How to Flip a GE1.5 Wind Turbine from Upwind to Downwind

Don't try this at home

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NAWEA/WindTech 2023 Conference

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Agenda

- Why (and why not) downwind?
- Goal of the experiment
- Failure modes and effects analysis (FMEA)
- Loads and deflection analysis in OpenFAST
- Test plan
- Next steps

Why Downwind?

Most wind turbines fly upwind rotors

However, downwind is a recurring R&D theme:

- ~~Reduction in capital expenditures (CapEx)~~
- Increase in ~~turbine~~ and/or farm annual energy production (AEP)
- Advantages in floating wind applications

?

CapEx of Land-Based Downwind

Why CapEx could go down:

✓ Relaxed constraint of blade/tower clearance allows for more flexible and lighter blades

✓ Smaller swept area reduces aero thrust

Why CapEx might NOT go down (substantially):

× Blades spring back during shut down

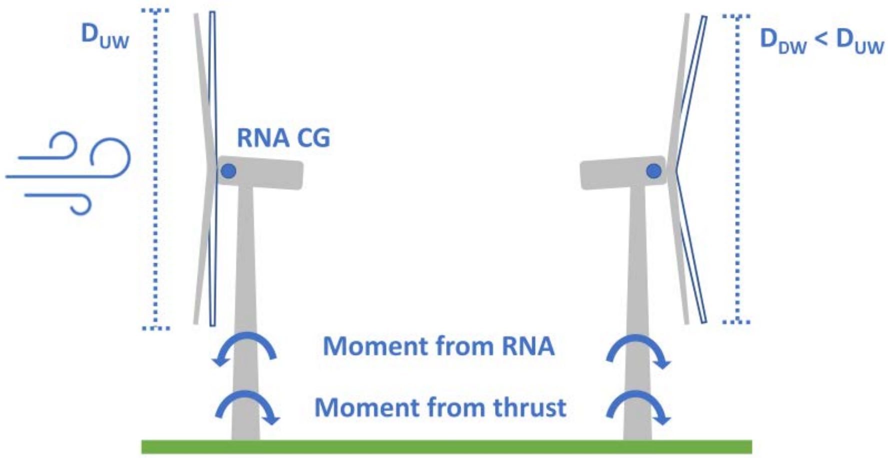
× Without a redesign of the nacelle, the center of gravity (CG) of the rotor nacelle assembly (RNA) generates a gravity moment at tower top that adds to the aero thrust

Mixed trends, which don't support a radical change in platform design
Look at DOI: 10.1002/we.2676 for a detailed discussion

Turbine AEP of Land-Based Downwind

Turbine AEP:

- Generally reduced because of reduced swept area, unless blades are extended, which in turn increases CapEx
- Nacelle blockage does not seem to be a thing, see Anderson et al 2020
  DOI 10.1088/1742-6596/1618/6/062062



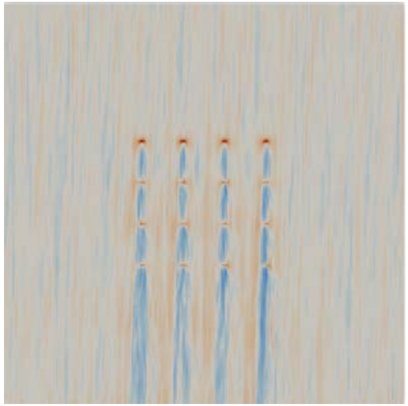
Plant AEP of Land-Based Downwind

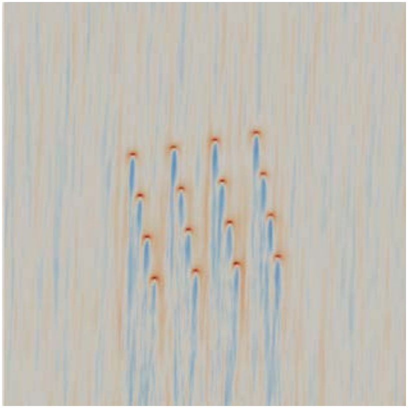
At the plant level, literature shows promising results, see DOI 10.5194/wes-6-663-2021

