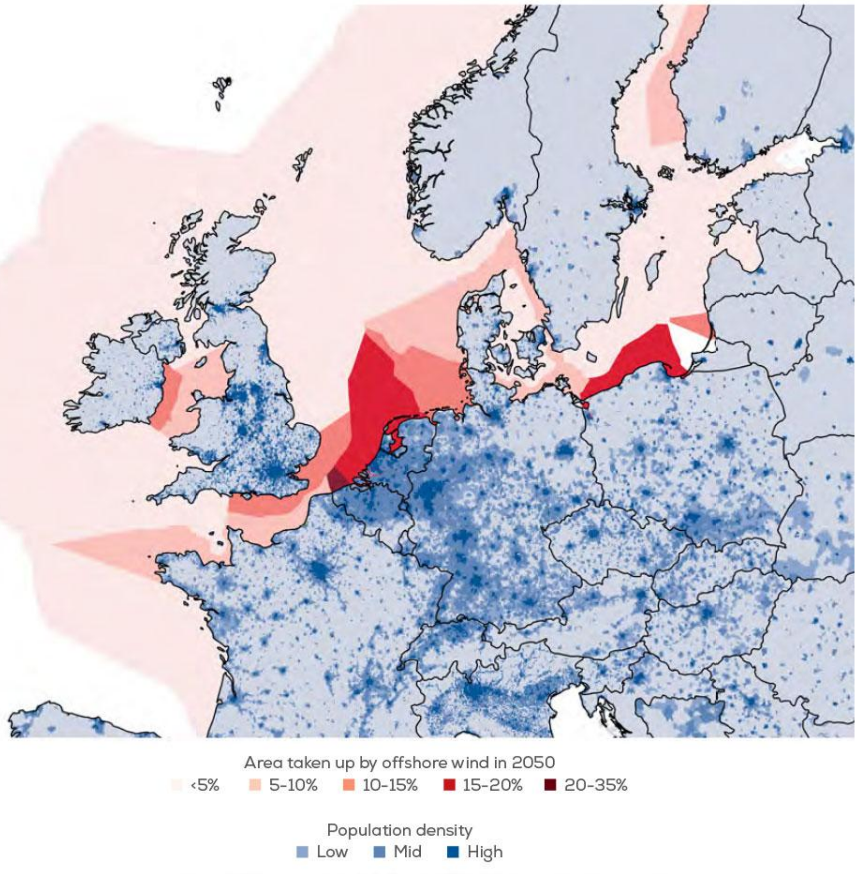
FIGURE 3
Breakdown by sea basin and country of 450 GW of offshore wind

COUNTRY/AREA	CAPACITY (GW)
UK	80
Netherlands	60
France (excl. Mediterranean)	40
Germany	36
Denmark	35
Norway	30
Poland	28
Ireland	22
Sweden	20
Finland	15
Belgium	6
Lithuania	4
Latvia	3
Estonia	1
Total	380

COUNTRY/AREA	CAPACITY (GW)
Rest of Mediterranean	31
France (Mediterranean)	17
Spain	13
Portugal	9
Total	70

380 GW of offshore wind in the North Seas would require less than 3% of the total area of the North Seas.

FIGURE 4
Location of 380 GW of offshore wind in 2050 by percentage of total sea area (without spatial exclusions), by sub-region



European union:

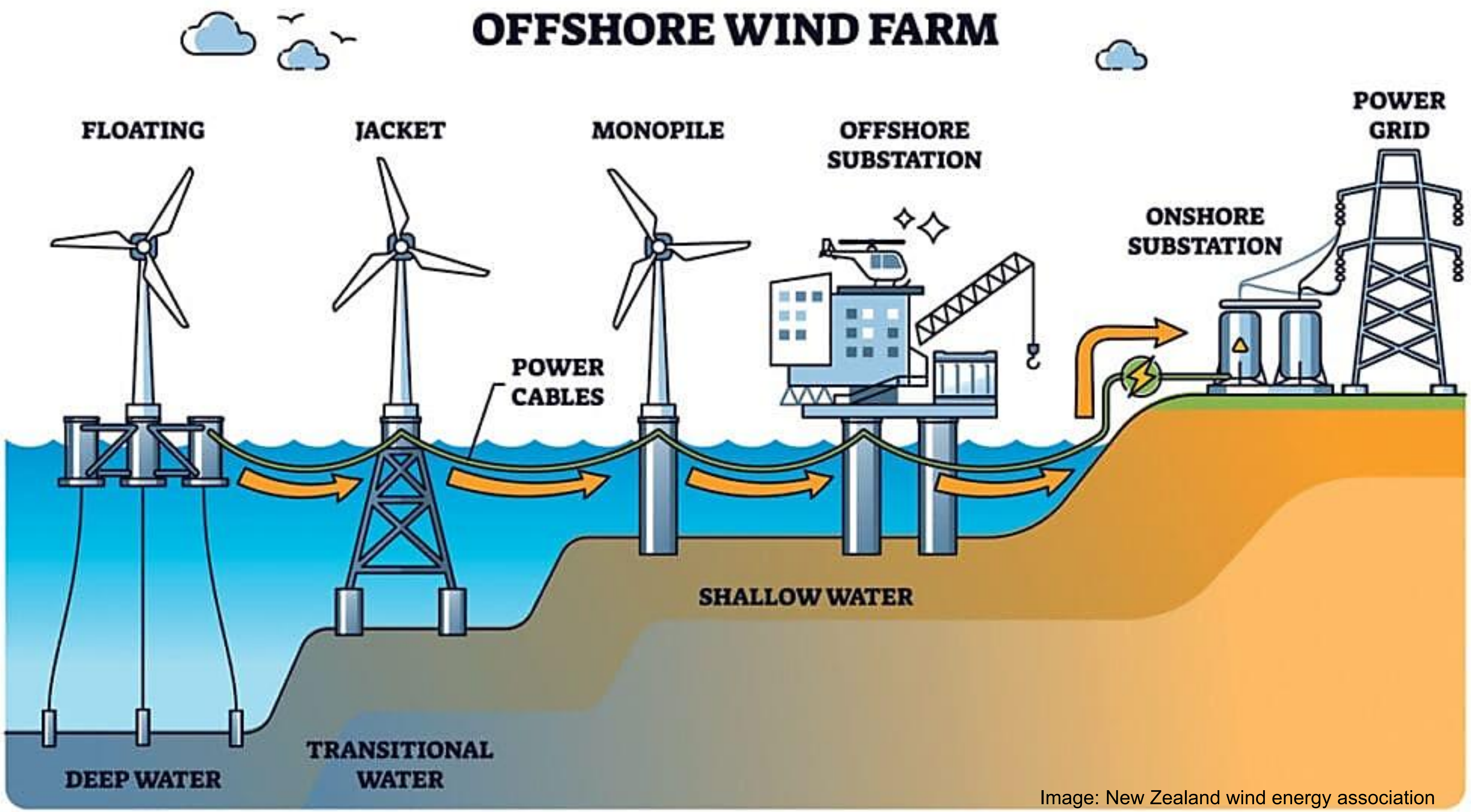


Image: New Zealand wind energy association

The Industry Shift

Maturing markets and disappearing subsidies demand new optimization technologies. The industry has shifted to data-driven models to optimize new turbine design and improved O&M strategies.

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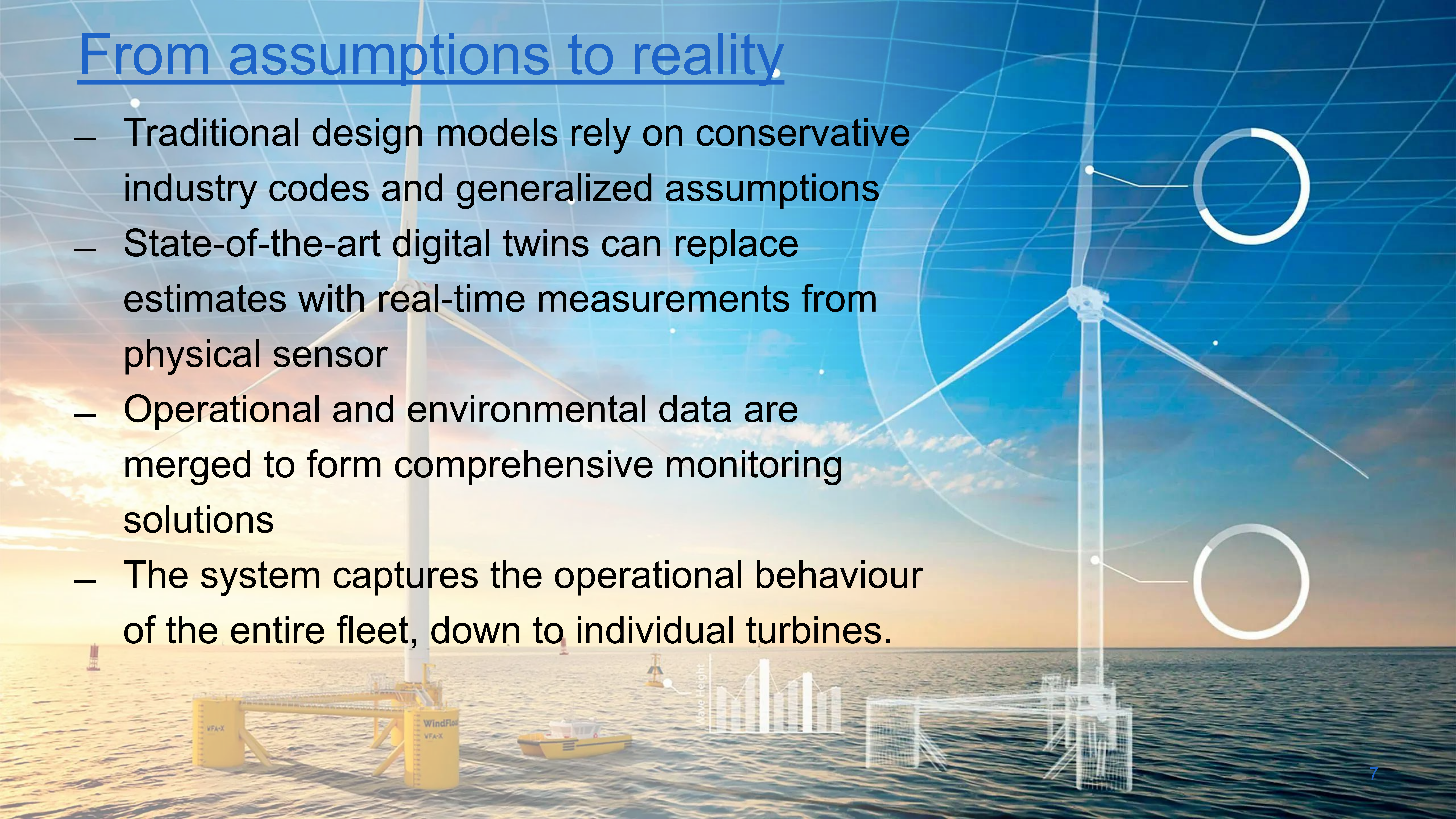
From assumptions to reality

- Traditional design models rely on conservative industry codes and generalized assumptions to account for uncertainties

Material fatigue resistance	Fatigue damage modeling	Long-term environmental conditions
Aerodynamic and hydrodynamic loads	Global dynamic response	Long-term operational conditions
Designed vs as-built tolerances	Unforeseen events	…

From assumptions to reality

- Traditional design models rely on conservative industry codes and generalized assumptions
- State-of-the-art digital twins can replace estimates with real-time measurements from physical sensor
- Operational and environmental data are merged to form comprehensive monitoring solutions
- The system captures the operational behaviour of the entire fleet, down to individual turbines.



