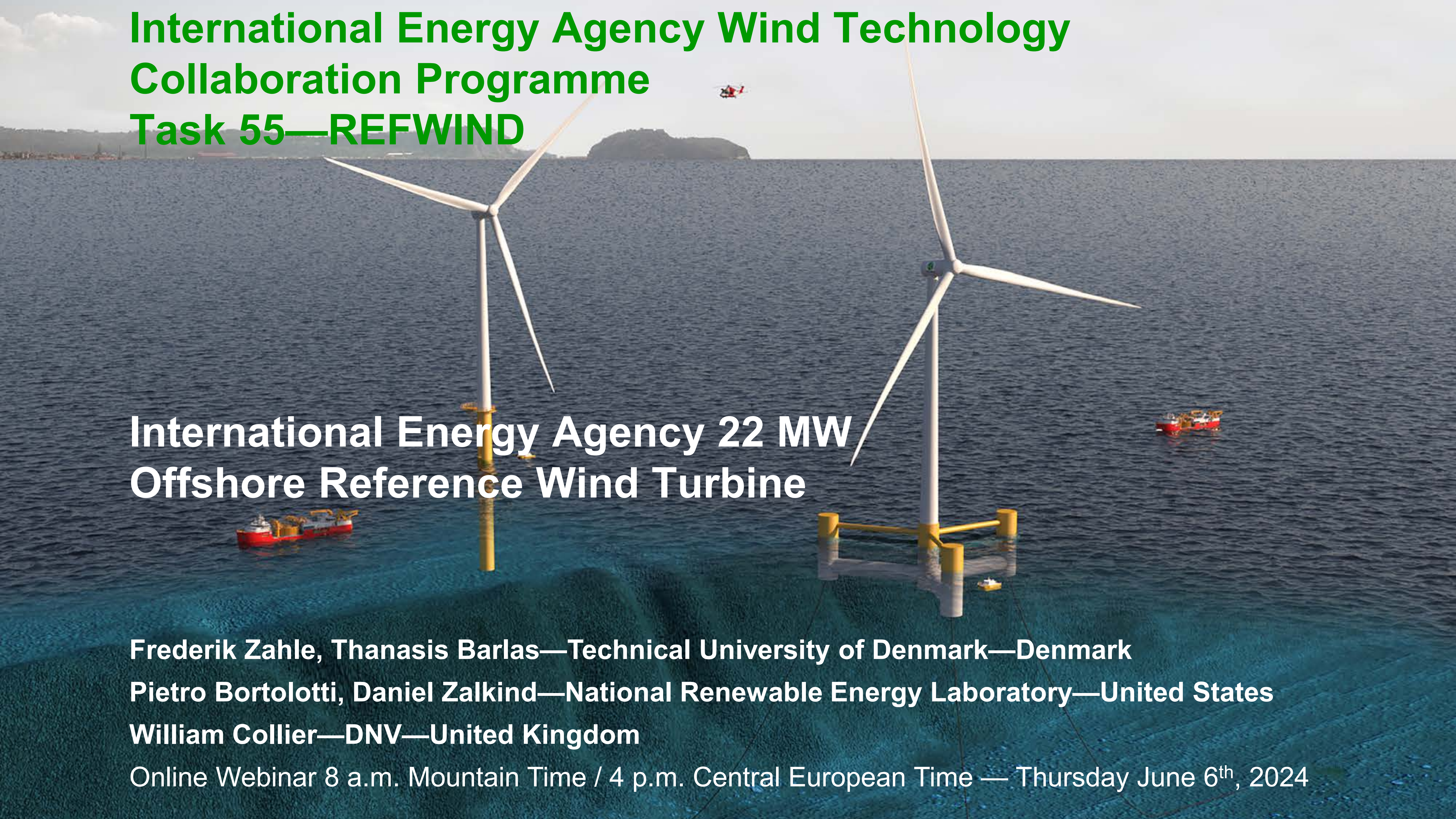


International Energy Agency Wind Technology Collaboration Programme
Task 55—REFWIND

International Energy Agency 22 MW Offshore Reference Wind Turbine

Frederik Zahle, Thanasis Barlas—Technical University of Denmark—Denmark

Pietro Bortolotti, Daniel Zalkind—National Renewable Energy Laboratory—United States

William Collier—DNV—United Kingdom

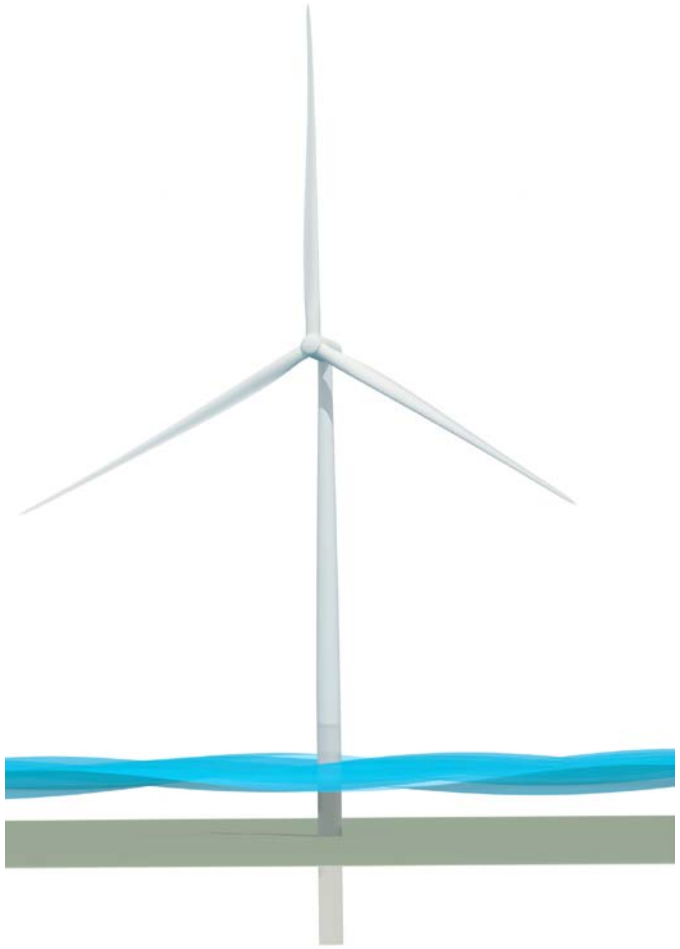
Online Webinar 8 a.m. Mountain Time / 4 p.m. Central European Time — Thursday June 6th, 2024

Outline

- Presentation (30 minutes):
  - Background and overview of the turbine (Frederik)
  - Rotor design (Frederik)
  - Drivetrain, tower, and monopile design (Pietro)
  - Floating platform design (Daniel)
  - Aeroelastic stability and design loads (Frederik)
  - Code-to-code comparison (Will)
  - Outlook (Frederik)
- Questions (30 minutes)

Background

- Several reference wind turbines (RWTs) are now available to the research community, three of which were released through the International Energy Agency (IEA) Wind Task 37.
- RWTs form an important basis for many research projects and are also used in industry.
- In light of the continued innovation and upscaling of wind turbines, an effort was needed to release new open-source reference turbines.
- In Task 55, there will be a continued focus on releasing new RWTs and maintaining the existing ones.
- The first step is the release of the IEA 22 MW RWT.



The IEA 22 MW Reference Wind Turbine

- Developments of 2X MW RWTs were initiated independently by both the National Renewable Energy Laboratory (NREL) and the Technical University of Denmark (DTU) in individual projects.
- The IEA 22 MW RWT became a joint effort initiated in Task 37, which has now been finalized in Task 55.
- DTU:
  - Rotor design
  - Extensive loads validation and stability analysis of both bottom-fixed and floating platforms
  - Coordination of the final technical report
- NREL:
  - Drivetrain, tower, monopile, and floater designs
  - Review of the rotor design
  - Extensive modeling in OpenFAST including stability analysis
- Collaboration with other partners:
  - DNV led and the Technical University of Berlin participated in a code-to-code verification between OpenFAST, HAWC2, Bladed, and QBlade

Technical Report

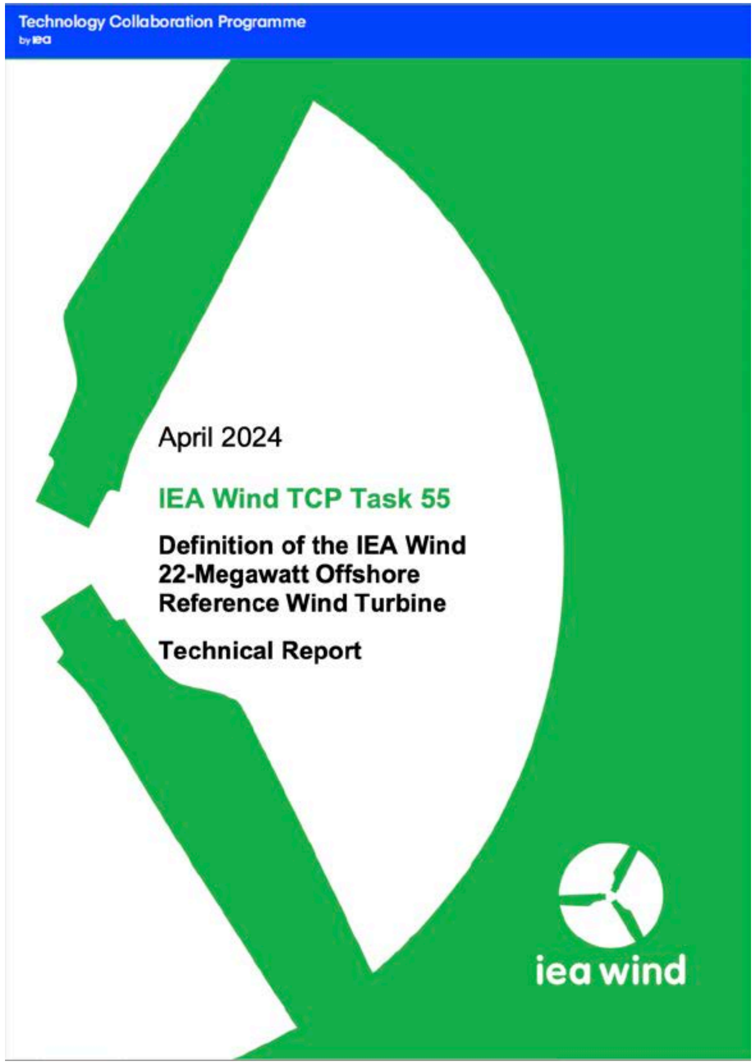
Frederik Zahle, Thanasis Barlas, Kenneth Lønbæk,

Pietro Bortolotti, Daniel Zalkind, Lu Wang,

Casper Labuschagne, Latha Sethuraman, Garrett Barter (2024).

Definition of the IEA Wind 22-Megawatt Offshore Reference Wind Turbine.

Technical University of Denmark, International Energy Agency. DTU Wind Report E-0243, https://doi.org/10.11581/DTU.00000317



Technology Collaboration Programme
by iea

April 2024

IEA Wind TCP Task 55

Definition of the IEA Wind 22-Megawatt Offshore Reference Wind Turbine

Technical Report

iea wind

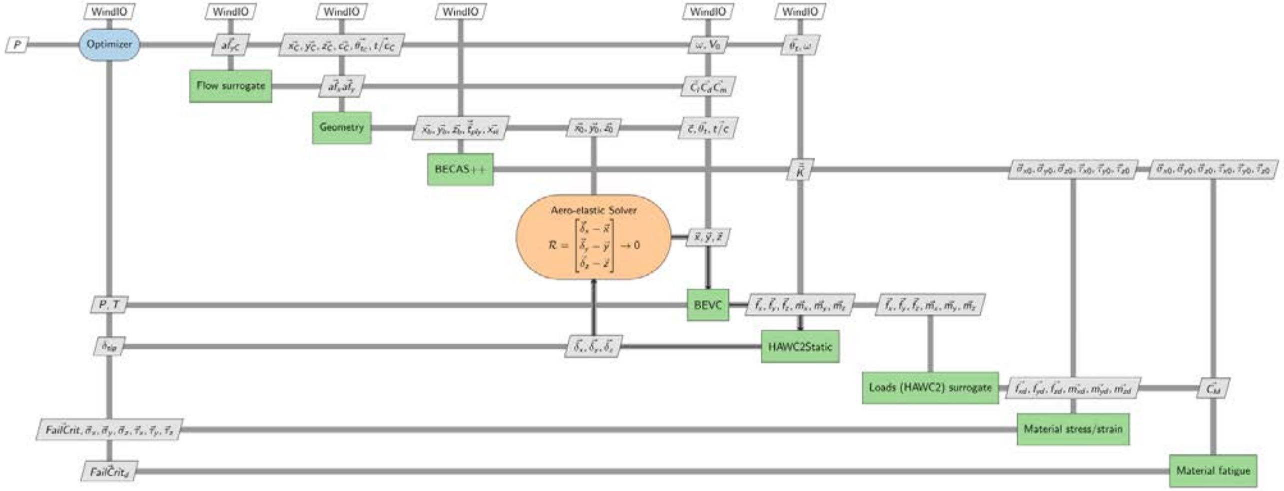
IEA15 Versus IEA22

Quantity	IEA15	IEA22	Quantity	IEA15	IEA22
Class	1B		Configuration	3 bladed upwind direct-drive	
Nominal power (MW)	15	22	Rotor diameter (m)	242	284
Specific power (Wm^{-2})	326	347	Max. tip speed (ms^{-1})	95	105
Generator	Surface mounted PMSG	Interior PMSG	Hub height (m)	150	170
Blade mass	68.6	82.3	Generator mass (t)	369	508
Nacelle mass no hub (t)	631	821	RNA mass (t)	953	1,216
FB tower mass (t)	853	1,574	Floating tower mass (t)*	1,263	1,574
Monopile mass (t)	1,319	2,097	Floater hull mass (t)	4,014	5,711