At NREL, new results return lights and shadows

- Great improvements when turbines are aligned with inflow
- AEP loss for a 4x4 wind farm with uniform wind rose
- Potential for bigger wind farms or different atmospheric boundary layers?
- Cory Frontin will present the full story at TORQUE 2024

Flux of stream-aligned momentum at 0 and 10 deg inflows for downwind wind farm with 20 deg tilt
Images from C. Frontin - NREL





Downwind for Floating?

Downwind floating may yield benefits:

- Increase rotor swept area under platform pitching (turbine greedy approach)
- Enhance platform yaw stability

Source: x1wind

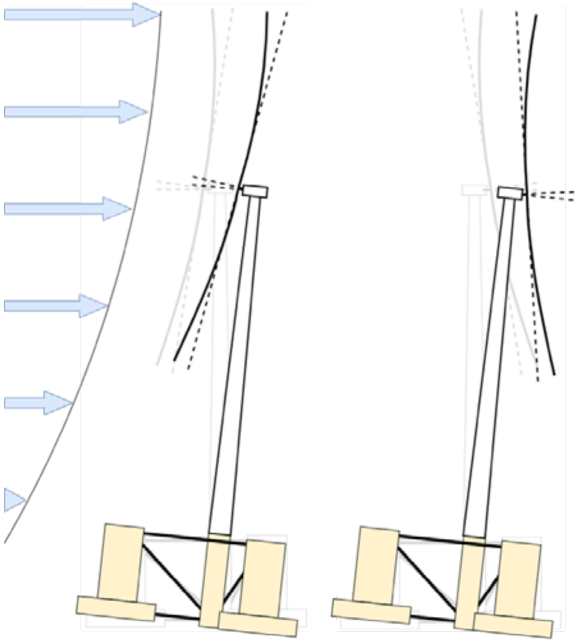
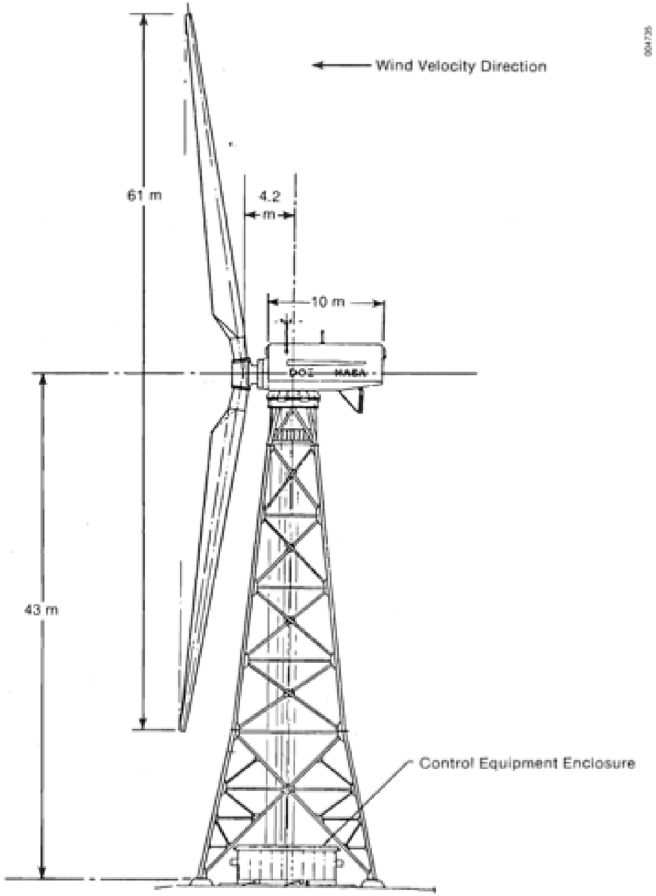


Illustration from M Chetan - NREL

Ok so, why NOT Downwind?