Capturing data for data-driven models of offshore turbines

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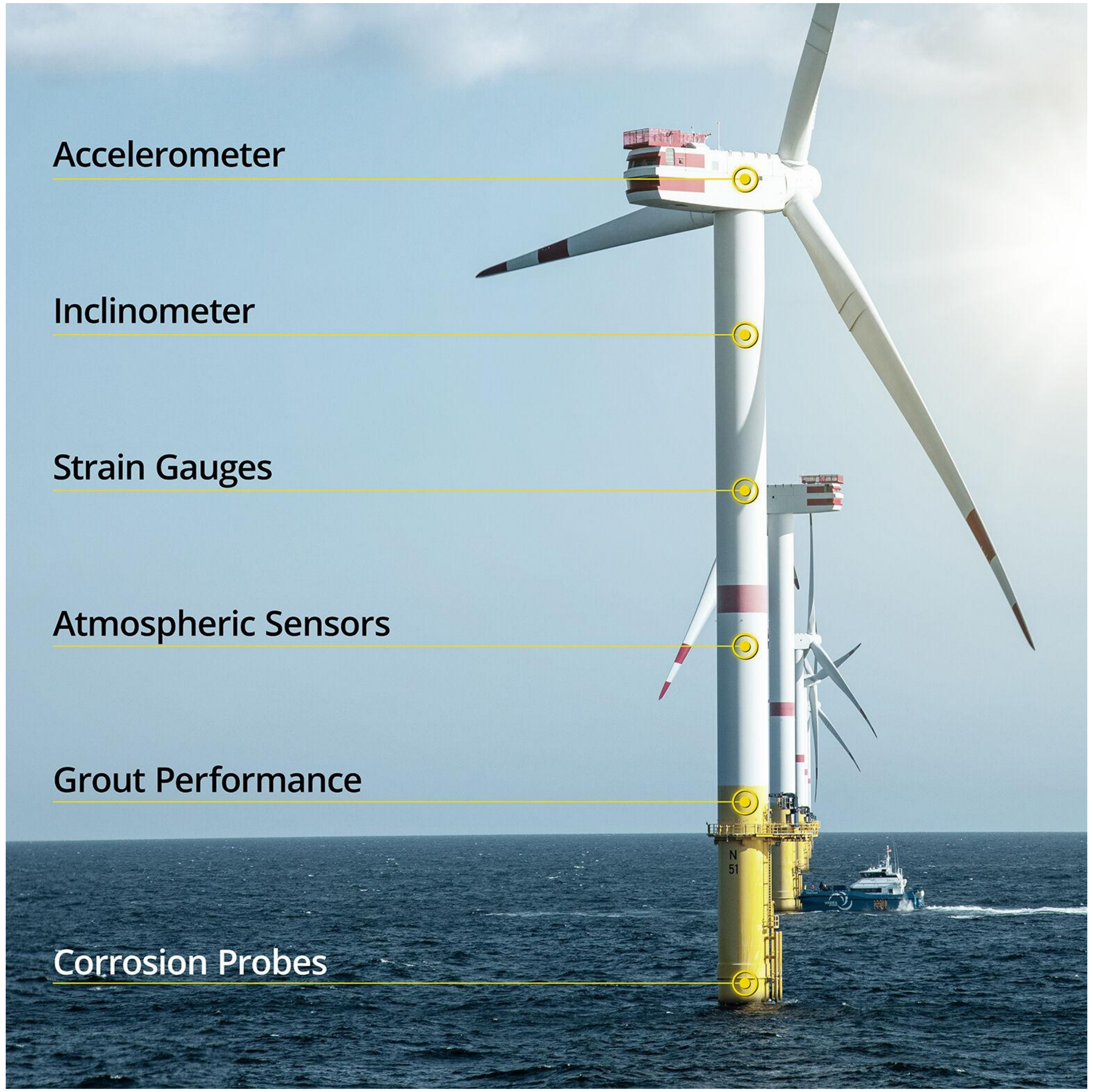
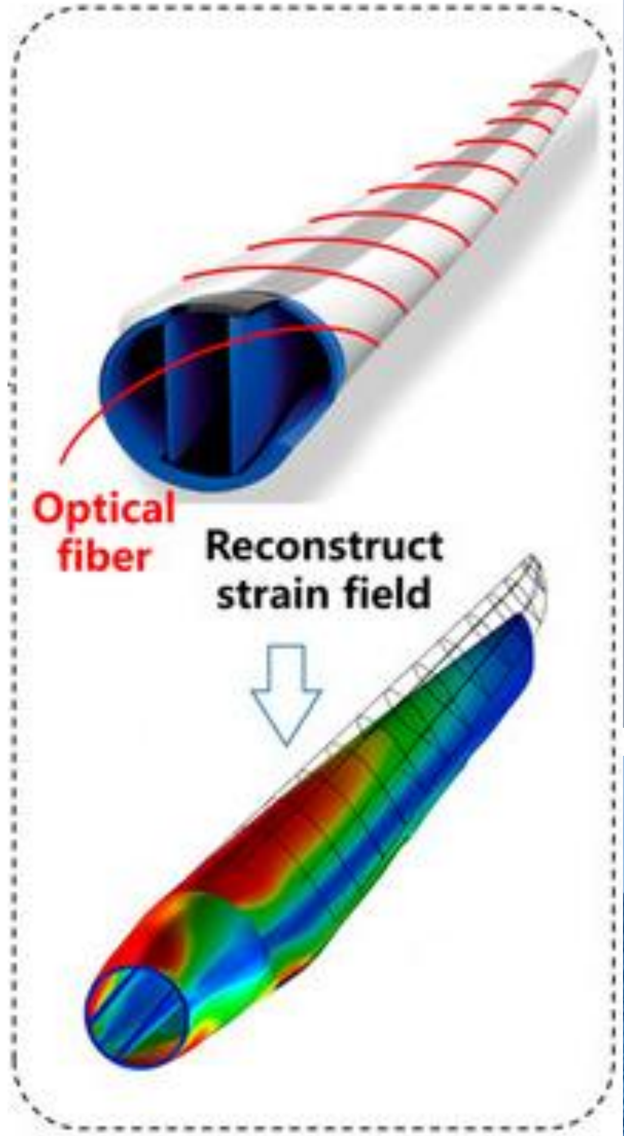
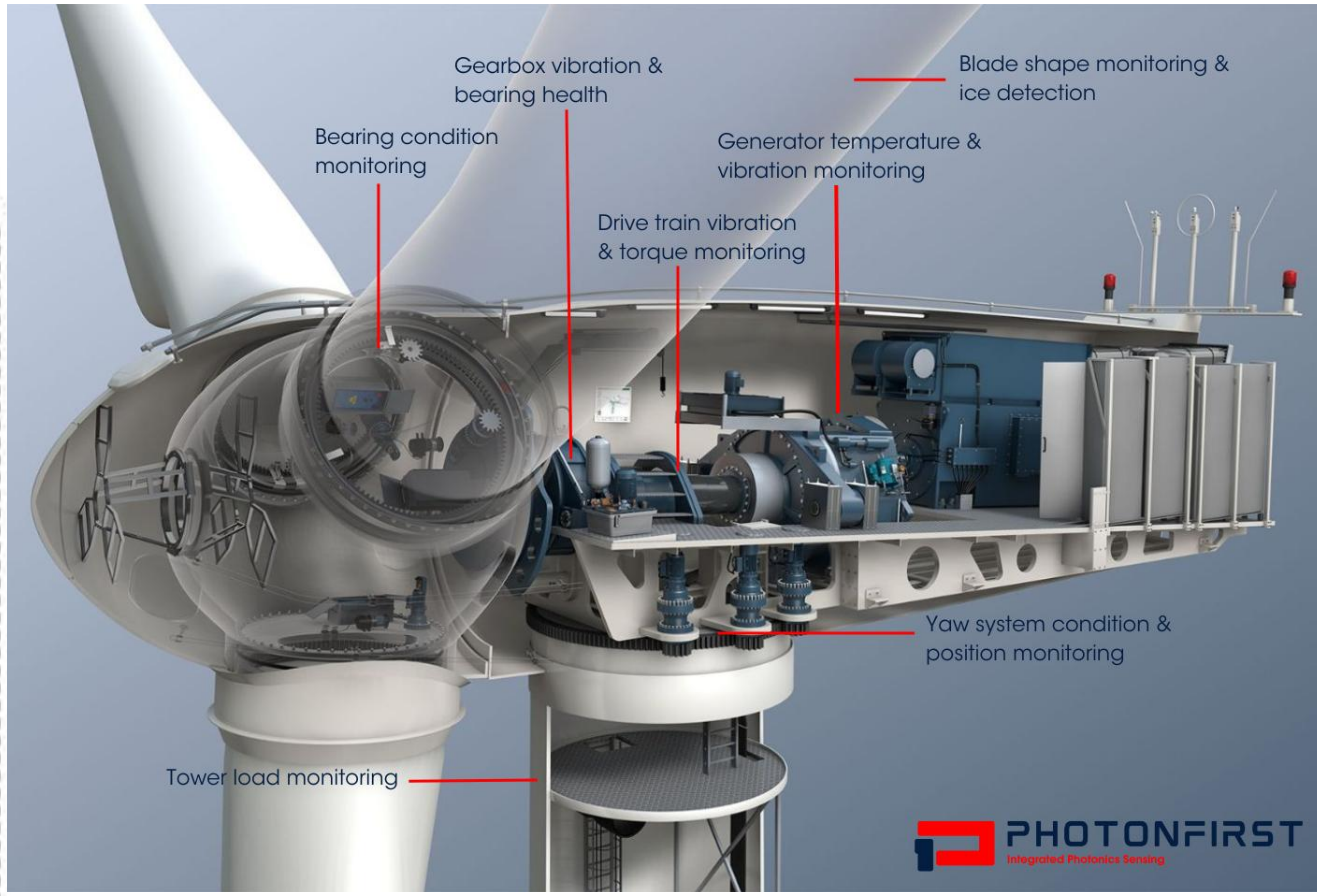
Structural health and load monitoring







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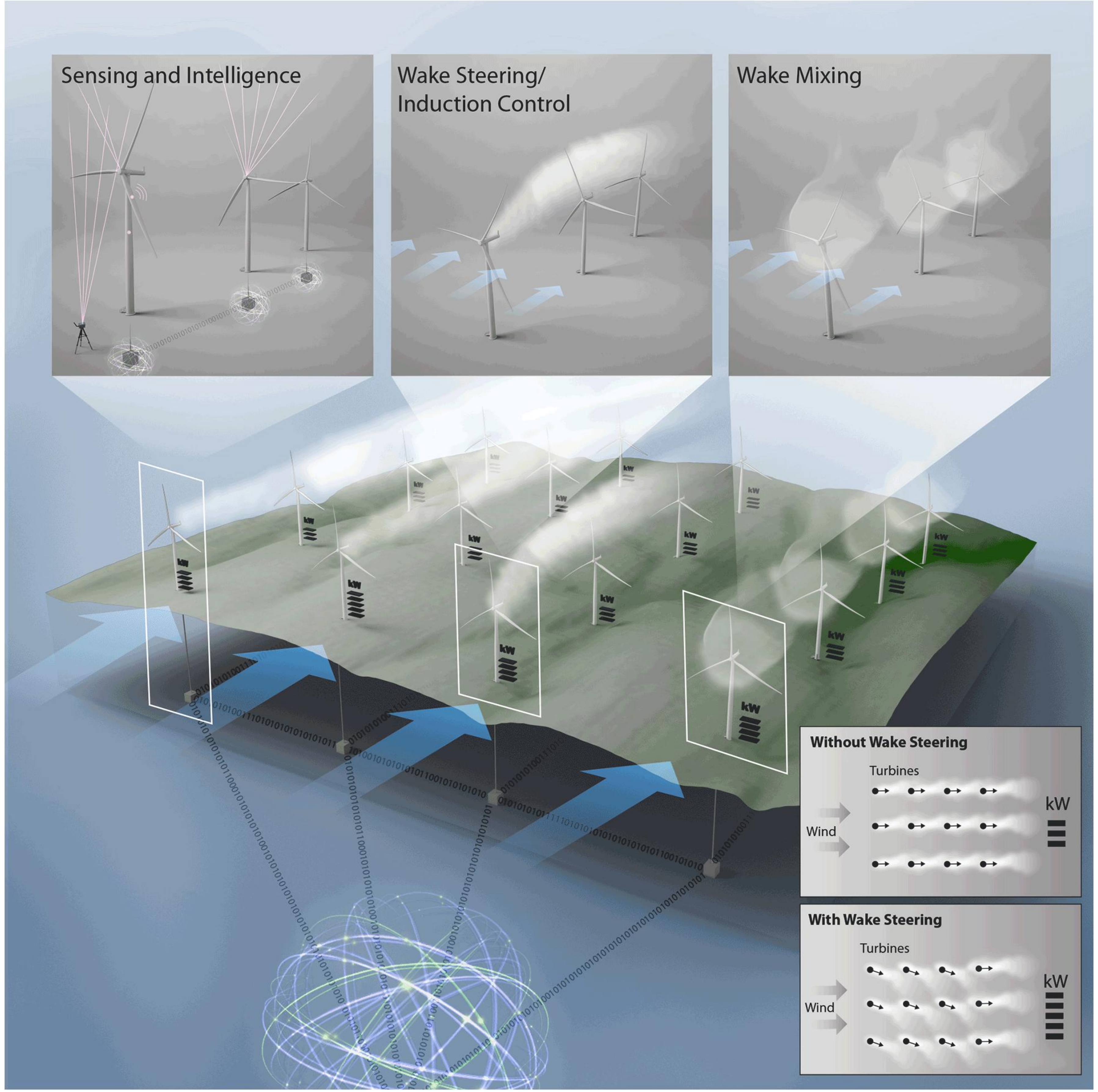
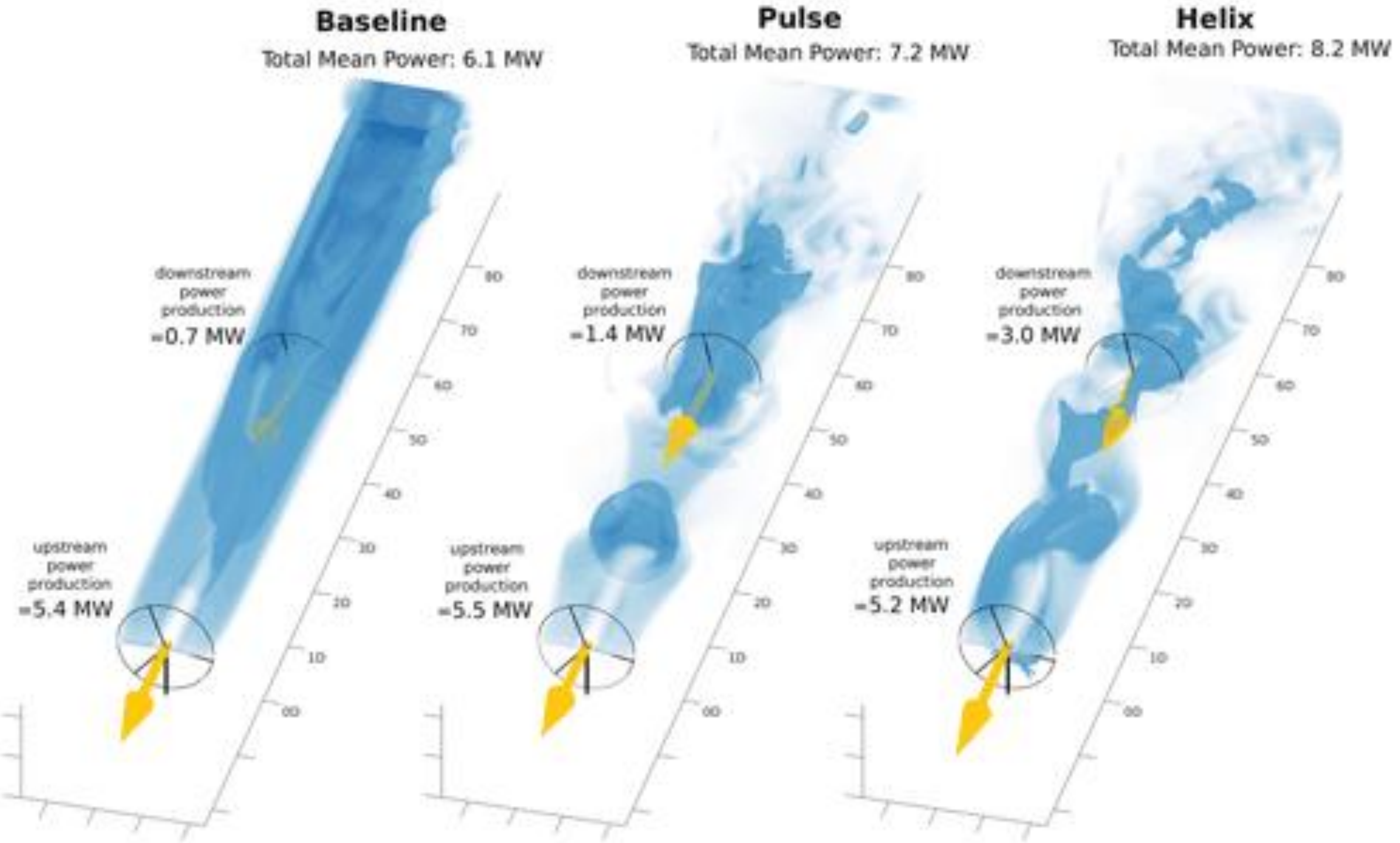
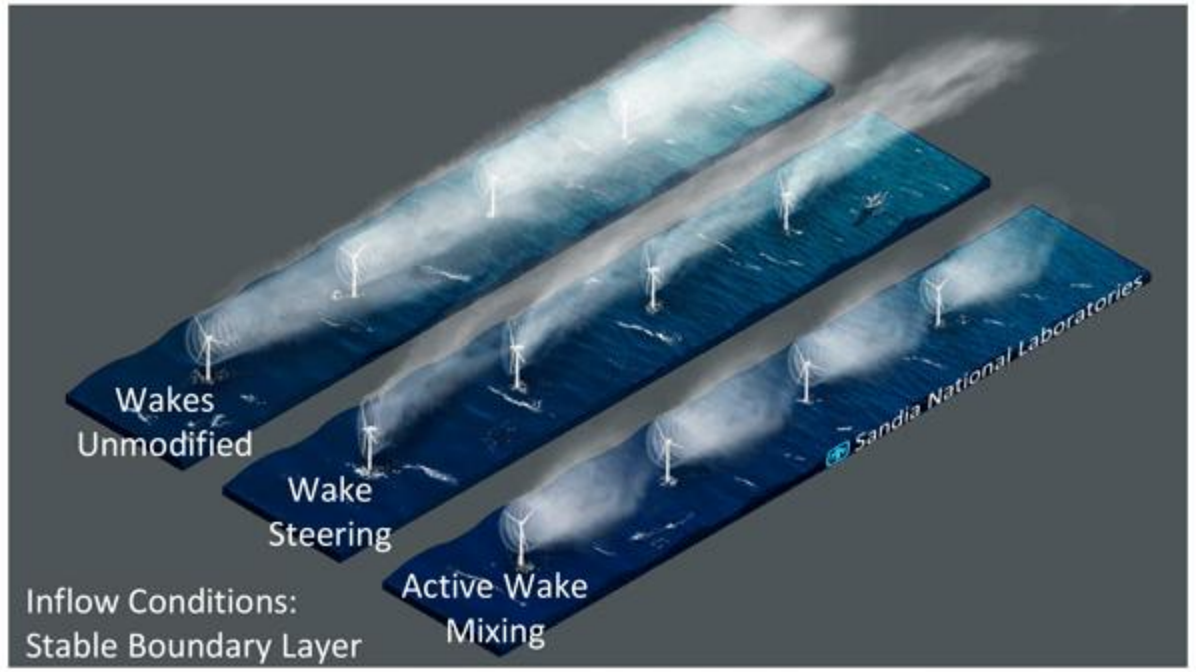
Farm level sensing and control



