SIEMENS Gamesa
RENEWABLE ENERGY

Creating from scratch R&D competences in France for wind energy

Paul Deglaire

Who am i?

Paul Deglaire

Position: Head of R&D France Siemens Gamesa
Location: Paris & Rouen

Personal info:

- Born in 1978 in Paris, France
- 1 year in RISOE/DTU for Wind MSc modules inside PhD education
- 4 years in Bremerhaven Germany
- 3 years in Sweden (PhD), 1 year in Switzerland (Indus), 6 months in UK (Fluid Mech)

Education :

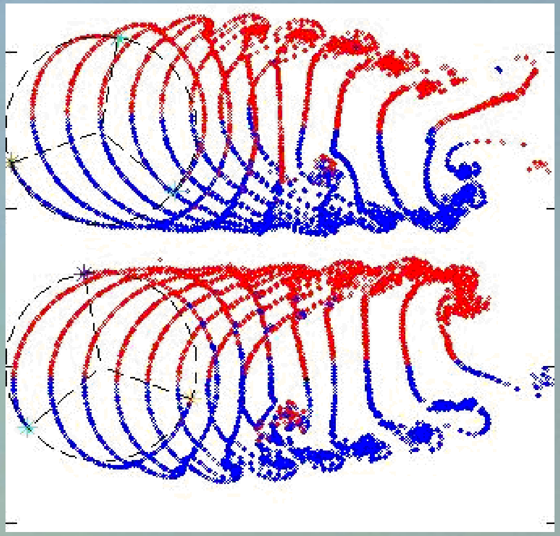
- Engineering degree ENPC, GMM 2004
- Industrial internship. Watch factory, 2003
- PhD in unsteady aerodynamics in Uppsala, 2007

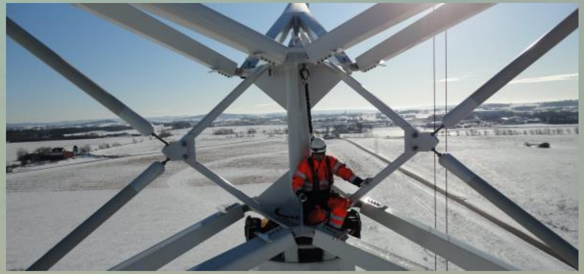
École des Ponts ParisTech
PIAGET
UPPSALA UNIVERSITET
DTU

PhD thesis: learning & training - continued

- **Title**
  - **Analytical Aerodynamic Simulation Tools for Vertical Axis Wind Turbines**

- **Numerical and experimental background**
  - **Target: be able to compute accurately the unsteady aerodynamic loads of a VAWT in real time.**
    - Theoretical development & implementation of a fast 2D vortex code using FMM algorithms together with analytical conformal mappings
    - Setting up one of the first aero-elastic model for double variable pitch counter rotating VAWTs (vortex + beam theory for blades and struts)
    - Leading the load design team of 12kW, 20kW and 200kW vertical axis machines of Vertical Vind AB
    - Performing first tests of the 12kW prototype
  - **4 journal publications and 4 conference articles**





Professional experience: learning & training - continued

2008: **R&D project manager** (2008) - Feasibility for hydro turbine for rivers & wave energy converters

2009 – 2010: **R&D coordinator** - Setting up the Technology and R&D roadmap of AREVA Wind for the future AD5-135 and AD8 with AREVA Wind CTO

2011 – 2013: **AD5-135 program manager-** Extended rotor diameter program. Responsible for the program execution (planning, performance, budget) from product definition to design freeze in close links with marketing and sales team

2013 – 2016: **Technical project manager**: development of new aeroelastic methodologies for Loads & control. Management of 5 PhDs

2017 – current : **R&D Manager** Siemens Gamesa Renewable Energy. Starting with 1 engineer, now more than 30 engineers today mainly in Rouen

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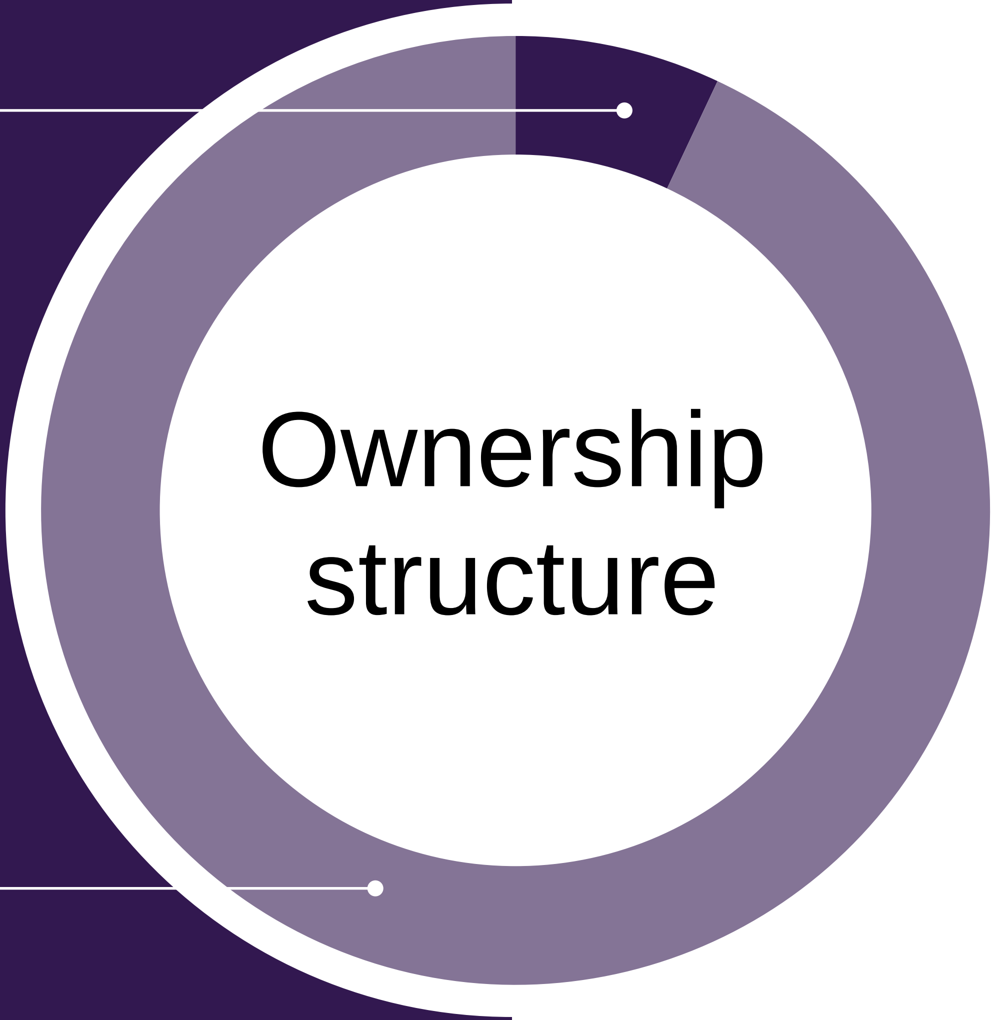
Where am I working?

Free-float shares

7%

Siemens Energy AG

93%



Siemens Gamesa is a leading global provider of wind power products and service solutions

- #1 in offshore
- Leading position in onshore and service

- Founded in April 2017 as a merger of **Siemens Wind Power** and **Gamesa**
- **A global company**, based in Zamudio (Vizcaya, Spain) and listed on the **Spanish Stock Exchange**
- It is traded in Barcelona, Bilbao, Madrid and Valencia

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The offshore wind turbine manufacturer with the longest, most extensive history in the industry

World’s first offshore project

1991: 4.95 MW | Vindeby, DK

First power plant-sized project

2011: 630 MW | London Array, UK

First large-scale offshore DD project

2018: 574 MW | Race Bank, UK

First subsidy-free offshore project

2022: 1.54 GW | HKZ, NL

Three business units strongly positioned in the market

Onshore

106.5 GW

installed since 1979

The **technological partner of choice** for onshore wind power projects.

Offshore

21 GW

installed since 1991

Most experienced offshore wind company with the most reliable product portfolio in the market.

Service

82 GW

maintained

Commitment beyond the supply of the wind turbine **to reach profitability goals.**

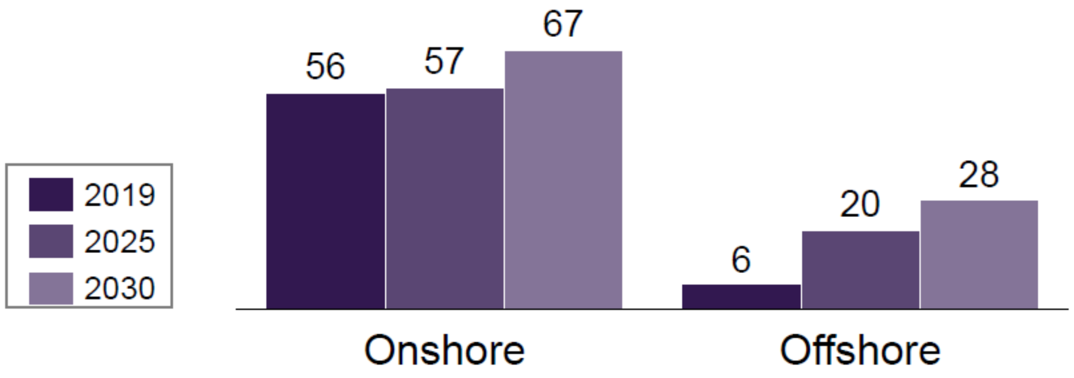
Very strong growth in Offshore and Service during next five years and beyond. Demand in Onshore remains solid

WTG

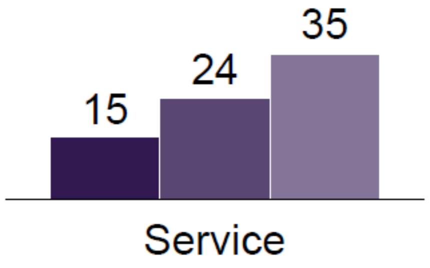
Service

Market Size

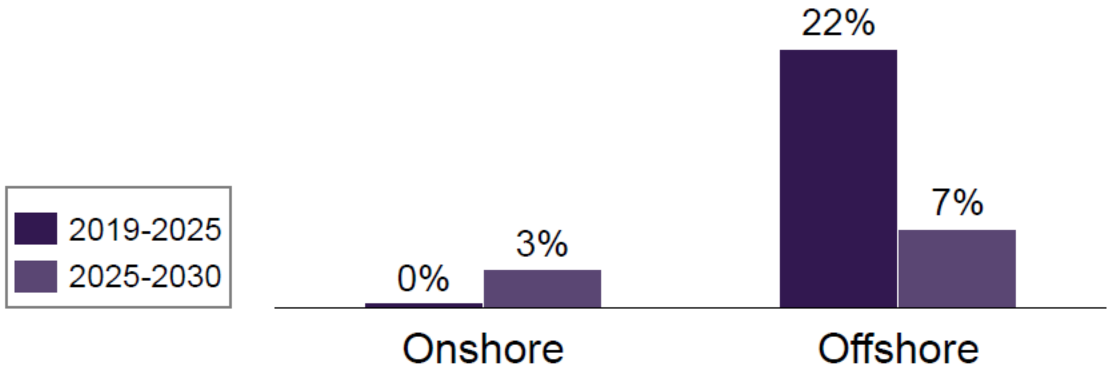
Annual installations (GW)[1]

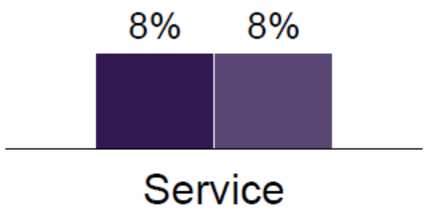


Annual O&M market size (€bn)[2]



Growth (CAGR %)





1) Source: Wood Mackenzie Global Wind Power Market Outlook Q2/2020 (until 2029), 2030 data based on SGRE own estimation
2) Source: Wood Mackenzie O&M reports (until 2028), 2030 data based on SGRE own estimation

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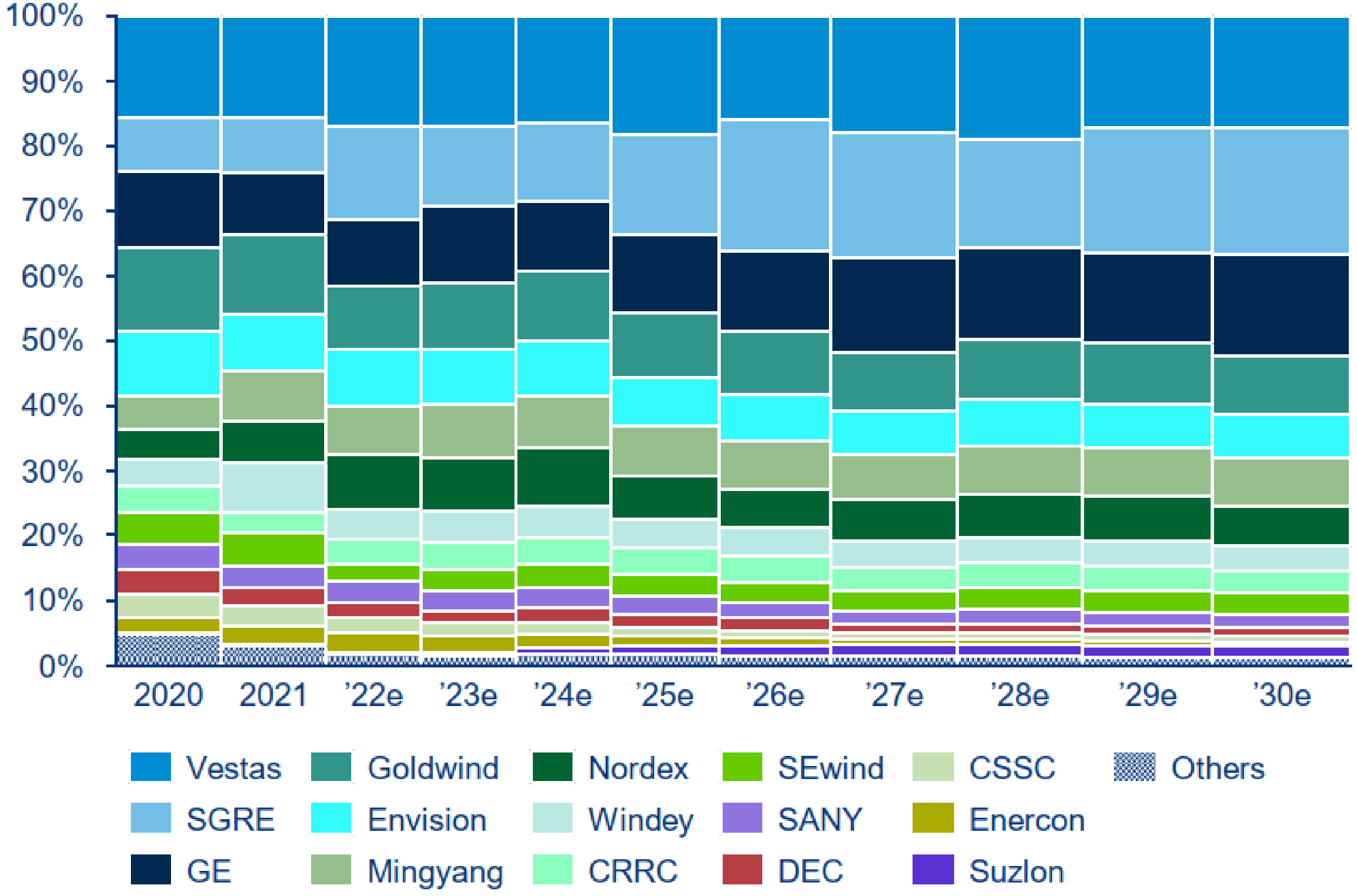
GLOBAL - Top three OEMs consolidate the global onshore and offshore markets

Nordex's supply chain restructuring, product technology evolution elevates them as top four western player

Global turbine OEM market share forecasts, onshore and offshore, 2020-2030e



Source: Wood Mackenzie

Top three Western OEMs: Vestas, SGRE, GE

Consolidate global turbine supply capturing 45% market share over this decade, driven by the combined strength of onshore and offshore businesses

Chinese leaders – Goldwind, Envision and Mingyang

Despite stiff competition from smaller OEMs, the top Chinese OEMs defend their share; They continue to scout for international opportunities, especially in LATAM, Middle East & Africa, and APeC.

Regional pioneers – Nordex and Enercon

Nordex emerges as a solid fourth global contender. It becomes the only western OEM to record increased order intake in 2021 vs 2019/20.

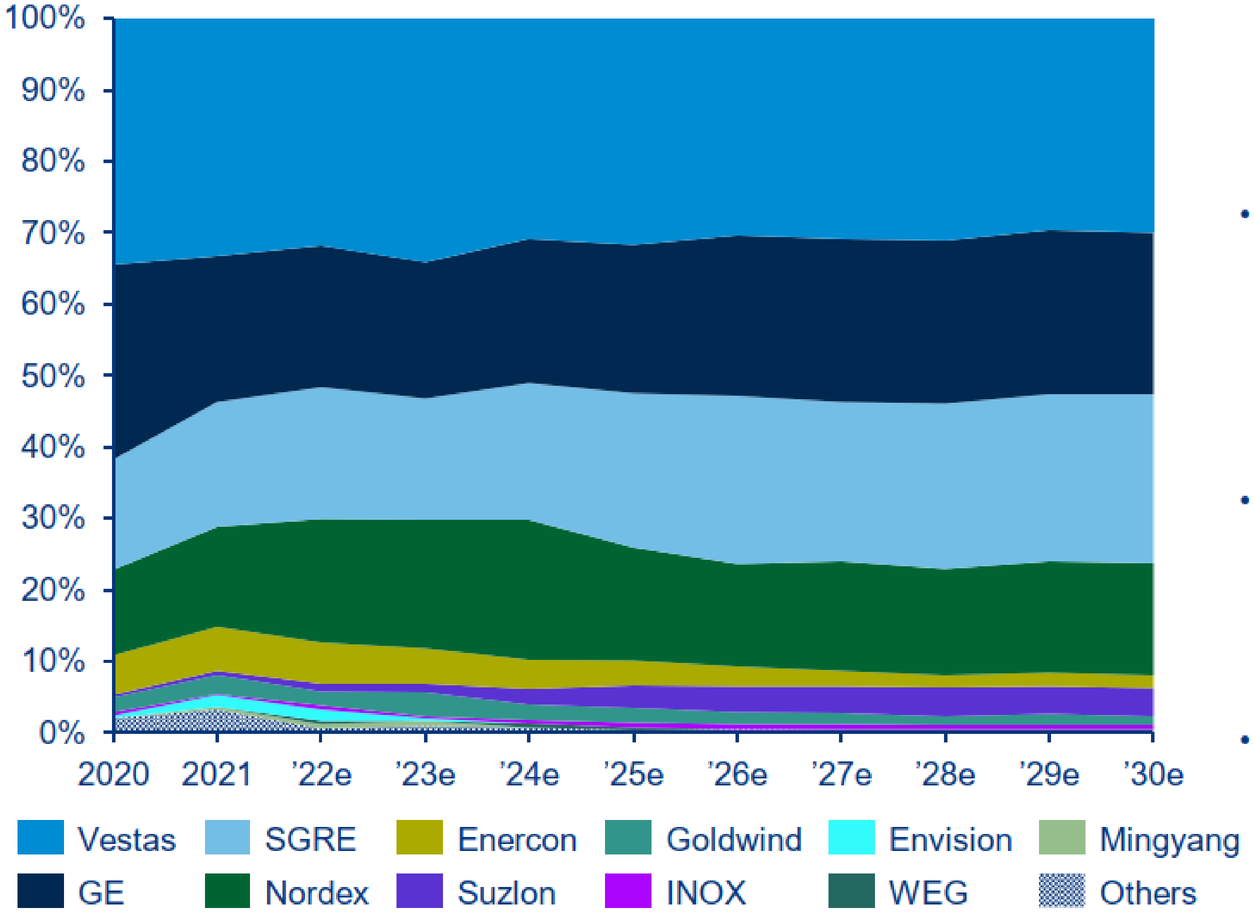
Enercon's technology restructuring and focus on onshore emerging markets has yielded positive results for the company, however profitable turn-around will determine its future success

Offshore leaders: SGRE, Vestas, GE and SEwind

SGRE dominates the global offshore markets with 15+GW of the offshore project pipeline. Vestas races against time to commercialize V236 to regain the lost ground. Meanwhile, GE is ramping up delivery of 4+GW of the backlog and 4+GW of the project pipeline. SEwind dominates China while transitioning to in-house technology.