*Floating tower of the IEA15 had a bug, but floating tower of IEA22 is likely too light. NREL will lead a redesign.
PMSG: permanent magnet synchronous generator; RNA: rotor-nacelle assembly FB: fixed bottom

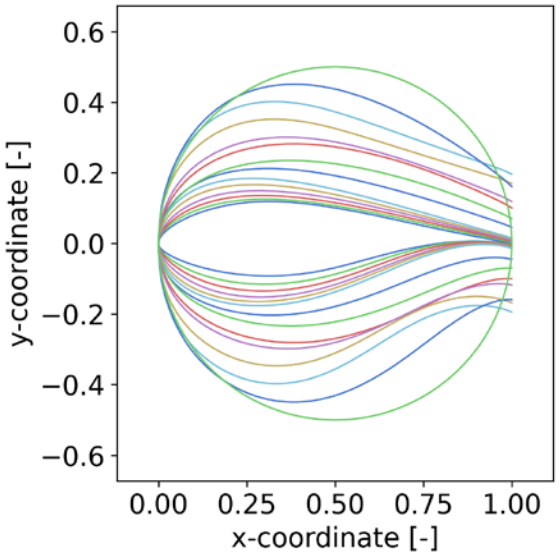
Rotor Design

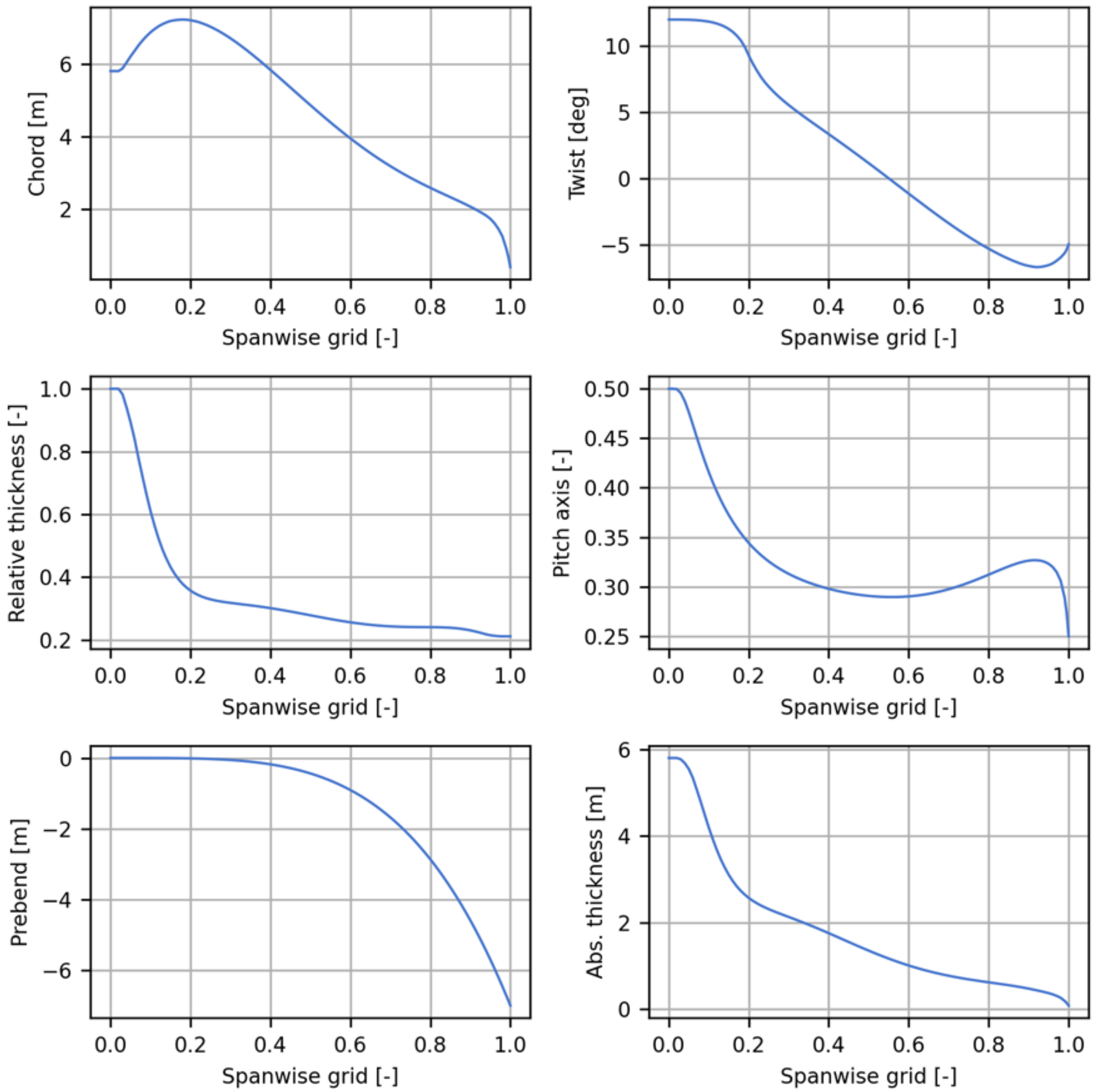
- Rotor designed using DTU's AESOpt framework
- Annual energy production maximization subject to mass, loads, deflection, strain, and frequency constraints
- Simultaneous design of the aerodynamic planform, internal structure, and steady-state operating schedule



Aerodynamic Geometry

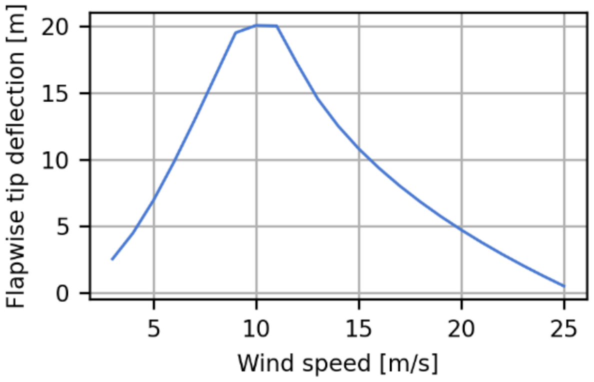
- Root diameter of 5.8 m
- Maximum chord of 7.2 m
- Prebend of 7 m
- Uses the FFA-W3 airfoil family, including flatback airfoils for the root
- Airfoil polars computed using the incompressible 2D computational fluid dynamics solver EllipSys2D at representative Reynolds numbers

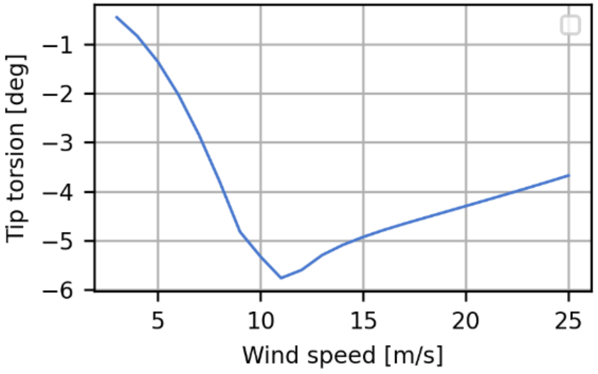


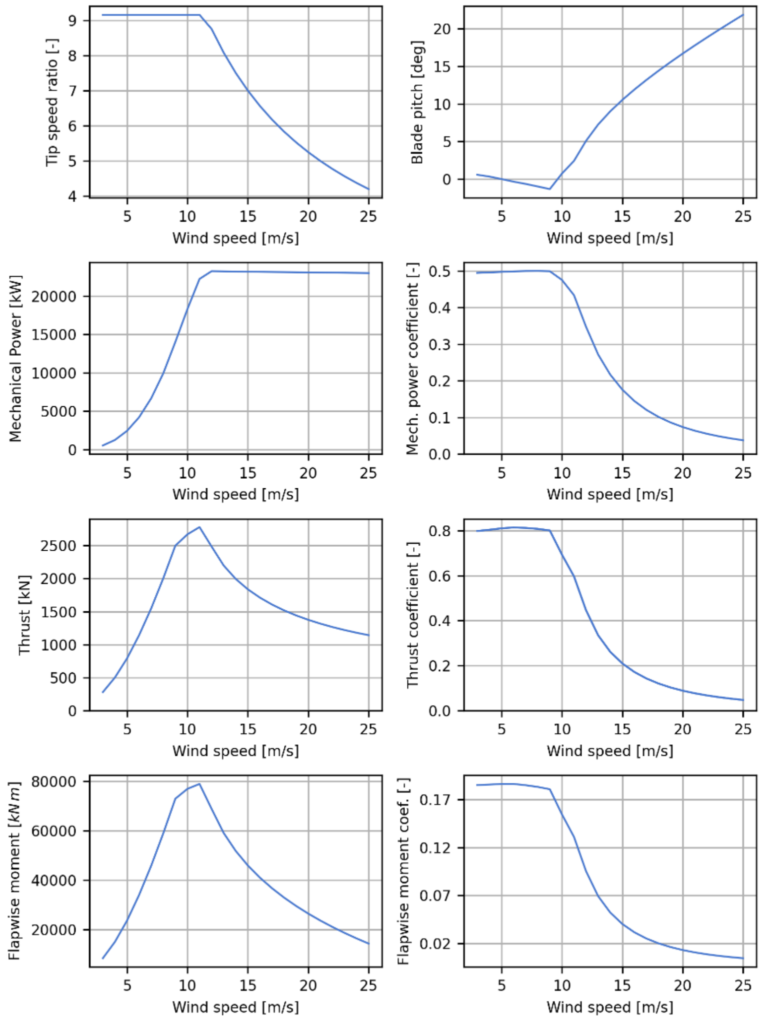


Steady-State Performance

- The turbine features a moderate peak shaving pitch ramp, which was the result of the optimization problem solved
- max(steady-state thrust) < 2900 kN
- max(steady-state blade root flapwise moment [MxBR]) < 80000 kN m
- Blade steady-state torsion constrained to not exceed −6 degrees
- Rotor performance will not be predicted correctly without consideration of deflection and torsion.



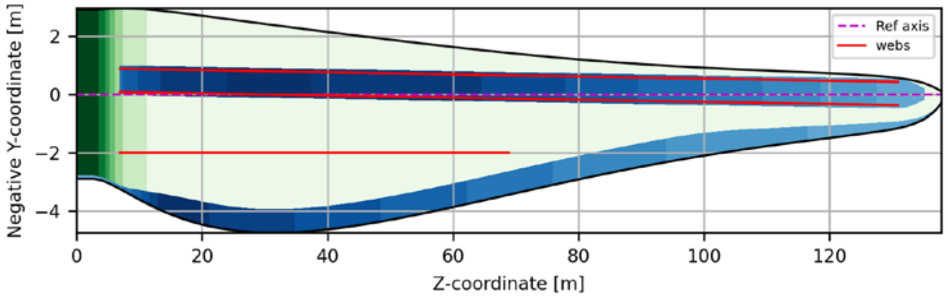


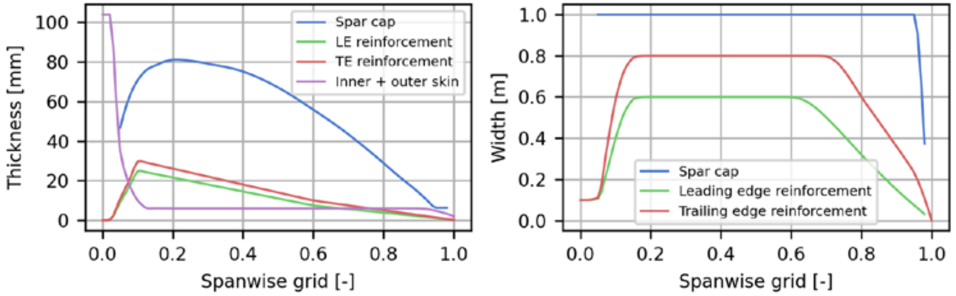


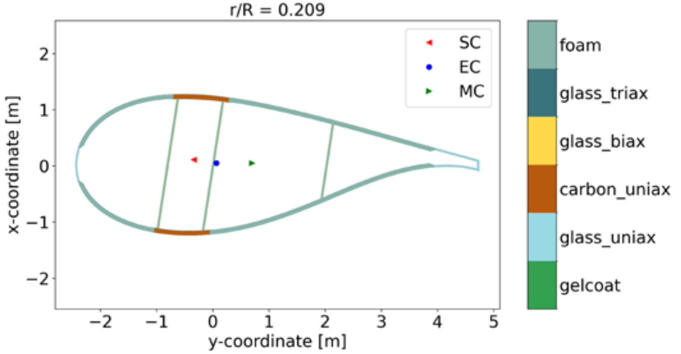
Structural Design

- The blade features a conventional layout with:
  - Carbon-based load carrying spar caps
  - Two main shear webs
  - Rear shear web on the blade inner part
- Materials based on the NREL/Sandia Big Adaptive Rotor [BAR] project (Camarena et al. 2022*)
- Total mass reduced significantly relatively to the IEA 15 MW in part due to higher modulus carbon and glass
- Stiffness properties defined based on BEam Cross section Analysis Software [BECAS] computations and a relatively simple meshing procedure
- This is a conceptual design, structural design not verified with 3D finite element analysis [FEA] (yet)