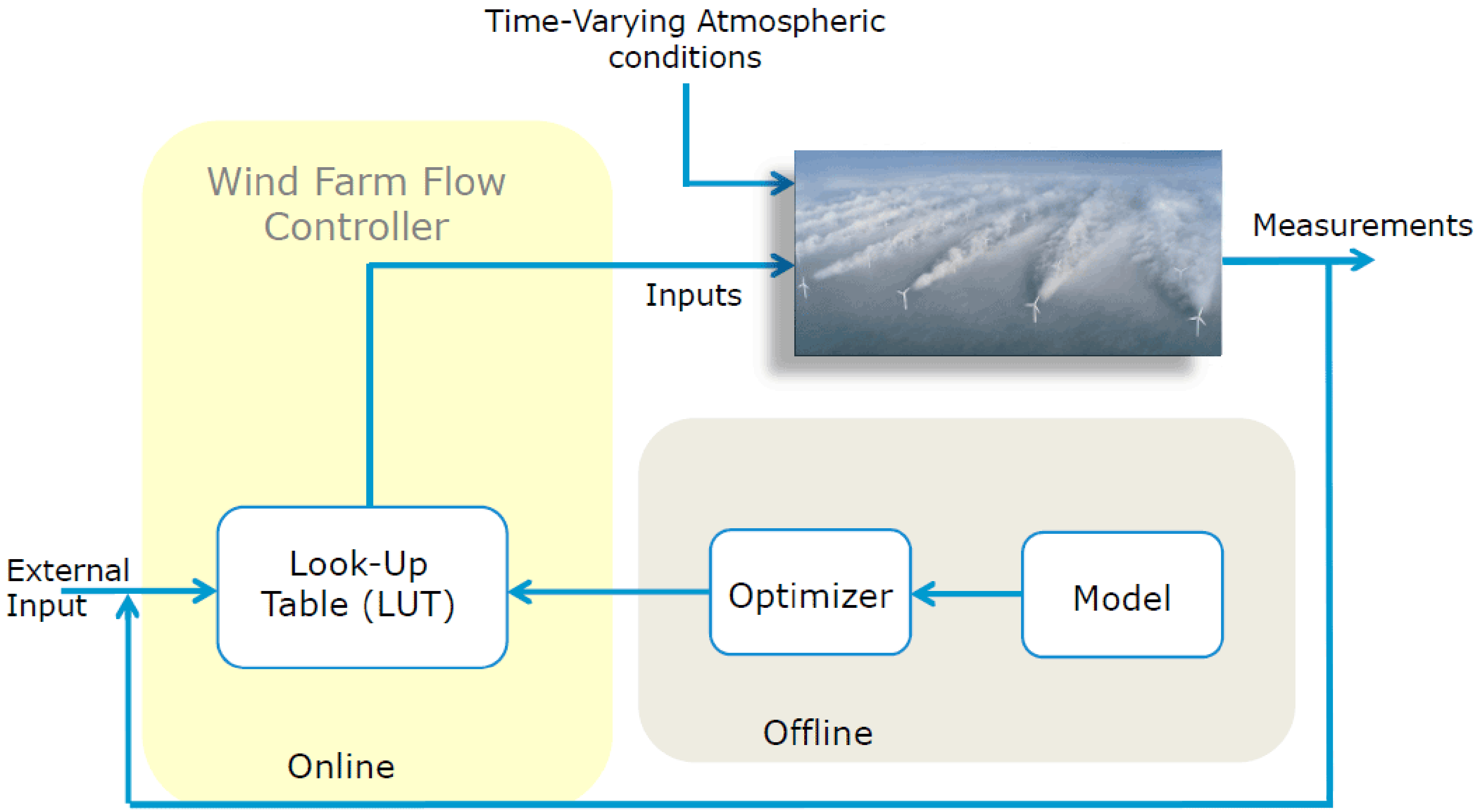


Meyers, Johan, et al. "Wind farm flow control: prospects and challenges." Wind Energy Science Discussions 2022 (2022): 1-56. https://doi.org/10.5194/wes-7-2271-2022



Wind farm flow control

Current practice open-loop control



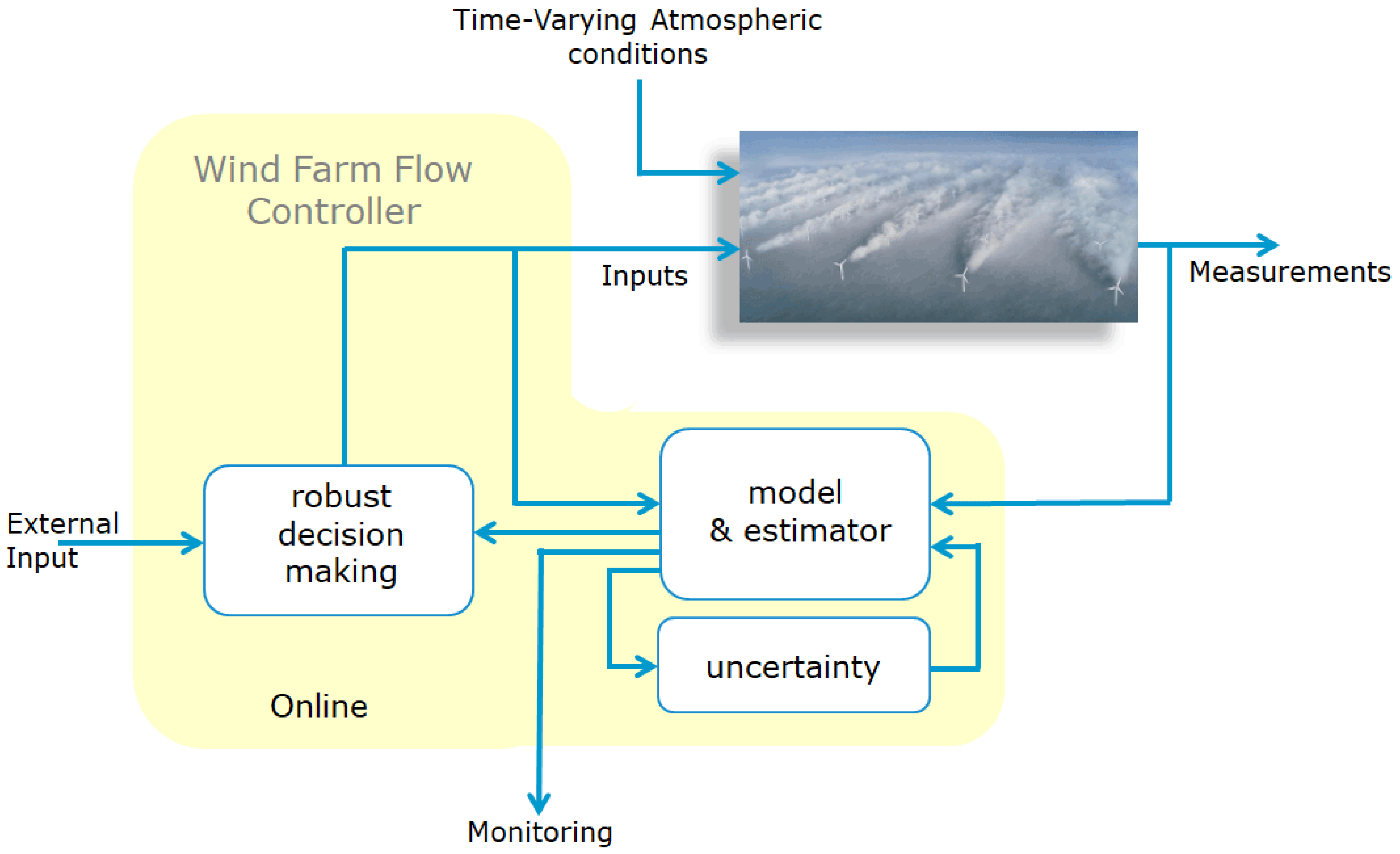
- Offline-calibrated, steady-state models
- Optimized ford different wind directions, wind speeds, turbulence conditions, etc. which are fed into a LUT with optimal control settings
- If the model misunderstands the wake interaction between two specific turbines, the wind farm will consistently lose power efficiency under those specific wind conditions.

Performance strongly depends on the model accuracy and is prone to unmodeled disturbances

Meyers, Johan, et al. "Wind farm flow control: prospects and challenges." Wind Energy Science Discussions 2022 (2022): 1-56. https://doi.org/10.5194/wes-7-2271-2022
(Horns Rev-I wake picture courtesy: Vattenfall. Photographer is Christian Steiness).

Wind farm flow control

Future wind farm flow control
Closed loop-control



- Real-time optimization framework that accounts for model uncertainty and unknown uncertainties
- Allows active wake steering, minimizing impact on neighboring turbines

Result: data-driven calibrated models that can be used for real-time decision making = digital twin

Target: Increasing AEP → how does it affect the individual assets?

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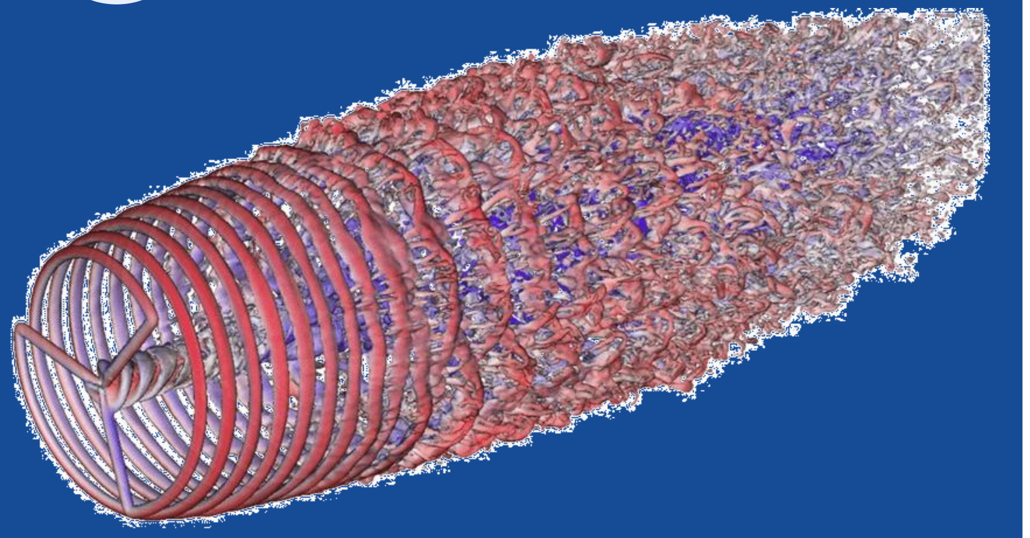
Meyers, Johan, et al. "Wind farm flow control: prospects and challenges." Wind Energy Science Discussions 2022 (2022): 1-56. https://doi.org/10.5194/wes-7-2271-2022
(Horns Rev-I wake picture courtesy: Vattenfall. Photographer is Christian Steiness).

From aerodynamic wakes to structural loads

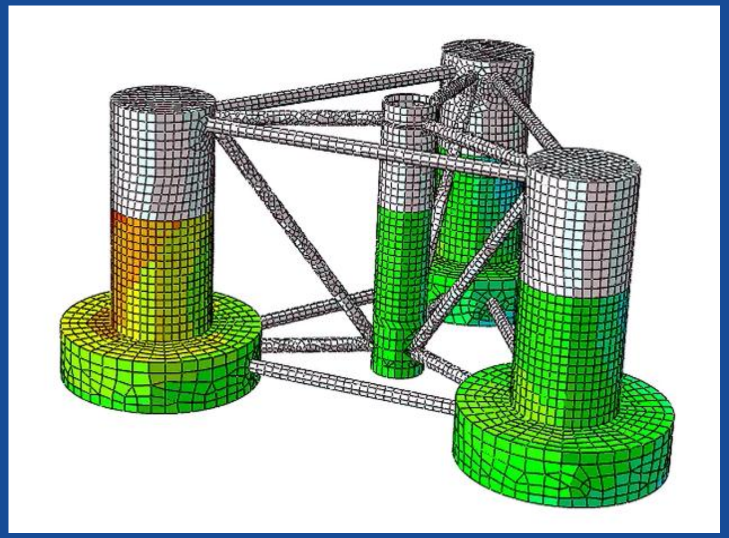
Tracing the causal chain from farm-level flow control optimization to component-level fatigue life consumption.