Global Ex. China - Top four turbine OEMs dominate the market with an 85% share in 2021, and rise to 95% by the end of this decade

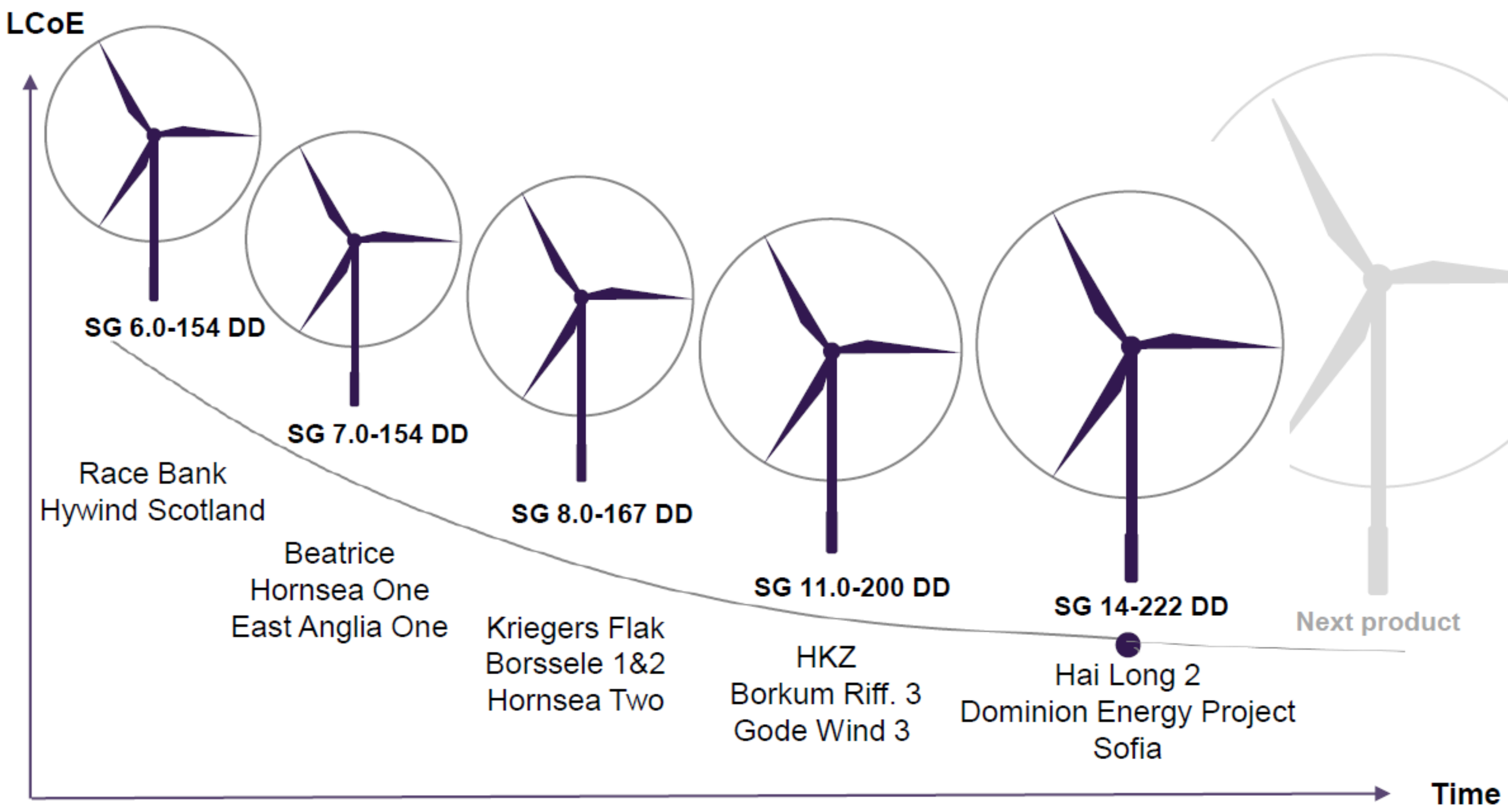
Onshore turbine OEM market share forecast, global market, excl. China, 2020-2030e



Source: Wood Mackenzie

- **Vestas** continues to dominate the global onshore market. Its new sales activity in over 40 countries decouples the company from any demand swings in the regional markets. Vestas' onshore project development strategy yields results more quickly. The company has amassed 20GW of the development pipeline and targeting 30-40GW in the mid-long term
- **SGRE** onshore is plagued with profitability concerns due to external market factors, internal technology and supply ramp-up of the SG 5.X platform. More than EUR 2bn worth of contracts to be executed at a near-zero margin. SGRE is well-positioned to capitalise on growth in markets like India, Spain, Brazil, Nordics and Africa. IP conflict with GE in the US has temporarily slowed down the activity but is expected to pick up in the next two years
- **GE** has successfully diversified into new markets, mitigating the high reliance on its home turf, the US. Australia, Nordics, Spain and India will be critical future markets for GE. The company continues to tap into emerging markets in Eastern Europe by leading those markets by edging out peers. However, cost-out initiatives on current and future Cypress variants are essential for future success
- **Nordex** successfully leveraged product and technology investments in the Delta4000 series and demonstrated commercial success. The company continues to drive sales, and supply chain restricting will ensure profitable execution of these orders. Nordex managed a record order intake in 2021, just shy of 8GW, spanning 20+ markets globally

Each evolution of the direct drive platform delivers significant AEP upsides with reduced risk and time-to-market



~30 years experience and **~16 GW installed**

+1,000 Direct Drive offshore **turbines installed** with **+1,000 in pipeline**

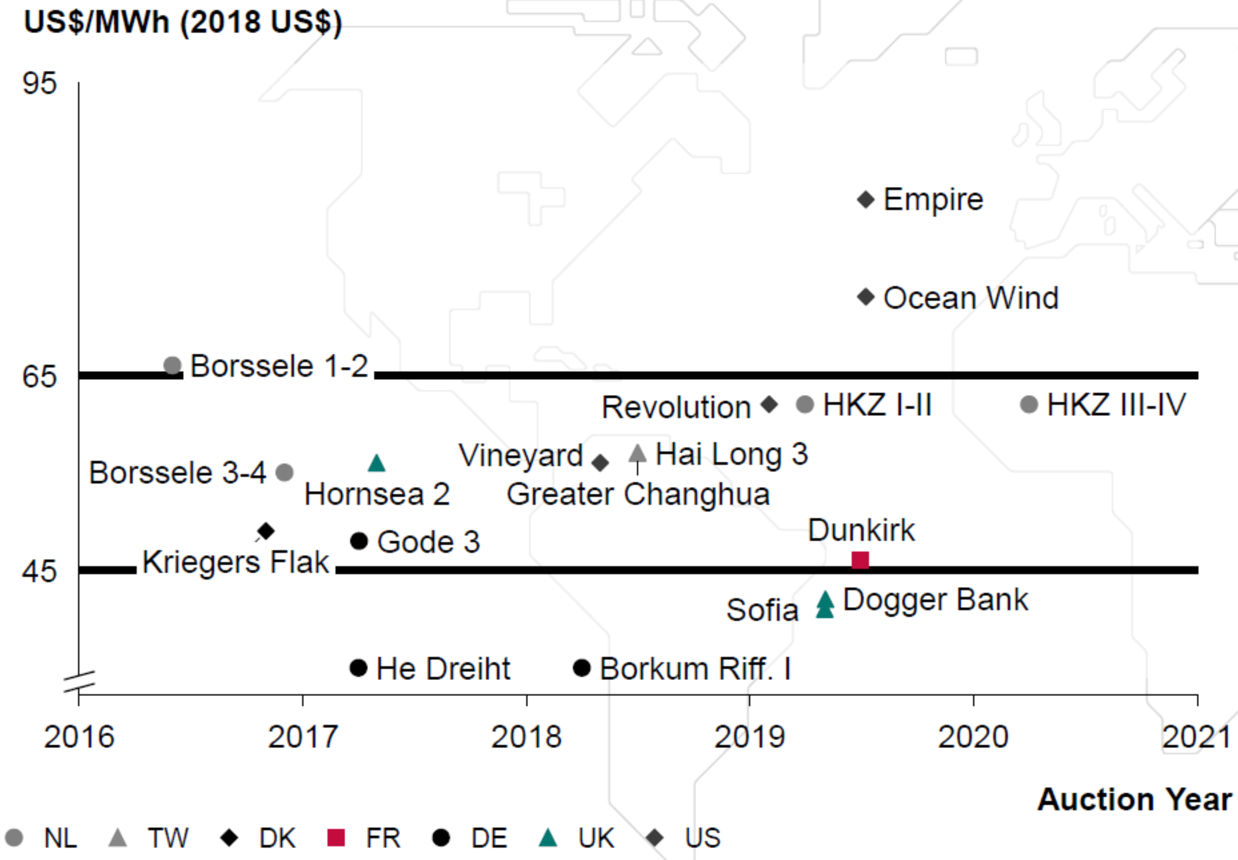
Evolutionary product development allow for **low risk and continuous cost-out**

Enabling 1st subsidy free offshore wind farm HKZ

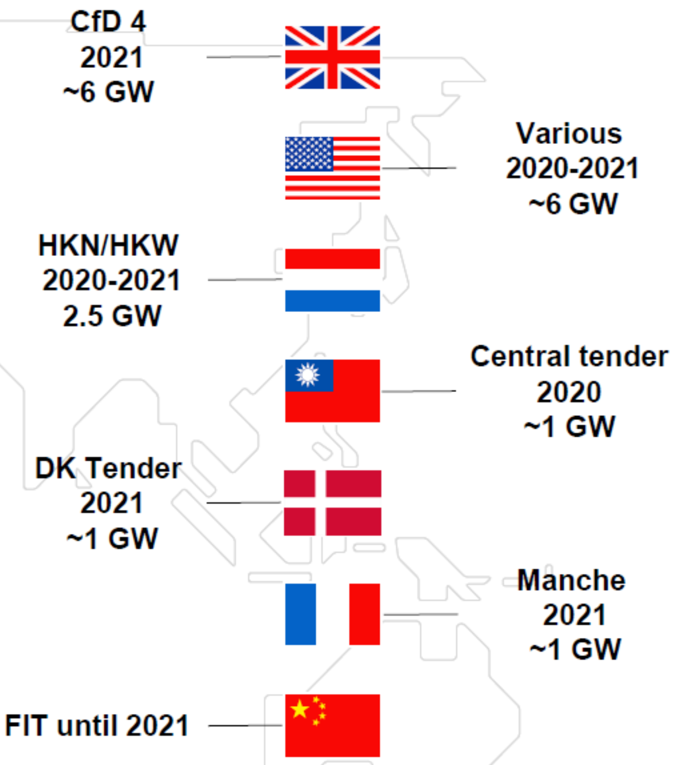
Our new baby (SG14-222) with B108 blades

Installation of auction era projects and pipeline underway, which will be enhanced by a significant pipeline of upcoming auctions

Levelized offshore wind prices[1]



2020 and 2021 expected auctions and tenders



1) Source BNEF 2019

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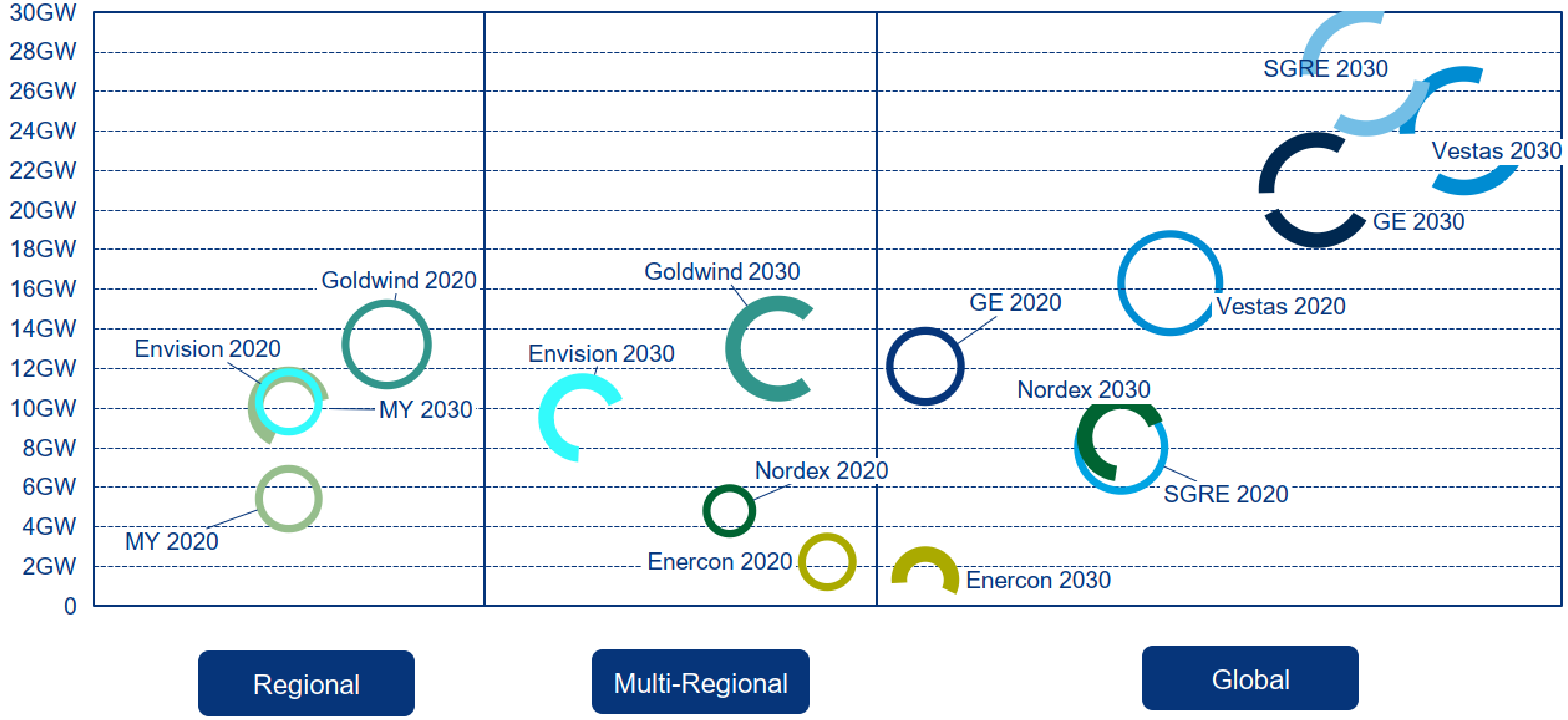
Competition is truly fierce

Offshore growth further elevates top three OEMs commercial positioning

Chinese OEMs Goldwind and Envision scout for international projects to expand margins and market share

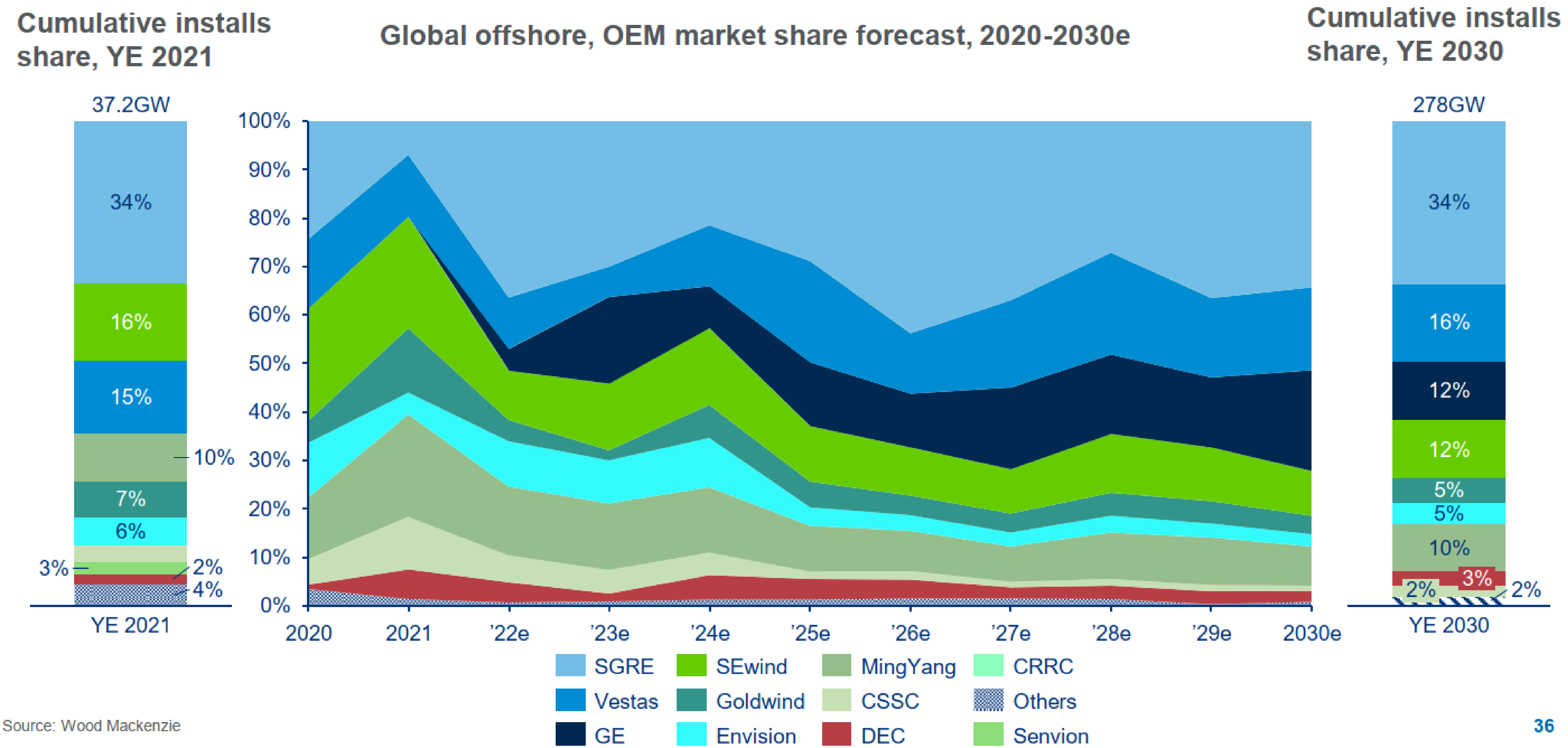
Annual onshore and offshore turbine installations (GW)



Source: Wood Mackenzie

Global Offshore: SGRE maintains leadership with shy of 100GW cumulative by 2030

SEwind maintains leadership in China, despite fierce competition from Mingyang



Source: Wood Mackenzie

Historical development of Product Portfolio to match market and customer needs

Commercializing offshore | **Evolving proven technology** | **Maximizing profitability**

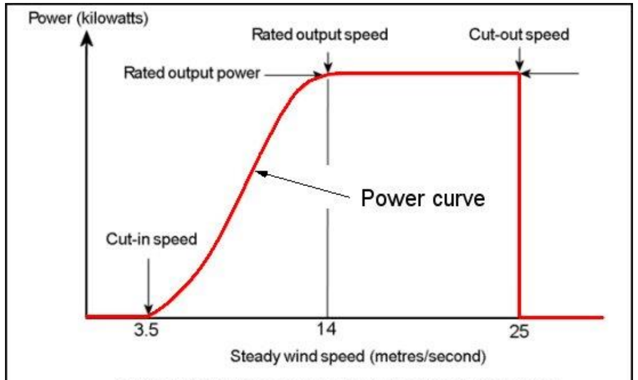
2006 | 2009 | 2012 | 2014 | 2016 | 2017 | 2018 | 2019 | 2020

Offshore Geared

SWT-3.6-107
SWT-3.6-120
SWT-4.0-120
SWT-4.0-130

Offshore Direct Drive

SWT-6.0-120
SWT-6.0-154
SWT-7.0-154
SWT-8.0-154
SG 8.0-167 DD
SG 10.0-193 DD
SG 11.0-193 DD
SG 11.0-200 DD
SG 14-222 DD



Typical wind turbine power output with steady wind speed.