Combination of unproven advantages and historical disgrace

In 1980's, downwind wind turbines suffered from excessive noise (but had truss towers with higher aspect ratios and stiff blades)



MOD-1 downwind turbine from https://www.nrel.gov/docs/legosti/old/1166.pdf

Goal of the Experiment

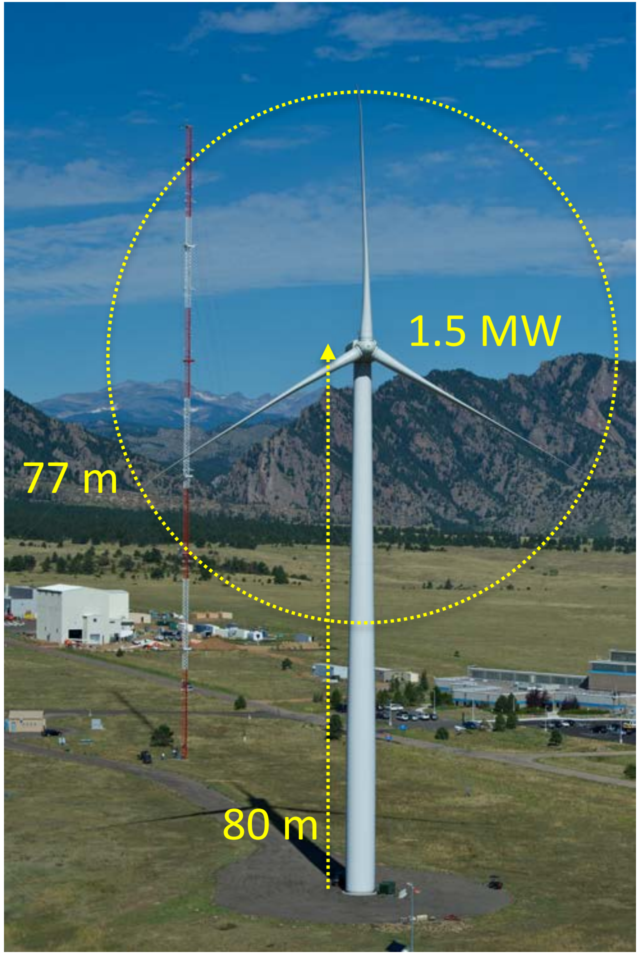
Generate a unique dataset to validate noise and aerodynamic models, and advance understanding of barriers of downwind wind turbine technology

Validate positive anecdotal experience around downwind (Hitachi, CART)

Where: NREL Flatirons Campus, DOE 1.5MW

How: pitch and yaw 180 deg, and rotate counter-clockwise

When: Winter/Spring 2024



FMEA @ NREL

FMEA framework based on International Electrotechnical Commission (IEC) 60812:2006

Risks ranked by Risk Priority Number (RPN)

1. Excessive ultimate loads
2. Violation of minimum blade tower clearance
3. Overheating of generator and gearbox because of air exhaust direction
4. Damages to drivetrain (main bearing, gearbox) because of reversed thrust
5. Functionality of pitch actuators
6. …
7. …
20. Compromised lightning protection system

