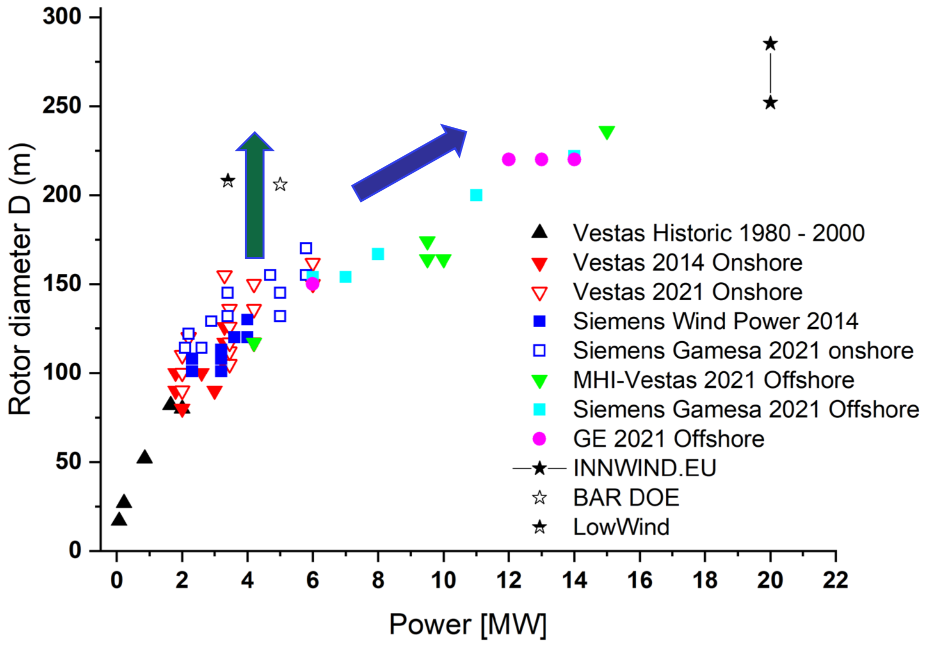
Aerodynamics & Blade technology 1

Achievements and perspectives in blade aero-structural design

Frederik Zahle, 5 October 2021

Rotor design trends

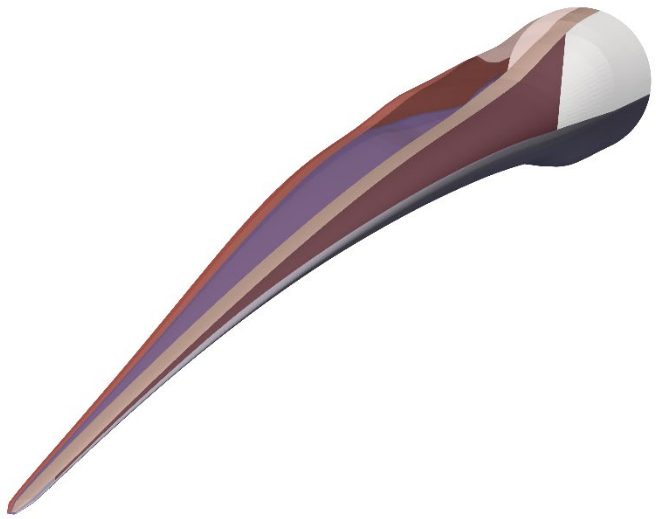
- Historically, land-based and offshore rotor design followed the same growth curve.
- As the industry has matured, and with the advent of rotors going beyond ~5-6 MW, turbines have evolved differently for the two markets.
- For land-based rotor design a strong trend is towards lower specific power, highly slender and flexible blades,
- For offshore rotor design upscaling of generator capacity has dominated, and will likely continue beyond the newest 15 MW announced.

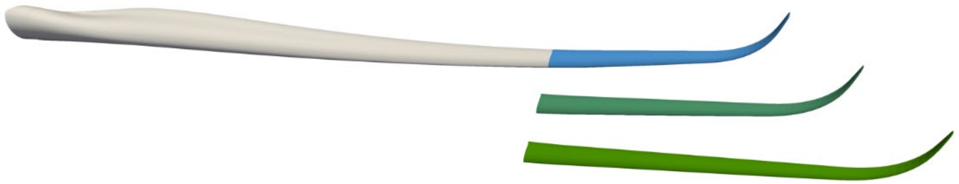


A.B. Abrahamsen, DTU Wind Energy, July 2021

We are NOT done with blade design!