*https://doi.org/10.5194/wes-7-19-2022

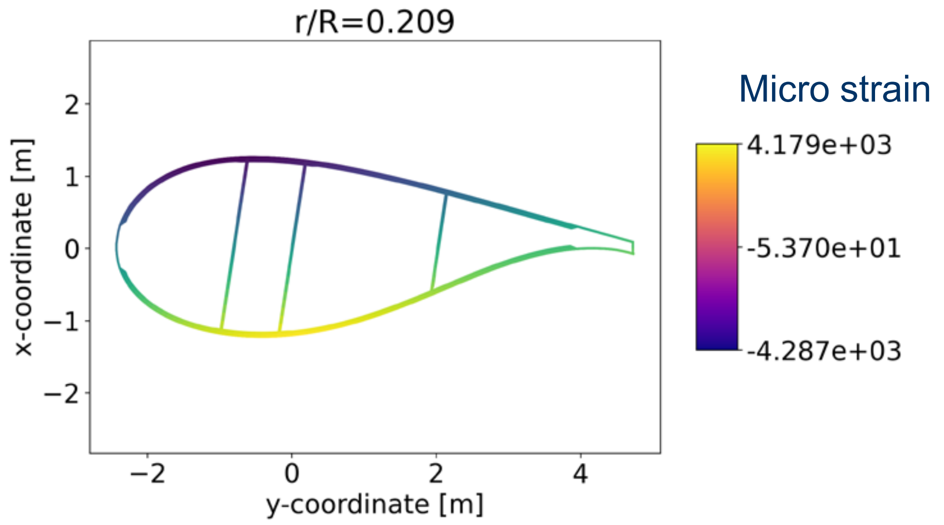


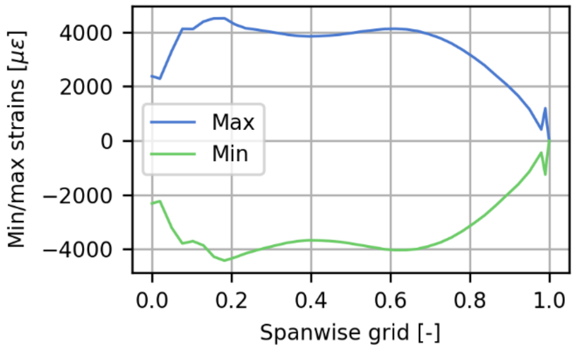


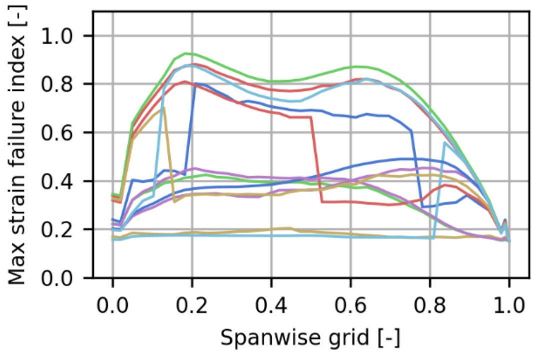


Strength Analysis

- Ultimate design material strength was evaluated based on the design load cases (DLCs) 1.2 and 1.3 computed with HAWC2
- Peak strains of ±4500με
- With a partial safety factor [PSF] of 2.205 this is within the design limits
- Fatigue at material level not evaluated
- Buckling capacity not evaluated



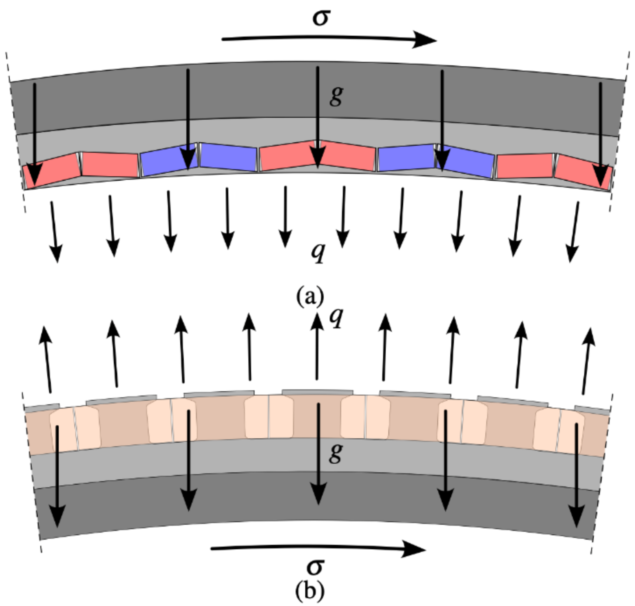




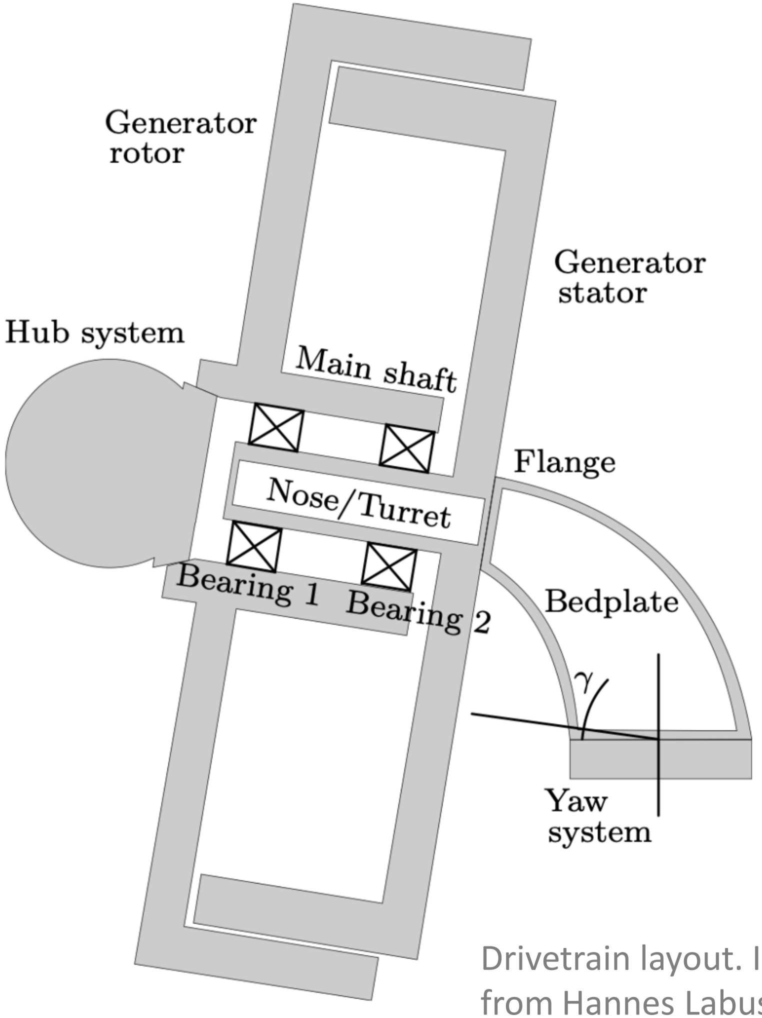
Drivetrain Design

Direct-drive configuration like IEA15:

- Generator—Outer rotor with interior permanent magnets, inner stator
- Two main bearings housed on a stationary turret
- Turret is cantilevered from the bedplate, which transfers loads to the yaw bearings



Illustrations of the loads acting on the generator's (a) rotor and (b) stator. Image from Hannes Labuschagne.



Drivetrain layout. Image from Hannes Labuschagne.

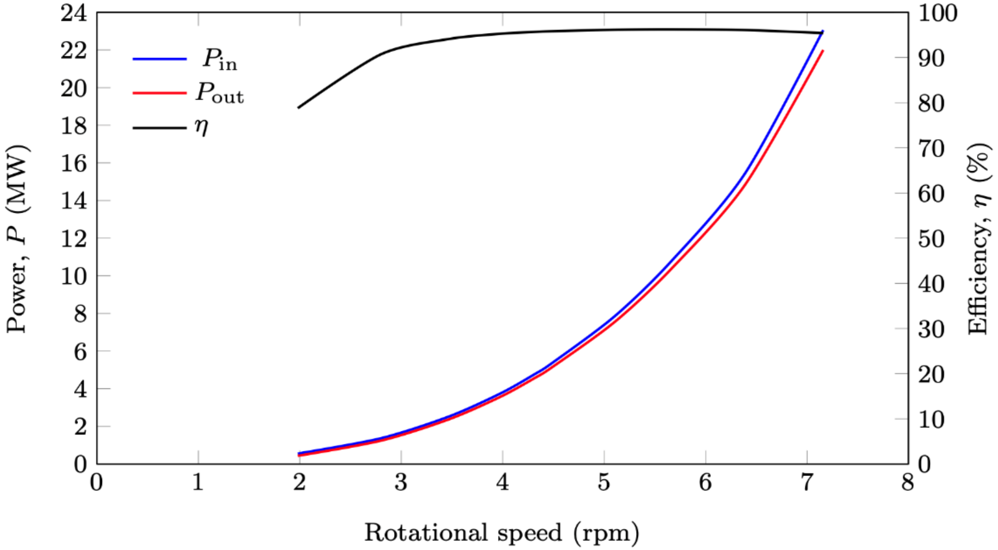
Design Process

Generator design performed with a combination of:

- Design optimization in mid-fidelity electromagnetic solver pyFEMM
- High-fidelity checks in Altair FLUX and Altair Hyperstudy, Ansys Mechanical, Ansys Workbench, and Solidworks
- NREL leveraged previous work described in DOI 10.1016/j.apenergy.2023.121272

Drivetrain components designed in low-fidelity Wind Plant Integrated Systems Design and Engineering Model's (WISDEM's) module DrivetrainSE

Drivetrain efficiency as a function of rotor speed. Image from Hannes Labuschagne. Efficiency at rated 95.3%



Masses

	Mass (t)	Share of Total Nacelle Mass (%)
Hub system	120	12.3%
Shaft	4	0.4%
Bearings	55	5.6%
Generator	508	51.9%
Turret	6	0.6%
Bedplate	75	7.7%
Break	39	4.0%
Converter and transformer	61	6.2%
Heating, ventilation, and air conditioning	13	1.3%
Platform and cover	59	6.0%
Yaw system	38	3.9%
Nacelle no hub no yaw	**821**	83.9%
Nacelle hub yaw	**978**	100%
Rotor nacelle assembly	**1216**	

Fixed-Bottom Tower and Monopile

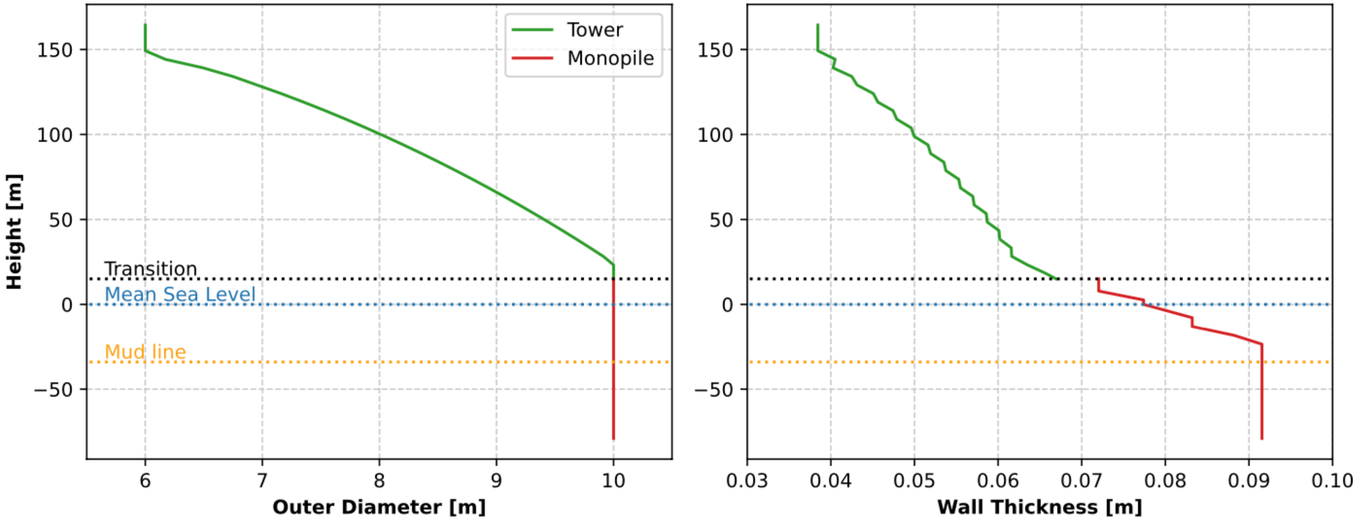
Tower	Quantity	Monopile	Quantity
Hub height	170 m	Water depth	34 m
Vertical distance tower top to rotor apex	5.614 m	Length in seabed	45 m
Tower start above mean sea level	15 m	Total monopile length	94 m
Tower length	149.386 m	Mass transition piece	100 t
Blade clearance to mean sea level	~30 m		