1 Farm level



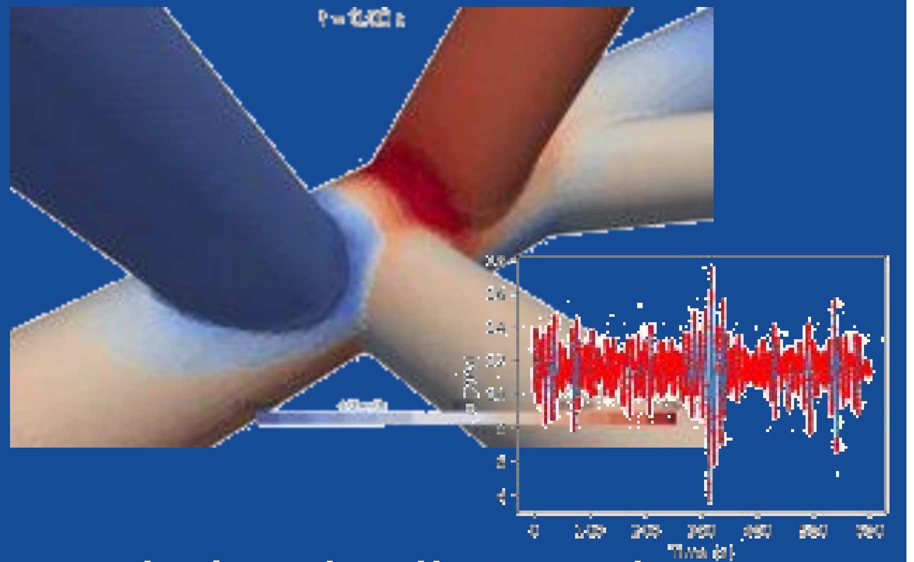
Wake steering optimizes farm-level yield but fundamentally alters inflow conditions, creating asymmetric rotor loading and wake-induced turbulence for downstream assets.

2 Turbine level



Aerodynamic variations translate directly into dynamic load amplification, propagating cyclical bending moments and thrust variations throughout the entire support structure.

3 Component level



Dynamic loads dictate the fatigue governing stresses at weld imperfections, leading to fatigue degradation at critical structural joints.

Rethinking fatigue resistance models: The challenges associated with *perfect* models

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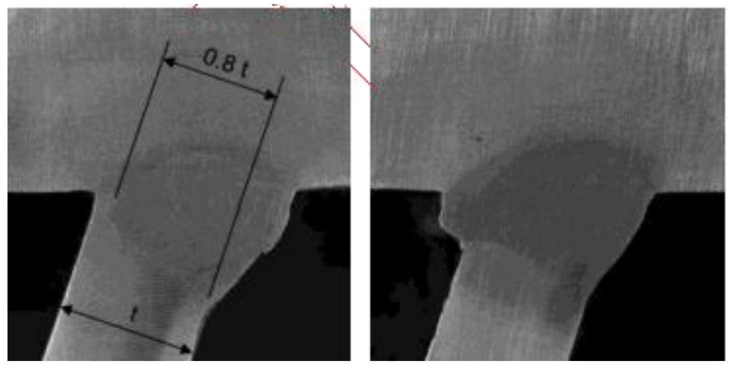
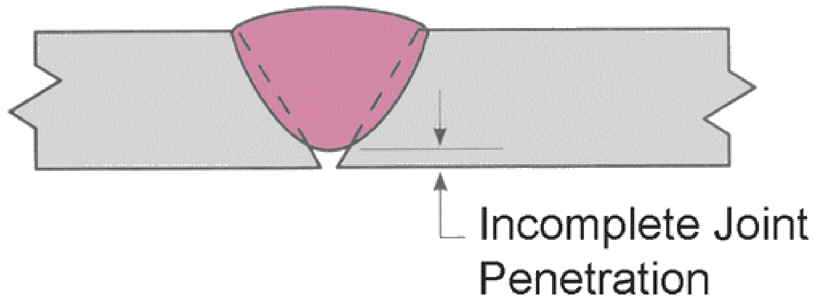
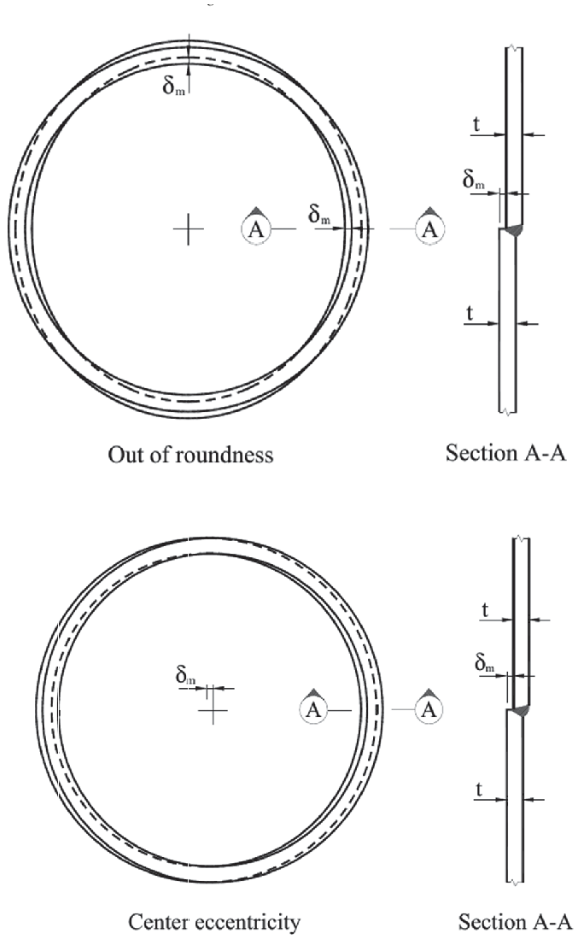
The challenge of fatigue in critical structures

As-design models are idealized, but reality is not. How do we bridge this gap?

As-built structures differ from the as-designed (ovality, misalignment, weld profile, incomplete weld);







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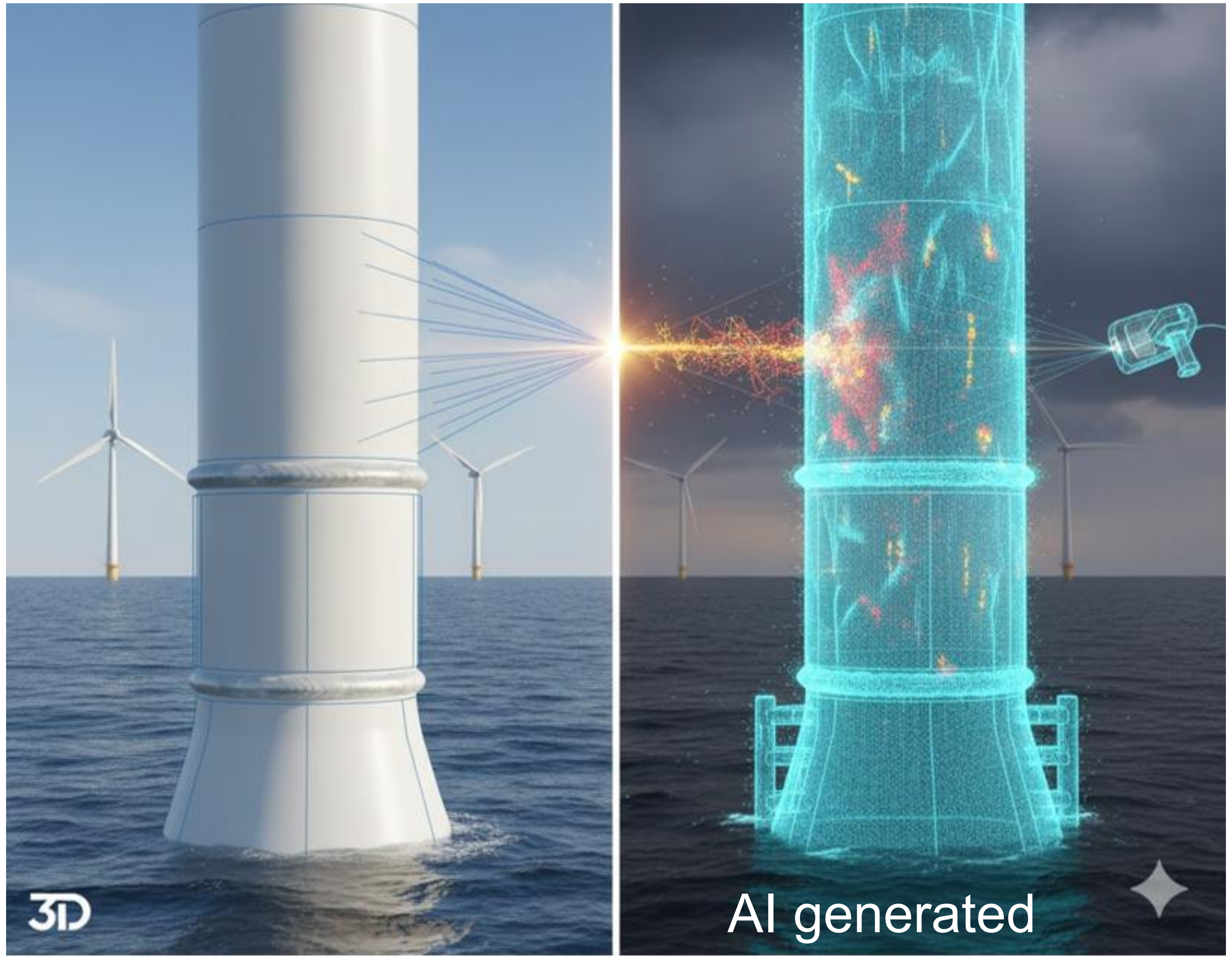
The challenge of fatigue in critical structures

As-design models are idealized, but reality is not. How do we bridge this gap?

A new approach: from idealisation to reality
We create **exact** digital copies the structure



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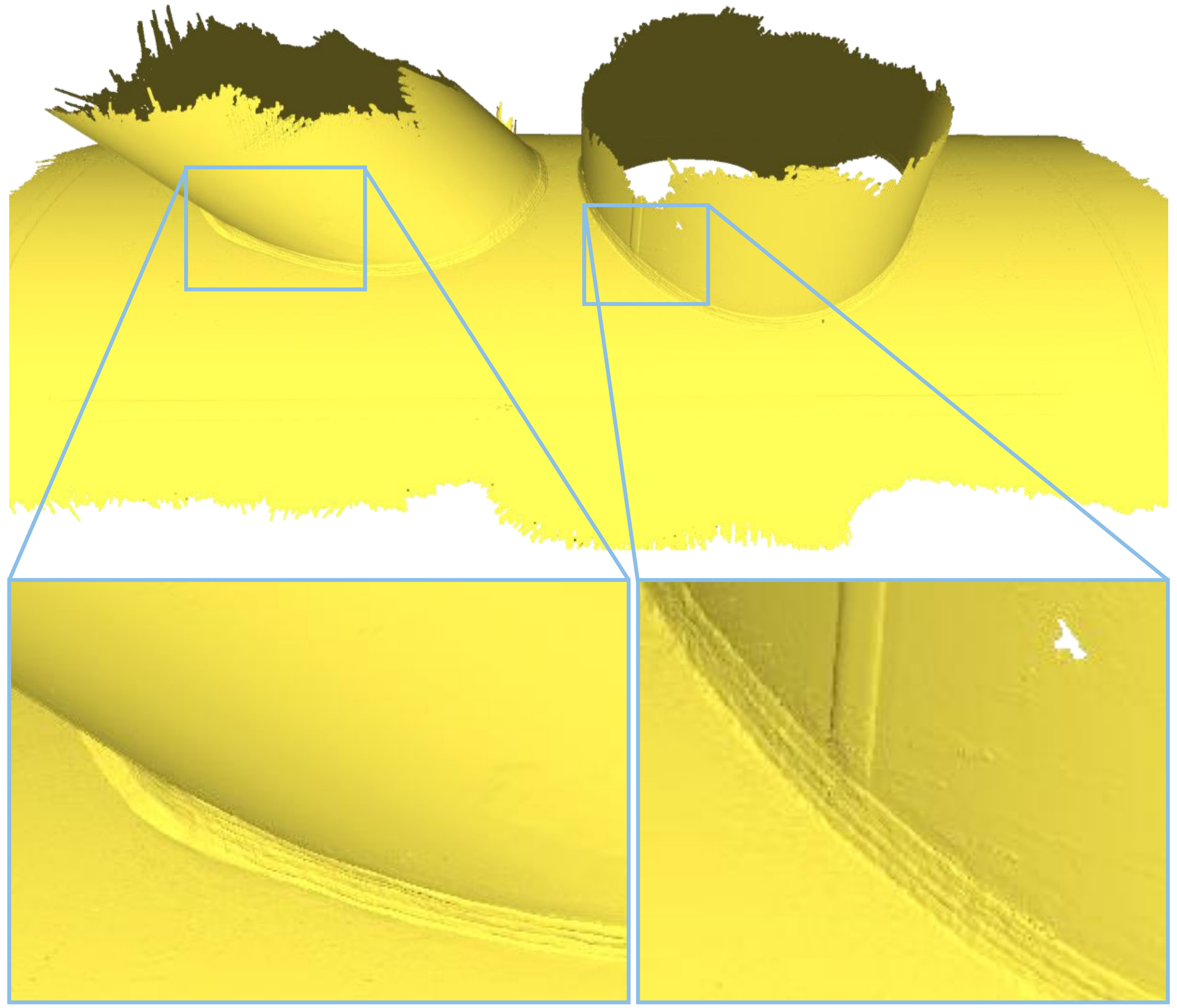
Capturing the 'as-built' reality with 3D scanning

Moving beyond idealised designs: We measure what is really there.

3D Laser Scanning: Capturing the overall macro-geometry of complex industrial joints.

Point cloud: Raw output of the scanner.