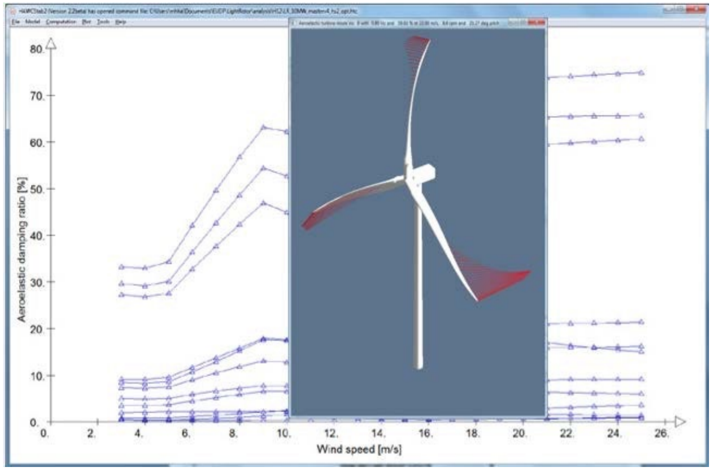
- The quest for longer, lighter and more load efficient blades continues to drive innovation in all areas related to blades such as
  - Materials,
  - Manufacturing processes,
  - Structural design,
  - Aerodynamics and aeroacoustics,
  - Controls,
  - Modularization.
- We have in Denmark been exceptionally good at fostering innovation through tight collaboration between the industry and the research community
- Continued focus on research is needed to remain industry leaders.

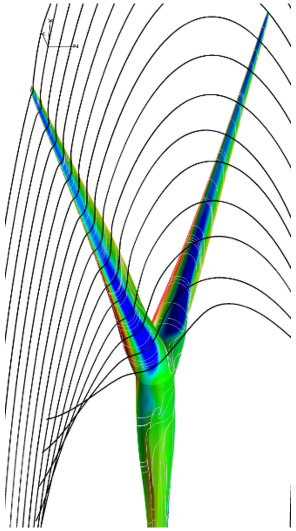


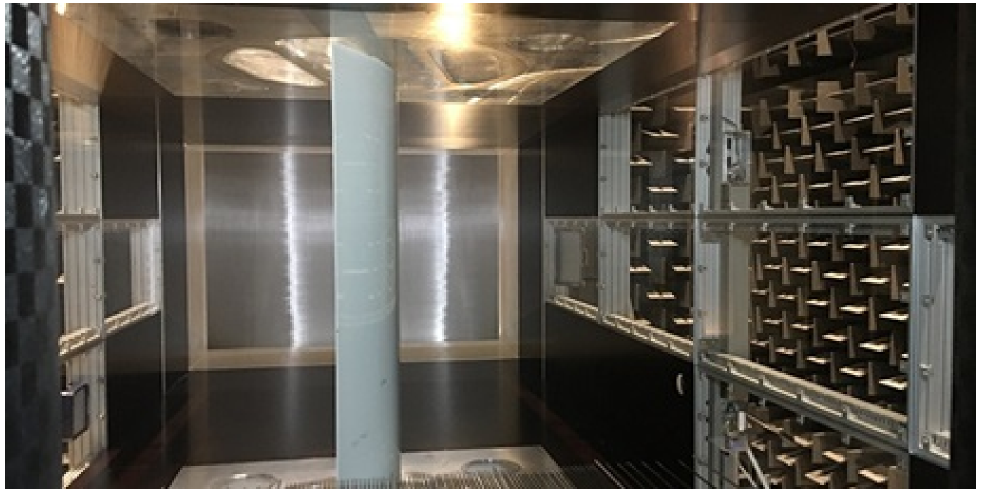


Design basis for modern wind turbines

- Design innovation is rooted in state-of-the-art modeling.
- Accurate characterisation and physical modelling of a wind turbine has been key to making today's wind turbines possible.
- At DTU Wind Energy a number of wind turbine analysis and design tools have been developed, which are used both in our research and in industry.
- Experimental facilities such as the Paul La Cour Wind Tunnel and Large Scale Facility are corner-stones in this development.