Tower and Monopile Design Process

We designed tower and monopile in WISDEM with steady state loads:

- Max outer diameter 10 m (we later received feedback that 9 m is max state of the art)
- Max stress and buckling constraints
- Diameter-to-thickness ratios between 80 and 160
- Monotonically decreasing wall thickness
- Minimum frequency of 0.15 Hz

Tower mass: 1,574 t
Monopile mass: 2,097 t

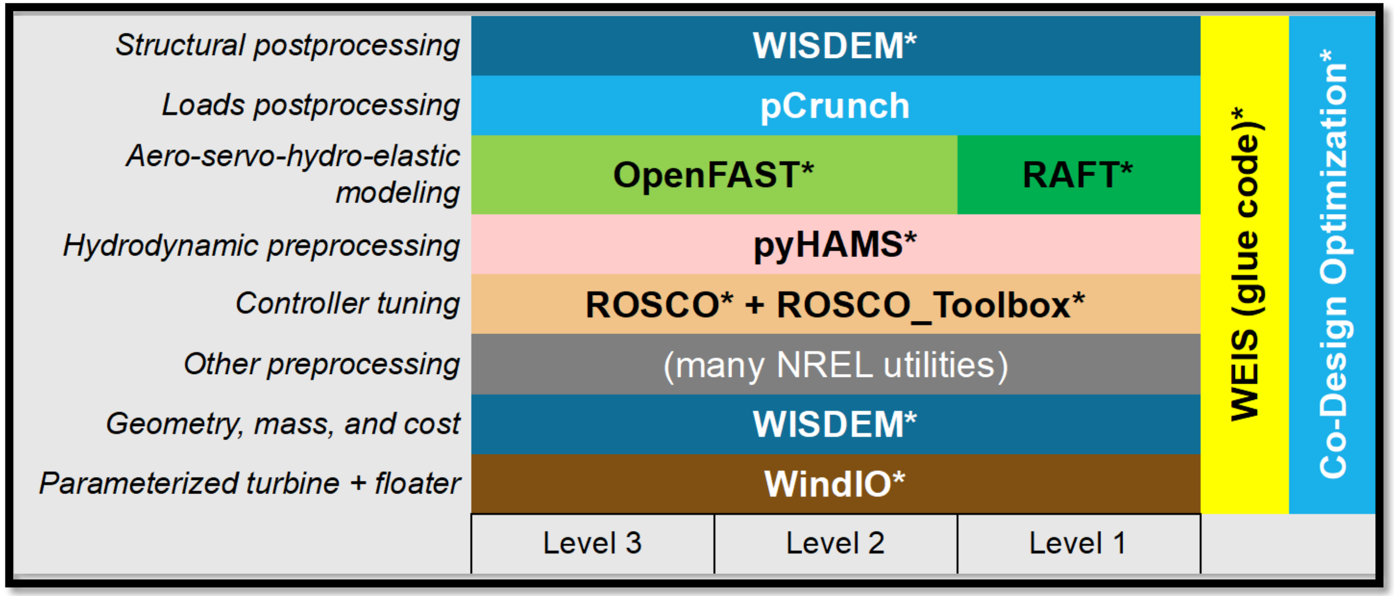


Mode	1	2	3
Fore-aft	0.16 Hz	0.82 Hz	1.70 Hz
Side-side	0.16 Hz	0.74 Hz	1.61 Hz
Torsion	4.72 Hz	-	-

Floater Design—Modeling

WISDEM/WEIS design environment

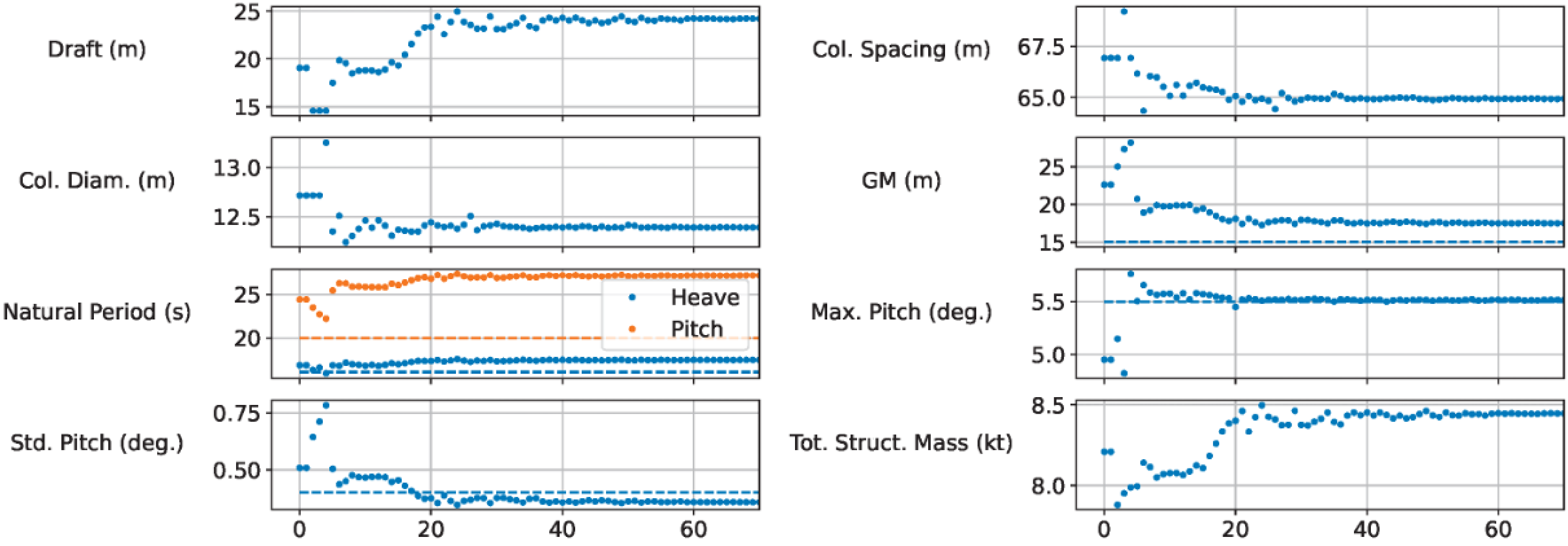
- WISDEM for geometry, ballasting, related constraints
- RAFT for dynamics, maximum pitch angle calculation
- OpenFAST for verification of dynamics



	Level 3	Level 2	Level 1
Structural postprocessing	**WISDEM***		
Loads postprocessing	**pCrunch**		
Aero-servo-hydro-elastic modeling	**OpenFAST***		**RAFT***
Hydrodynamic preprocessing	**pyHAMS***		
Controller tuning	**ROSCO* + ROSCO_Toolbox***		
Other preprocessing	(many NREL utilities)		
Geometry, mass, and cost	**WISDEM***		
Parameterized turbine + floater	**WindIO***		

WEIS: Wind Energy with Integrated Servo-control;
RAFT: Response Amplitudes of Floating Turbines;
ROSCO: Reference Open-Source Controller

Platform Design Optimization

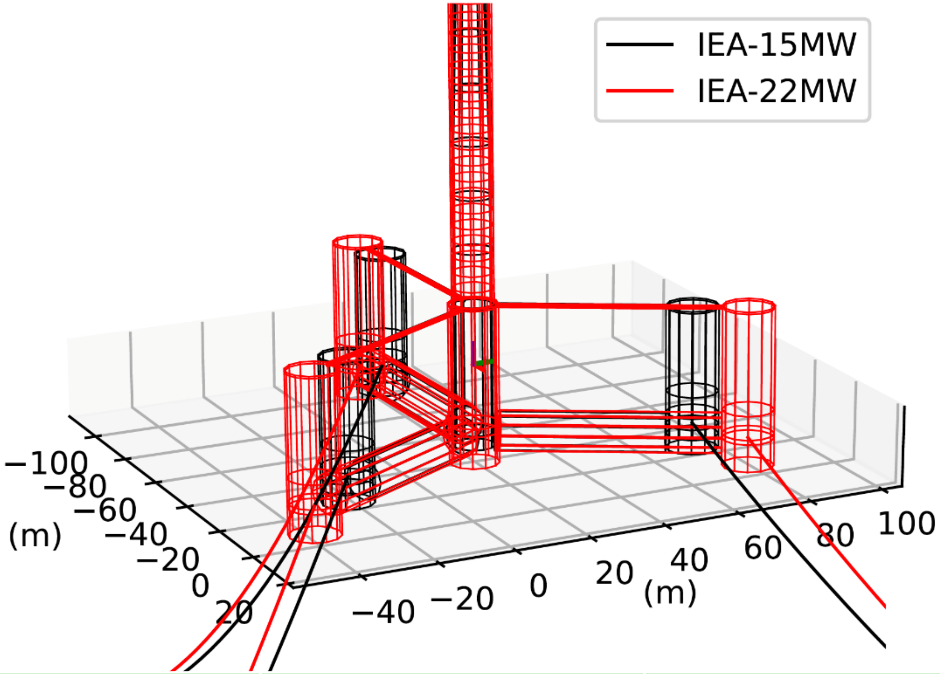


Col. = Column
GM = Metacentric height
Std. = Standard deviation

Semi-Sub Platform Design Variables

Design Variable	IEA-22	IEA-15
Draft	25 m	20 m
Freeboard	15 m	15 m
Column spacing	65 m	51.8 m
Column diameter	12.5 m	12.5 m
Pontoon diameter	10.0 m	9.6 m

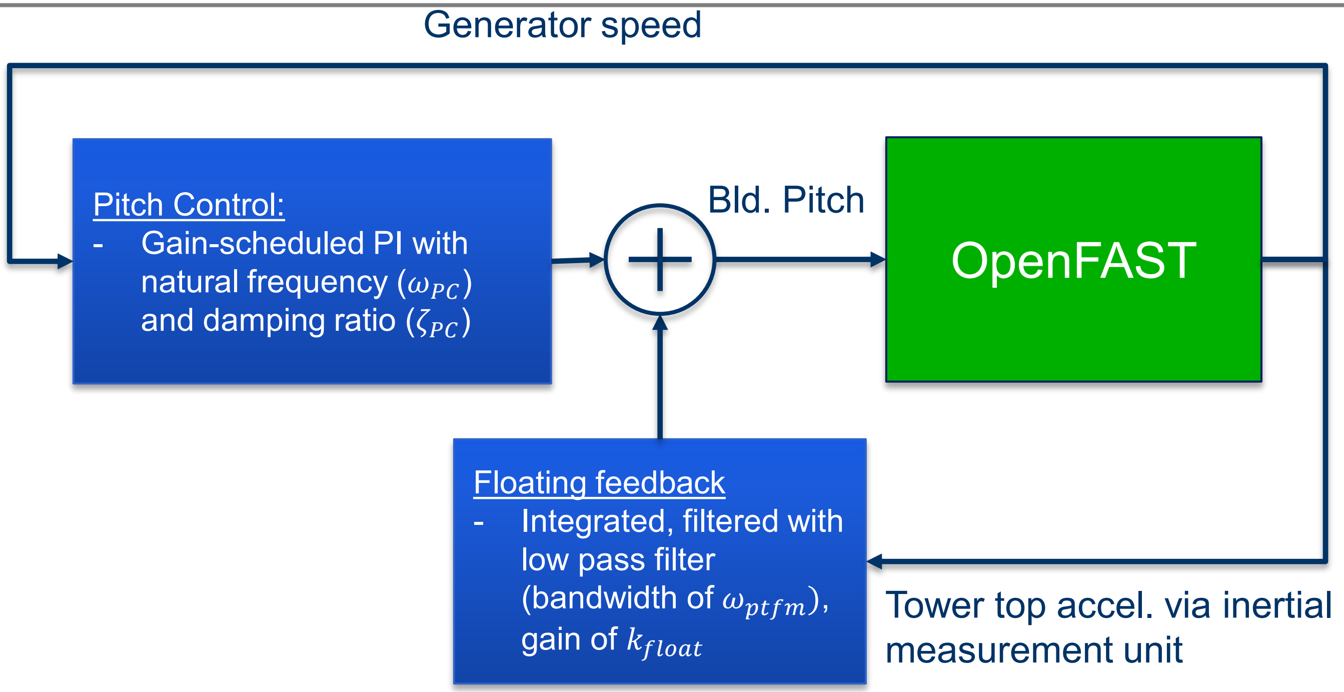
Mass	IEA22	IEA15
Hull mass	5710 t	4014 t
Slurry mass	0 t	2540 t
Sea water mass	15454 t	8439 t
Total mass	21165 t	14993 t
Platform center of gravity	-15.25 m	-12.9 m