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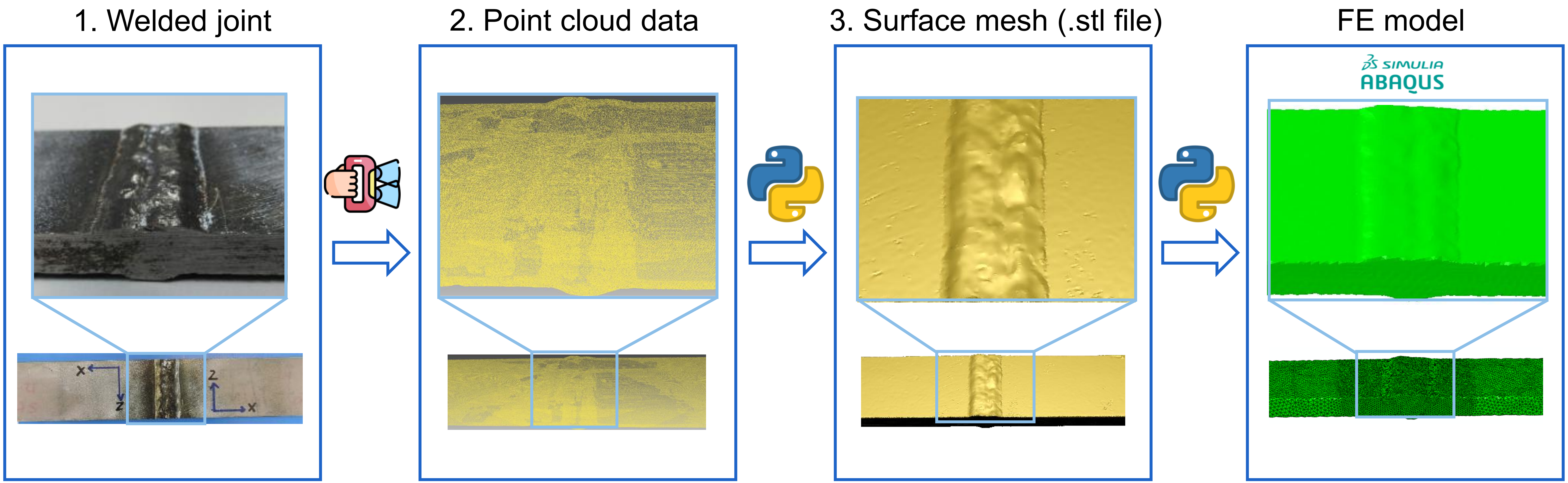
From point cloud to simulation model

Overall workflow of the developed framework



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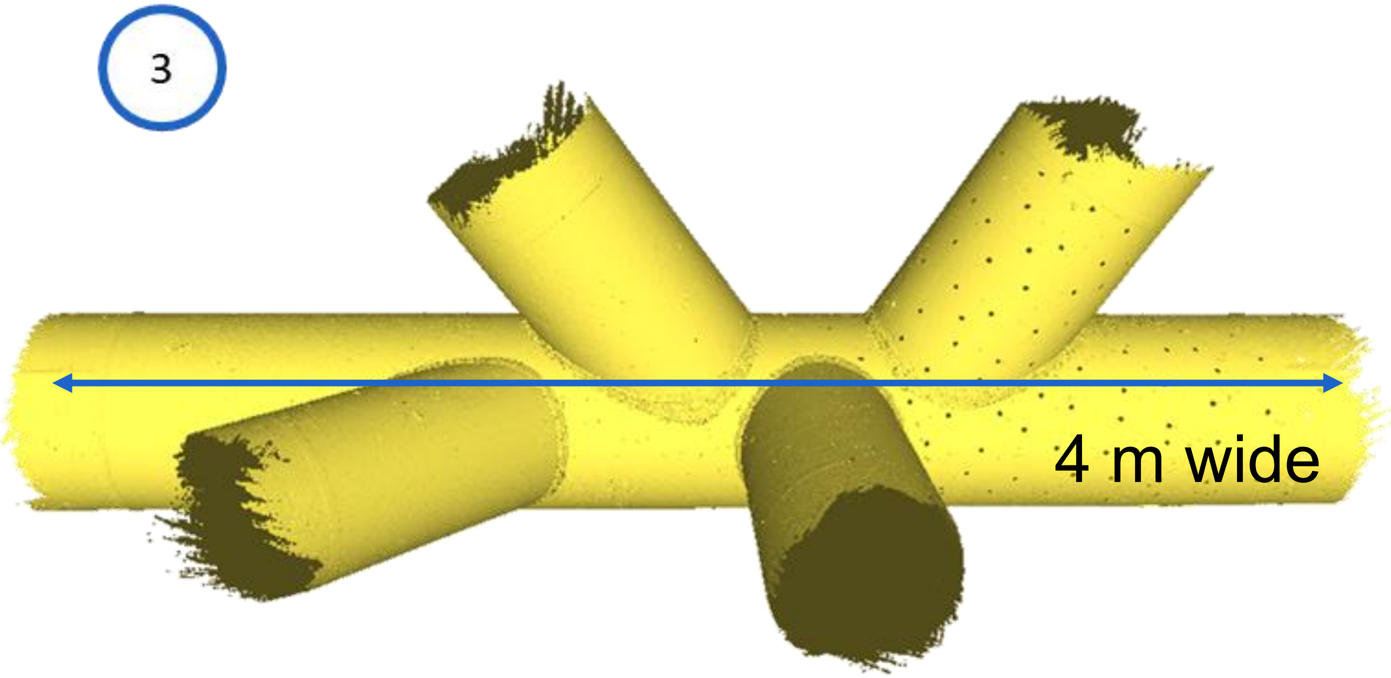
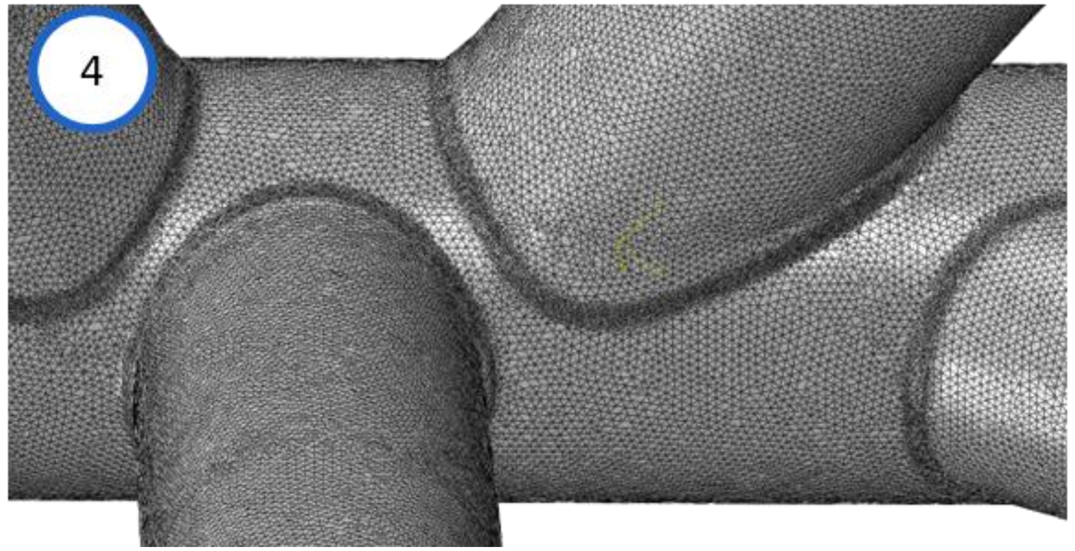
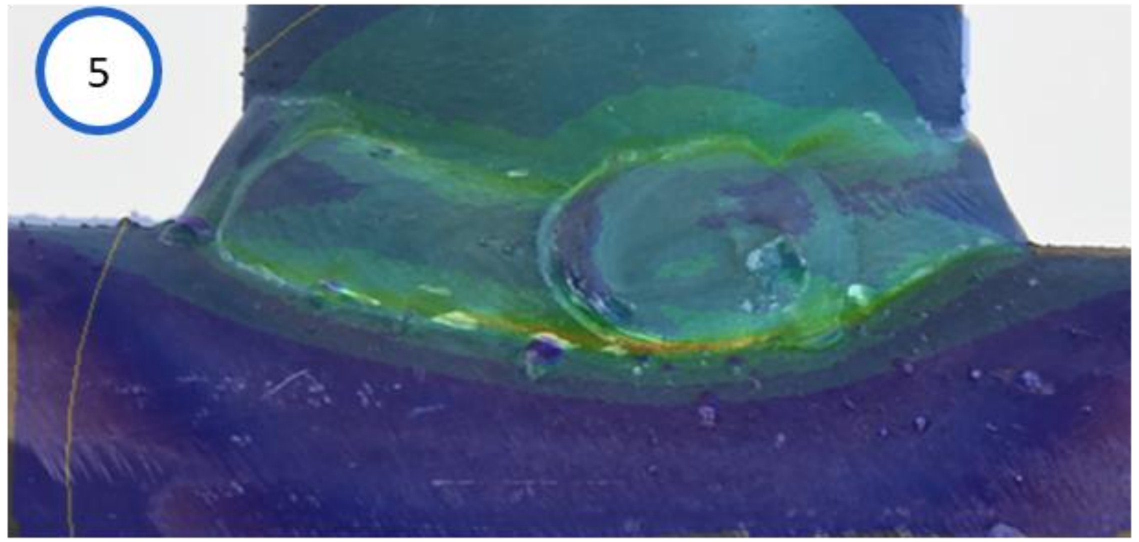
Effect of as-built geometry on fatigue strength

Application to a full-scale offshore joint







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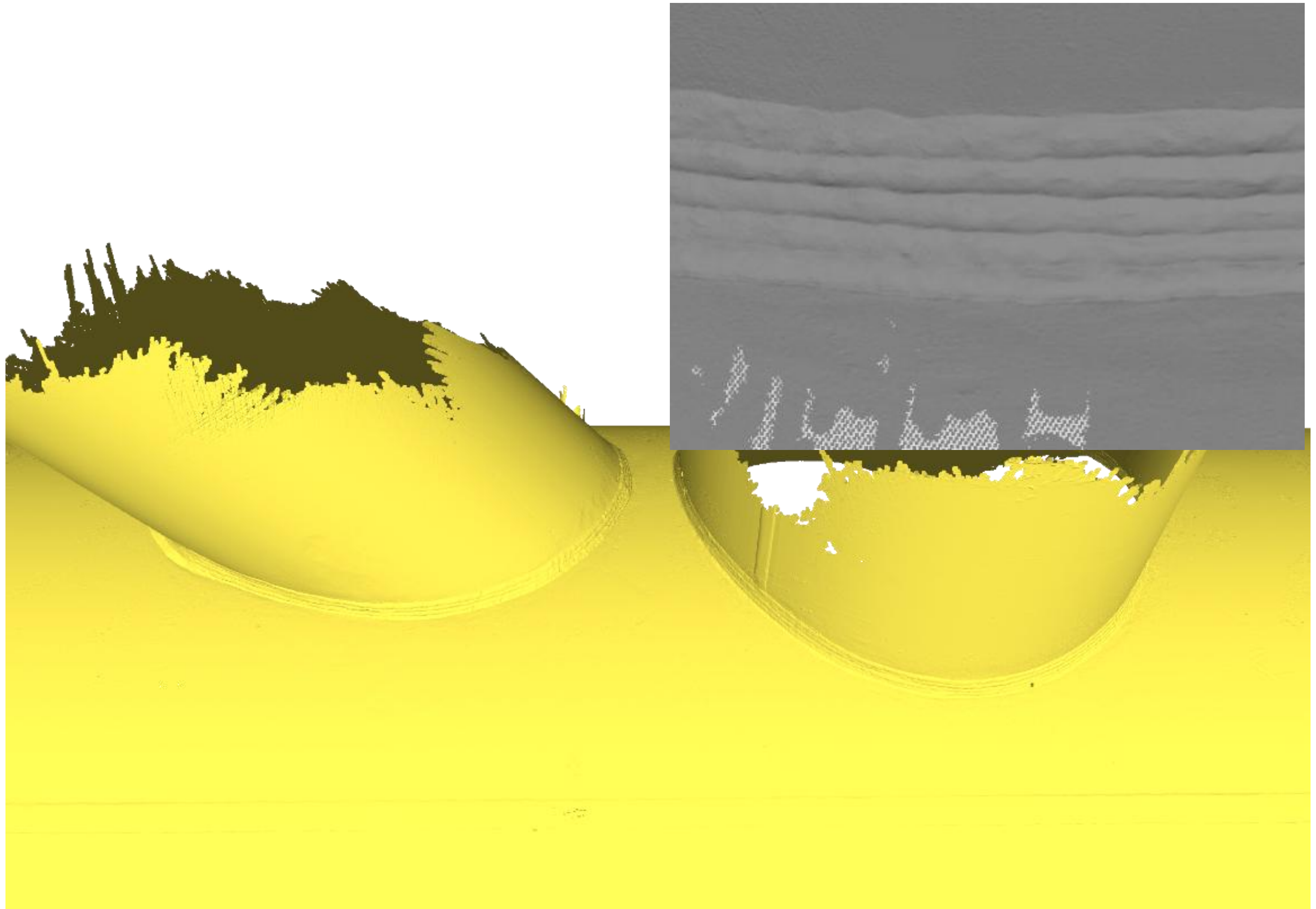
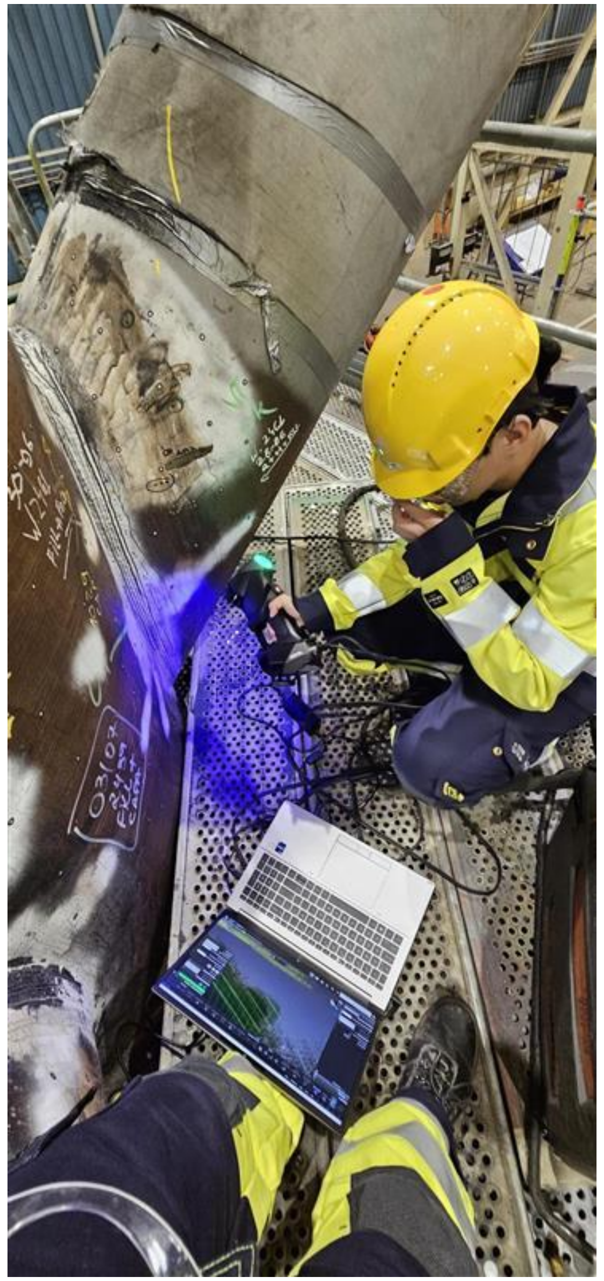
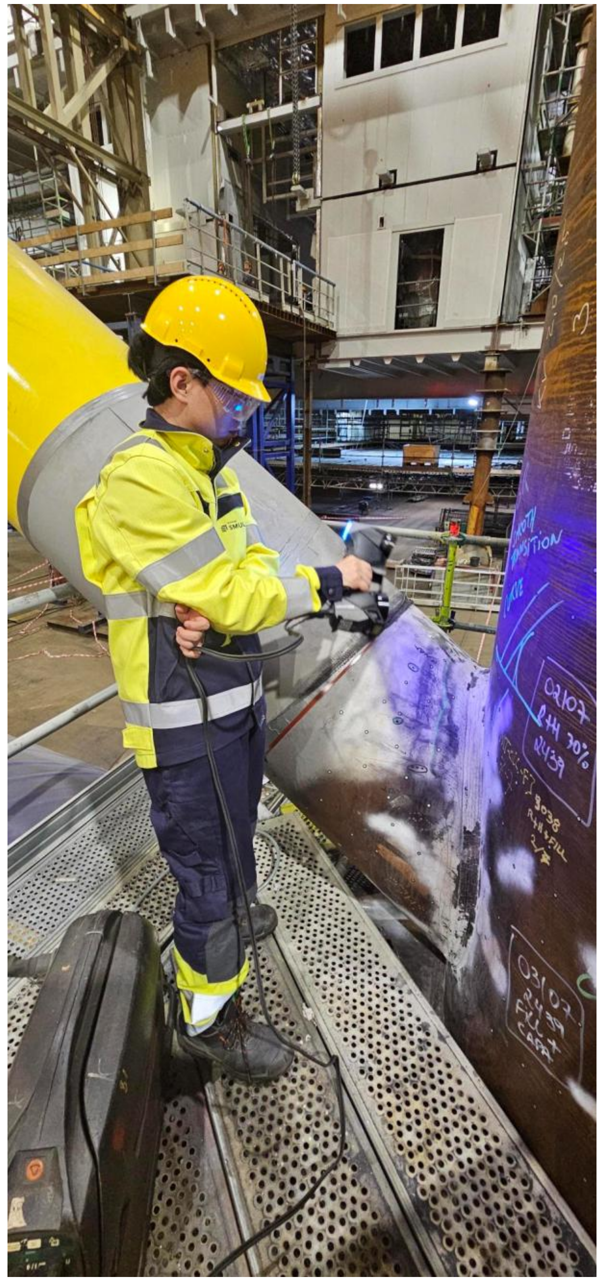
Effect of as-built geometry on fatigue strength