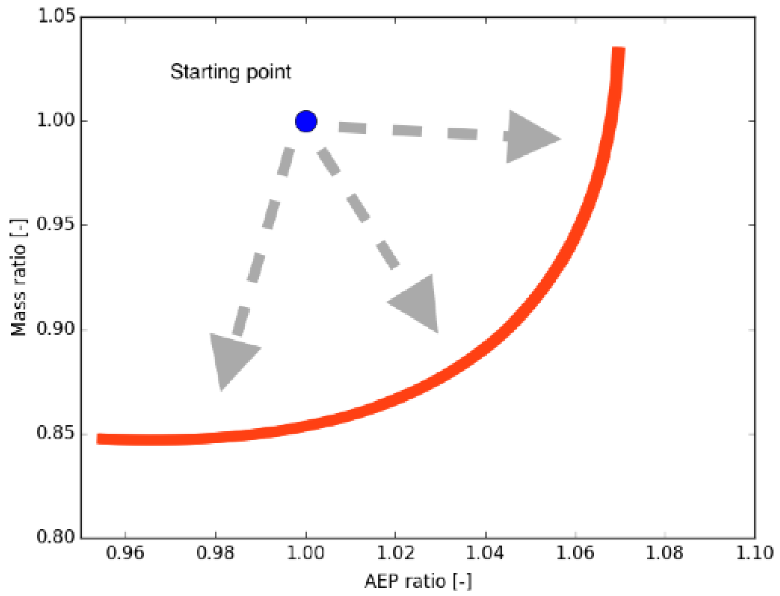






The Case for (M)ultidisciplinary (D)esign, (A)nalysis and (O)ptimization

- Blade design consists of 100s-1000s of design parameters, which can be difficult to handle manually.
- In MDAO several analysis disciplines are coupled to enable us to explore the interaction of key design inputs and output,
- Using numerical optimization, the complex and often conflicting constraints and objectives can be explored systematically.
- We can optimize for macro-parameters such as AEP or LCoE, but at the same time constrain details in the design such as aeroelastic stability.



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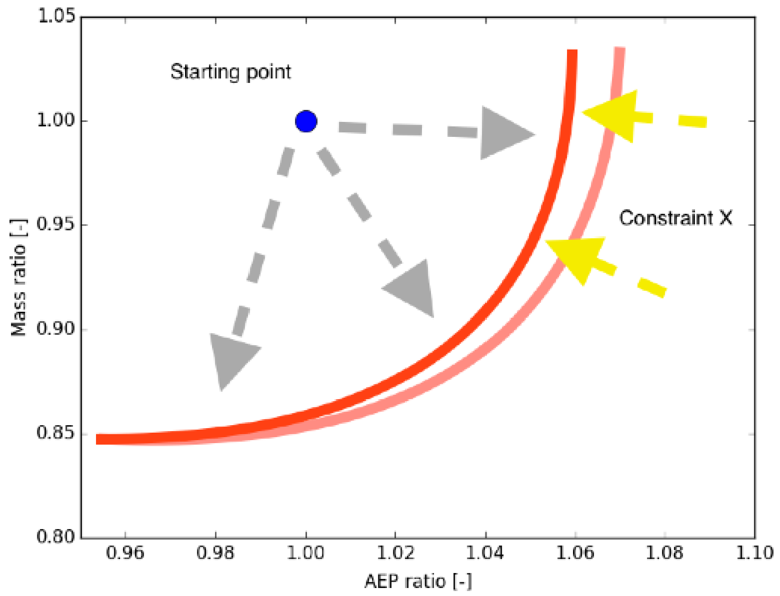

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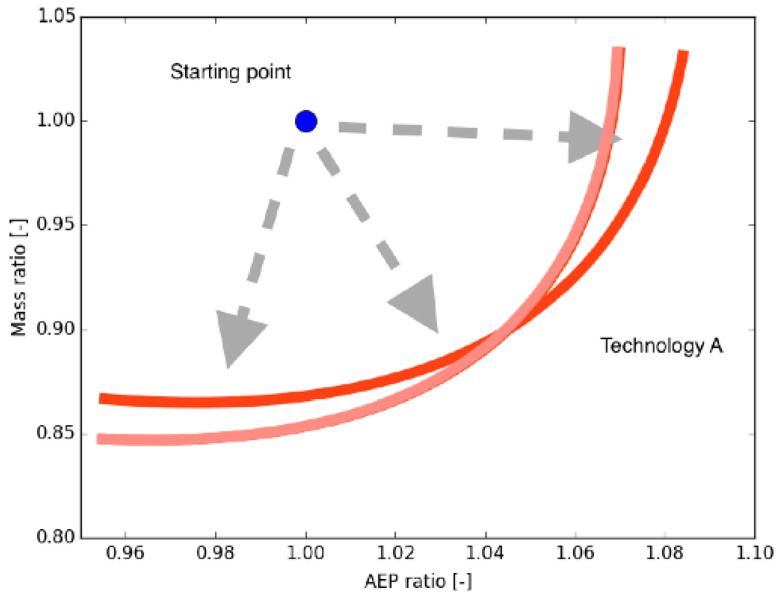