Natural Period	IEA22	IEA15
Surge/sway	123 s	114.4 s
Heave	17 s	12.8 s
Pitch/roll	27 s	25.9 s
Yaw	86 s	76.6 s

Reference Open-Source Controller (ROSCO) Optimization

- Geometry
  - IEA-22 MW turbine with optimized platform
- Optimization
  - Design Variables
    - Pitch control bandwidth (ω_{PC}), damping (ζ_{PC}) at various wind speeds
    - Floating feedback gain (k_{float}) and filter bandwidth (ω_{ptfm})
  - Constraints
    - Generator overspeed
  - Merit Figure: Tower base damage equivalent loads
- Modeling
  - OpenFAST with DLC 1.1 (Gulf of Maine metocean conditions)



Generator speed

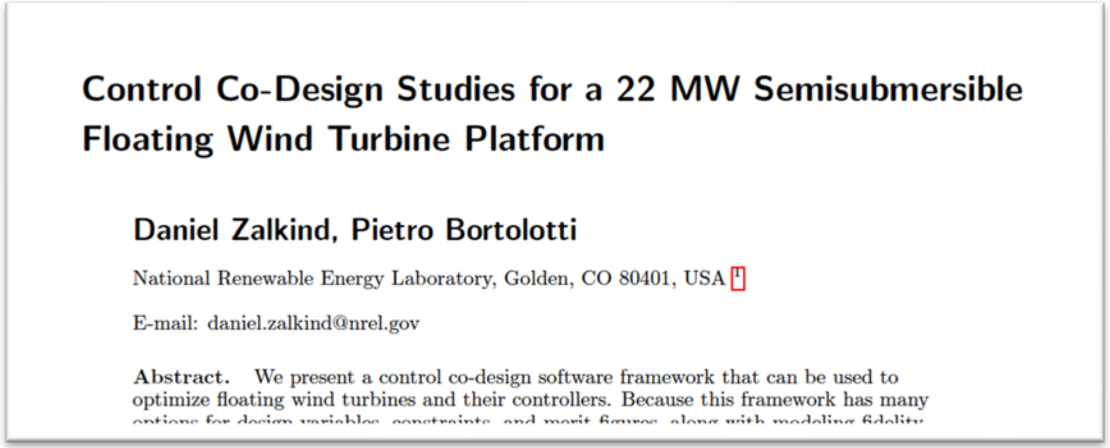
Pitch Control:
- Gain-scheduled PI with natural frequency (ω_{PC}) and damping ratio (ζ_{PC})

Bld. Pitch

OpenFAST

Floating feedback
- Integrated, filtered with low pass filter (bandwidth of ω_{ptfm}), gain of k_{float}

Tower top accel. via inertial measurement unit



Control Co-Design Studies for a 22 MW Semisubmersible Floating Wind Turbine Platform

Daniel Zalkind, Pietro Bortolotti

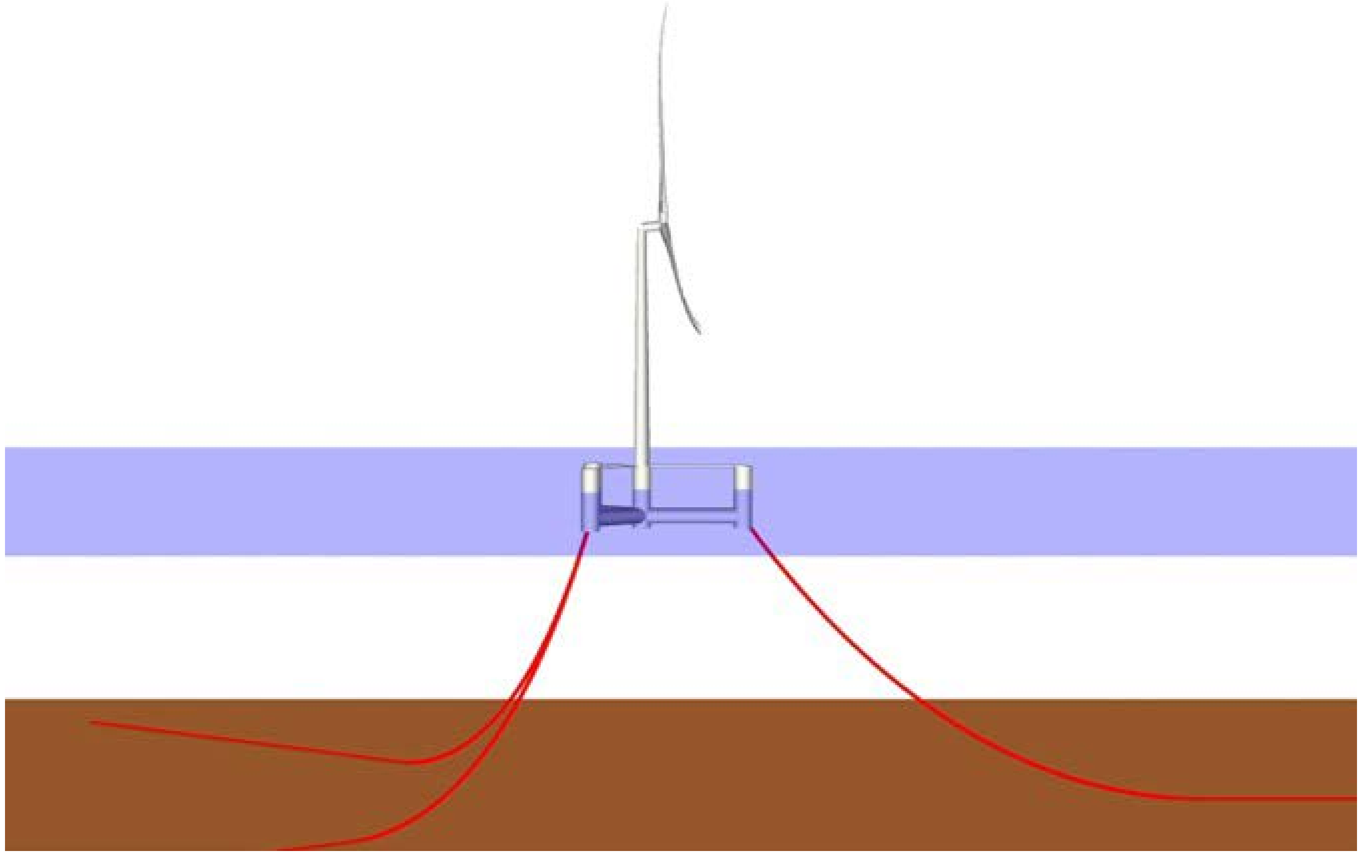
National Renewable Energy Laboratory, Golden, CO 80401, USA

E-mail: daniel.zalkind@nrel.gov

Abstract. We present a control co-design software framework that can be used to optimize floating wind turbines and their controllers. Because this framework has many

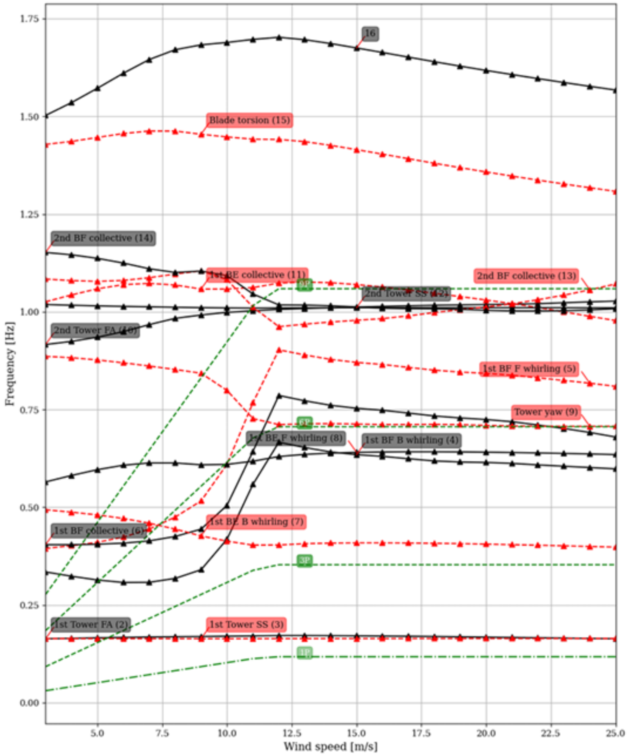
HAWCStab2/HAWC2 Model

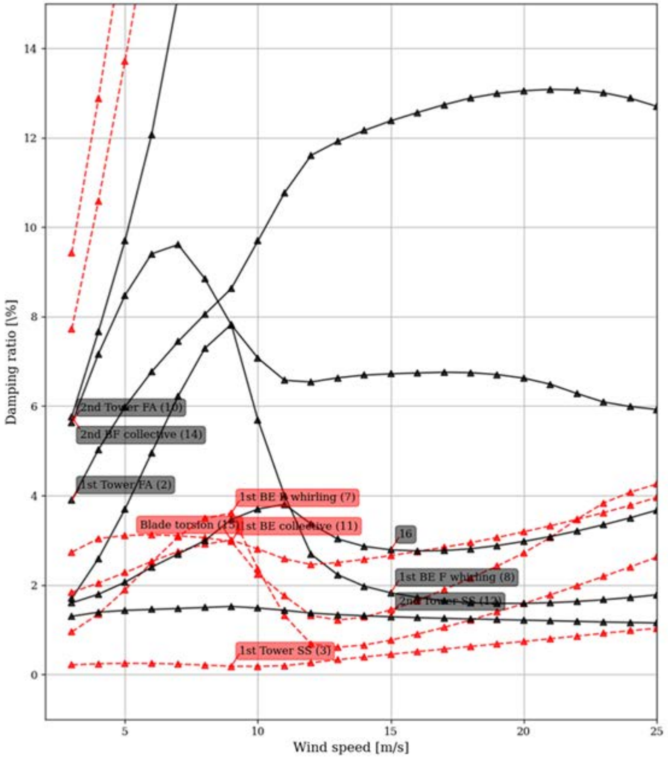
- Developed by Thanasis Barlas (DTU)
- Model setup
  - Two configurations: monopile and floating
  - Stiff bodies with concentrated masses (tower top, connector, shaft, hub)
  - Timoshenko linear beam (monopile, tower)
  - Multi-body with Timoshenko linear beams (blades)
  - No soil
  - DTU Wind Energy Controller (pole at 0.01-0.03 Hz, tower top velocity feedback)
  - Floater model setup (stiff with lumped properties, ESYS), WAMIT, ESYS mooring, hydro drag elements

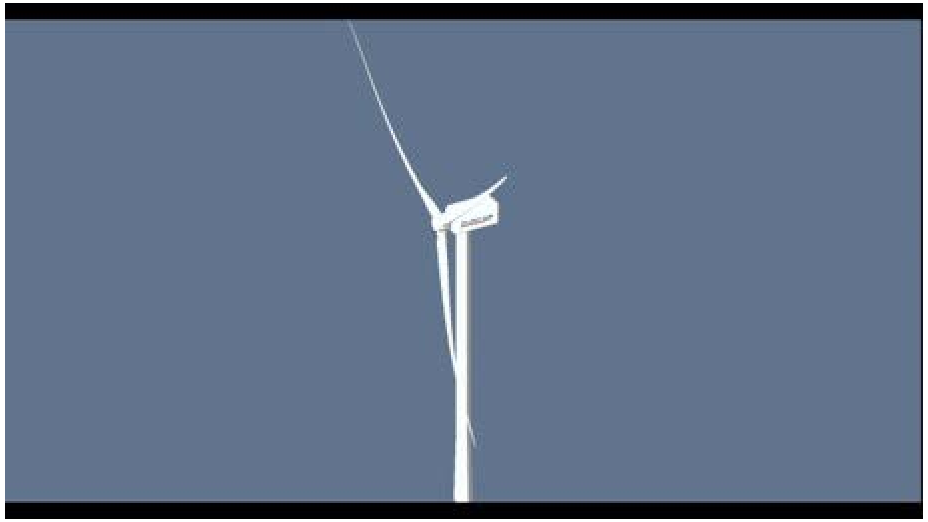


HAWCStab2

- Structural damping tuning (0.5% 1st flap/edge, 2% 1st torsion, 0.5% 1st tower/monopile fore-aft / side - side)
- Aeroelastic modal analysis (unsteady airfoil aerodynamics, dynamic inflow)
- All stable, lowest damping tower S-S
- Controller tuning (pole at 0.01-0.05 Hz, 0.7 damping)