Application to a full-scale offshore joint







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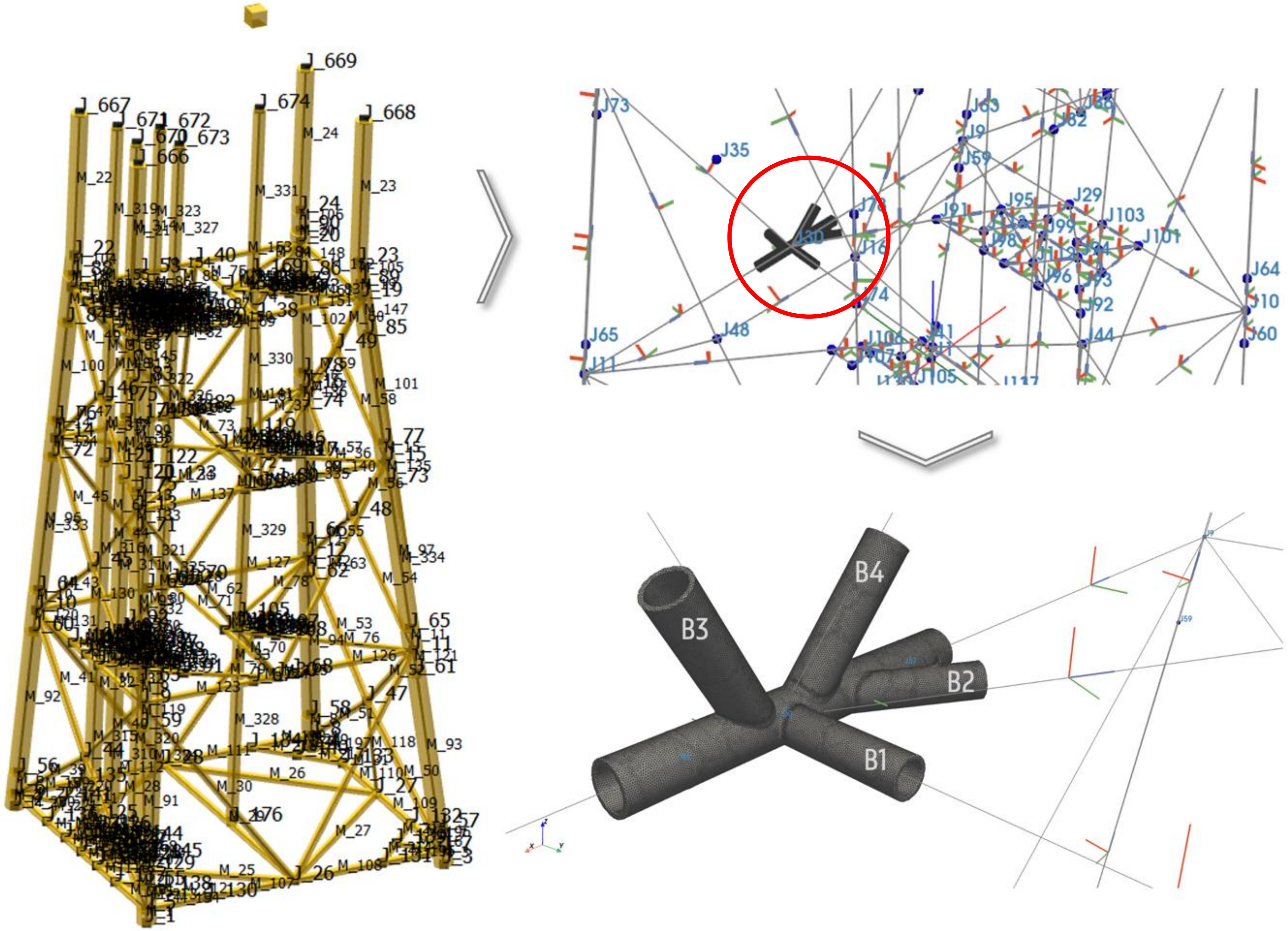
Coupling high-fidelity model to global model

- Global low-fidelity model for calculation of overall structural response
- Global–to–local coupling introduces structural loads onto the local finite element model



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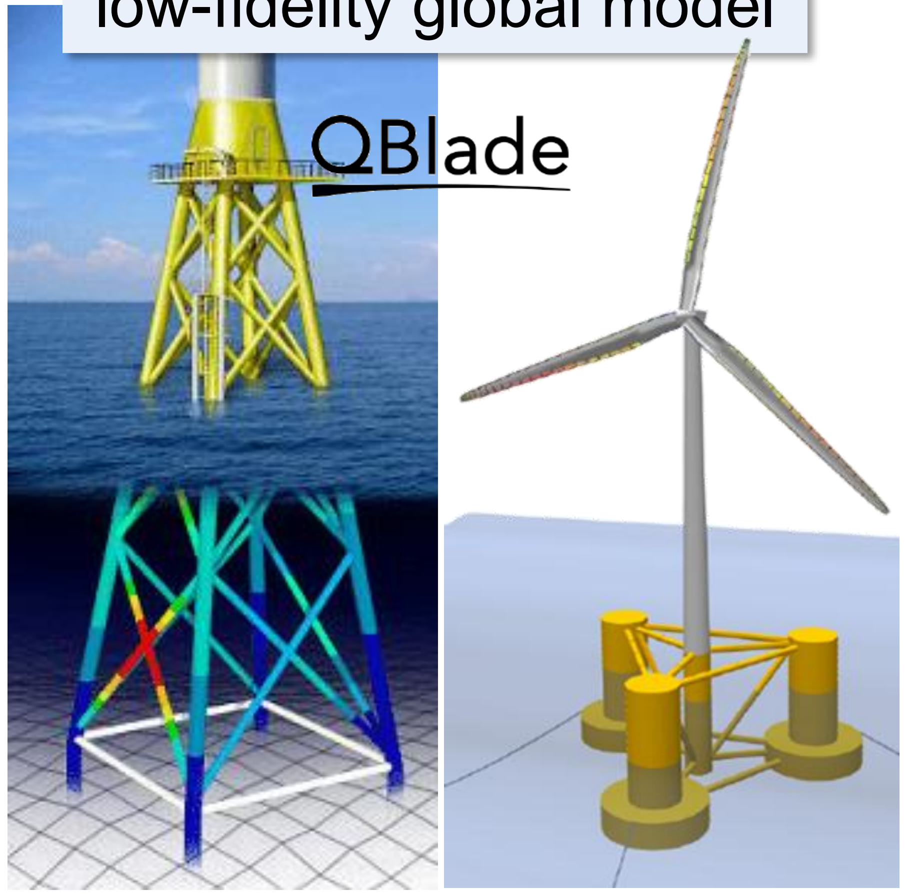
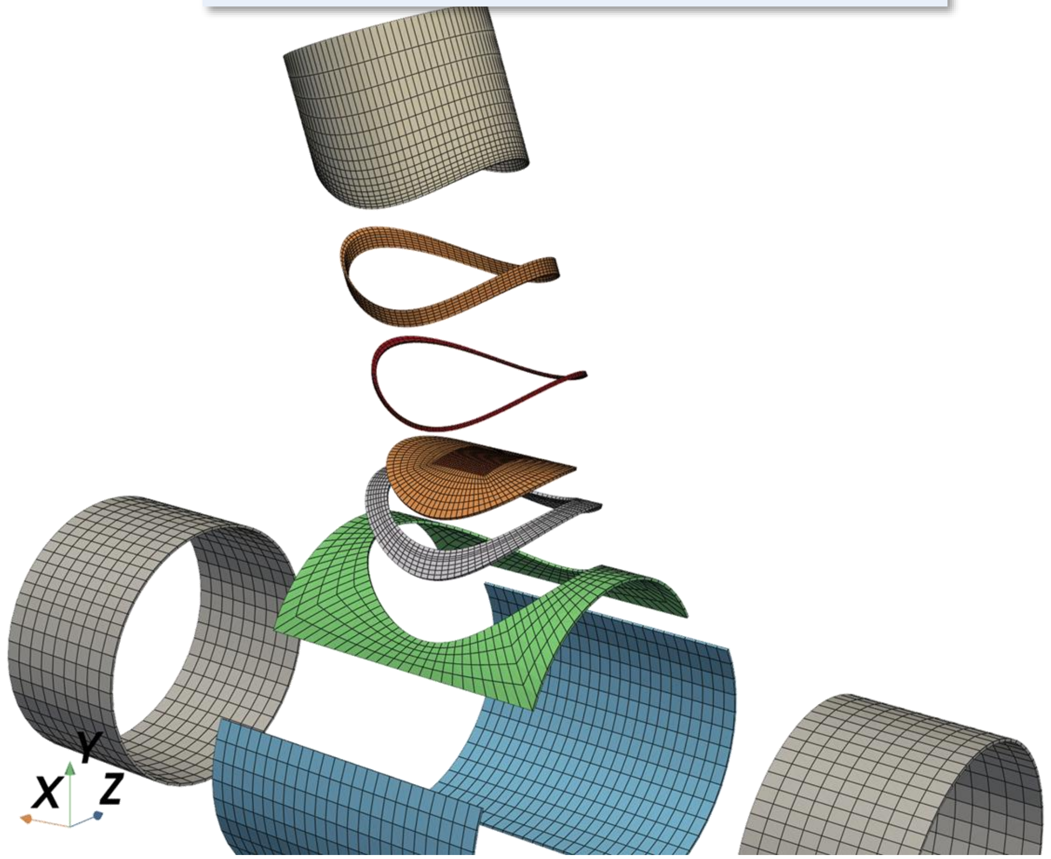
HFJoint: High-fidelity wind turbine simulations

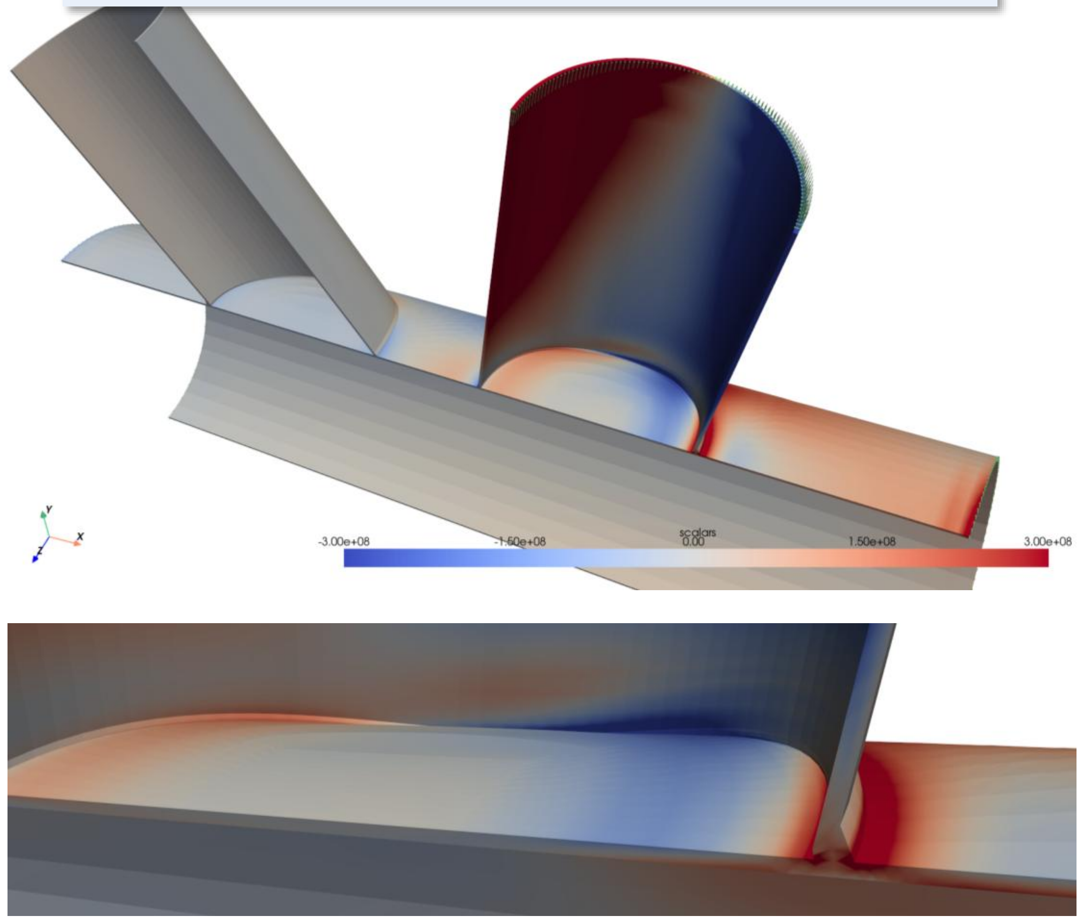
Aero-hydro-servo-elastic low-fidelity global model