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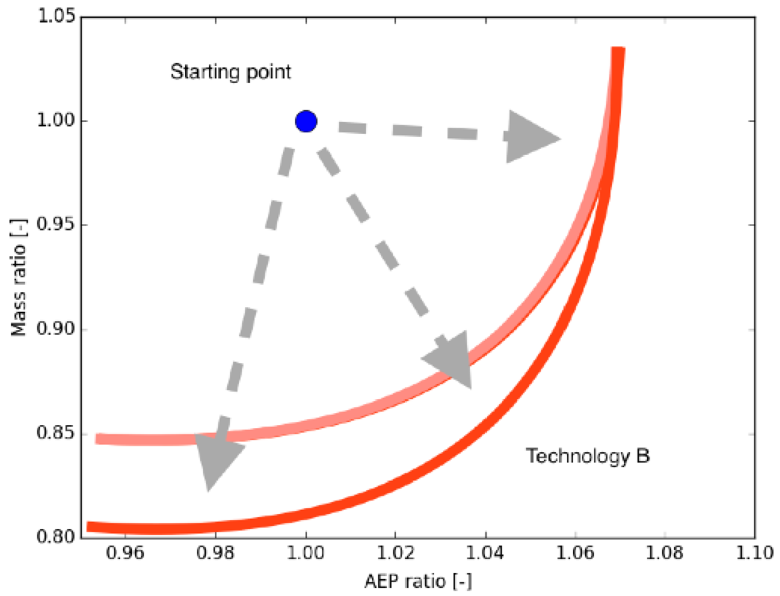
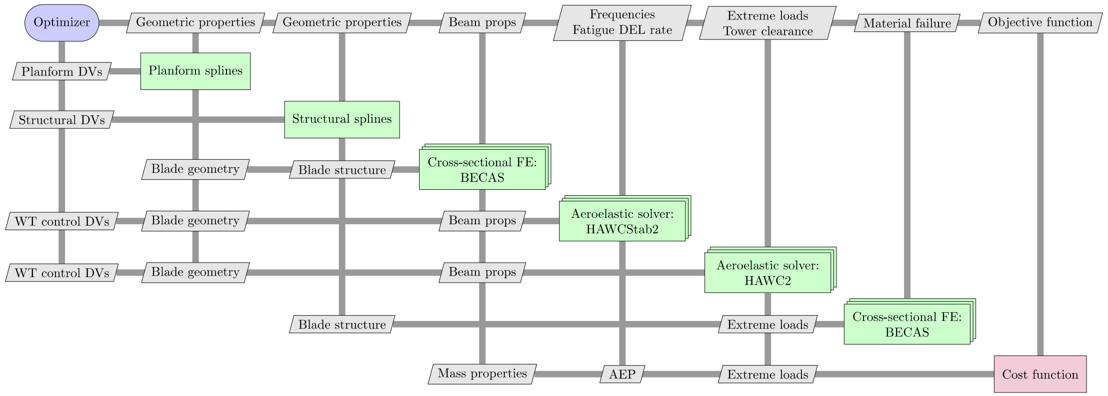
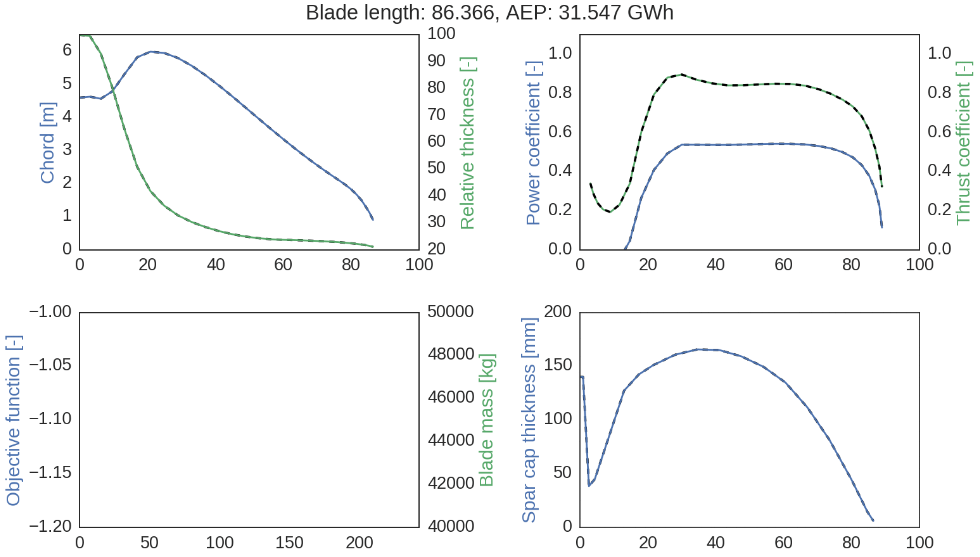