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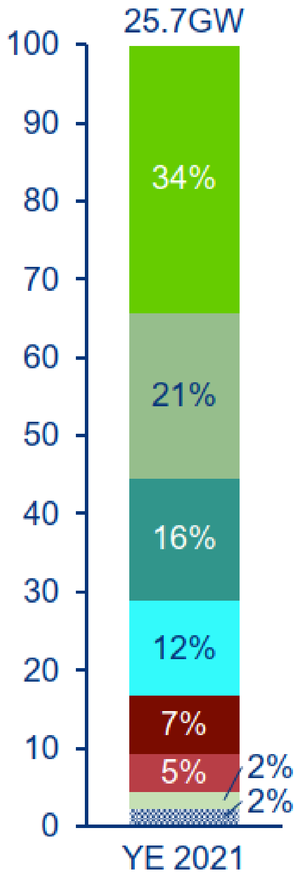
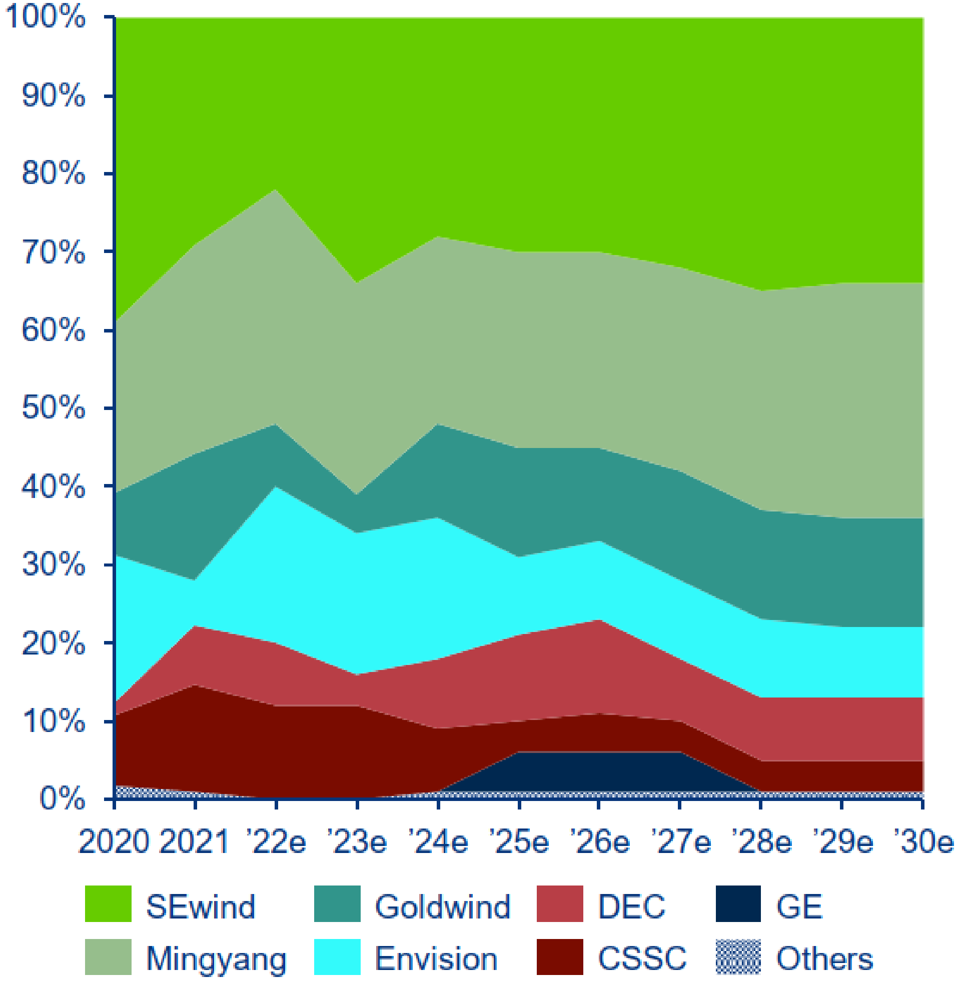
China Offshore: MingYang to replicate the success of MySE-5.X-155 with MySE 11.0-230

SEwind accelerates in-house direct drive technology with “Petrel” platform launching SEW 11.0-208

Cumulative market share, YE 2021



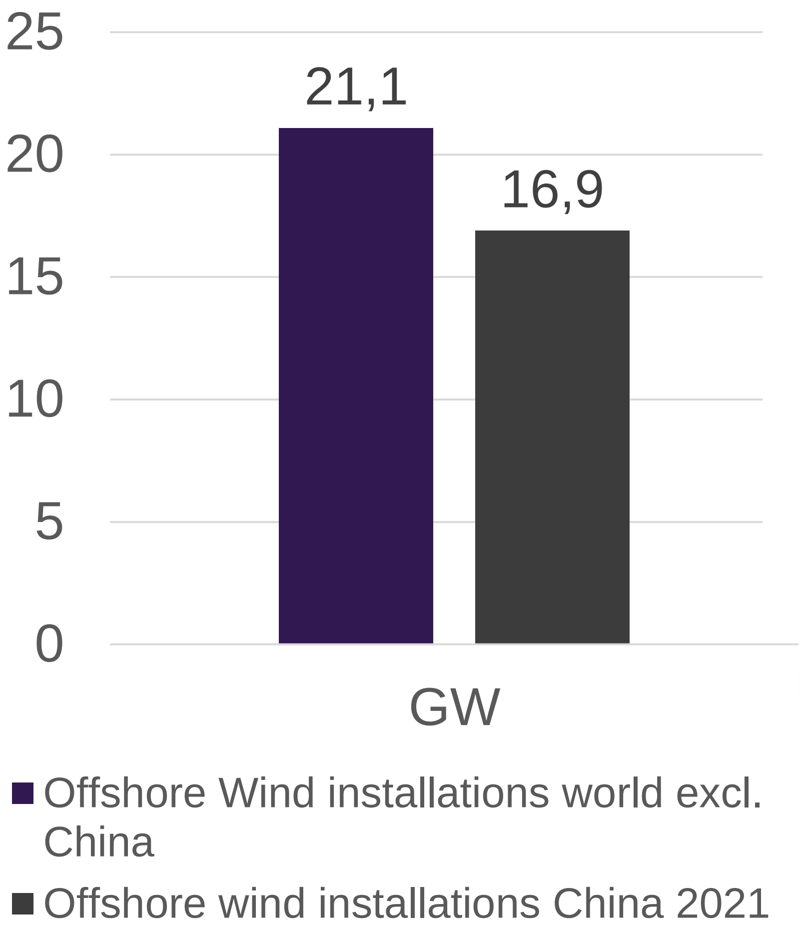
China offshore OEM market share forecast, 2020-2030e

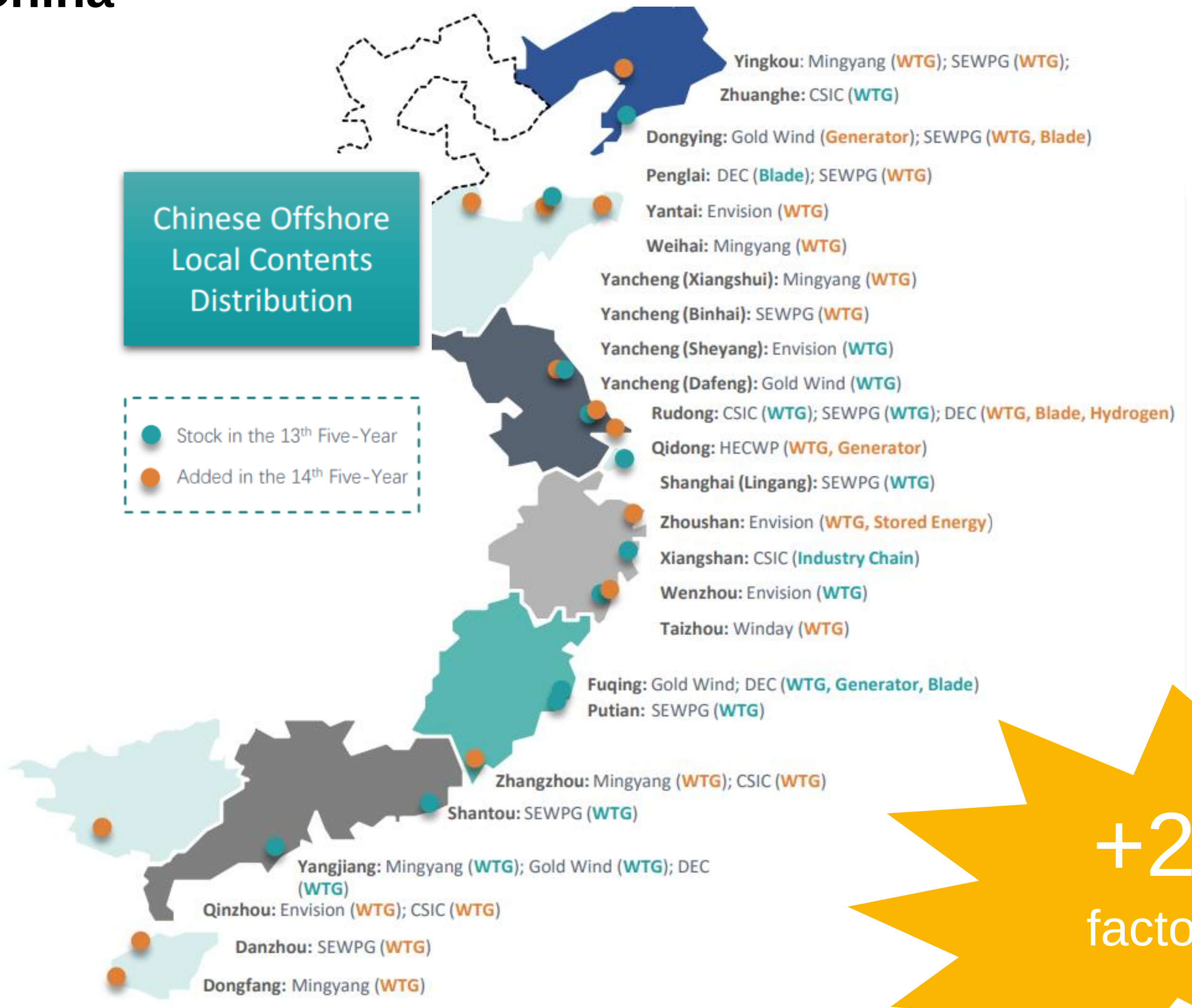


- **SEwind** leads the market, despite increased competition from peers. The company leveraged SGRE’s technology license (60+% of its cumulative 8.7GW offshore installs) to garner a share in the market
  - SEwind developed in-house technology the "Petrel" platform its first 10+MW platform- SEW11.0-208 direct-drive turbine with carbon fibre blades. The company also launched an 8.0MW MSGD turbine EW8.0-208 to cater to low wind speed sites
- **Mingyang** benefits from Guangdong offshore growth, with more than 80% of 5.3GW of cumulative capacity. After successfully delivering 4.2GW (Split equally between MySE5.X-155 and MySE6.X-180) Mingyang is gearing up for the grid parity projects with three 10+MW turbines, MySE 11-203, MySE11.0-230 and MySE16.0-242
- **Goldwind** managed to garner share with the GW171/6.X platform, after initial struggles to commercialise the 5.X/6.XMW platforms. The company shifted the technology strategy by moving to MSGD architecture for the next-generation turbines with GW242-12.0MW
- **Envision** lost its second position to Mingyang despite strong with supply deals with leading developers like CGN, Huaneng and CHN Energy. Envision focuses on gradual technology evolution compared to peers. The company is racing ahead with EN-190/8.0 and EN-200/7.0 turbines for medium-low wind sites

Source: Wood Mackenzie

Impressive installation rate in China





+22
factories

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The context / global

Electricity prices are going up

Raw material and logistics costs are increasing quickly

EU green recovery amplifies R&D opportunities

Increased competition in the ON& OF market

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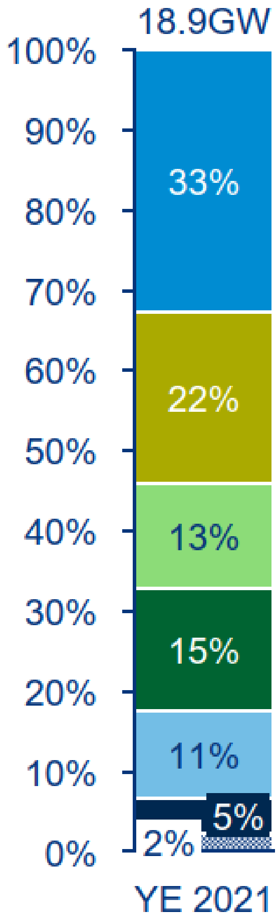
R&D in France… why France?

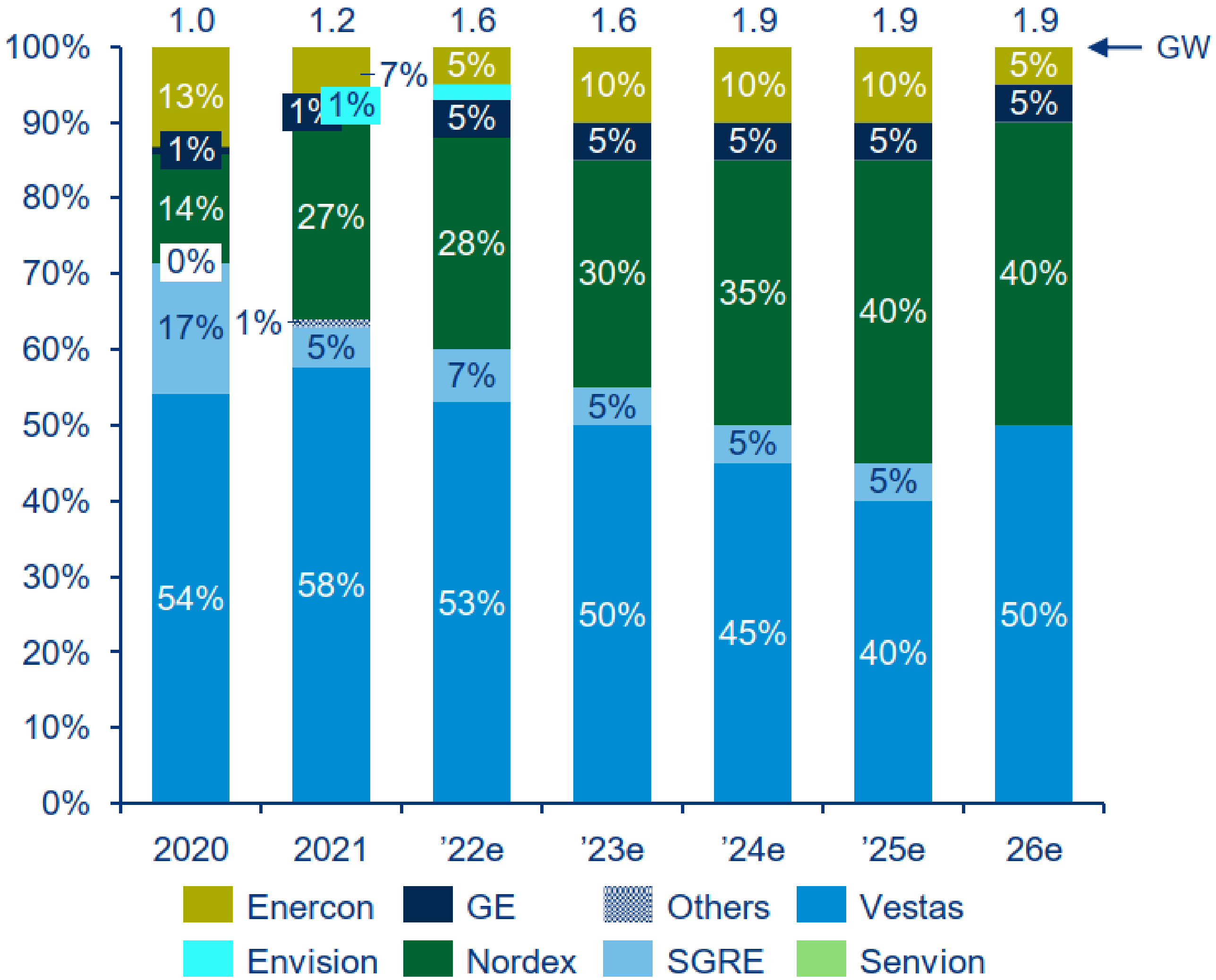
France Onshore: Envision sets presence by commissioning first projects with EN-131

Smaller project sizes and permitting hurdles restrict OEMs ability to install latest generation turbine technologies

Cumulative market share, YE 2021



France's onshore OEM market share forecast, 2020-2026e



- **Nordex** historic focus on project development and turbines with low noise blades elevated its share in the market
  - Nordex still leverages N117 (40%+ of the total orders in 2021) technology in France to win new contracts
- **Vestas** scales up the technology benchmark by positioning V150 in the market to defend its share
  - Vestas dominates the market with broad product offerings from 2.0-4.2MW from ten product variants
- **SGRE** is deploying the sub-3.XMW product suite in France with mediocre success
- **Enercon** increases focus on local product strategy by pitching the segment of E-115 and E-126 EP3 turbines operating at 2.99MW for 3.0MW and below in auctions
  - Local footprint proves advantageous in lowering the landed cost of the turbines and prompting asset owners to choose Enercon turbines

Source: Wood Mackenzie


Dunkerque
600 MW
Centre Manche (1) (AO4)
1,000 MW
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Centre Manche (2) (AO8)
1,500 MW
Dieppe - Le Tréport
500 MW
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Courseulles-sur-Mer
450 MW
Fécamp
500 MW
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Saint-Brieuc
500 MW
Bretagne sud (AO5)
250 MW
Groix - Belle Ile
30 MW
Floatgen (demonstrator)
2 MW
Saint-Nazaire
480 MW
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Yeu-Noirmoutier
500 MW
Oléron (AO7)
500 - 1,000 MW
Over 7 GW
under development
1st floating wind
commercial tender
5,000 jobs
in marine
renewable energy
Gruissan
30 MW
Faraman
24 MW
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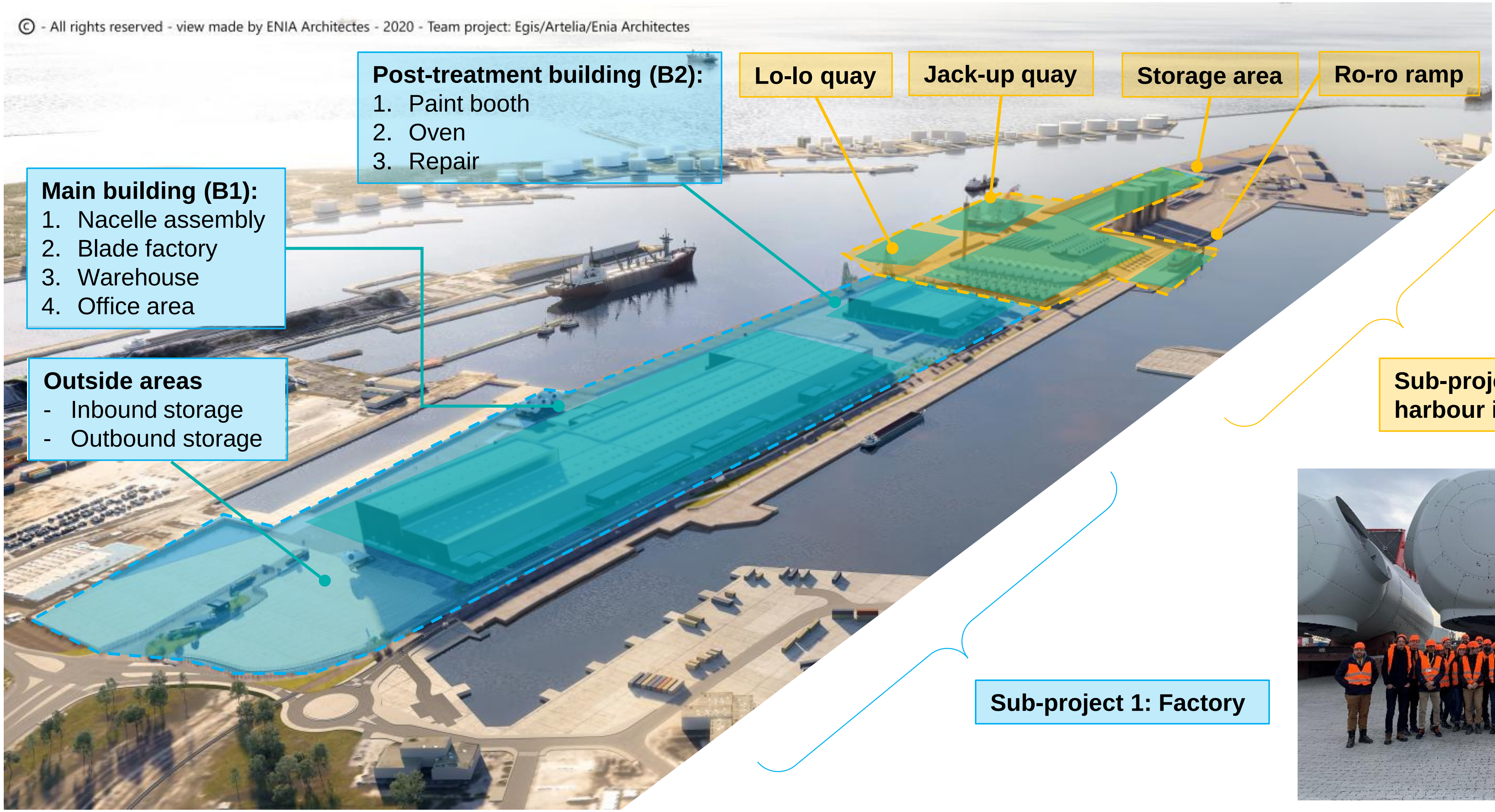
Leucate
30 MW
Méditerranée (AO6)
2 x 250 MW
Fixed offshore wind
Floating offshore wind
Operating
Under construction
Under permitting procedure
Ongoing tender
Public consultation

Overall project view



Sub-project 2: Installation harbour infrastructures

Sub-project 1: Factory

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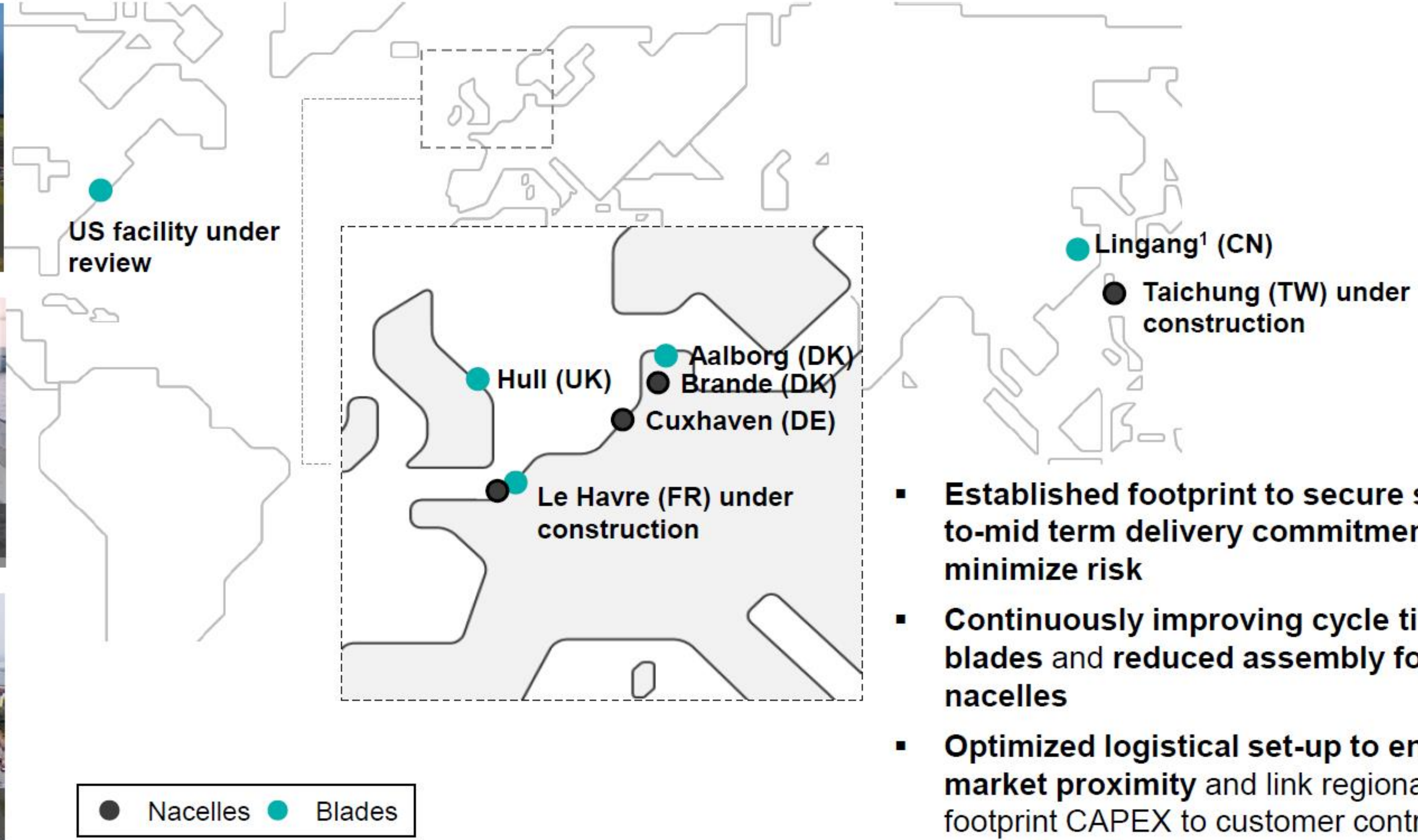
Optimized and regionalized footprint to deliver world class products globally, with clear link to customer demand