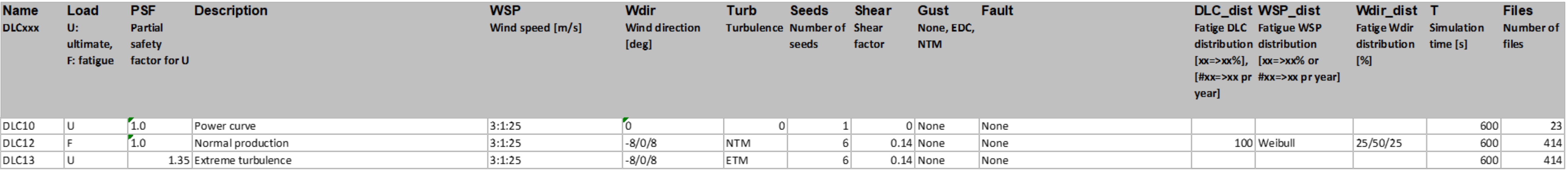




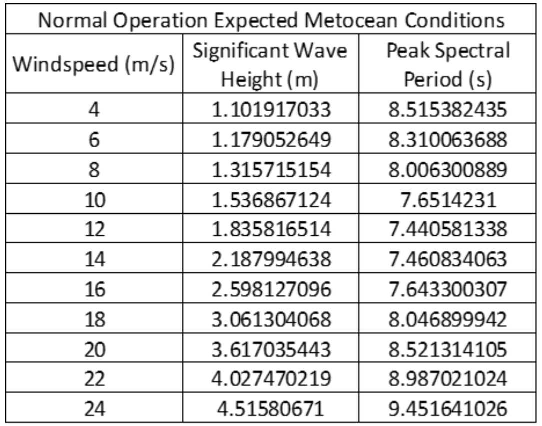
1st backwards whirling edge mode

Design Loads

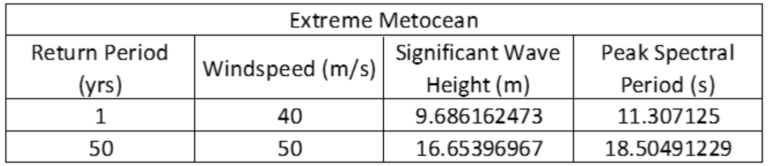
- Design load basis setup
- Simple Design Load Cases (DLC), no wind-wave misalignment



Name DLCxxx	**Load** U: ultimate, F: fatigue	**PSF** Partial safety factor for U	**Description**	**WSP** Wind speed [m/s]	**Wdir** Wind direction [deg]	**Turb** Turbulence	**Seeds** Number of seeds	**Shear** Shear factor	**Gust** None, EDC, NTM	**Fault**	**DLC_dist** Fatige DLC distribution [xx=>xx%], [#xx=>xx pr year]	**WSP_dist** Fatigue WSP distribution [xx=>xx% or #xx=>xx pr year]	**Wdir_dist** Fatige Wdir distribution [%]	**T** Simulation time [s]	**Files** Number of files
DLC10	U	1.0	Power curve	3:1:25	0	0	1	0	None	None				600	23
DLC12	F	1.0	Normal production	3:1:25	-8/0/8	NTM	6	0.14	None	None	100	Weibull	25/50/25	600	414
DLC13	U	1.35	Extreme turbulence	3:1:25	-8/0/8	ETM	6	0.14	None	None				600	414



Normal Operation Expected Metocean Conditions		
Windspeed (m/s)	Significant Wave Height (m)	Peak Spectral Period (s)
4	1.101917033	8.515382435
6	1.179052649	8.310063688
8	1.315715154	8.006300889
10	1.536867124	7.6514231
12	1.835816514	7.440581338
14	2.187994638	7.460834063
16	2.598127096	7.643300307
18	3.061304068	8.046899942
20	3.617035443	8.521314105
22	4.027470219	8.987021024
24	4.51580671	9.451641026



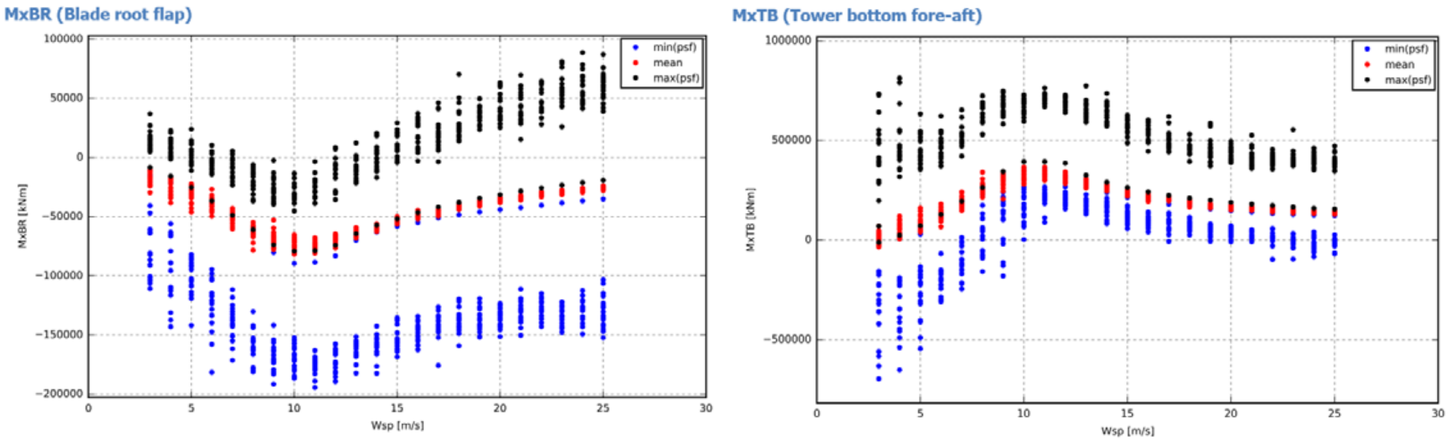
Extreme Metocean			
Return Period (yrs)	Windspeed (m/s)	Significant Wave Height (m)	Peak Spectral Period (s)
1	40	9.686162473	11.307125
50	50	16.65396967	18.50491229

Hansen MH, Thomsen K, Natarajan A, Barlas A. Design Load Basis for onshore turbines - Revision 00. DTU Wind Energy, 2015. 20 p. (DTU Wind Energy E; No. 0074(EN)).
Natarajan A, Hansen MH, Wang S. Design Load Basis for Offshore Wind turbines: DTU Wind Energy Report No. E-0133. 2016. 32 p.
Stewart, G. M., Robertson, A., Jonkman, J., & Lackner, M. A. (2016). The creation of a comprehensive metocean data set for offshore wind turbine simulations. Wind Energy, 19(6), 1151–1159. https://doi.org/10.1002/we.1881

Design Loads

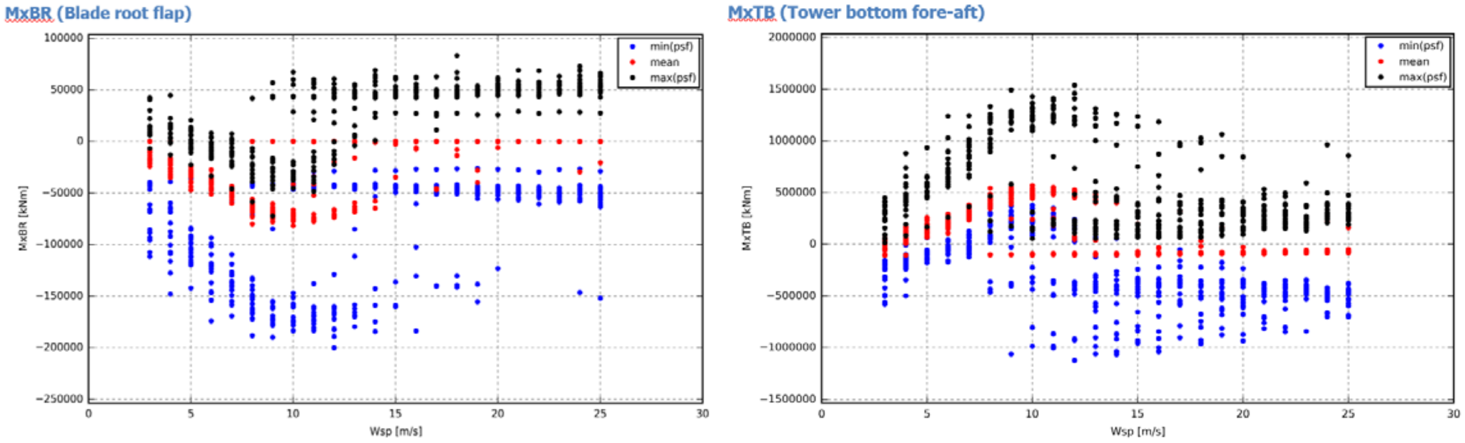
- Design loads computed for both fixed-bottom and floating platform,
- So far for DLC 1.2, DLC 1.3
- HAWC2 results comparing bottom-fixed and floating:
  - Comparable
  - Significantly higher tower bottom fore-aft (MxTB) in floating configuration
- Work in progress to align design loads predictions across aero-elastic toolchains

Bottom-fixed


MxBR (Blade root flap)

MxTB (Tower bottom fore-aft)

Floating


MxBR (Blade root flap)

MxTB (Tower bottom fore-aft)

Aeroelastic Code Comparison

Code comparison study

- Bladed, HAWC2, OpenFAST, QBlade
- Offshore monopile model

Why code comparison?

- Evaluate tool consistency/uncertainty
- Expose differences for further study
- Provide aligned models to community
- Baseline result set for other tools to compare

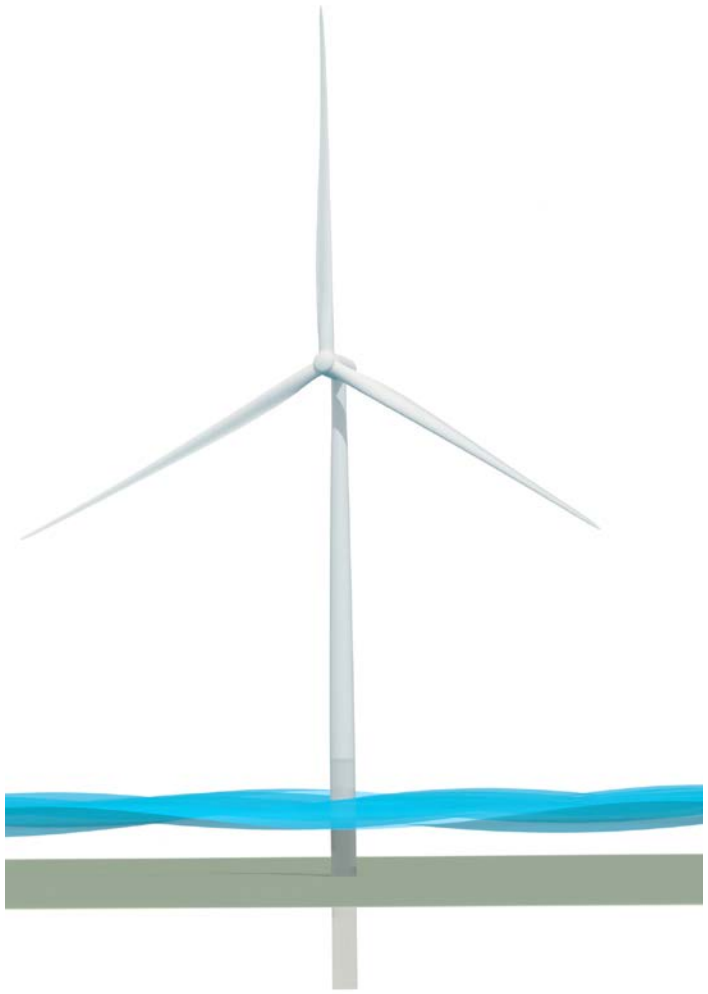
BLADED

HAWC2

OpenFAST

NREL Transforming ENERGY

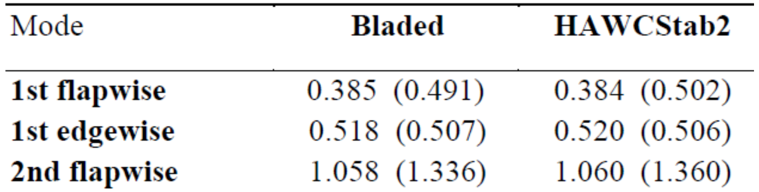
QBlade



Aeroelastic Code Comparison

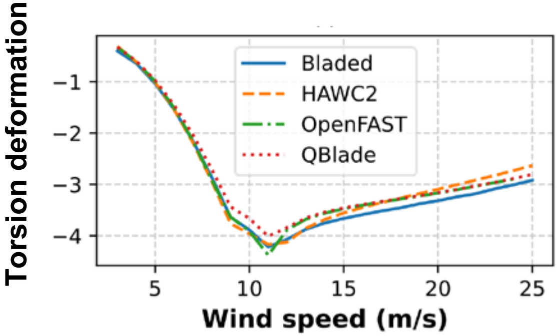
Comparison types

Masses and frequncies

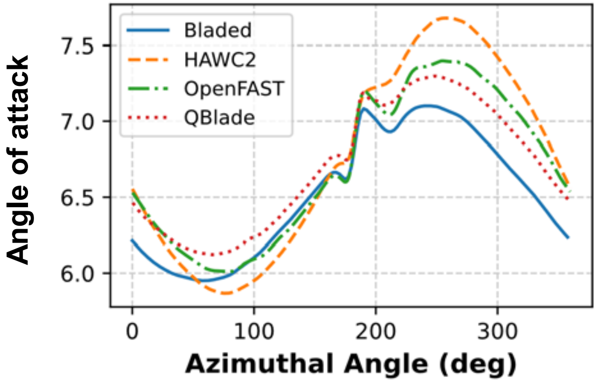


Mode	Bladed	HAWCStab2
1st flapwise	0.385 (0.491)	0.384 (0.502)
1st edgewise	0.518 (0.507)	0.520 (0.506)
2nd flapwise	1.058 (1.336)	1.060 (1.360)