Integrated aerostructural design

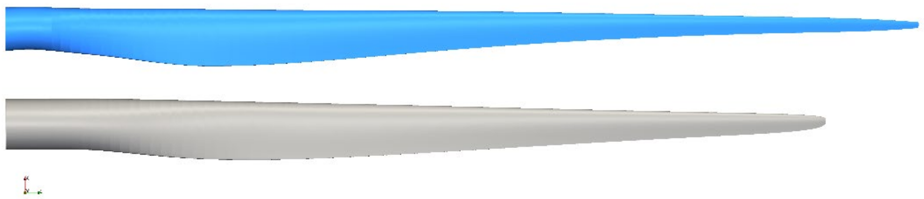
- Our in-house developed HAWTOpt2 enables simultaneous and fully coupled design of the blade aerodynamic shape and internal structural geometry as well as macro control parameters,

- HAWTOpt2 leverages the proven analysis codes BECAS, HAWCStab2 and HAWC2, combined into a numerical optimization framework.





[IEA Wind 10 MW RWT]

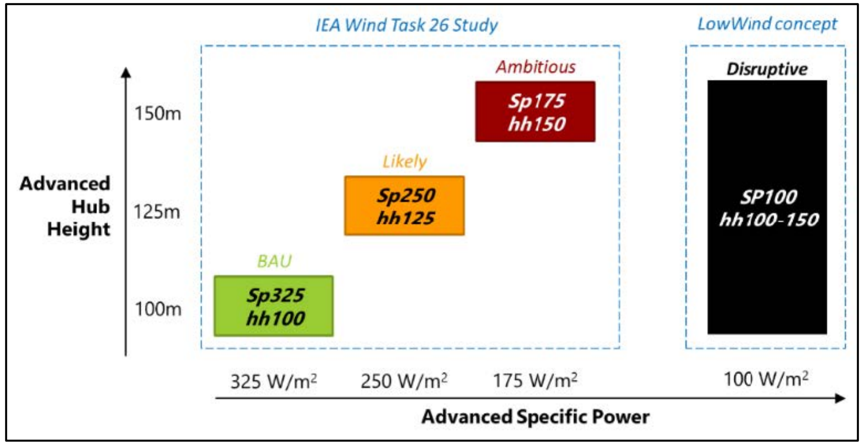


Low Wind (EUDP, PM HAa Madsen)

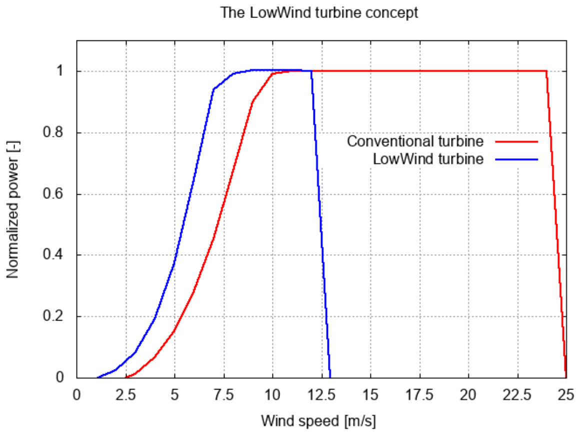
- With increased share of renewable energy in the electricity grid, the *value* of energy rather than *cost* of energy becomes a key design driver,
- In the Low Wind project we seek to explore the possibilities of designing and deploying wind turbines with an ultra-low specific power of 100 W/m^2.

- We have explored both upwind and downwind turbine concepts,

- Energy system modelling confirms that low wind turbines could be very attractive due to their high production during low wind periods.



LowWind vs current technology forecasts. Figure reproduced from IEA Wind TCP Task 26 report with the LOWWIND concept inserted.

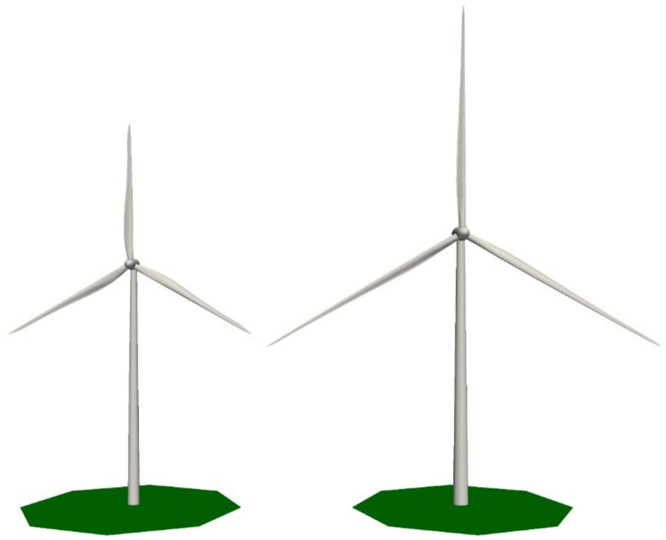


Low Wind RWT

- The Low Wind RWT (LW RWT) was designed in the first part of the project as a basis for the various conceptual design studies.
- It features a rotor with 58% longer blades than the IEA 3.4 MW RWT