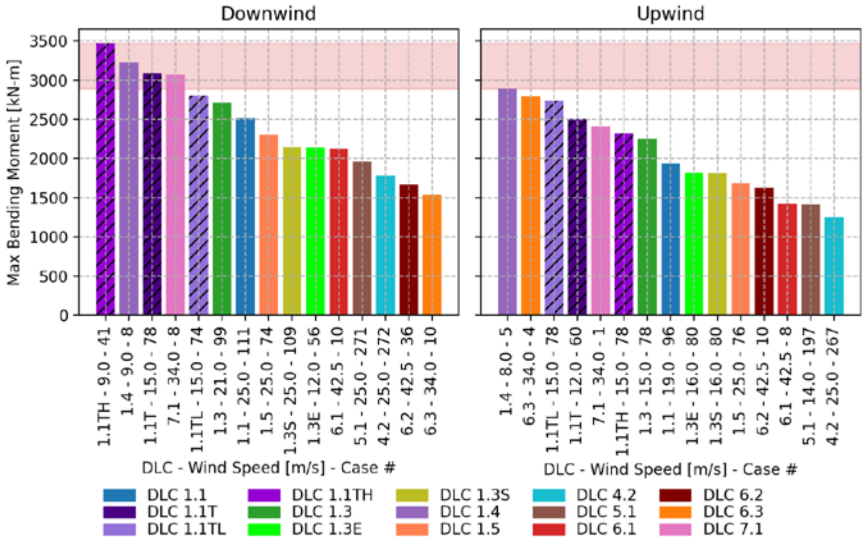
Design Load Cases (DLC)

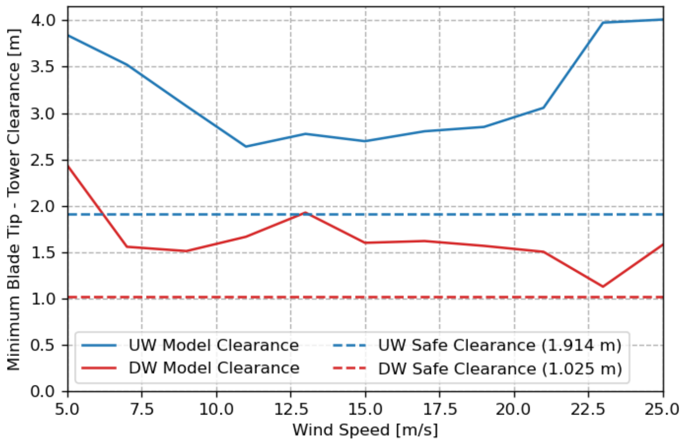
DLC	Wind Speeds, m/s	Shear Exp	Seeds per wind speed	# Cases	# Cases Excluded
1.1 Normal Operation	3.5 - 25	0.2	6 seeds	114	
1.1 NWTC Turbulence	3.5 - 25	0.2	6 seeds	114	
1.1 NWTC Turbulence, Low Shear	3.5 - 25	-0.1	6 seeds	114	2
1.1 NWTC Turbulence, High Shear	3.5 - 25	0.6	6 seeds	114	1
1.3 Extreme Turbulence	3.5 - 25	0.2	6 seeds	114	
1.3 Emergency Stop	3.5 - 25	0.2	6 seeds	114	
1.3 Normal Shutdown	3.5 - 25	0.2	6 seeds	114	
1.4 Coherent Gust	6 - 16	0.2	1 seed, 2 directions	22	
1.5 Power Production	3.5 - 25	0.2	1 seed, 2 directions, 2 shears	76	
4.2 Normal Shutdown	6 - 25	0.2	6 seeds, 4 azimuths	288	
5.1 Emergency Stop	6 - 25	0.2	6 seeds, 4 azimuths	288	
6.1 Parked-Idling 8° Yaw Misalignment	42.5*	0.2	6 seeds, 2 yaw angles	12	
6.2 Parked-Idling Loss of Power	42.5*	0.2	6 seeds, 15 yaw angles	90	16
6.3 Parked-Idling 20° Yaw Misalignment	34*	0.2	6 seeds, 2 yaw angles	12	6
7.1 Parked-Idling with Fault	34*	0.2	6 seeds, 2 yaw angles	12	

* 1yr and 50yr storm turbulent wind speeds tuned for NREL Flatirons campus following https://doi.org/10.2172/1558599

Summary of Loads and Deflections in OpenFAST

1. OpenFAST model was validated in terms of natural frequencies and key loads
2. Combined shaft and tower top moments increase by approx. 10%
3. Loads on rotor and tower are storm-driven and don’t increase
4. A conservative approach recommends to limit operations below rated wind speed to minimize risk of tower strikes