Automatic load mapping to auto-generated solid element submodel



In-house developed lightweight structural FEM solver



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FLOATFARM

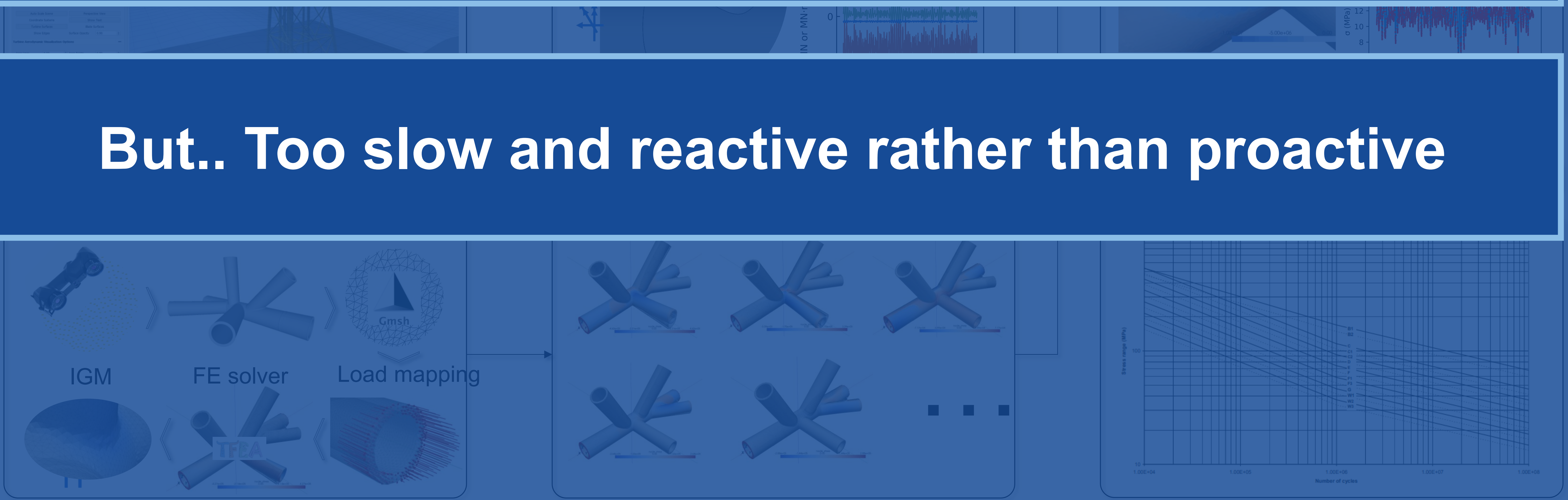
Funded by the European Union

General framework for structural DT

General framework

Goal achieved: reduced scatter on fatigue life assessments through the use of as-built representation of the structural joints and load spectra based on real measurements

But.. Too slow and reactive rather than proactive



Bringing it together: Towards real-time, health-aware turbine and farm level control

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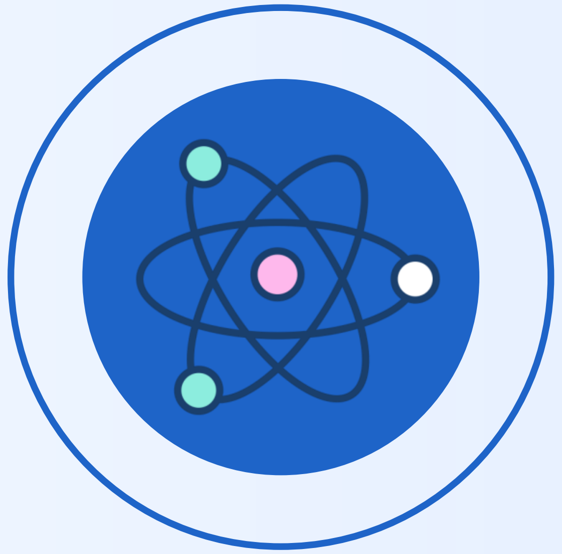
Digital twin maturity matrix: offshore wind

	Gen 1 Static / Design	Gen 2 Data-driven dashboards	Gen 3 Real-time hybrid
Data Flow	Unidirectional	Unidirectional	Bi-directional
Core technology	FEA / CFD / MBD	IoT sensors	PINNs + GNN/ROMs
Output	Post-mortem diagnostics	Reactive alerts	Real-time optimization
Extrapolation	None	Poor	Robust under varying conditions

The modelling paradigm

Pure physics-based

High fidelity, interpretable but computationally probitive



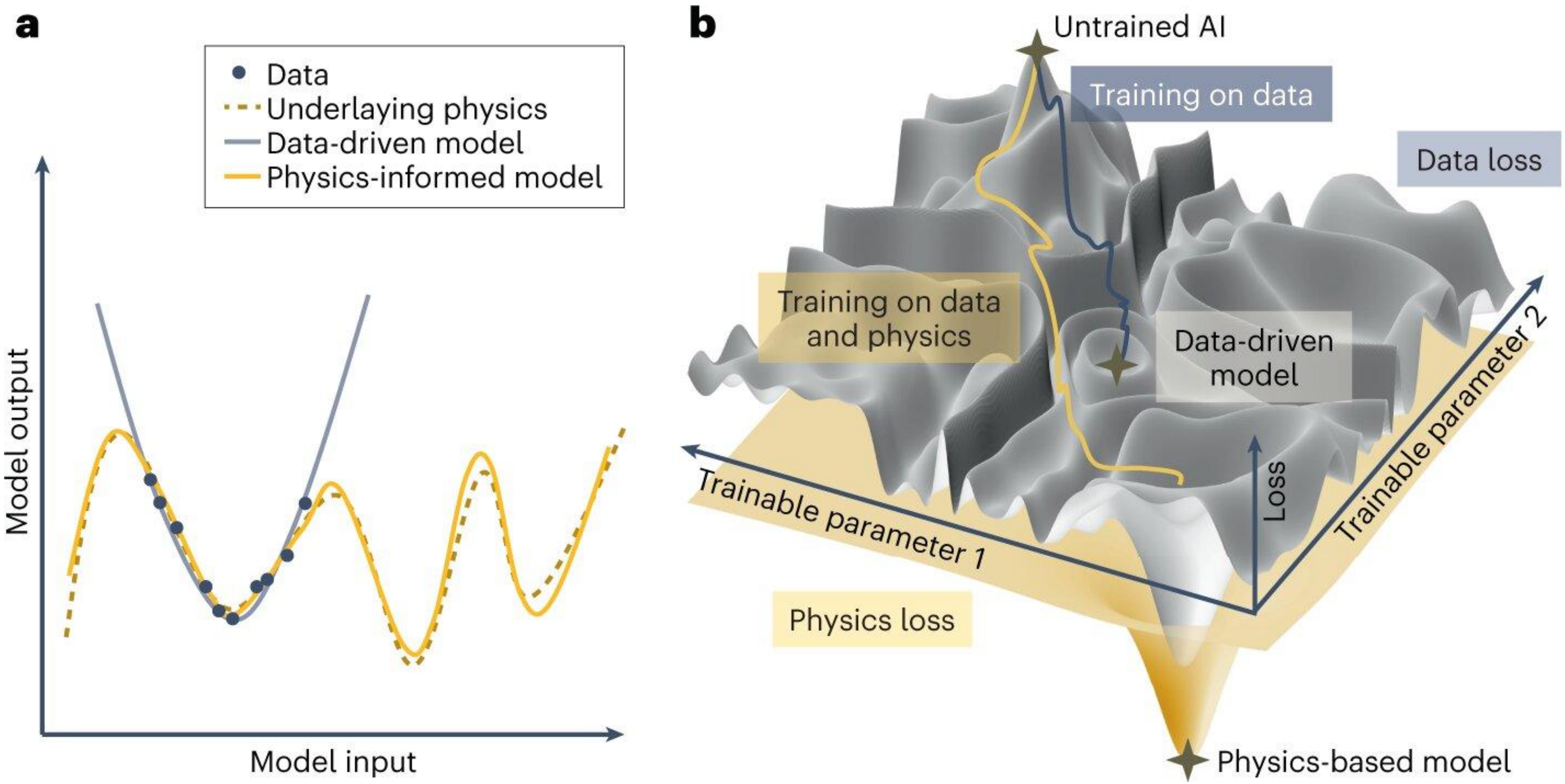
Hybrid AI-Physics

Fast, robust Interpretable

Pure data-driven

Fast, scalable, but black-box and physically inconsistent.

Physics-informed data-driven modeling



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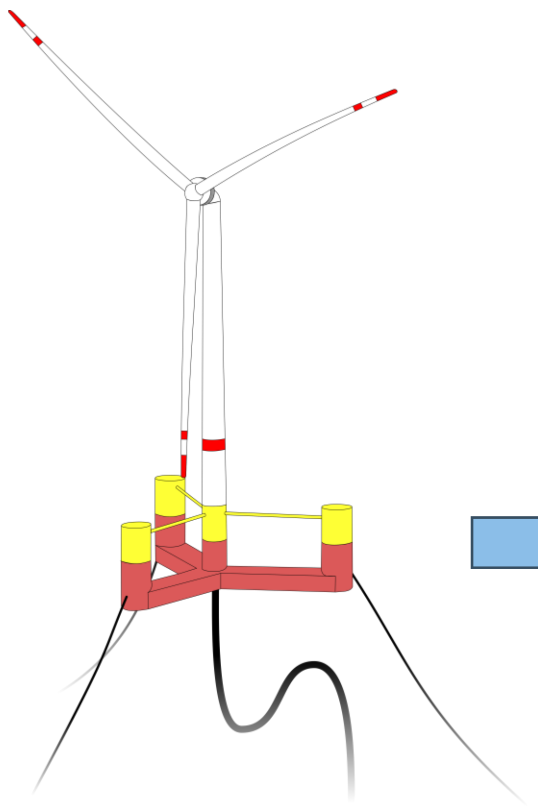
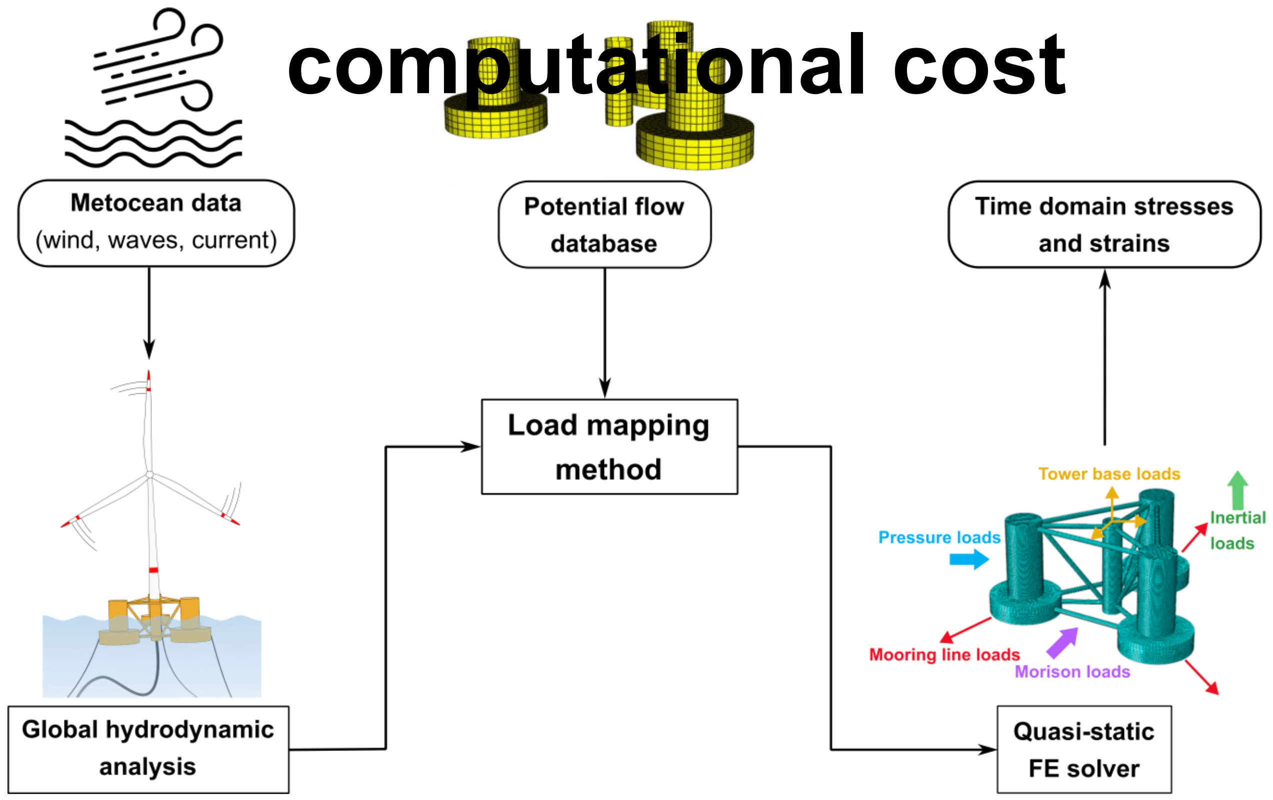
The computational barrier: determining real-time structural behaviour