Quantity	IEA 3.4 MW	LW RWT
AEP (V=6.5, k=2.4) [GWh]	11.754	17.131
Blade Mass [kg]	16,441	31,652
Blade topology	two shear webs	one shear web
Spar cap material	Glass	Carbon
Max Rotor Speed [rpm]	11.75	7.3
Max Tip Speed [rpm]	80.0	80.0
Cut-in wind speed [m/s]	4	2
Cut-out wind speed [m/s]	25	13
Rated wind speed [m/s]	9.8	8
Airfoils	DU	FFA-W3
Rotor Diameter [m]	130	208
Hub Diameter [m]	2.0	2.0
Hub Height [m]	112.5	127.5

See H Aa Madsen et al, 2020

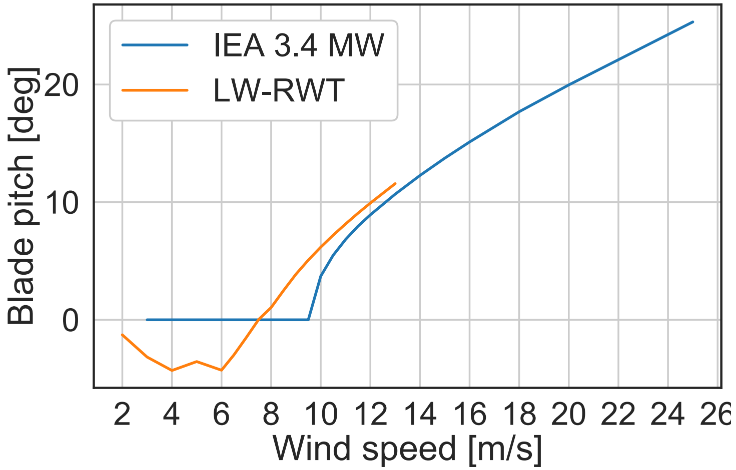


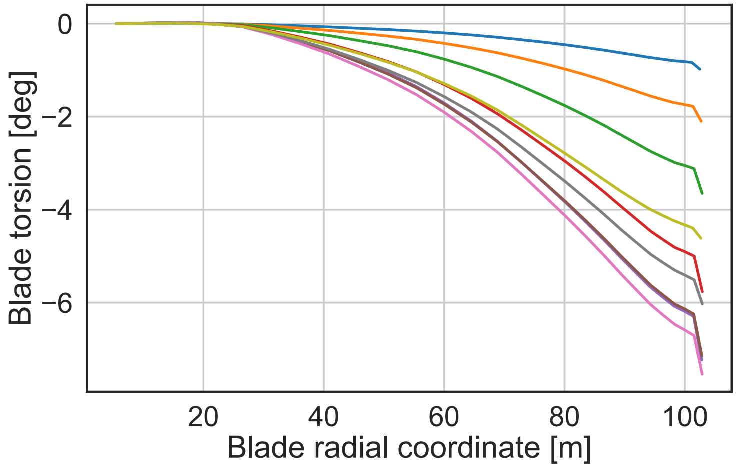
IEA - 130m diameter - 3.4MW turbine, IEA-RWT

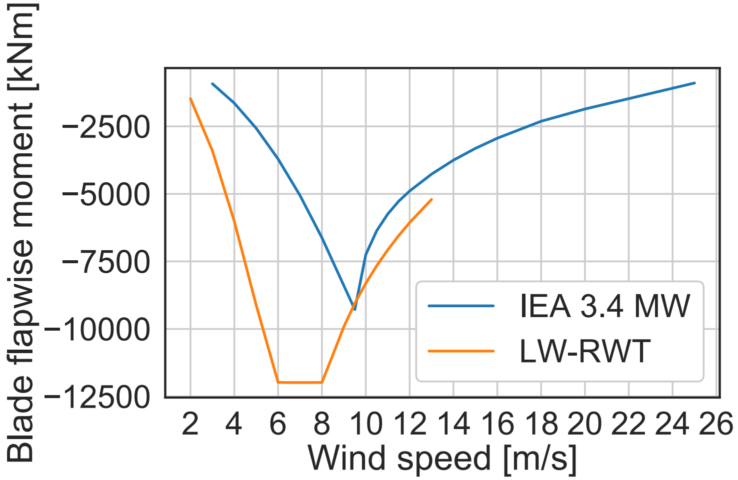
LW-208m diameter - 3.4MW turbine, LW-RWT

Low Wind RWT

- To reduce blade flapwise and tower bottom loads, two key design characteristics are combined:
  - Peak shaving: The rotor pitches towards feather to alleviate peak loads,
  - Bend-twist coupling: At maximum loading the blade torsions 7 deg. reducing flapwise loads significantly.
- Based on HAWCStab2 we could place constraints on blade aeroelastic stability within the design process which was crucial for these slender and flexible designs.