- **Established footprint to secure short-to-mid term delivery commitments** and **minimize risk**
- **Continuously improving cycle time for blades** and **reduced assembly for nacelles**
- **Optimized logistical set-up to ensure market proximity** and link regional footprint CAPEX to customer contracts

1) Shared with Onshore

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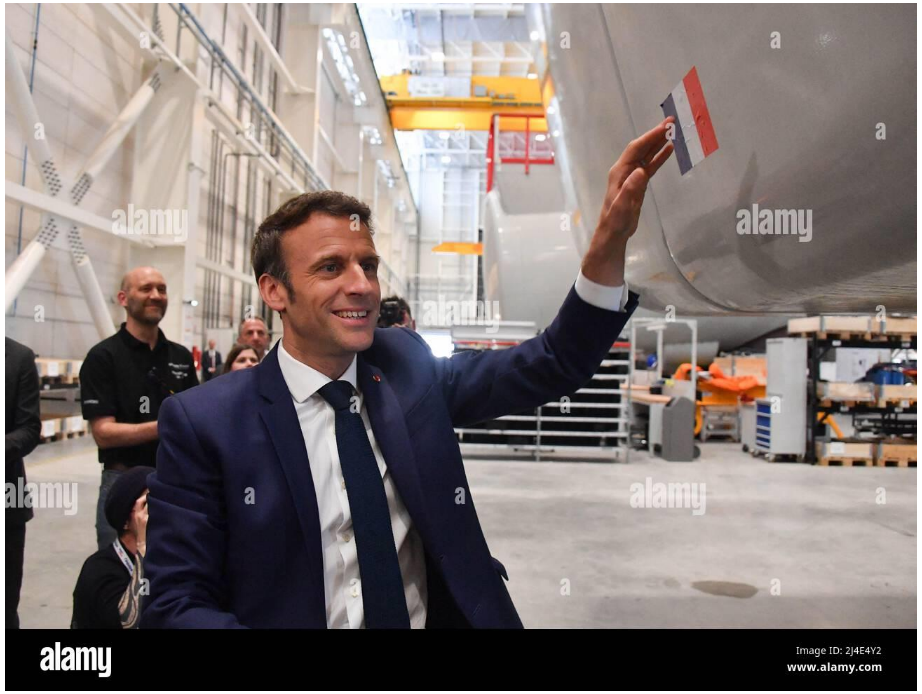
French offshore Sector Deal signed on March 14th 2022

French State :

1. Increases wind offshore volumes to a **<u>minimum tender award volume of 2 GW/year for offshore wind from 2025</u>;**
2. Sets the target of 20 GW of offshore wind allocated by the State by 2030 to reach a capacity of **<u>18GW in service in 2035</u>** and 40 GW in 2050;
3. Carry out **planning work** associated with the achievement of this objective, by façade, for the development of the next Energy Planning Law (2023);

Offshore Wind Sector (via SER/FEE wind asso.s) :

1. **<u>Quadruple the number of jobs</u>** in the sector to occupy, by 2035, at least 20,000 jobs (direct and indirect) in the territory;
2. Commit more than €40 billion in investments to carry out the projects over the next 15 years.
3. Achieve **<u>local content of up to 50%,</u>** calculated on all project costs, for each of the offshore wind projects committed (same formula as UK Sector Deal and largely in line with current French projects sourced locally);
4. Implement exemplary projects in terms of integration into the environment, both human and natural, in which they fit.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The keys to mount an R&D center from scratch in an outsider country

- Get a good story telling for politics
- They will help to finance if you create jobs
- Ensure you are the cheapest in the continent

- Be transparent on your internal problems
- They will appreciate to grow common knowledge

- Never say no to a new scope
- And adapt the team size to the new scope

- Understand the reasons of why the market could grow (2005 – 2020)
- Then fingers crossed…

- **Don’t do anything that others can do**
- **Our choice: focus on complexity that takes years to build**
- **Our intuition: industry will need much earlier than anticipated**

- Keep on onboarding interns from best schools everywhere in the world
- Onboard people that you can learn from with intense curiosity
- Keep all good talents by all means

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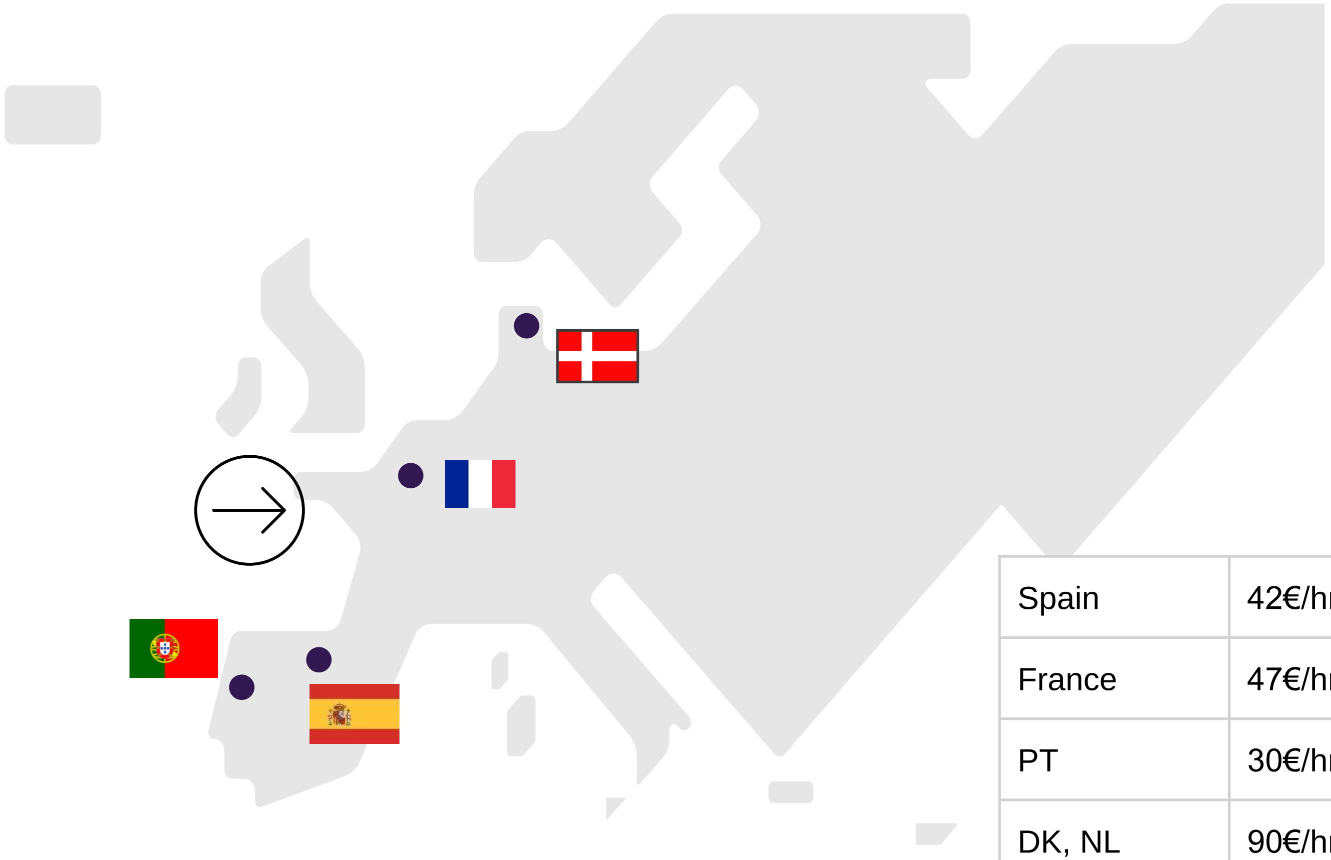
R&D centers

Flotte installée de
+90 GW

+1,200
Ingénieurs R&D

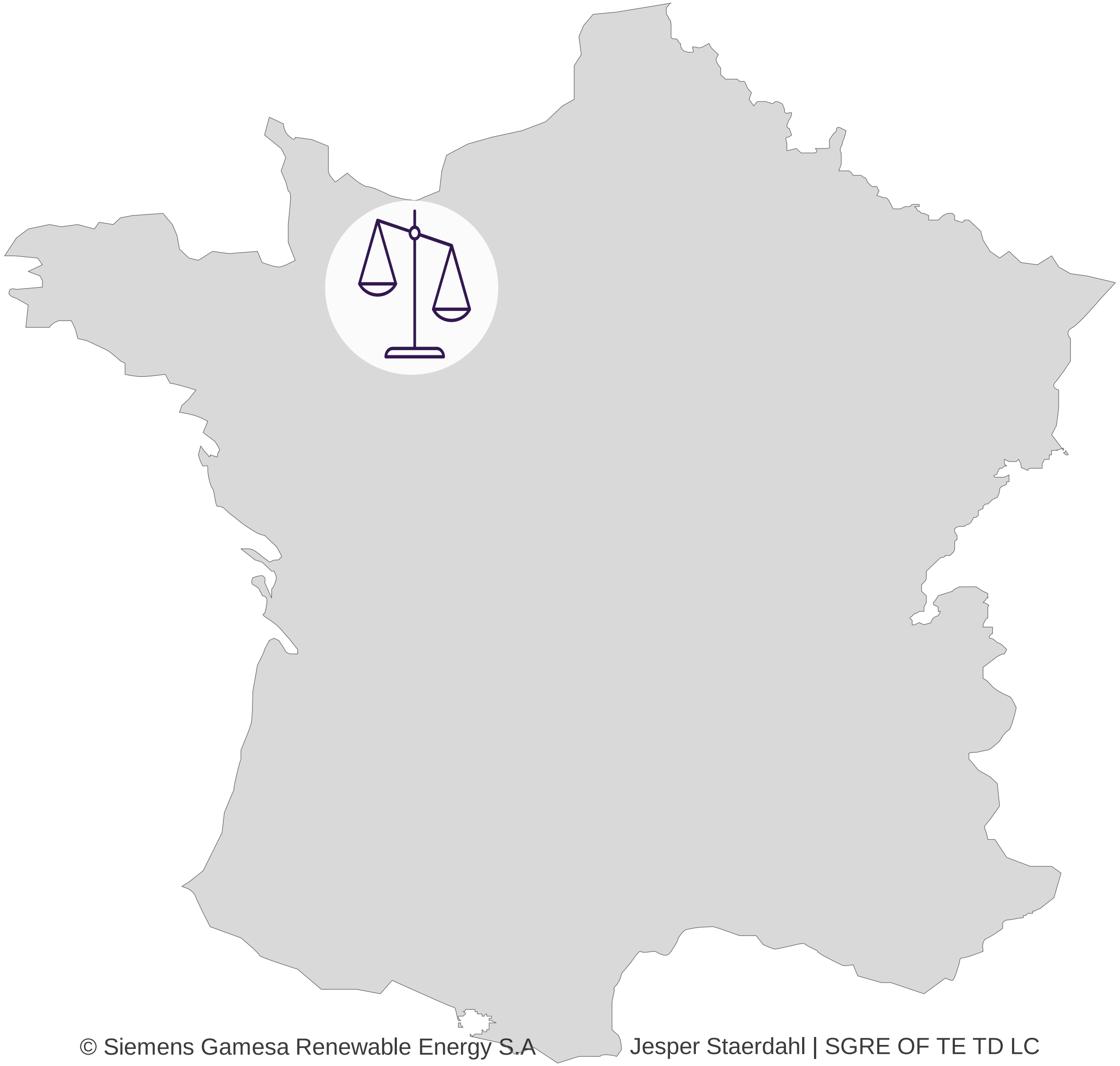
Are we competitive ? Depends on funding we gather

Strategic: create capacity to cover peak loads for load engineers



Spain	42€/hr
France	47€/hr
PT	30€/hr
DK, NL	90€/hr
IN	25€/hr

3 R&D missions



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FR team main assets

A skilled team of developers having expertise knowledge on offshore wind turbine and mathematics

Good funding local opportunities

The proximity to a large capacity informatic cluster

Strong partnerships local academics using best in class tools developed for aeronautics

Direct access to the best offshore wind database available in the world

List of R&D projects covered

Name	Related tech domain	Target	Running years	Main academic partner
WAKE OP => SCALE OP RÉGION NORMANDIE	Stability analysis, aero modeling (aero, wake winds), Load Emulators, Siting,	Mainly covering internal TD funding + YALES2 coupling	2019 – 2022 **=> 2025**	CORIA UMR 6614, INSA Rouen
INSA Post COVID initiative RÉGION NORMANDIE	VIV, Advanced aero and wake models (AL-LES)	Mainly internal TD funding + YALES2 coupling devl	2022 – 2023	CORIA UMR 6614, INSA Rouen
RIVERS	SLC, CMS	Funding of blade test	**Completed**	IRT Jules Verne
TOTAL CONTROL	Wakes, Siting Load Emulators	Wake model validation, Farm AEP boost	**Completed**	TU Delft
PRESTIGE / DTU	Stability analysis	VIV model devl and validation	2020 – 2023	DTU
STEP4Wind	Aero modeling, Siting, Load Emulators	Floating for Siting, Load Emulators, YALES2 coupling devl	2021 – 2024	TU Delft, CORIA UMR 6614
Powerkey	Wakes	Wake model validation	**Completed**	DTU
ITN Like	Wakes	Wake model validation	2022 follow up	universität Oldenburg
HELIX	Wakes	YALES2 coupling devl	2022-2024	TU Delft

Next aeroelastic code (VIV and SIV primarily): mid term: DTU PhD, long term: EPSRC (Imp College), UPM

- **New wind reconstruction techniques: better LIDAR models (TU Delft), ABL modeling, PIV (ECN)**

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Core competences

Advanced Aero & Aeroelasiticty

Duboc, Bastien (SGRE TE LCS TL MDFRA)

Derisking new NPDs for stand still and idling aeroelastic vibration risks (blade, rotors and towers)

Providing release of new loads aero models for BHawC

Deliver: VIV, SIV NPD studies, tests aero module BhawC release

Fleet analysis

Ahmed, Aqeel (SGRE TE LCS TL MDFRA)

Compile loads fleet feedbacks vs design, update DLCs, update models

Validate new NPDs in offshore wind farms

Optimize LC design toolchains towards advanced aero, wakes and winds

Deliver: fleet validation report, new DLCs, BhawC test suite

BHawC modularity and development

Peter F. Skjoldan

Simplify and standardize interface between BL aero and LC aero

Develop advanced models for wake, wind and aero
- low fidelity model validation

Deliver: BHawC release with couplings

Wind modelling

Warncke, Norbert (SGRE TE LCS TL MDFRA)

Reconstruct winds for prototype & fleet analysis

Improve accuracy of wind modeling for reduced loads from advanced measures: LIDARs etc

Deliver: wind module, wind box for NPDs

Wake modelling

Beaudet, Laurent (SGRE TE LCS TL MDFRA)

Optimize RNA and tower & foundation designs (cost and lifetime)

Optimize farm AEP AND loads outputs

Deliver low & mid fidelity wake models to other Depts

Deliver: wake models NPD wake loads

SIte load suitability

TBD

Optimize Siting processes

Optimize Service uprates for existing fleet – provide tools for fleet analysis

Optimize NPD loads processes

Deliver: Siting tool, OMR

Machine Learning

Panousis, Panagiotis (SGRE TE LCS SLC CMI)

Enable Load Surrogate Modeling

+ further use within LC

Deliver: ML blocks for NPDs/ Siting and OMR

NPDs

-

Classical NPD support at Turbine Loads

Standard Loads NPD deliverables

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Wind farm load design projects zoom

Advanced Aero & Aeroelasiticty	Fleet analysis	BHawC modularity and development	Wind modelling	Wake modelling	Turbine load suitability	Machine Learning	NPDs
Duboc, Bastien (SGRE TE LCS TL MDFRA)	Ahmed, Aqeel (SGRE TE LCS TL MDFRA)	*Peter F. Skjoldan*	Warncke, Norbert (SGRE TE LCS TL MDFRA)	Beaudet, Laurent (SGRE TE LCS TL MDFRA)	TBD	Panousis, Panagiotis (SGRE TE LCS SLC CMI)	-
Derisking new NPDs for stand still and idling aeroelastic vibration risks (blade, rotors and towers) Providing release of new loads aero models for BHawC	Compile loads fleet feedbacks vs design, update DLCs, update models Validate new NPDs in offshore wind farms Optimize LC design toolchains towards advanced aero, wakes and winds	Simplify and standardize interface between BL aero and LC aero Develop advanced models for wake, wind and aero - low fidelity model validation	Reconstruct winds for prototype & fleet analysis Improve accuracy of wind modeling for reduced loads from advanced measures: LIDARs etc	Optimize RNA and tower & foundation designs (cost and lifetime) Optimize farm AEP AND loads outputs Deliver low & mid fidelity wake models to other Depts	Optimize Siting processes Optimize Service uprates for existing fleet – provide tools for fleet analysis Optimize NPD loads processes	Enable Load Surrogate Modeling + further use within LC	Classical NPD support at Turbine Loads
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RENEWABLE ENERGY

Applications des modèles d’émulation de charges sur les éoliennes

Avant installation

Développement d’une nouvelle éolienne

- Extrapolations par rapport aux machines précédentes
- Estimations initiales de charges
- Analyse de scenarios hypothétiques (*“What-if”*)

Prototypage et certification

- Calculs itératifs de charges
- Validation sur prototype
- Certification

Adaptation conceptuelle site par site

- Estimation des charges pour les tours et les fondations
- Analyse de scenarios hypothétiques (*“What-if”*)

Design détaillé spécifique à un site

- Calculs itératifs de charges pour les tours et les fondations
- Certification

Propriétés de contrôle

Caractéristiques de l’éolienne

Conditions de vent

Conditions de vague

Conditions du fond marin

Modèle d’émulation de charges

Charges sur l’éolienne

Par exemple:

S’il y a un vent de 100 km/h, une intensité turbulente de 10% et des vagues de 3m de haut, quelles sont les forces qui s’appliquent sur le haut de la tour ?

Applications des modèles d'émulation de charges sur les éoliennes

Après installation

Installation

- Evaluation de la non-conformité

Opération & Maintenance

- Evaluation de l'état de santé des éoliennes
- Evaluation de la possibilité d'améliorer/optimiser les machines
- Capteur virtuel

Décommissionnement

- Extension de la durée de vie des machines

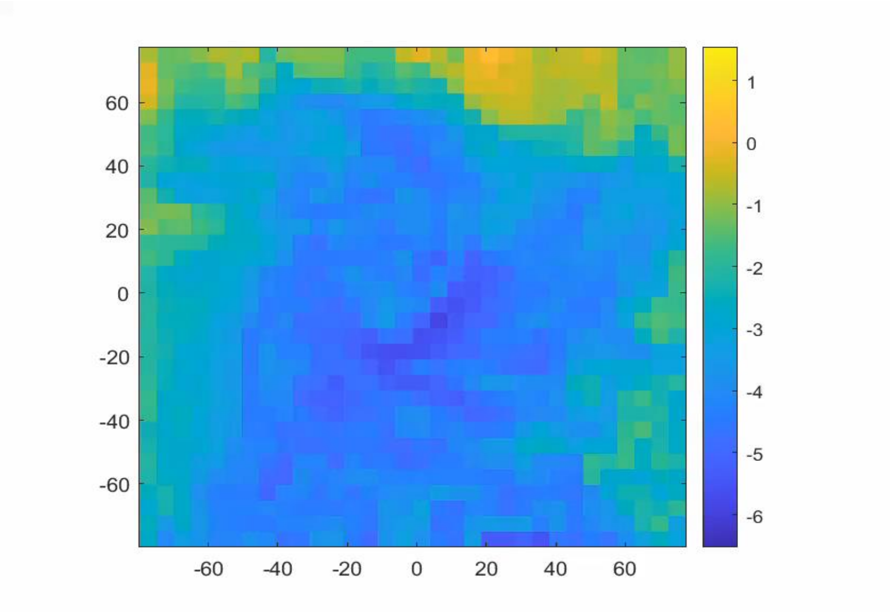
Données mesurées sur les éoliennes existantes → **Modèle d'émulation de charges** → **Charges sur l'éolienne**

Par exemple:

Si une éolienne produit 6MW, tourne à 10 tour/min et a un calage de pale de 10°, quelles sont les forces qui s'appliquent sur l'emplanture des pales ? Est-ce que c'est en dessous de la valeur utilisée pour le dimensionnement de la machine ?