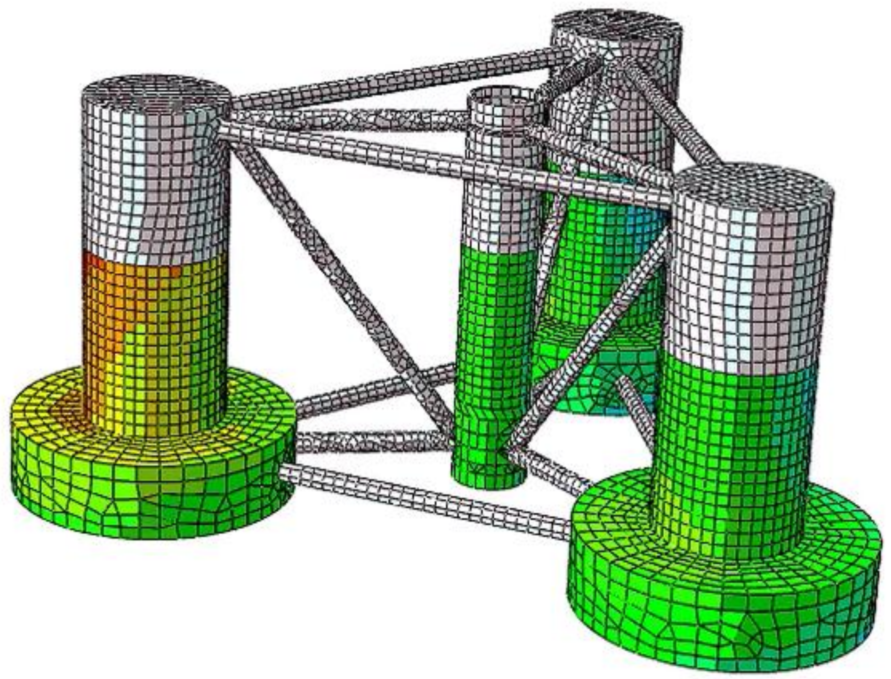


A floating offshore wind turbine (FOWT)

Prohibitive computational cost



Determination of aero- and hydrodynamic loads



Structural stresses used for fatigue life assessment

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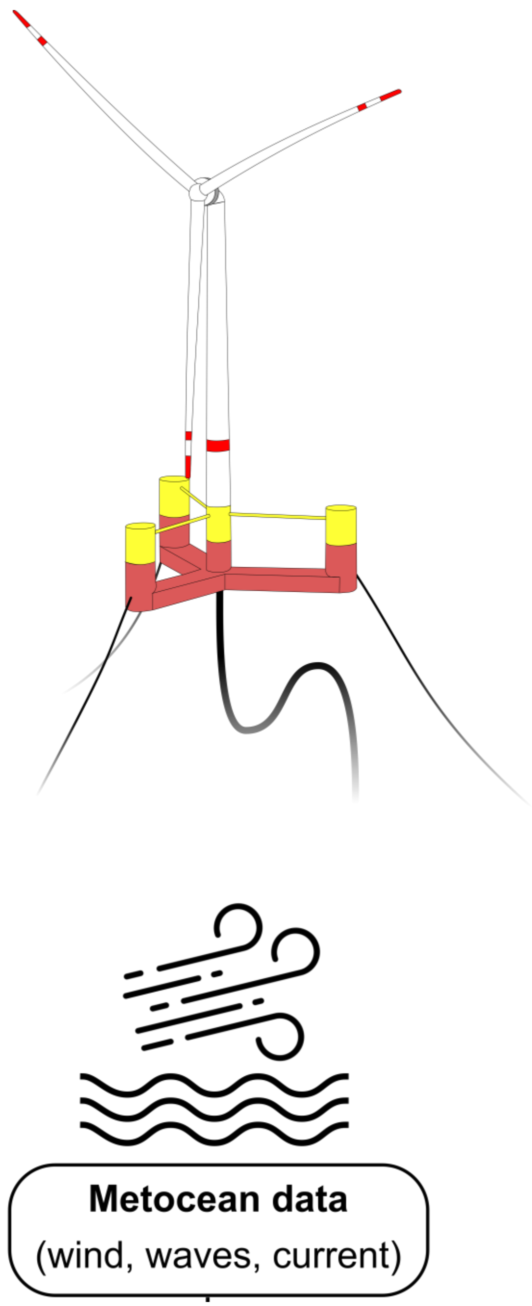
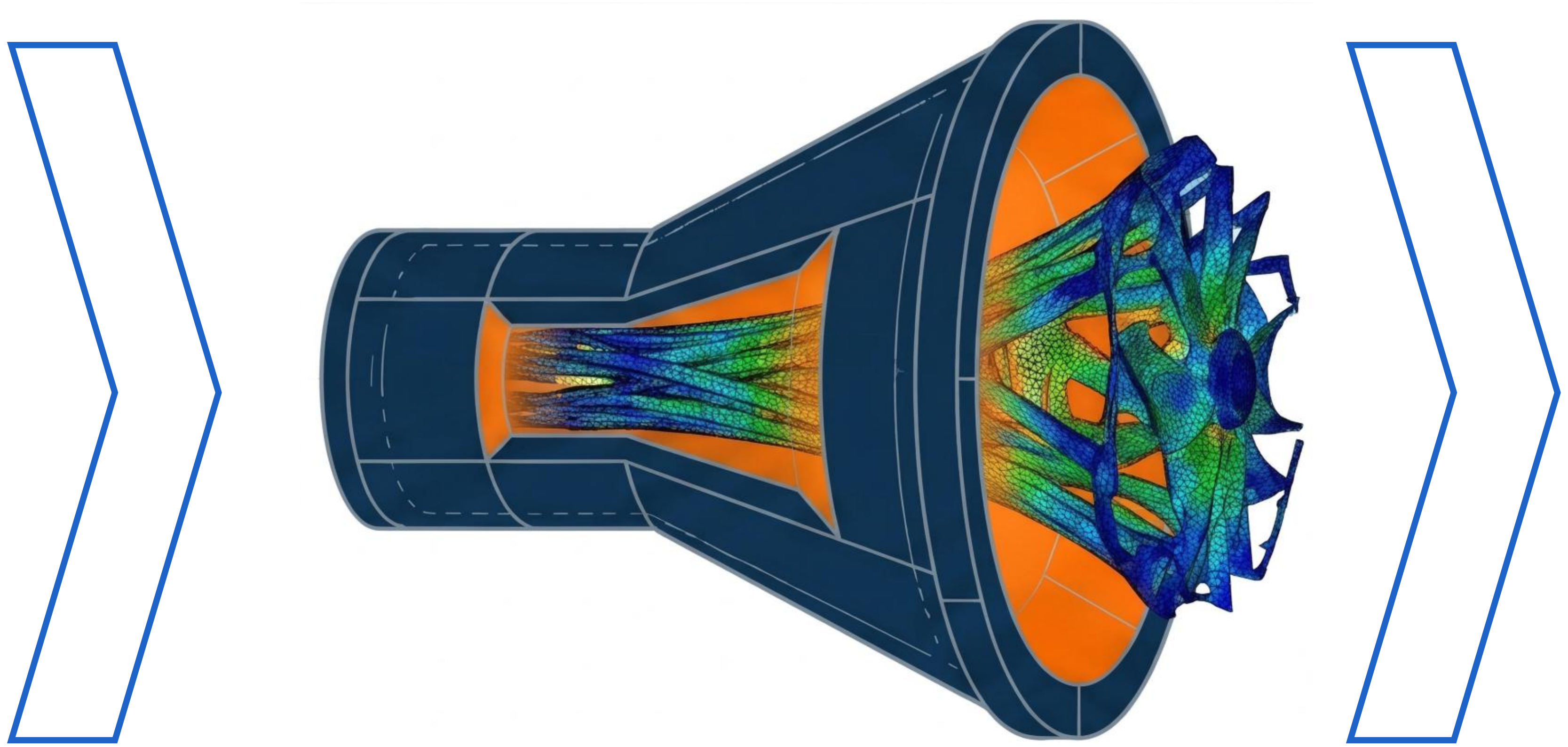
BEL - Float

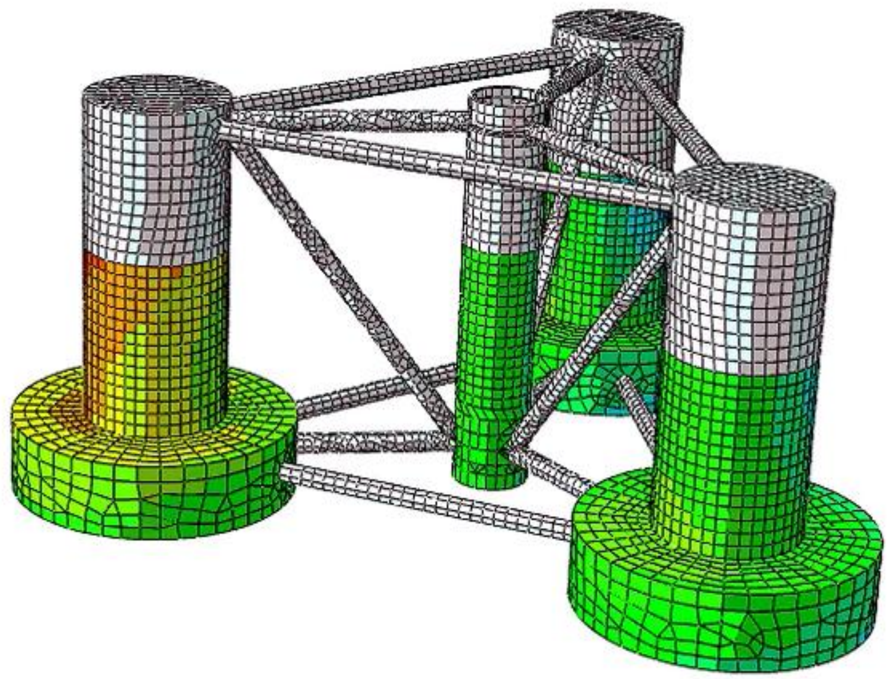
Catalyzing the Belgian industrial expertise in floating wind through academic innovation

Breaking the computational barrier

Reduced order models based on physics-informed neural-networks can distill complex systems into real-time computational models that adhere to empirical observations and physical laws







Physics-informed reduced order models

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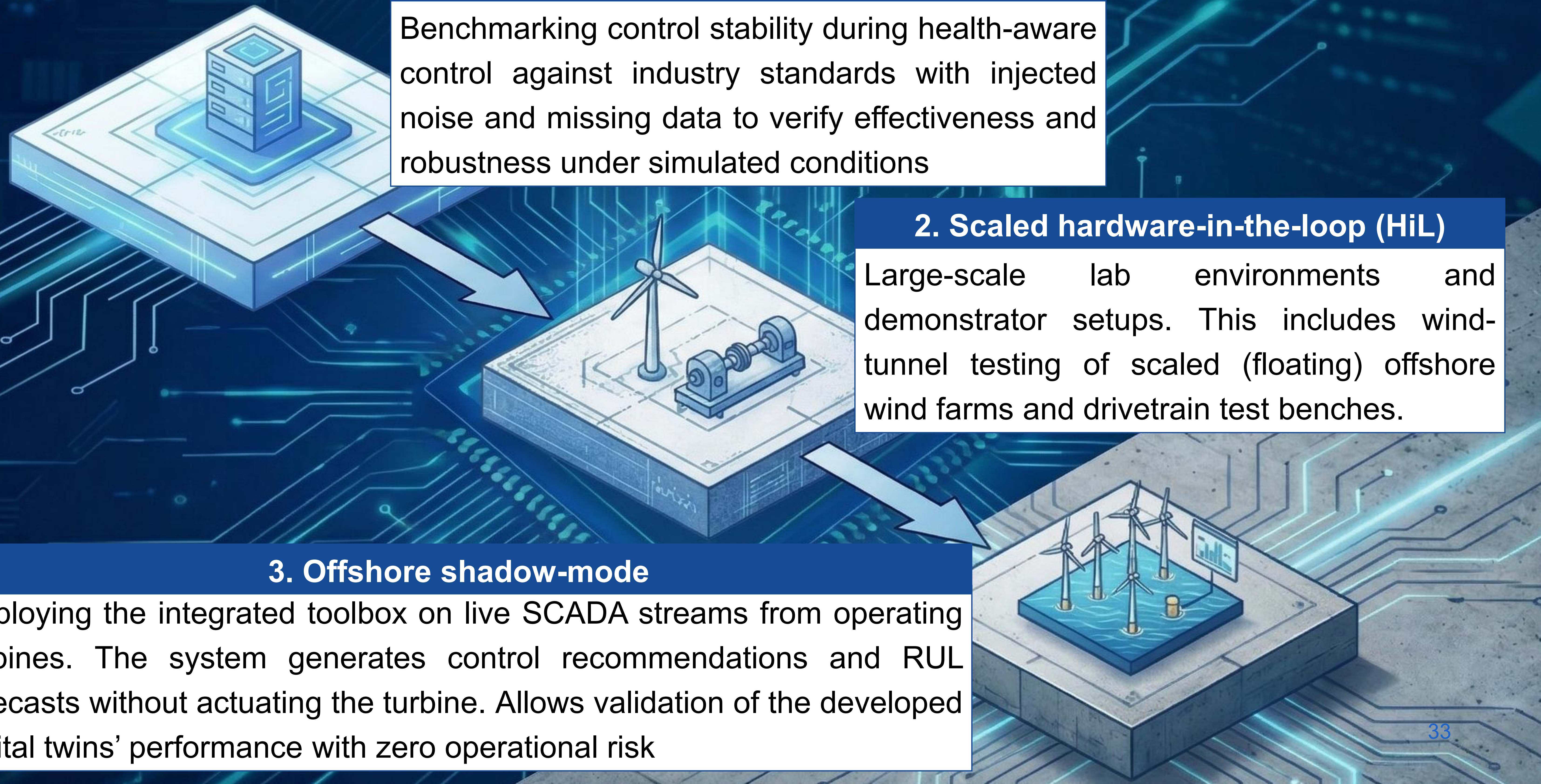
Anchoring the future: strategic timeline



1. Benchmarking co-simulations

Benchmarking control stability during health-aware control against industry standards with injected noise and missing data to verify effectiveness and robustness under simulated conditions

2. Scaled hardware-in-the-loop (HiL)

Large-scale lab environments and demonstrator setups. This includes wind-tunnel testing of scaled (floating) offshore wind farms and drivetrain test benches.

3. Offshore shadow-mode

Deploying the integrated toolbox on live SCADA streams from operating turbines. The system generates control recommendations and RUL forecasts without actuating the turbine. Allows validation of the developed digital twins' performance with zero operational risk

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