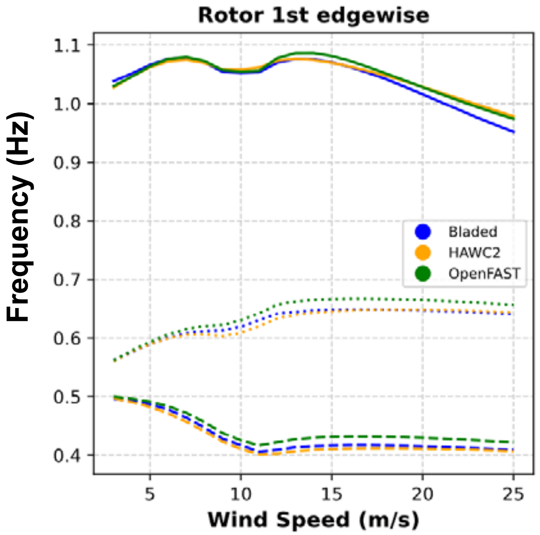
Steady state



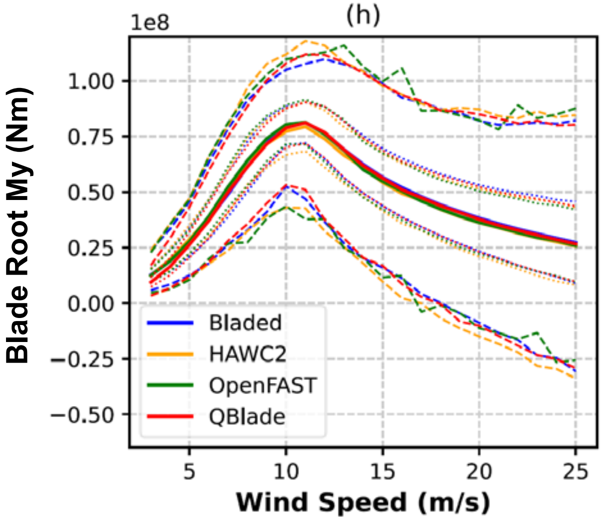
Azimuthal variation



Linear stability

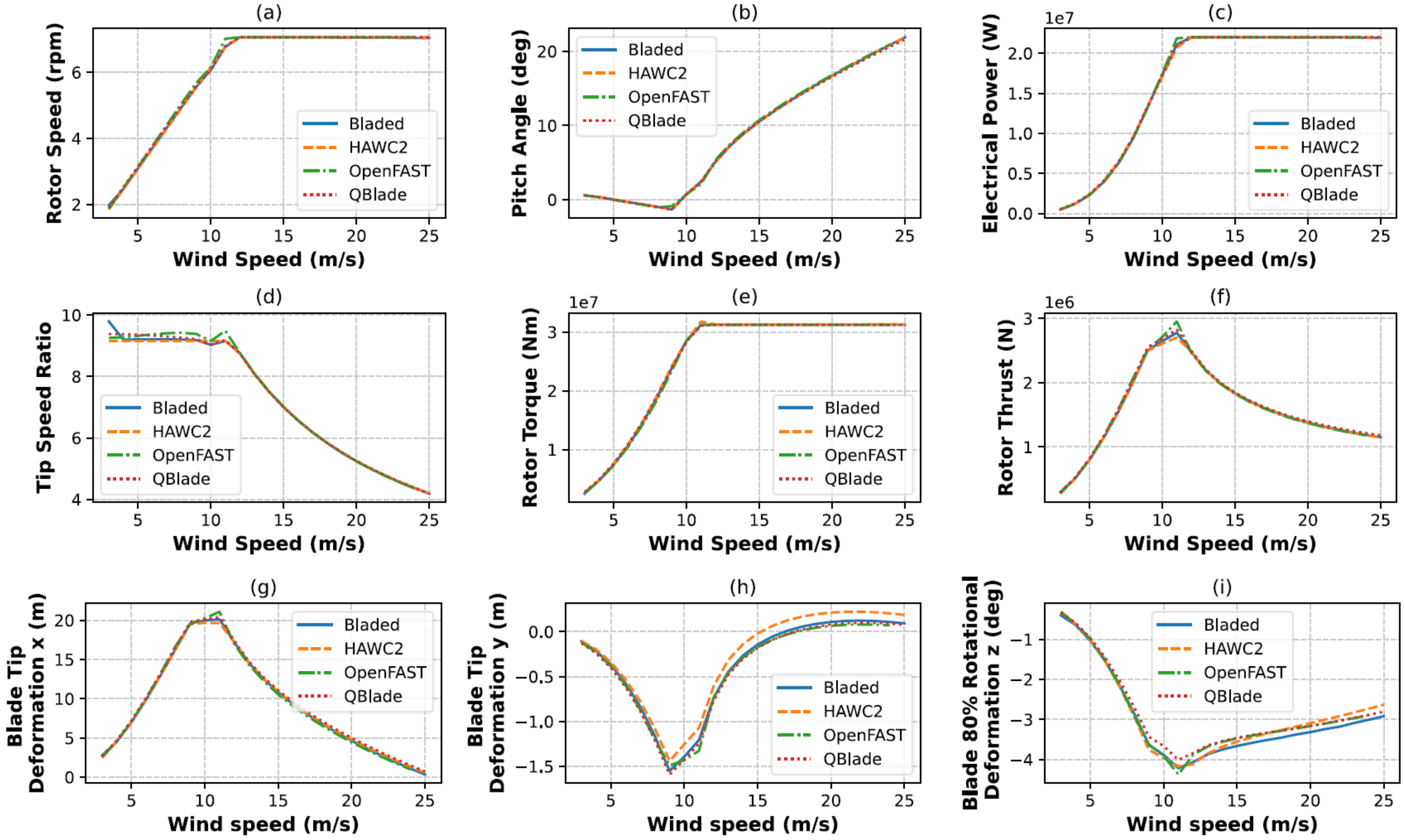


Time domain



Aeroelastic Code Comparison

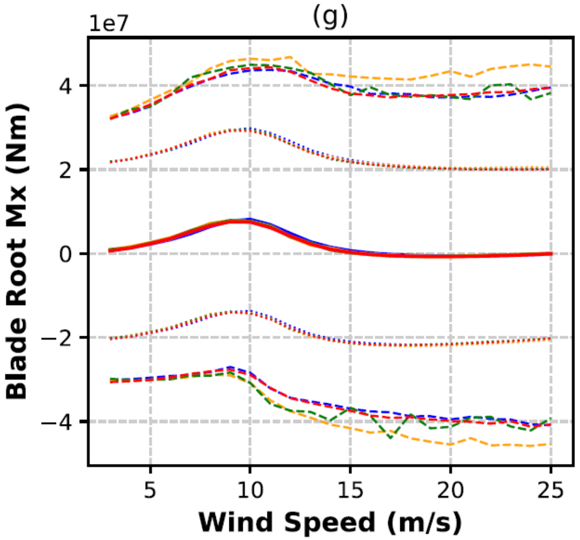
Steady state

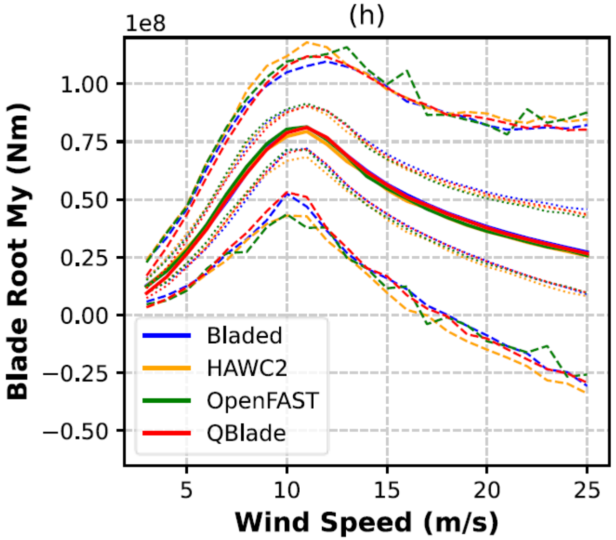


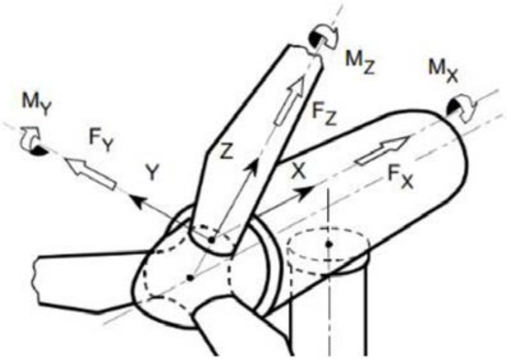
Aeroelastic Code Comparison

Time domain

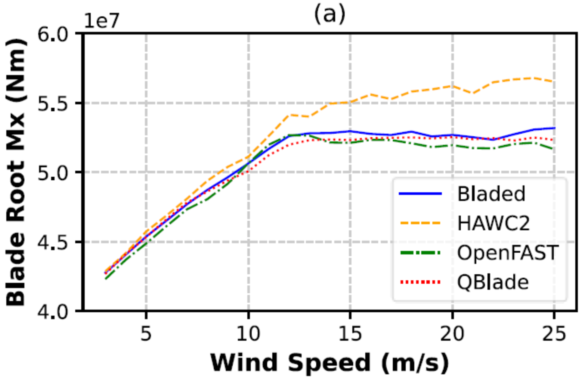
Statistics

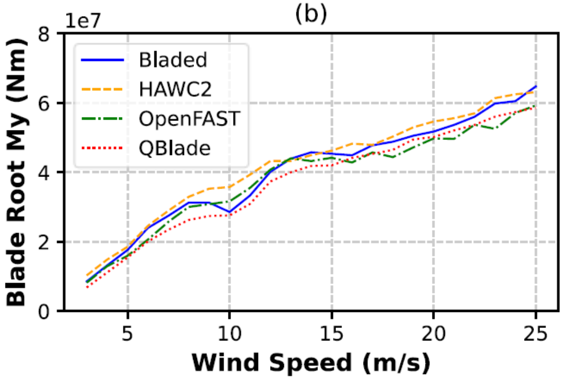






DELs





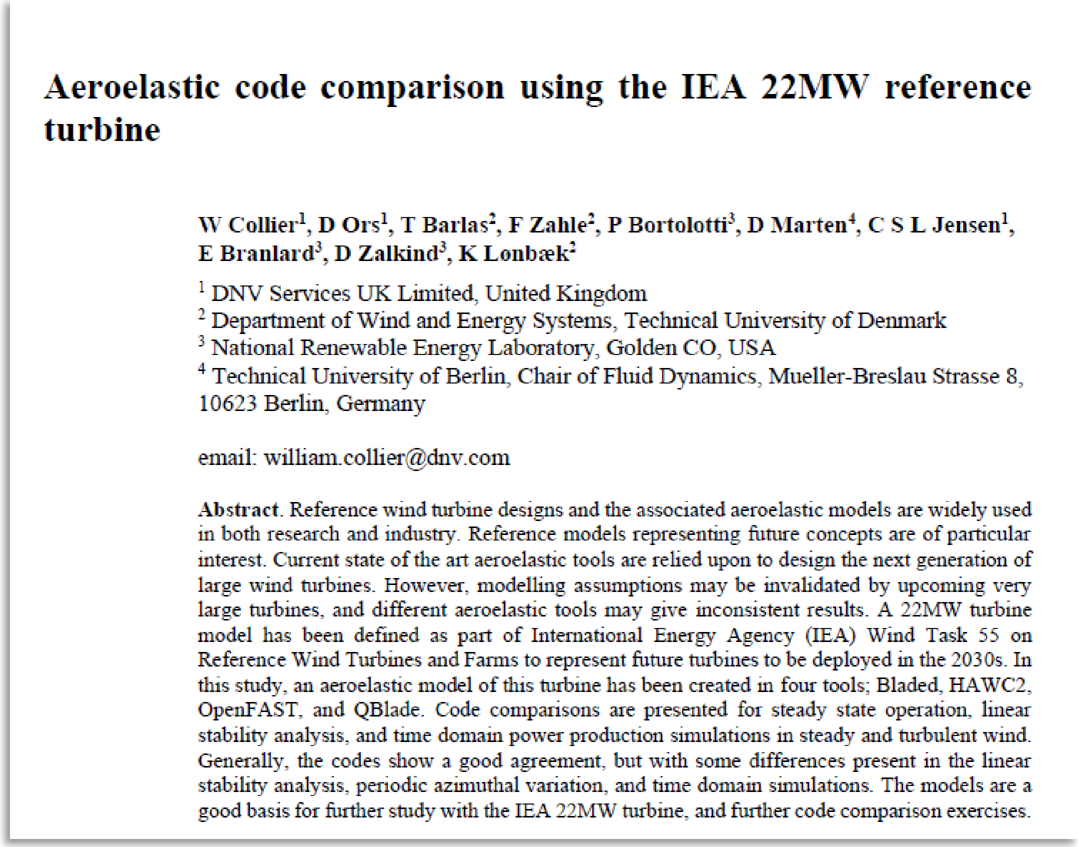
Aeroelastic Code Comparison

Study conclusions

Steady state aligned very well

Dynamic cases agree but some differences

- Azimuthal variation
- Stability analysis
- Time domain



Aeroelastic code comparison using the IEA 22MW reference turbine

W Collier[1], D Ors[1], T Barlas[2], F Zahle[2], P Bortolotti[3], D Marten[4], C S L Jensen[1], E Branlard[3], D Zalkind[3], K Lønbæk[2]