Advanced CFD setup – YALES2 BHawC

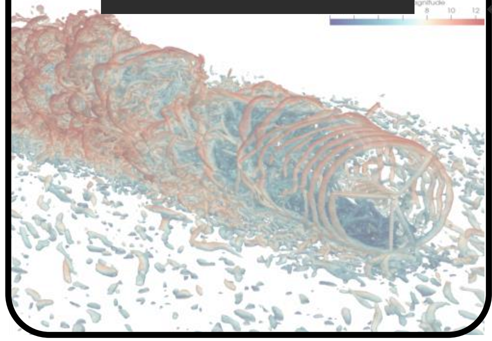
- BEM disabled and replaced by YALES2
- Simulation results from YALES can be captured and put back into BHawC using turbulence boxes
- Experimental process (only 1 simulation set is available)
- Enough to understand if the fundamental behaviours are captured!



YALES2

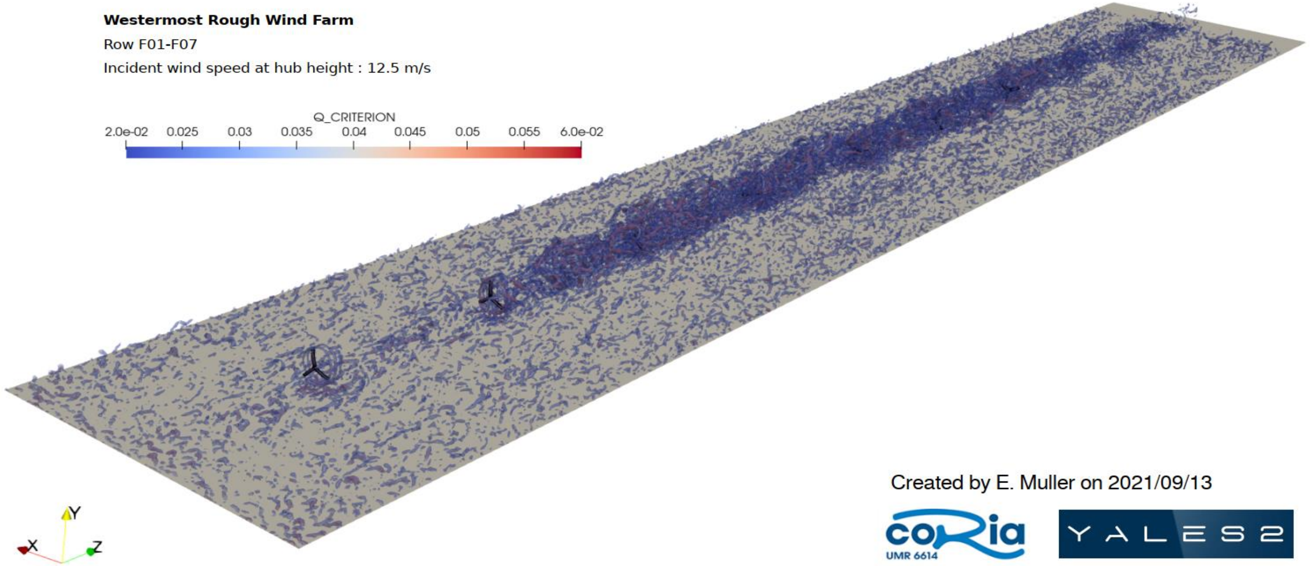
CORIA UMR 6614

- **Aerodynamics**
- **LES solver**



BHawC

- Hydrodynamics
- Structural mechanics
- Electric systems
- Control systems



SGRE TE L

Created by E. Muller on 2021/09/13

CORIA UMR 6614 YALES2

MDFRA sub CTAs/CTAs

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RENEWABLE ENERGY

Need of a Wake Modelling team

Why we need to focus on wakes?

- **Wakes have an impact on the business value of the wind turbines**
  - ↳ On the **production** of the overall wind farms due to velocity deficits within a wind farm and between the wind farms
  - ↳ On the **wind turbine lifetime** of **existing turbines** due to the wake-induced fatigue and extreme loads (translating to capital and operational costs)
  - ↳ On the **wind turbine design** of **new products** to ensure a conservative design and safe operation (potentially reducing competitiveness)

- **Without accurate models, the impact cannot properly be assessed**
  - ↳ So, the AEP is misestimated, and commercial offerings could be biased
  - ↳ And safety factors are kept high to counterbalance the inaccuracy of models, so, wind turbines are over-conservative in their design

- **The state-of-the art is reaching scientific barriers**
  - ↳ *Wakes* is one of the main topics identified by the scientific community as the grand challenges for wind energy
  - ↳ Wake models need to be improved and adapted to the applications and collaboration with the scientific community needs to be tighten

RESEARCH

REVIEW SUMMARY

RENEWABLE ENERGY

Grand challenges in the science of wind energy

Paul Veers*, Katherine Dykes*, Eric Lantz*, Stephan Barth, Carlo L. Bottasso, Ola Carlson, Andrew Clifton, Johney Green, Peter Green, Hannele Holttinen, Daniel Laird, Ville Lehtomäki, Julie K. Lundquist, James Manwell, Melinda Marquis, Charles Meneveau, Patrick Moriarty, Xabier Munduate, Michael Muskulus, Jonathan Naughton, Lucy Pao, Joshua Paquette, Joachim Peinke, Amy Robertson, Javier Sanz Rodrigo, Anna Maria Sempreviva, J. Charles Smith, Aidan Tuohy, Ryan Wiser

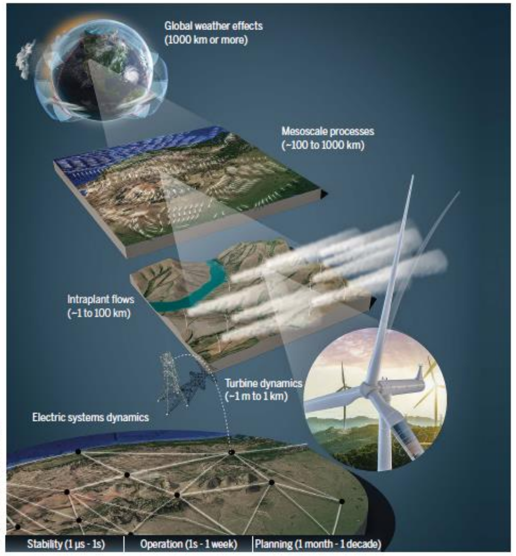
BACKGROUND: A growing global population and an increasing demand for energy services are expected to result in substantially greater deployment of clean energy sources. Wind energy is already playing a role as a mainstream source of electricity, driven by decades of scientific discovery and technology development. Additional research and exploration of design options are needed to drive innovation to meet future demand and functionality. The growing scale and deployment expansion will, however, push the technology into areas of both scientific and engineering uncertainty. This Review explores grand challenges in wind energy research that must be addressed to enable wind energy to supply one-third to one-half, or even more, of the world's electricity needs.

ADVANCES: Drawing from a recent international workshop, we identify three grand challenges in wind energy research that require further progress from the scientific community: (i) improved understanding of the physics of atmospheric flow in the critical zone of wind power plant operation, (ii) materials and system dynamics of individual wind turbines, and (iii) optimization and control of fleets of wind plants comprising hundreds of individual generators working synergistically within the larger electric grid system. These grand challenges are interrelated, so progress in each domain must build on concurrent advances in the other two. Characterizing the wind power plant operating zone in the atmosphere will be essential to designing the next generation of even-larger wind turbines and achieving dynamic control of the machines. Enhanced forecasting of the nature of the atmospheric inflow will subsequently enable control of the plant in the manner necessary for grid support. These wind energy science challenges bridge previously separable geospatial and temporal scales that extend from the physics of the atmosphere to flexible aeroelastic and mechanical systems more than 200 m in diameter and, ultimately, to the electrical integration with and support for a continent-sized grid system.

OUTLOOK: Meeting the grand research challenges in wind energy science will enable the wind power plant of the future to supply many of the anticipated electricity system needs at a low cost. The interdependence of the grand challenges requires expansion of integrated and cross-disciplinary research efforts. Methods for handling and streamlining exchange of vast quantities of information across many disciplines (both experimental and computational) will also be crucial to enabling successful integrated research. Moreover, research in fields related to computational and data science will support the research community in seeking to further integrate models and data across scales and disciplines. ■

ON OUR WEBSITE

Read the full article at http://dx.doi.org/10.1126/science.aau2027



The cascade of scales underlying wind energy scientific grand challenges. Length scales from weather systems at a global level down the boundary layer of a wind turbine airfoil and time scales from seasonal fluctuations in weather to subsecond dynamic control and balancing of electrical generation and demand must be understood and managed.

ILLUSTRATION: JOSH BAUER AND BESIKI KAZAISHVILI, NREL

The list of author affiliations is available in the full article online.
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Cite this article as P. Veers *et al.*, *Science* 366, eaau2027 (2019). DOI: 10.1126/science.aau2027

TOMORROW'S EARTH
Read more articles online at scim.ag/TomorrowsEarth

Veers *et al.*, *Science* **366**, 443 (2019) 25 October 2019

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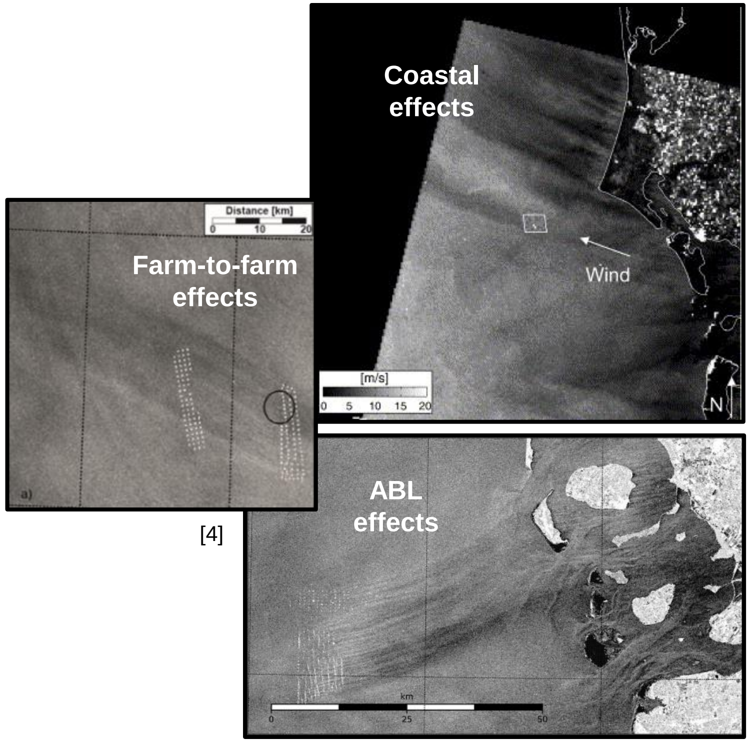
Wake scales – in scope

Meso-scale wake effects (farm-to-farm)



[2]

[4]

[3]

~10⁴ km	~10 km	~1 km	~100 m		~10 m	~1 m	~10 cm
~days	~hours	~minutes			~seconds		
Macroscale & Mesoscale	Inter-Wind Farm Scale	Intra-Wind Farm Scale	Rotor Scale	Single Blade Scale		Airfoil Scale	Boundary layer Scale

Lower limit

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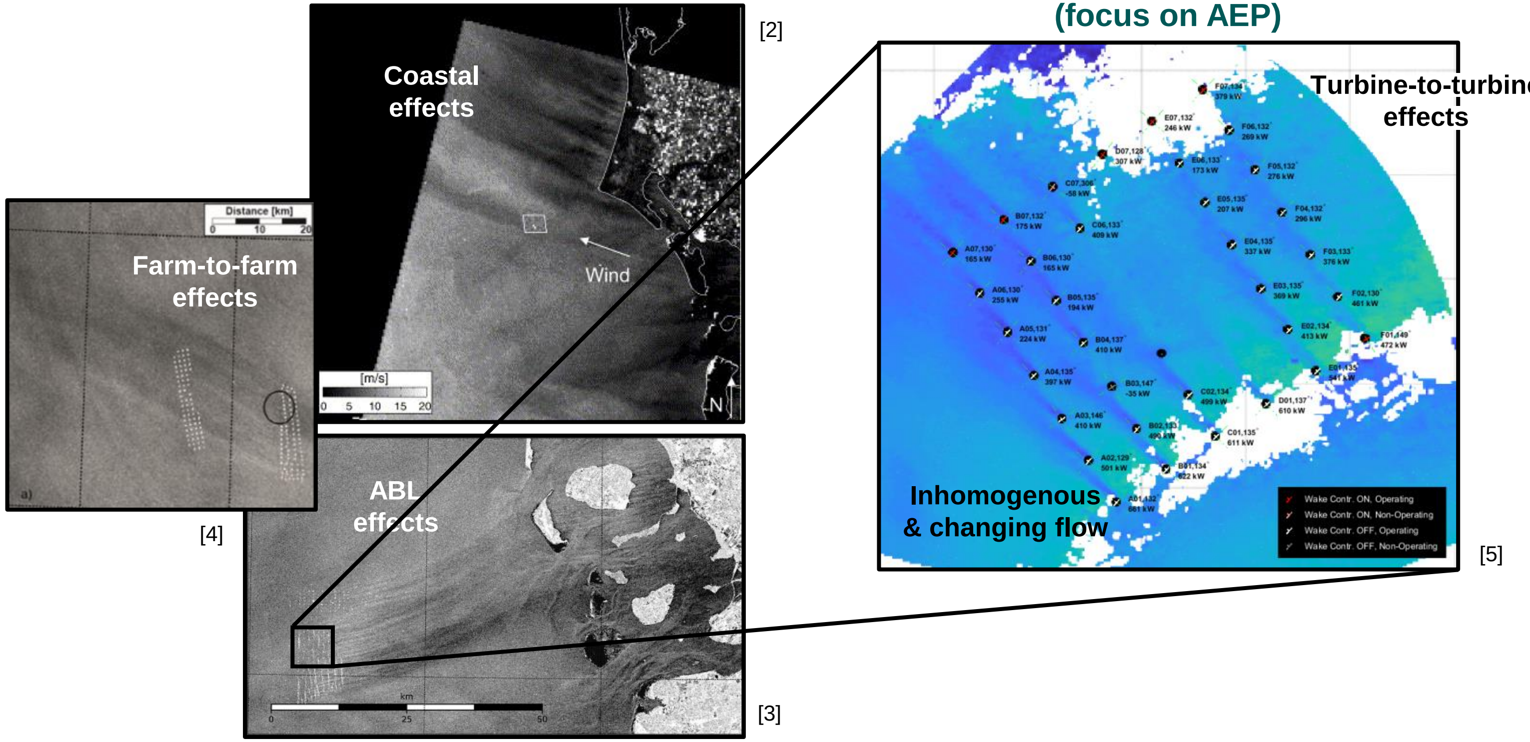
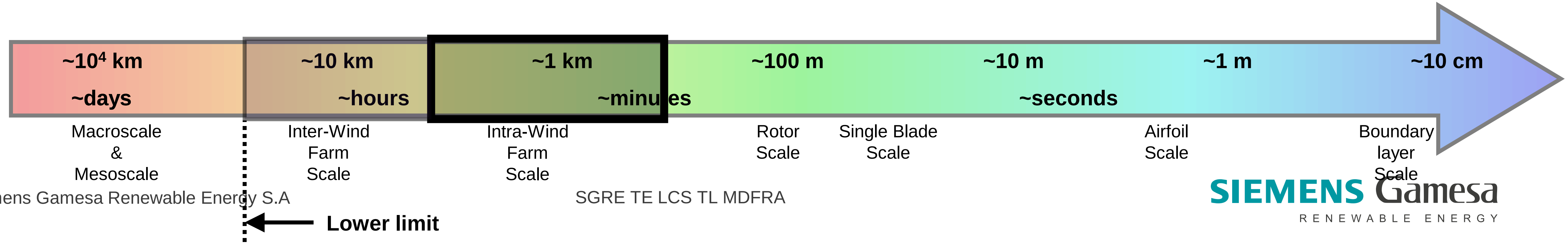
Wake scales – in scope

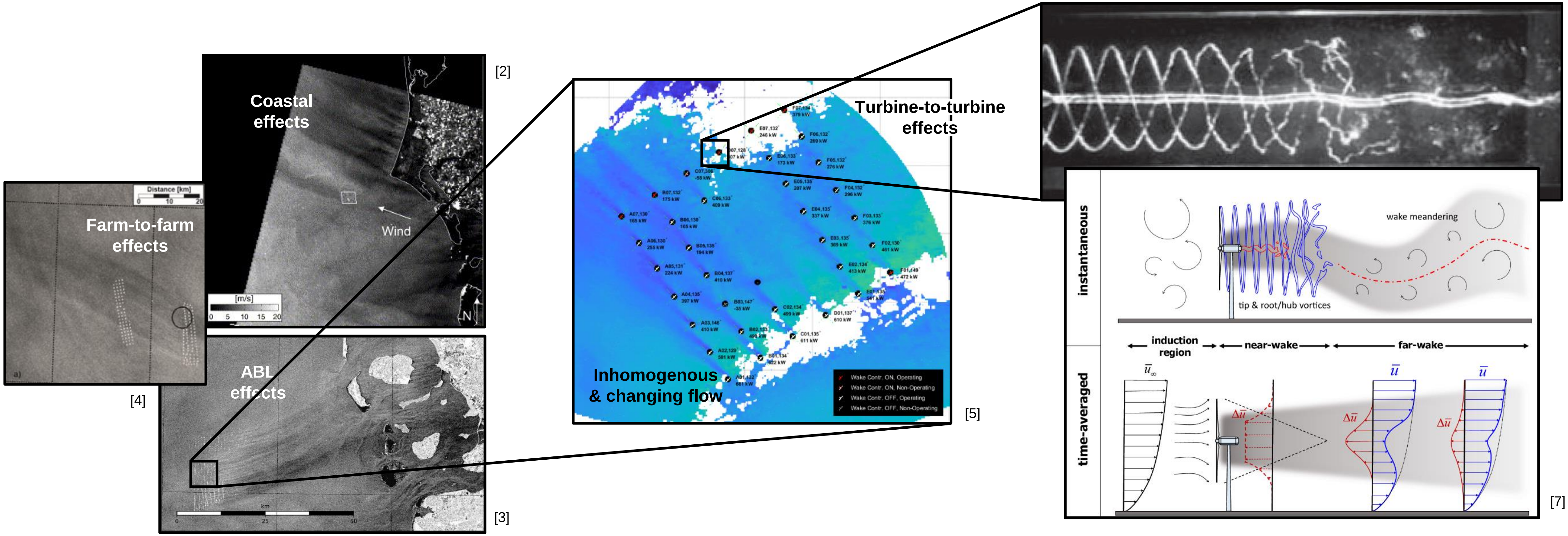
Intra-wind farm wake effects (focus on AEP)





Wake scales – in scope

Far wake effects
(focus on loads on downstream turbines)



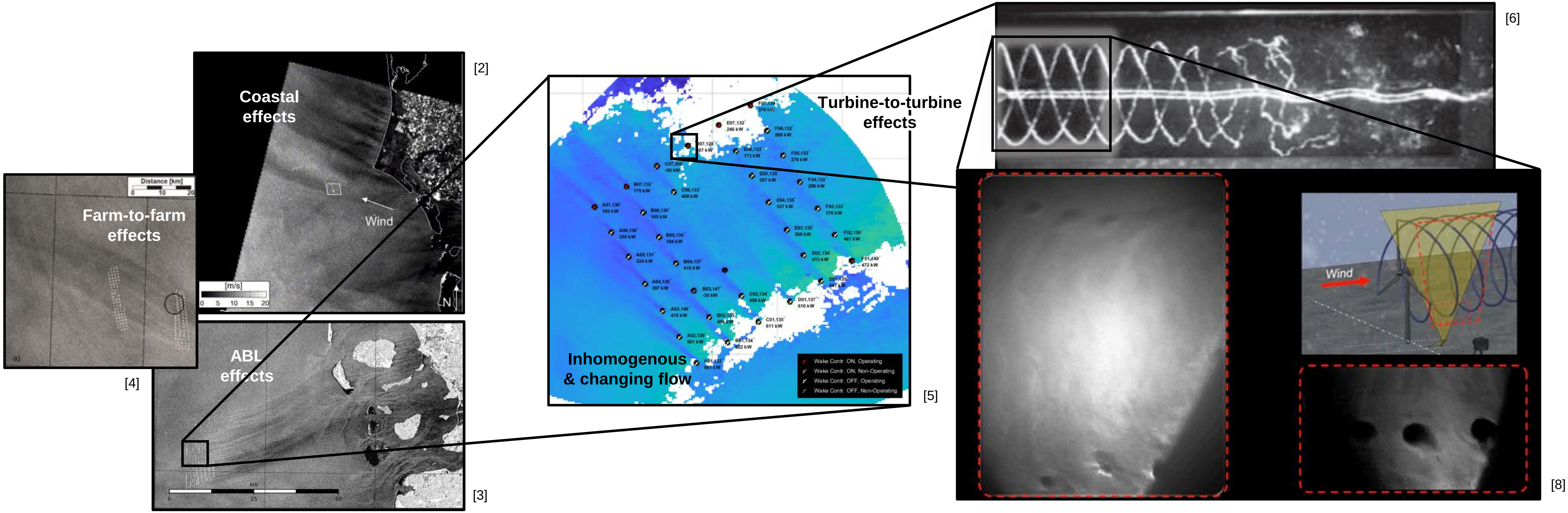
Far wake | Near wake

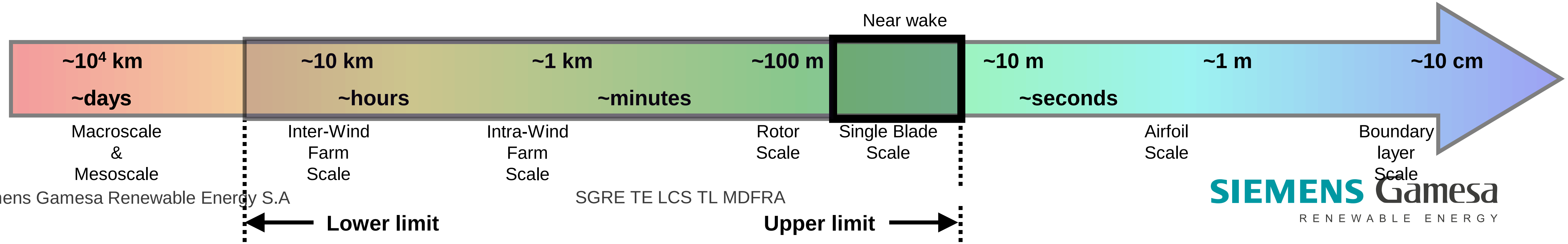
~10^4 km	~10 km	~1 km	~100 m		~10 m	~1 m	~10 cm
~days	~hours	~minutes			~seconds		
Macroscale & Mesoscale	Inter-Wind Farm Scale	Intra-Wind Farm Scale	Rotor Scale	Single Blade Scale		Airfoil Scale	Boundary layer Scale