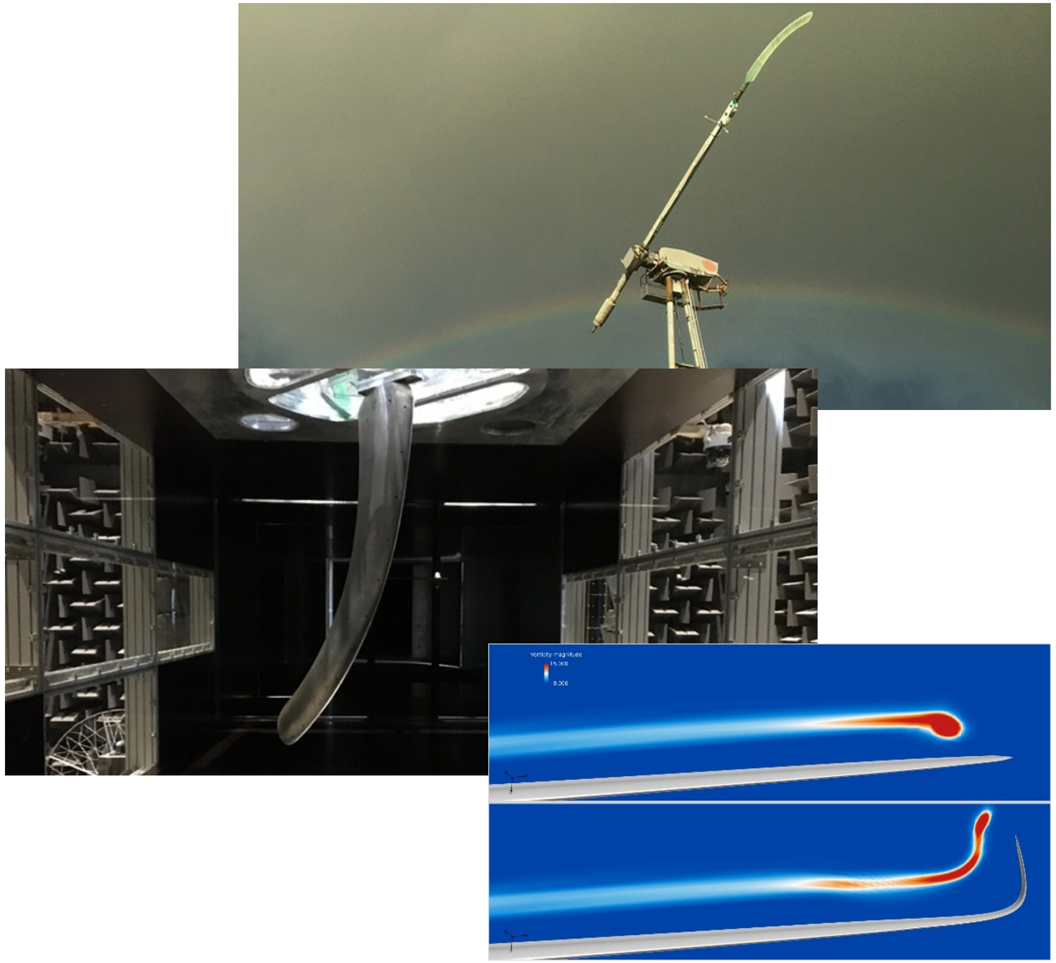






Smart Tip (Innovationsfonden, PM T. Barlas)