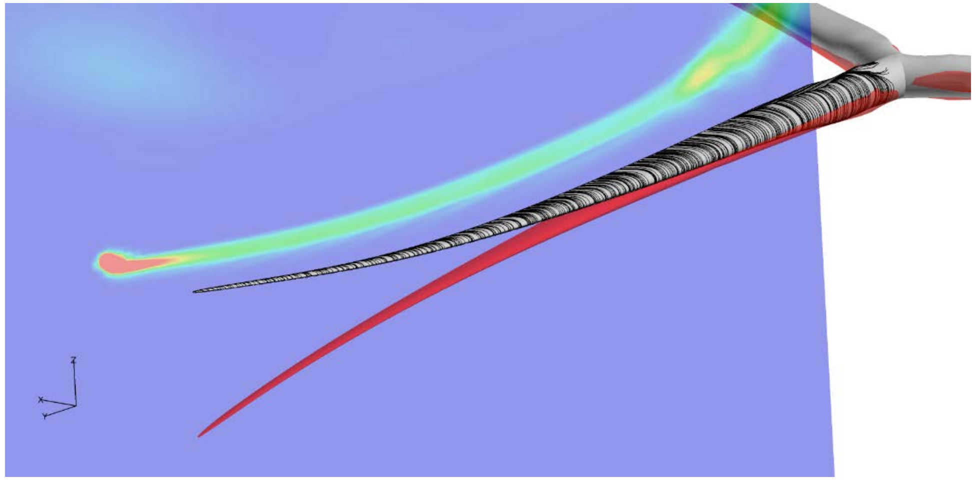
[1] DNV Services UK Limited, United Kingdom
[2] Department of Wind and Energy Systems, Technical University of Denmark
[3] National Renewable Energy Laboratory, Golden CO, USA
[4] Technical University of Berlin, Chair of Fluid Dynamics, Mueller-Breslau Strasse 8, 10623 Berlin, Germany

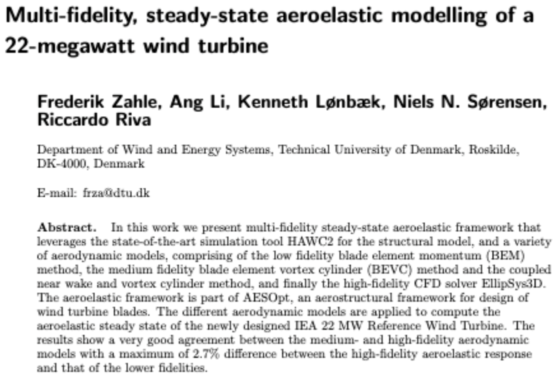
email: william.collier@dnv.com

Abstract. Reference wind turbine designs and the associated aeroelastic models are widely used in both research and industry. Reference models representing future concepts are of particular interest. Current state of the art aeroelastic tools are relied upon to design the next generation of large wind turbines. However, modelling assumptions may be invalidated by upcoming very large turbines, and different aeroelastic tools may give inconsistent results. A 22MW turbine model has been defined as part of International Energy Agency (IEA) Wind Task 55 on Reference Wind Turbines and Farms to represent future turbines to be deployed in the 2030s. In this study, an aeroelastic model of this turbine has been created in four tools; Bladed, HAWC2, OpenFAST, and QBlade. Code comparisons are presented for steady state operation, linear stability analysis, and time domain power production simulations in steady and turbulent wind. Generally, the codes show a good agreement, but with some differences present in the linear stability analysis, periodic azimuthal variation, and time domain simulations. The models are a good basis for further study with the IEA 22MW turbine, and further code comparison exercises.

High-Fidelity Aeroelastic Modeling

- A multi-fidelity aeroelastic modeling study has been carried out on the IEA 22 MW RWT using the CFD solver EllipSys3D and blade element theory coupled to HAWC2.





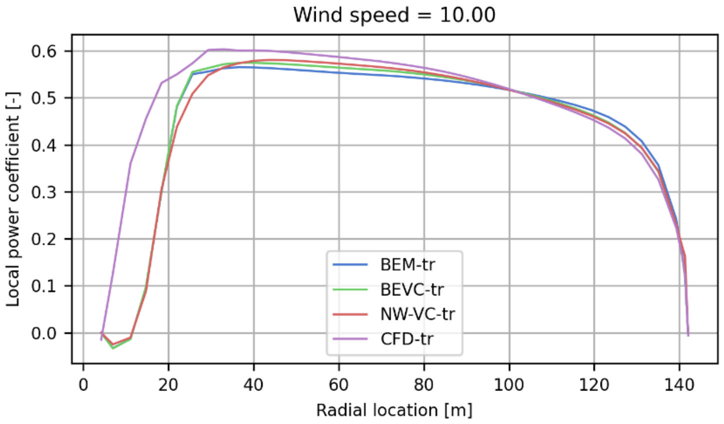
Multi-fidelity, steady-state aeroelastic modelling of a 22-megawatt wind turbine

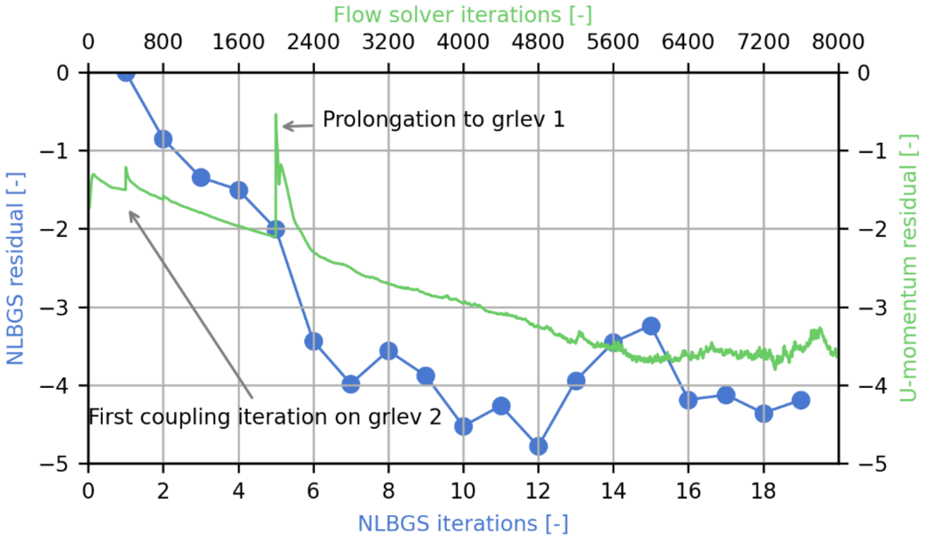
Frederik Zahle, Ang Li, Kenneth Lønbæk, Niels N. Sørensen, Riccardo Riva

Department of Wind and Energy Systems, Technical University of Denmark, Roskilde, DK-4000, Denmark

E-mail: frza@dtu.dk

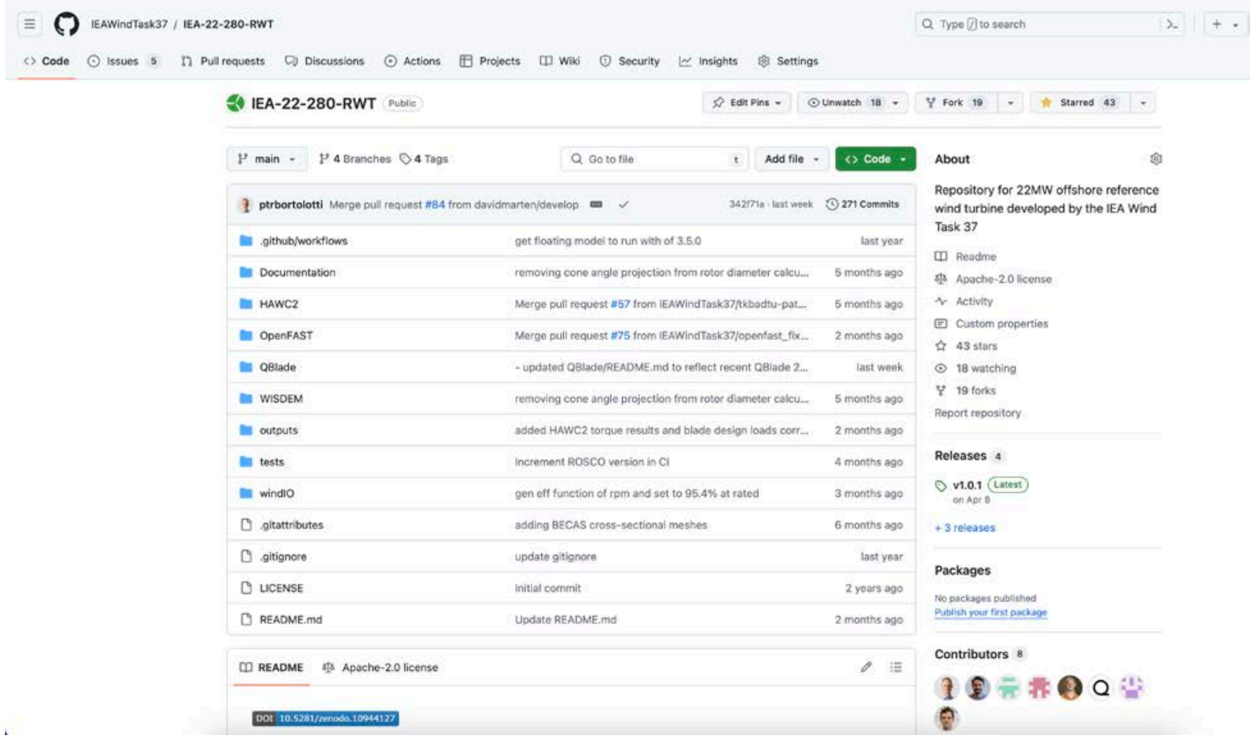
Abstract. In this work we present multi-fidelity steady-state aeroelastic framework that leverages the state-of-the-art simulation tool HAWC2 for the structural model, and a variety of aerodynamic models, comprising of the low fidelity blade element momentum (BEM) method, the medium fidelity blade element vortex cylinder (BEVC) method and the coupled near wake and vortex cylinder method, and finally the high-fidelity CFD solver EllipSys3D. The aeroelastic framework is part of AESOpt, an aerostructural framework for design of wind turbine blades. The different aerodynamic models are applied to compute the aeroelastic steady state of the newly designed IEA 22 MW Reference Wind Turbine. The results show a very good agreement between the medium- and high-fidelity aerodynamic models with a maximum of 2.7% difference between the high-fidelity aeroelastic response and that of the lower fidelities.





Availability

- The definition of the turbine is maintained on GitHub:
- https://github.com/IEAWindTask37/IEA-22-280-RWT
- Use GitHub to report issues.
- Updates and bugfixes will be pushed to this repository.



ptrbortolotti Merge pull request #84 from davidmarten/develop ✓ 342f71a · last week 271 Commits

.github/workflows	get floating model to run with of 3.5.0	last year
Documentation	removing cone angle projection from rotor diameter calcu...	5 months ago
HAWC2	Merge pull request #57 from IEAWindTask37/tkbadtu-pat...	5 months ago
OpenFAST	Merge pull request #75 from IEAWindTask37/openfast_fix...	2 months ago
QBlade	- updated QBlade/README.md to reflect recent QBlade 2...	last week
WISDEM	removing cone angle projection from rotor diameter calcu...	5 months ago
outputs	added HAWC2 torque results and blade design loads corr...	2 months ago
tests	Increment ROSCO version in CI	4 months ago
windIO	gen eff function of rpm and set to 95.4% at rated	3 months ago
.gitattributes	adding BECAS cross-sectional meshes	6 months ago
.gitignore	update gitignore	last year
LICENSE	Initial commit	2 years ago
README.md	Update README.md	2 months ago

About

Repository for 22MW offshore reference wind turbine developed by the IEA Wind Task 37

Readme
Apache-2.0 license
Activity
Custom properties
43 stars
18 watching
19 forks
Report repository

Releases 4

v1.0.1 Latest
on Apr 8

+ 3 releases

Packages

No packages published
Publish your first package

Contributors 8

What’s Next With This Design?

- The tower is too light for floating; we need to redesign it.
- The monopile-top and the tower outer diameters of 10 m are beyond what’s technically possible today; 9 m would be more realistic.
- The interpolation of airfoils at blade root creates non-smooth shapes; revised root airfoils are needed.
- A full 3D finite element structural model of the blade is under development, which will likely result in updates to the structural design.
- 3D computational fluid dynamics-ready geometry and meshes will be made available.

What's Next With IEA Wind Task 55 REFWIND?

- Reference offshore wind farm made of 22 MW wind turbines
- New reference land-based wind turbines

This work was authored [in part] by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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