Lower limit | **Upper limit**

Wake scales – in scope

Near wake effects
(focus on loads on the turbine generating the wake)





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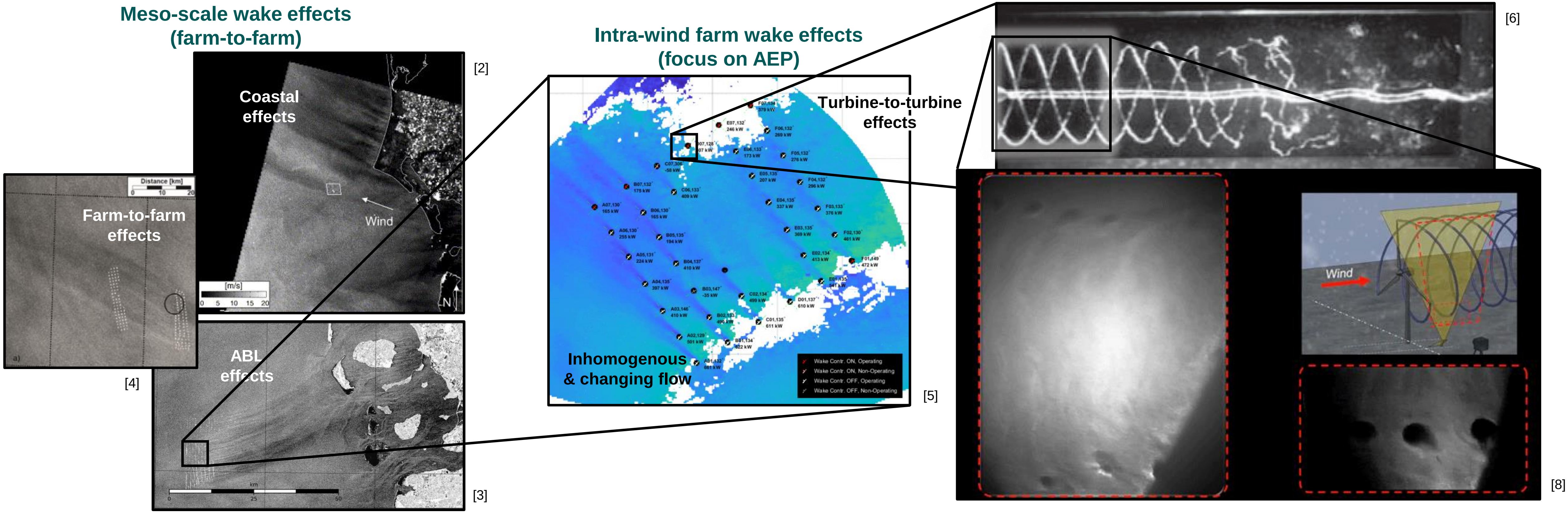
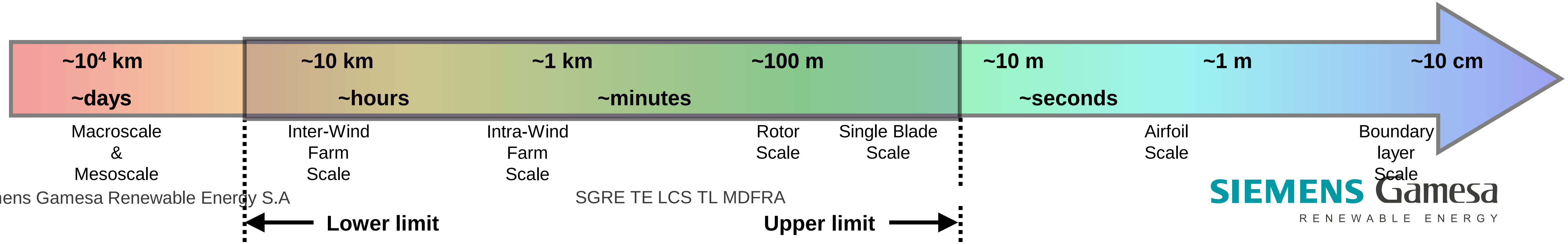
Wake scales – in scope

Meso-scale wake effects (farm-to-farm)

Intra-wind farm wake effects (focus on AEP)

Near and far wake effects (focus on loads)





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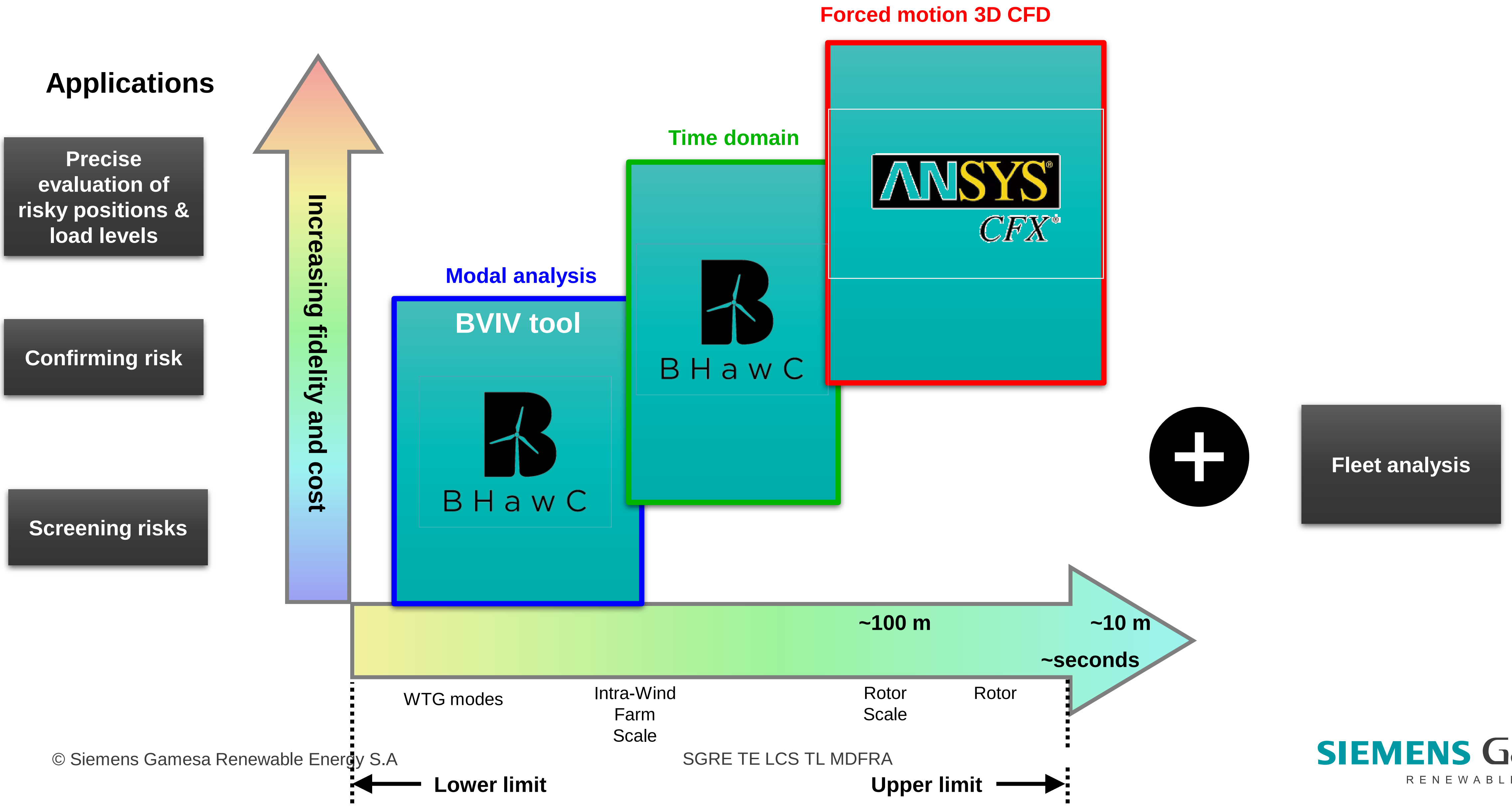
3 level approach



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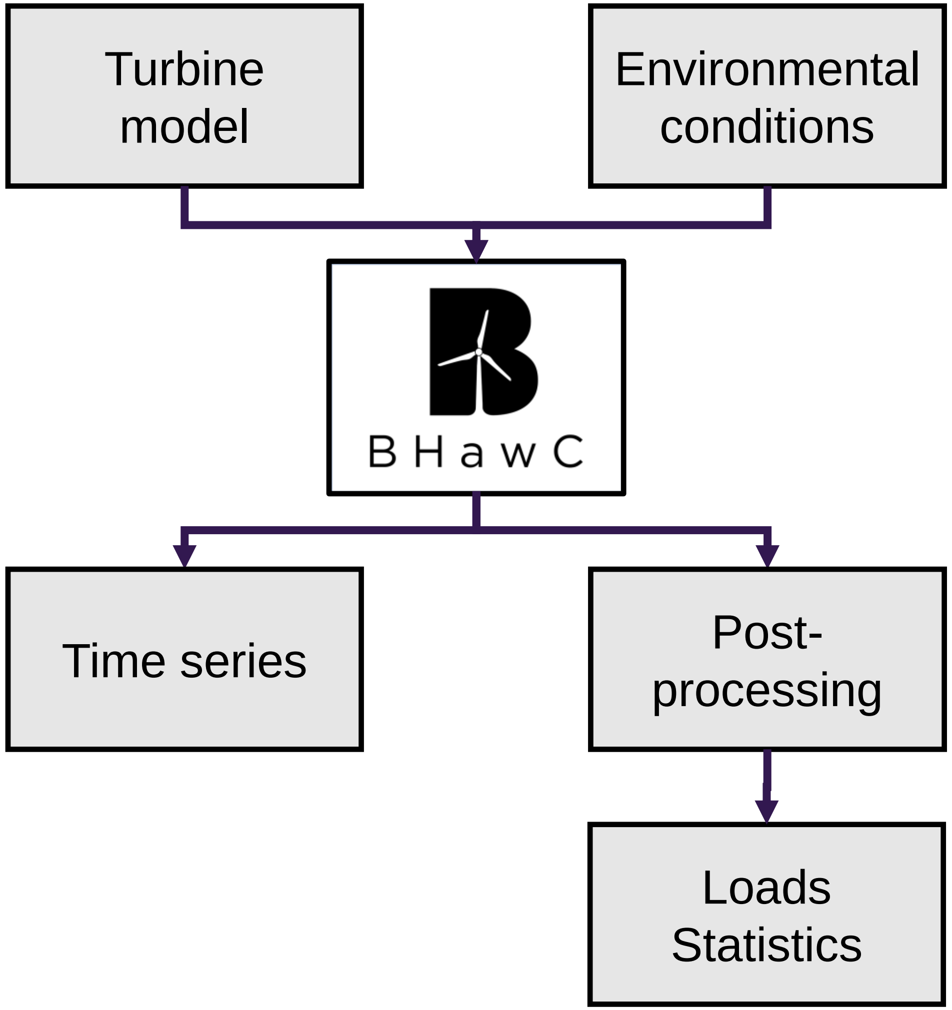
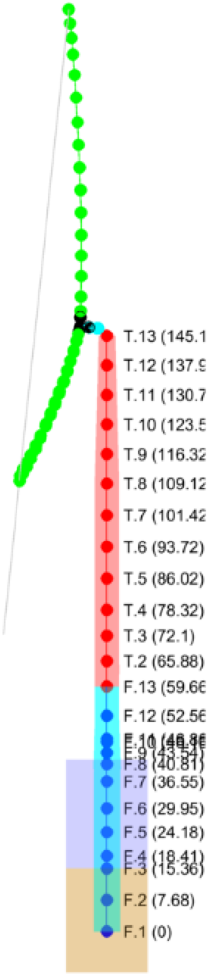
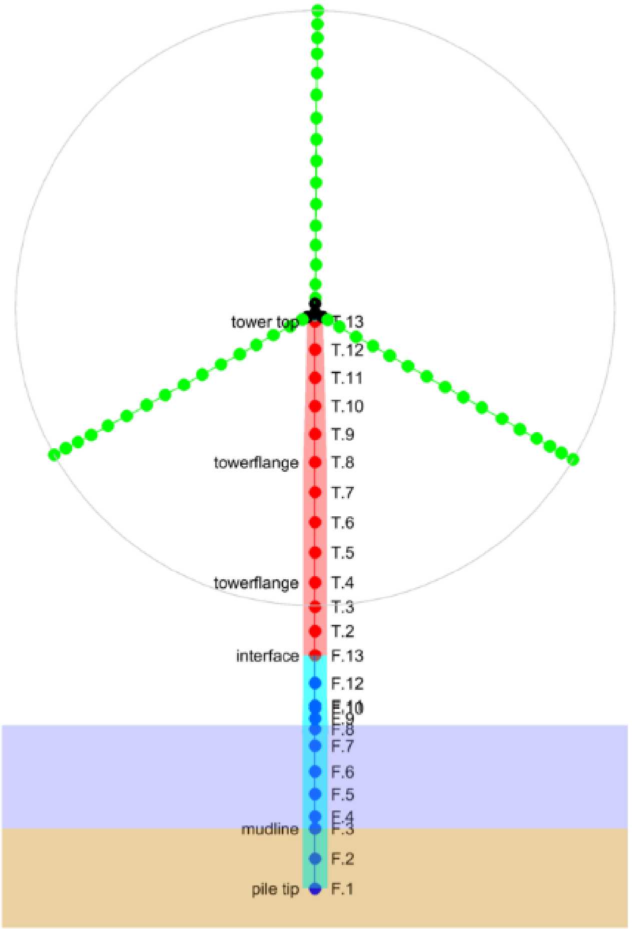
Numerical Loads Calculation



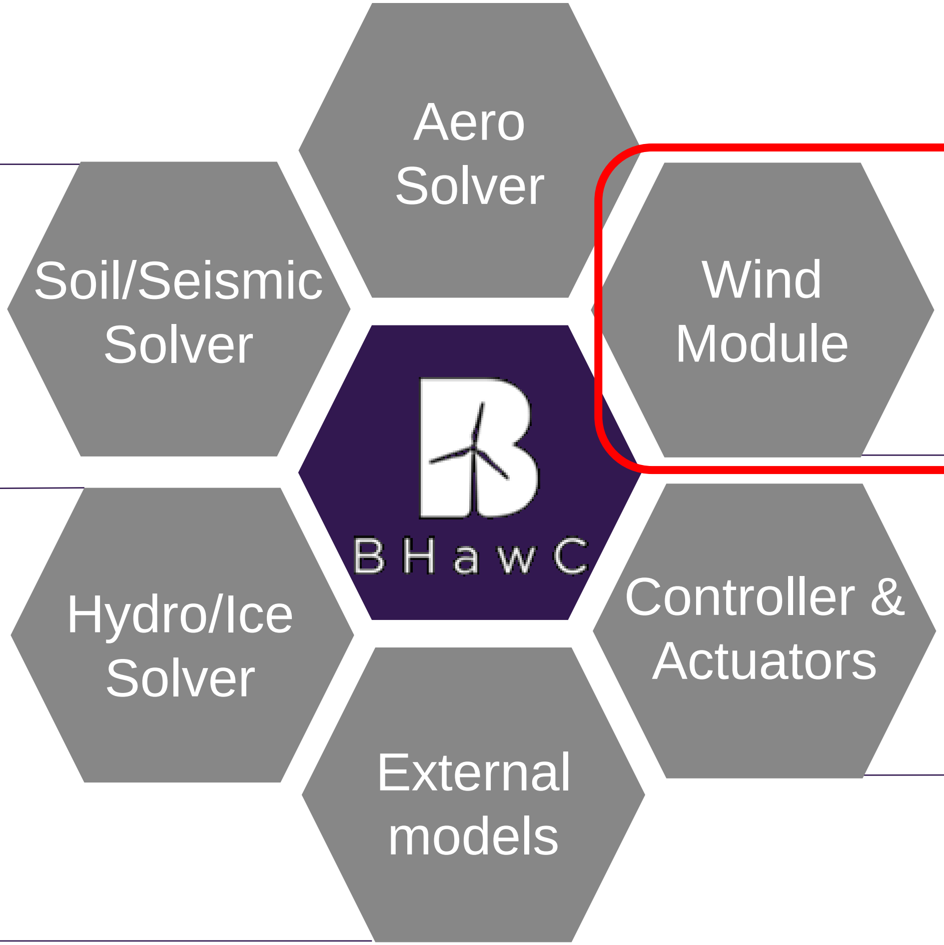




Environmental Models for Loads Simulations

- Blade Element Momentum Theory
- Lifting Line/Boundary Element/Vortex Methods
- CFD (RANS/URANS/DES/LES)

- Viscoelastic, soil-spring models
- Seismic excitations



- Full domain flow/inflow conditions
- Shear, gusts, turbulence
- Wakes & wake superposition

- Surface waves (ocean, ships)
- Ocean, tidal currents
- Ice impact, break-up of ice floes

- Pitch system
- Generator
- Active add-ons

- Various needs

- Unclear/undefined
- Not implemented
- Started, incomplete
- Working prototype
- Working/slow
- Tested/Complete
- Tuning/Rewrite

Feature Overview BHawC 9.5 Wind Module

Main feature: fully modular code!

Supported pre-9.5 feature set:

✓ All shear types besides « Special »

✓ All gusts

✓ Turbulence interpolation, low memory

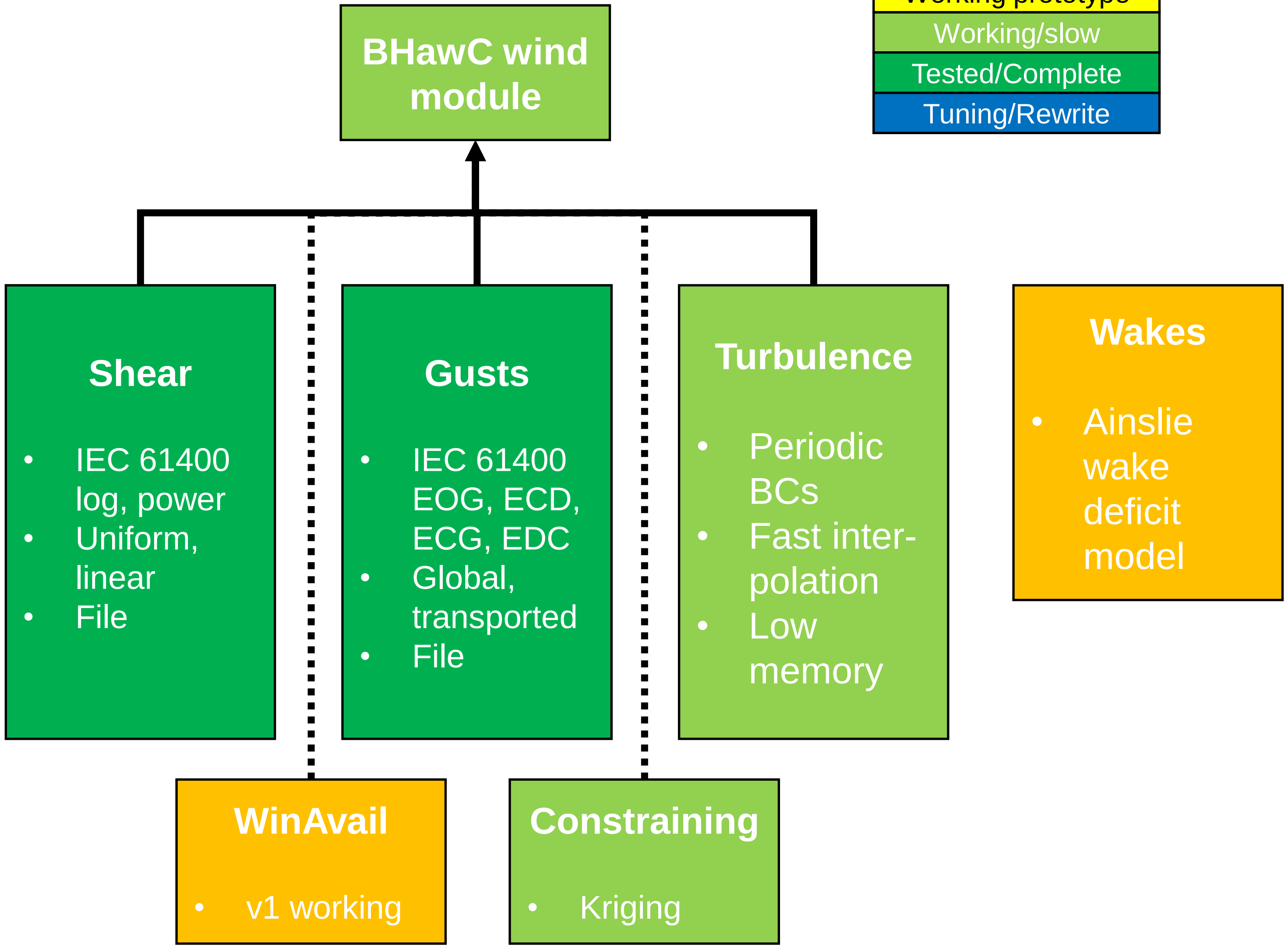
Known issues:

☠ File turbulence scaling does not match 9.4, differences in scaling computation

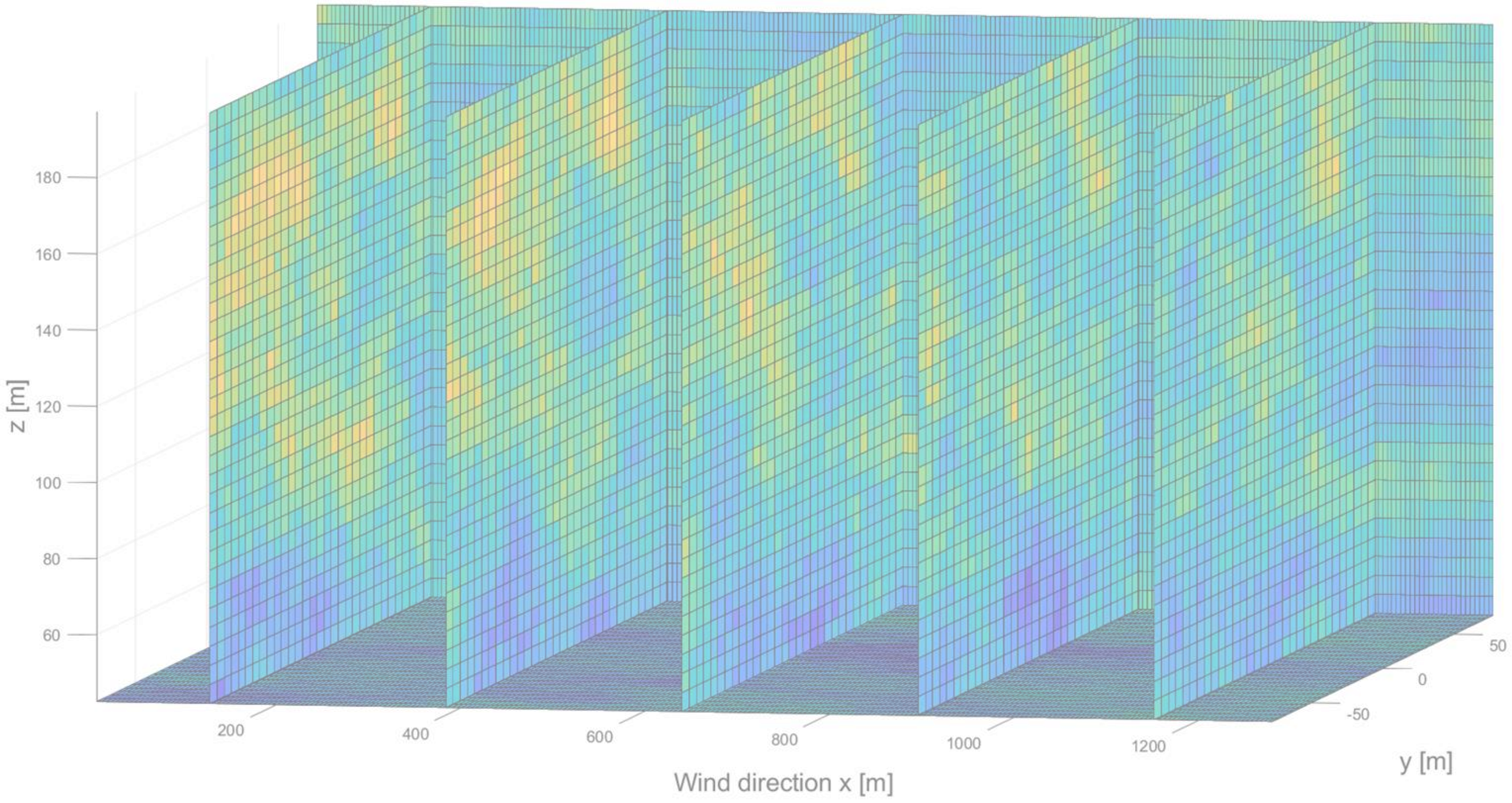
Added functionality:

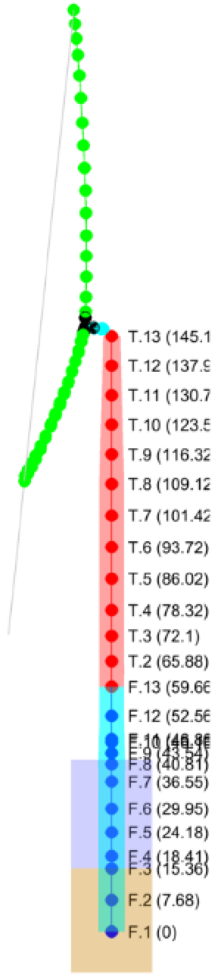
✓ Transported gusts

✓ Periodic Boundary Conditions in turbulence interpolation



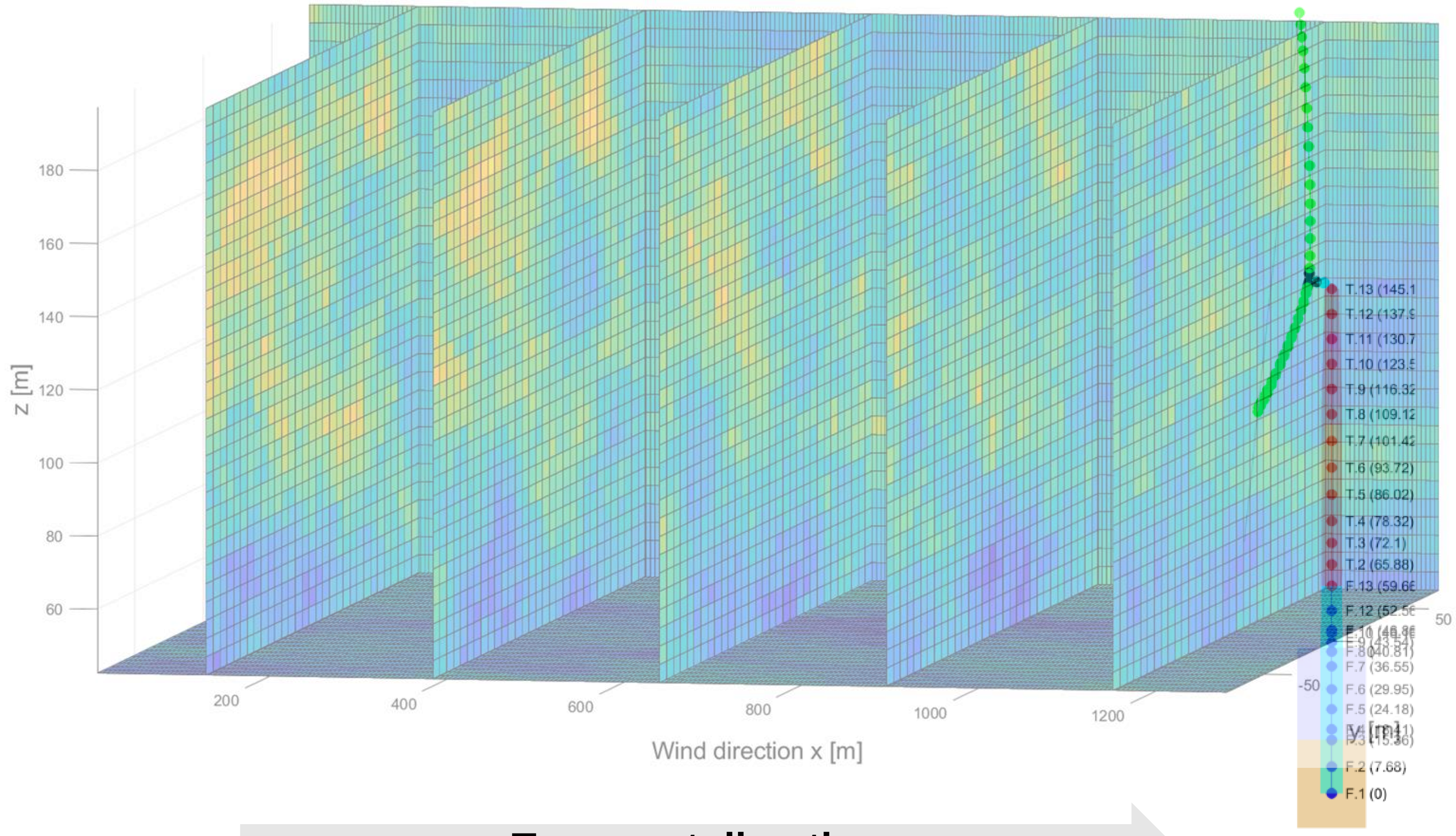
Linearized Transport Phenomenologically: t=0s





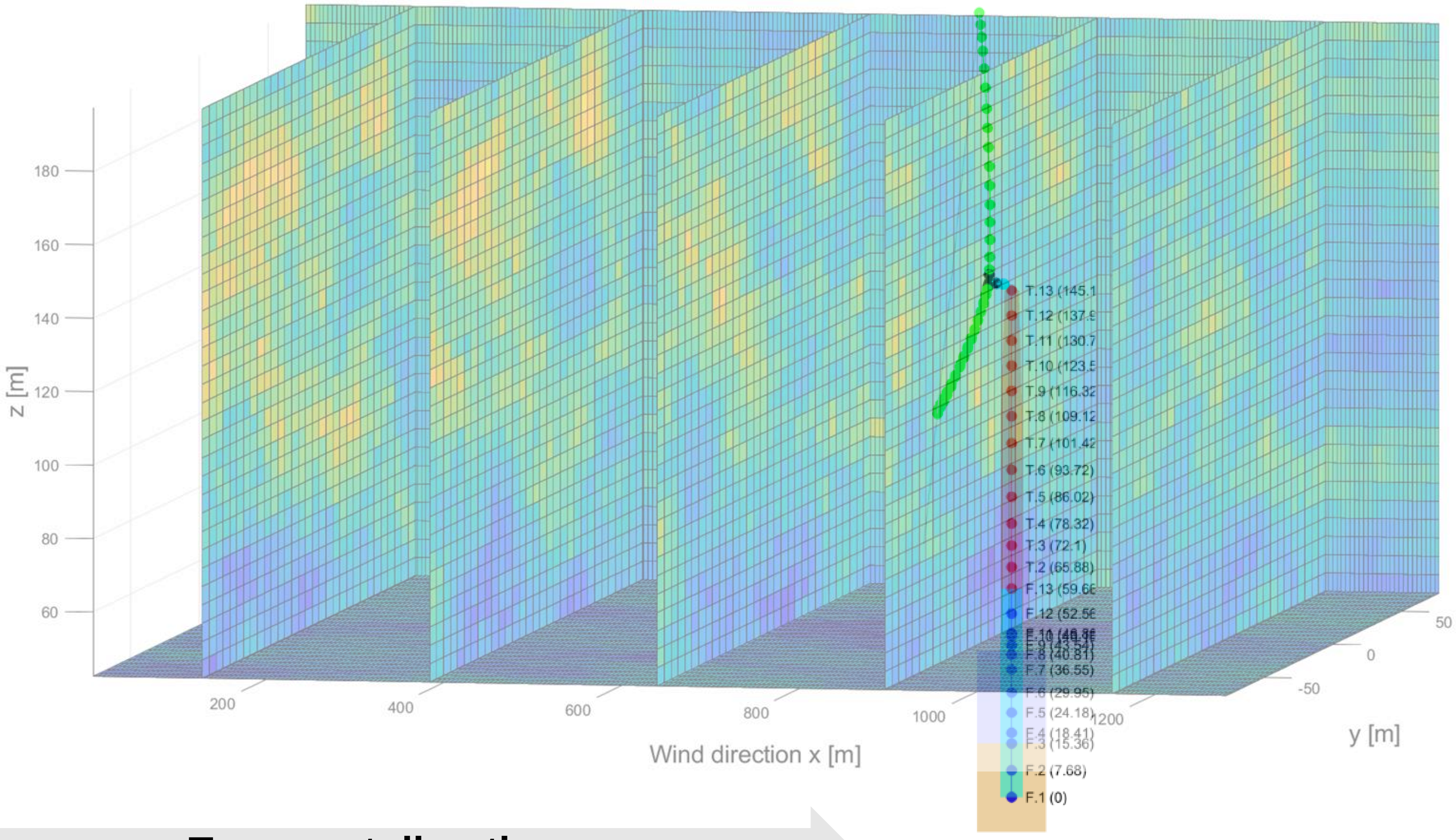
Transport direction

Linearized Transport Phenomenologically: t=10s



Transport direction

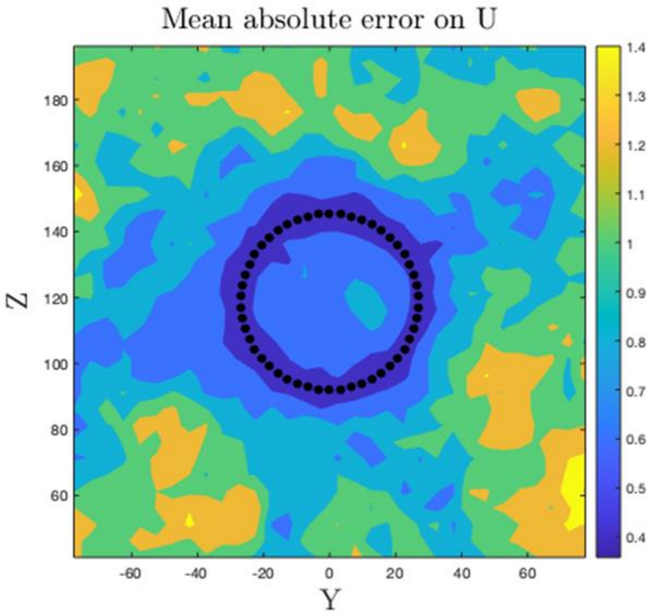
Linearized Transport Phenomenologically: t=20s

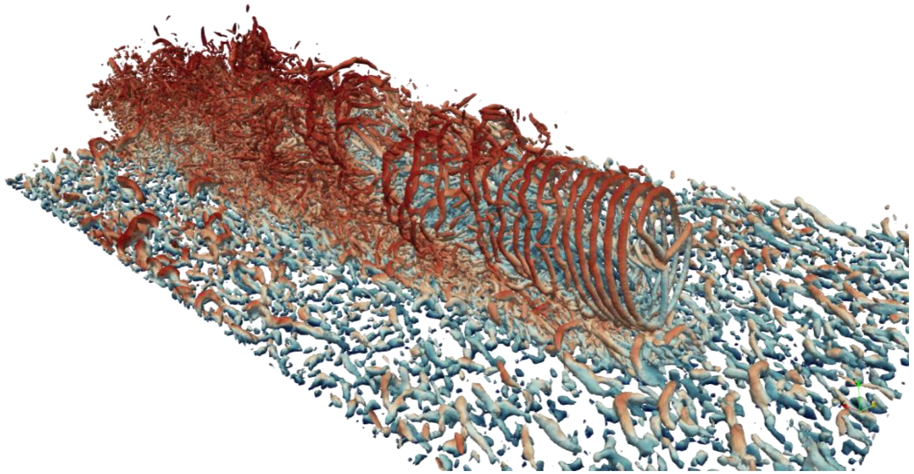


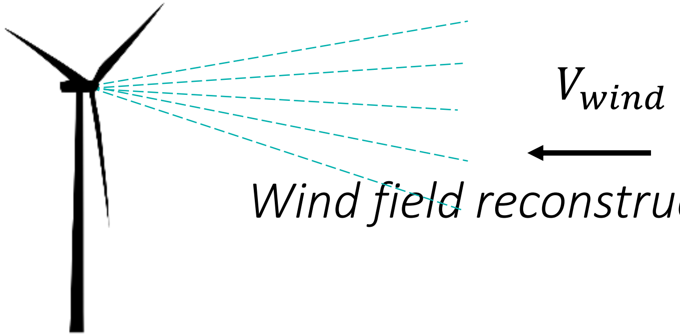
Transport direction

Wind field reconstruction

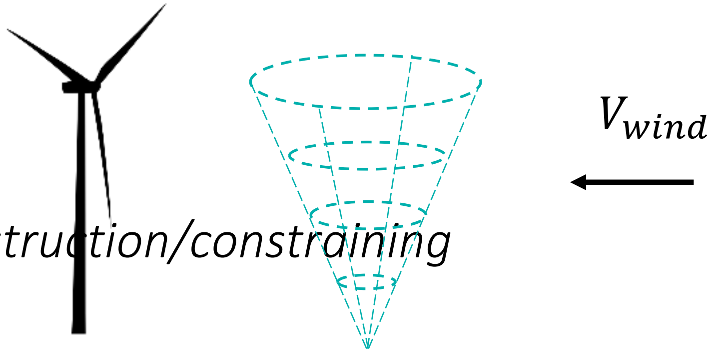
Can we extract more information on the wind field from the lidar measurement process?







Wind field reconstruction/constraining



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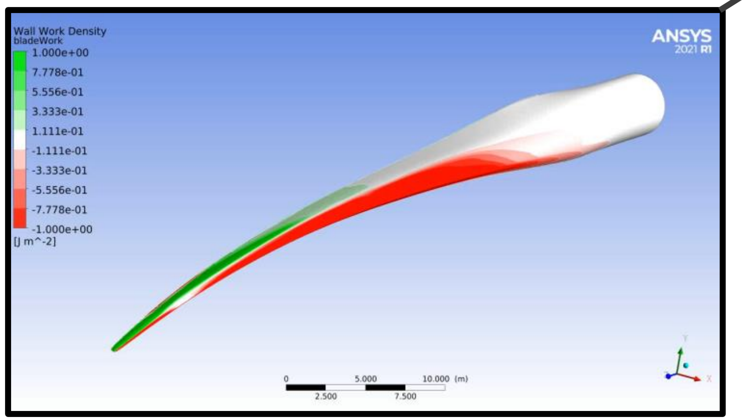
O-Series Validation Report

Relate the operation of new farm (for new turbine type) with the loads/controls design indicators

- Using high frequency data
- Early operation period (1st three/six months) - detect anomalies quicker
- Check for main indicators (in terms of fatigue/ULS/Modes excited) and controller handles

"Advanced aerodynamics" team – AALA project (OF + ON)

Vortex/Stall Induced Vibrations



- **Simulation of VIV**
  - Dev of methodology
  - PRESTIGE project
  - Application to NPD
  - Eng. tools
- **Tests on prototypes**
- **Tower VIV**
- **SIV**
- **Analysis of fleet events**
- **0-series validation**

"Advanced aerodynamics" team – AALA project (OF + ON)

Advanced aerodynamics (mostly) in BHawC

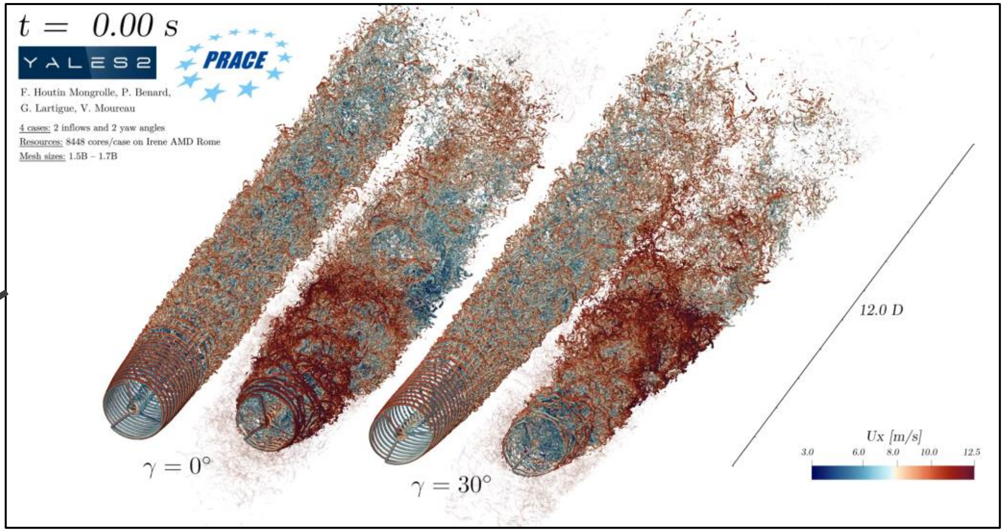


(This is Norbert)






- **Modularization of BHawC**
- **BEM improvements**
  - Improved DS modeling
  - Comparisons to HAWC2
- **LES/AL for wakes and floating turbines**
  - Coupling BHawC/YALES2
  - PhD Ricardo