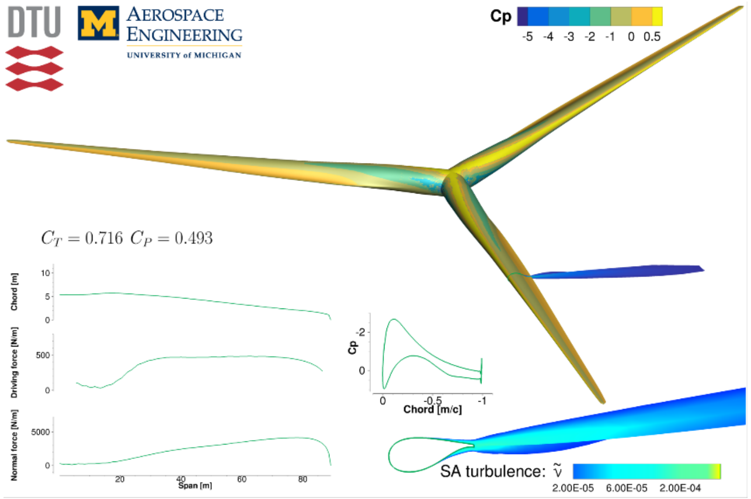
- The project explored blade tip designs through integrated design optimization using aeroelastic tools at multiple levels of fidelity,
- In the project, aerodynamic models suitable for modeling advanced tips were implemented and validated.
- Validation and demonstration of the designs in a range of experiments and full scale field testing.
- Surrogate-based aeroelastic design using HAWC2 using improved aerodynamic models (T. Barlas et al)
- Surrogate-based aerodynamic design using CFD (Zahle et al., Madsen et al)



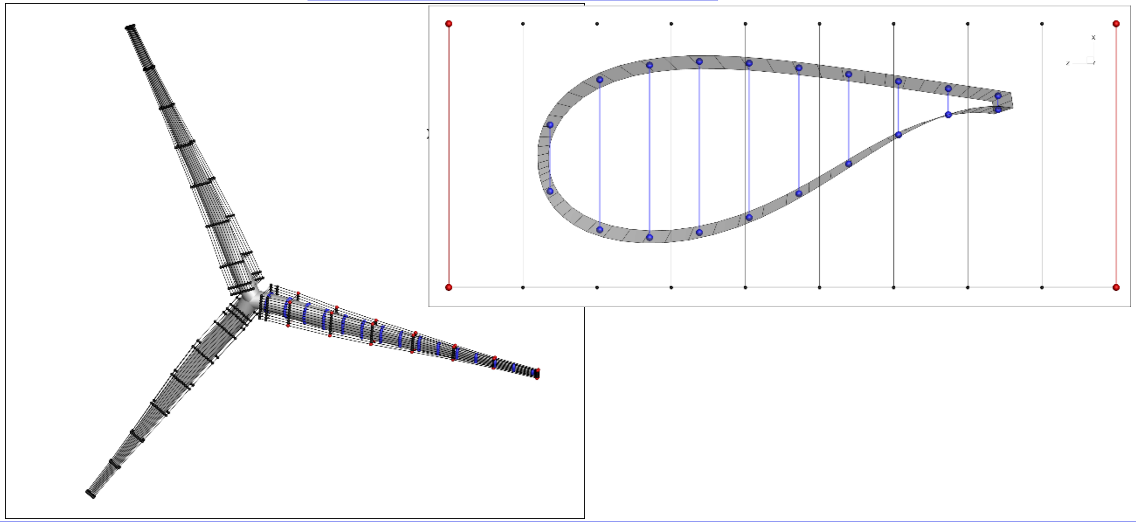
Source: windenergy.dtu.dk

High-fidelity modelling in blade design

- High-fidelity modeling such as Computational Fluid Dynamics is increasingly becoming feasible to use in the conceptual design phase,
- With HFM, we can accurately model complex flows and explore the full 3D freeform design space.
- Adjoint-based design enables large-scale optimization with 100s-1000s of design variables but requires a large development effort in the CFD solver,
- We have used an established design framework to demonstrate the feasibility of CFD-based design, and work is in progress to build an adjoint solver for our in-houce CFD code EllipSys3D.



M Madsen et al, 2019

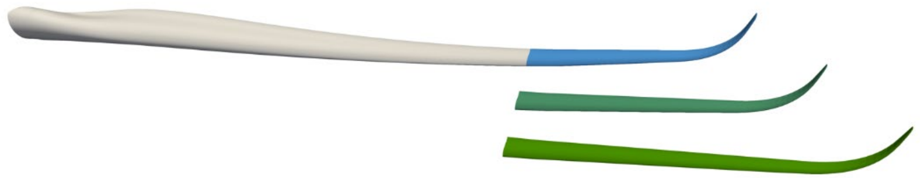


Future perspectives

- Research in integrated design (MDAO) has shown great potential for continuing to facilitate innovation in blade design.

- We have come far with aeroelastic tailoring, but further research is needed to expand the design space to fully free-form aerostructural design based on a mix of fidelities.

- New design paradigms such as blade segmentation and manufacturing processes such as additive manufacturing could lead to radically new designs.



Aircraft wing manufactured with tow steering, credit: Aurora Flight Sciences

DTU