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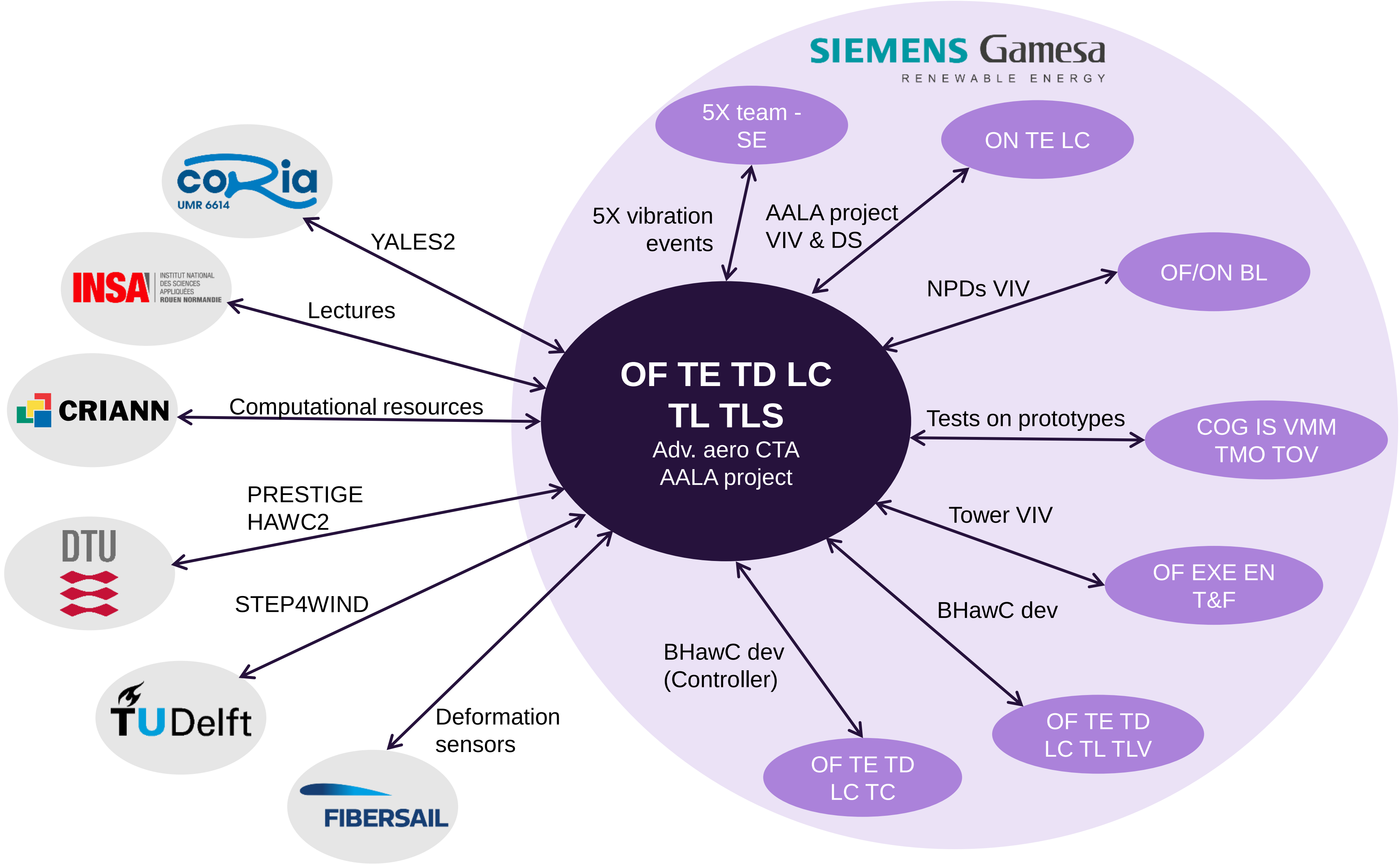
Interfaces



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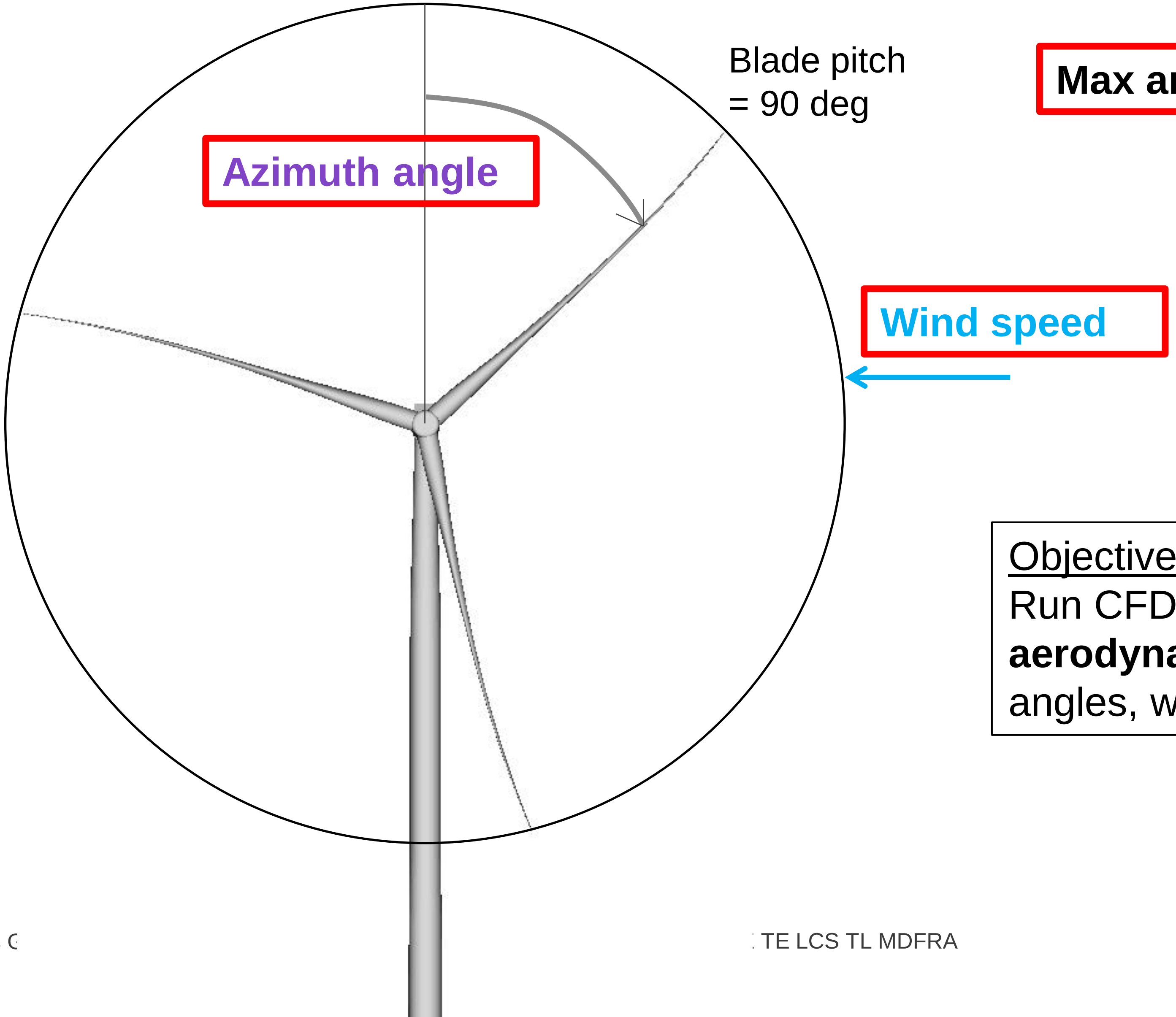
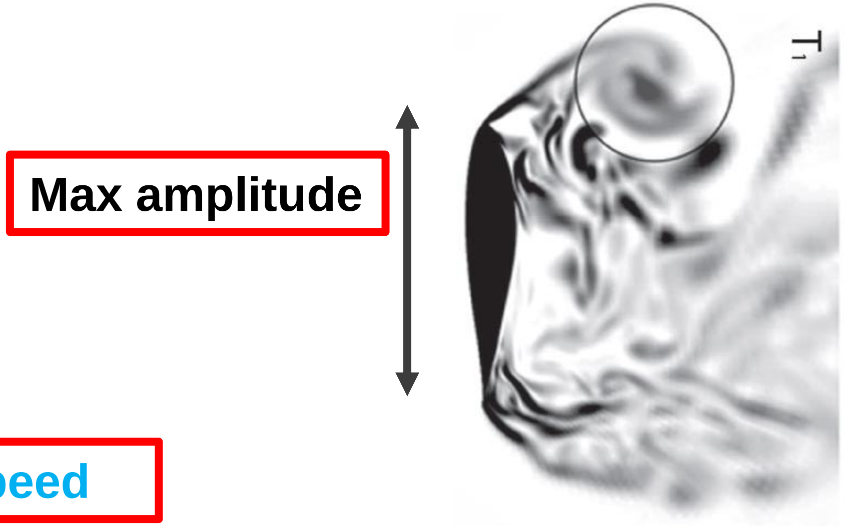
RENEWABLE ENERGY
OF TE TD LC
TL TLS
Adv. aero CTA
AALA project
5X team - SE
ON TE LC
OF/ON BL
COG IS VMM TMO TOV
OF EXE EN T&F
OF TE TD LC TL TLV
OF TE TD LC TC
5X vibration events
AALA project VIV & DS
NPDs VIV
Tests on prototypes
Tower VIV
BHawC dev
BHawC dev (Controller)
coRia UMR 6614
INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES ROUEN NORMANDIE
CRIANN
DTU
TU Delft
FIBERSAIL
YALES2
Lectures
Computational resources
PRESTIGE HAWC2
STEP4WIND
Deformation sensors

Overview of VIV





Objective:
Run CFD simulations to evaluate the **global aerodynamic damping** for several azimuth angles, wind speeds and max amplitudes

Study of Vortex Induced Vibrations & other aero instabilities

- **Rare events**, not much data → not well understood
- Objectives: **better understand VIV - predict stability of our next turbine generations – impact on ULS/FLS**

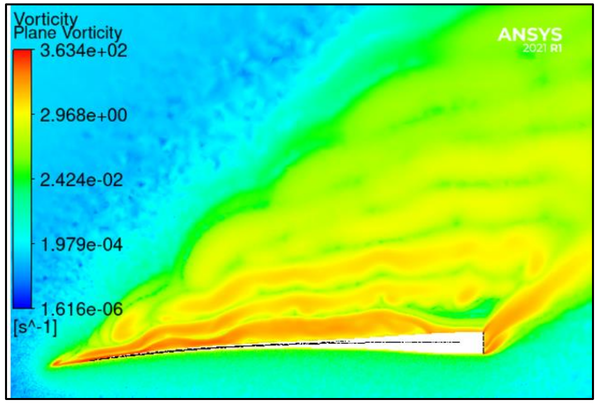
Numerical simulations on aerodynamic instabilities:
1) improve understanding of aerodynamic instabilities,
2) stability assessment (NPD)

Measurements:
1) assess stability turbine,
2) gather data for validation CFD

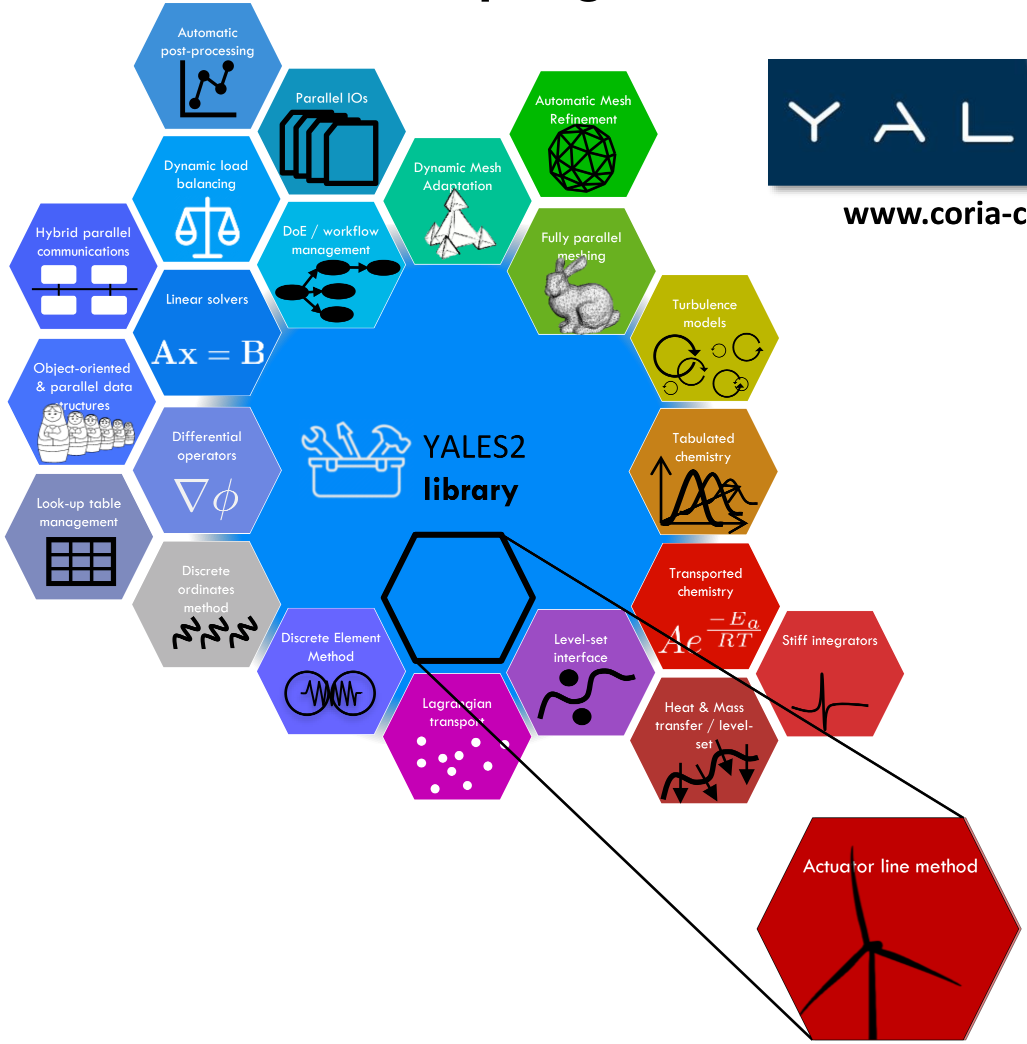
- VIV (CFD methodology development)
- PRESTIGE DTU

- SIV (Stall Induced Vibrations)
- DWI (Downwind idling)

- Fleet measurements

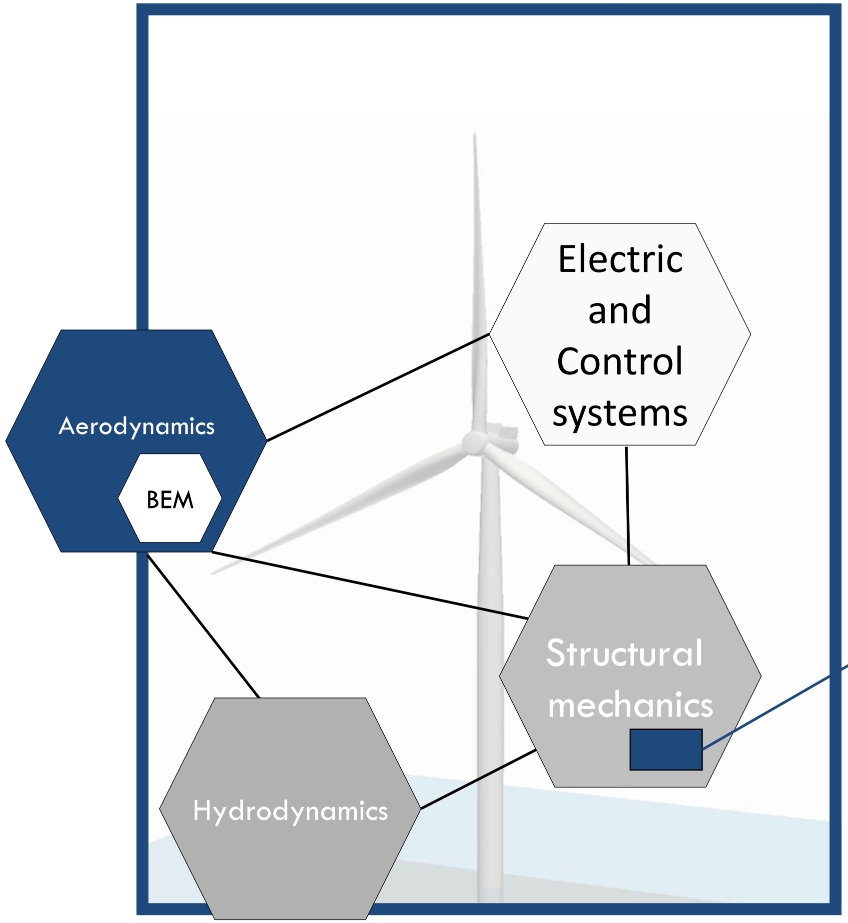


Framework: coupling to BHawC



YALES2 ⇄ BHawC

www.coria-cfd.fr



Inputs:

Turbine characteristics

Control properties

Wind conditions

Weather conditions

Wave conditions

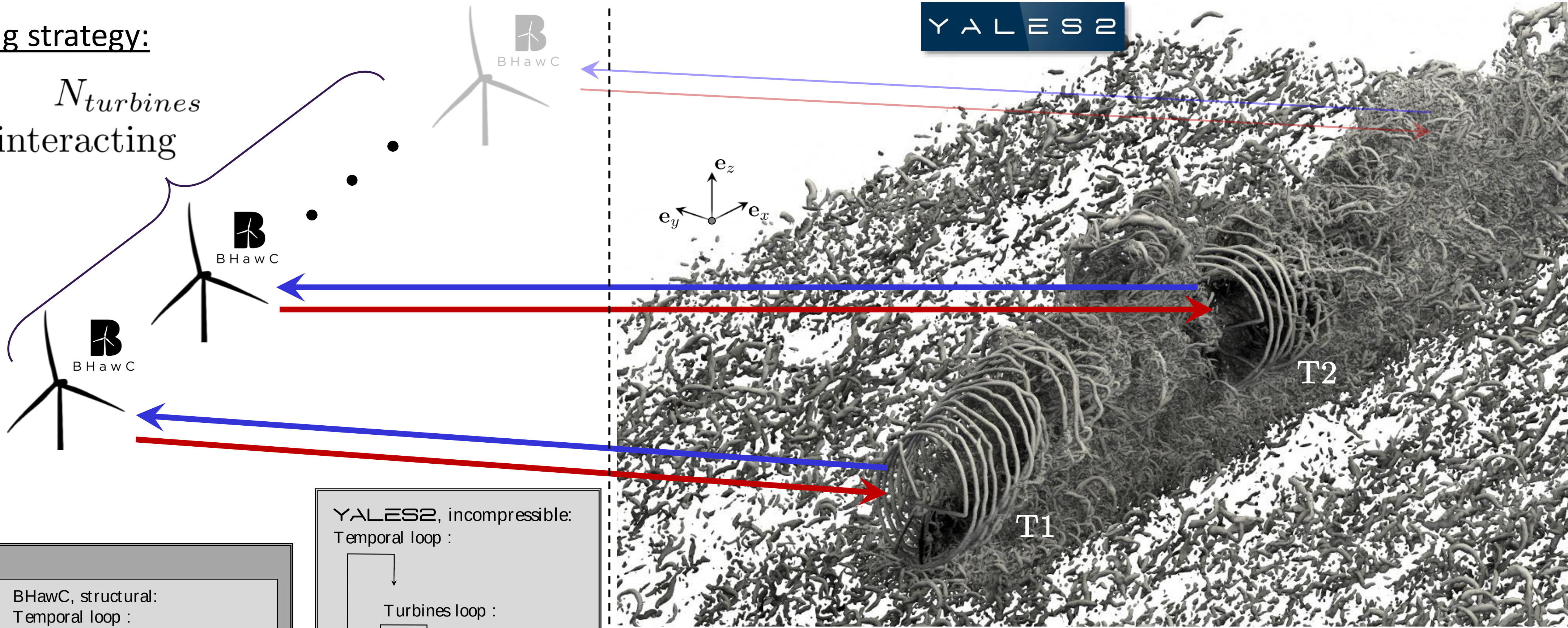
Soil conditions

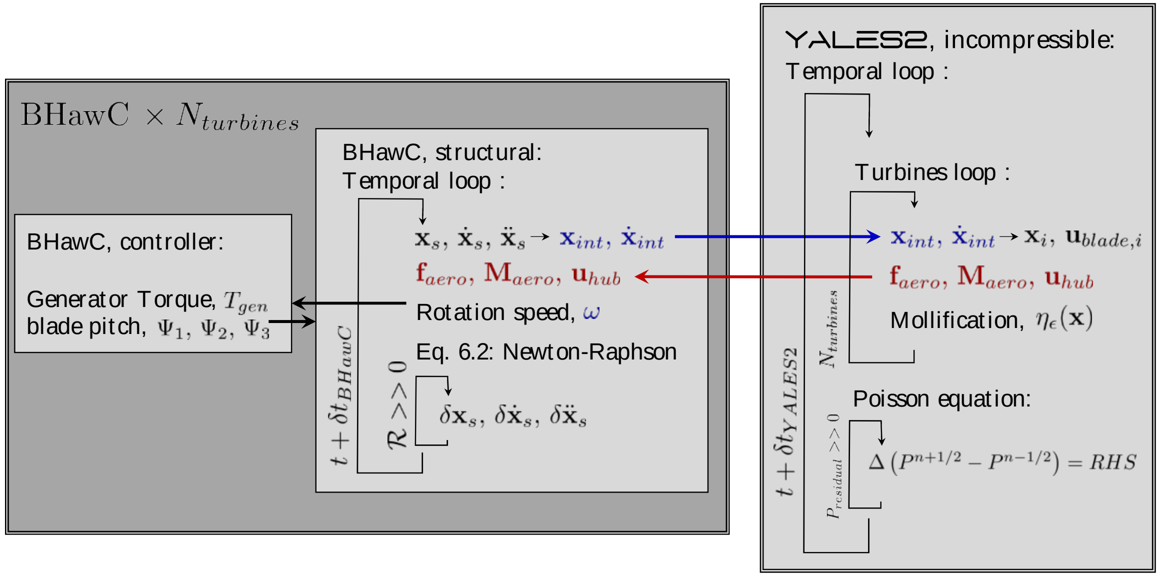
Structural solver:

- Finite beam element solver
- linear two-node Timoshenko beam elements
- Substructures for: foundation, tower, nacelle, drivetrain, shaft, hub, and blades

Framework: coupling to BHawC

Global coupling strategy:





- Several turbine can be used at the same time
- MPI communication for the positions/orientations and forces/moments

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