Third Party Review

Gulf Wind Technology (GWT), based in New Orleans and led by several former GE employees, helped us with three tasks:

- Task 1 – Blind FMEA
- Task 2 – Comparison of FMEAs
- Task 3 – Vetting of load analysis

GWT and NREL agree that we can move ahead with experiment, pending the implementation of several safety measures

Test Plan – Safety Measures

- Ensure functionality of pitch system
- Start at very low wind speeds and slowly ramp up
- Test normal and emergency shutdowns
- Validate performance of supervisory controller
- Monitor existing temperature signals
- Monitor main bearing front cover strain
- Monitor particle counter in the gearbox oil

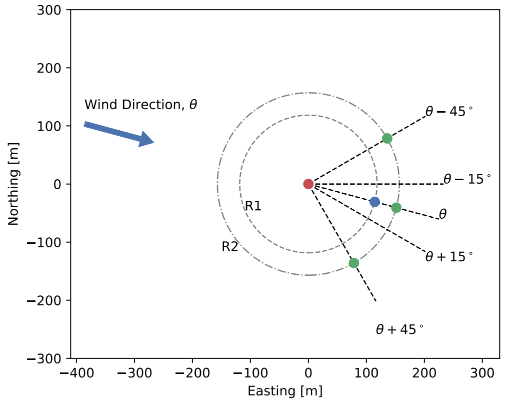
Test Plan – Instrumentation

Number of 10-min Samples

TI (%) \ Wind Speed (m/s)	0	3	5	7	9	11	13	15	17
40									
20		2	5	5	5	5			
0			3	5	5	5			

We will record:

1. Existing met-tower, turbine, and supervisory control and data acquisition channels
2. 400-minutes of load data along main turbine components at varying wind speed and turbulence intensity
3. Aeroacoustics emissions in the audible range at the IEC location (blue dot) and in the low frequency at the three locations used in NREL/TP-5000-79664 (green dots)

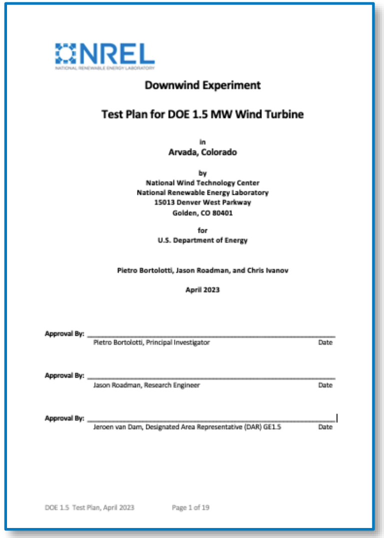


Ongoing Work

1. Install supervisory controller with automatic shutdown
2. Spoof pitch systems and wind vane, and park turbine
3. Install laser distance sensors along tower
4. Install strain gauge on front cover of mean bearing
5. Deploy aeroacoustic array
6. Obtain approvals to proceed with experiment
7. **January 2024 - Start testing!**
8. May 2024 - Revert turbine to upwind
9. Repeat data collection to obtain a benchmark dataset

Essentially, we're trying to trick the black-box controller (items 1–2)

Safety measures (items 3–4)



NREL

Downwind Experiment

Test Plan for DOE 1.5 MW Wind Turbine

in

Arvada, Colorado

by

National Wind Technology Center
National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401

for

U.S. Department of Energy

Pietro Bortolotti, Jason Roadman, and Chris Ivanov

April 2023

Approval By: ______ Pietro Bortolotti, Principal Investigator ______ Date

Approval By: ______ Jason Roadman, Research Engineer ______ Date

Approval By: ______ Jeroen van Dam, Designated Area Representative (DAR) GE1.5 ______ Date

DOE 1.5 Test Plan, April 2023 Page 1 of 19

Q&A

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NREL/PR-5000-87862

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Modal Validation

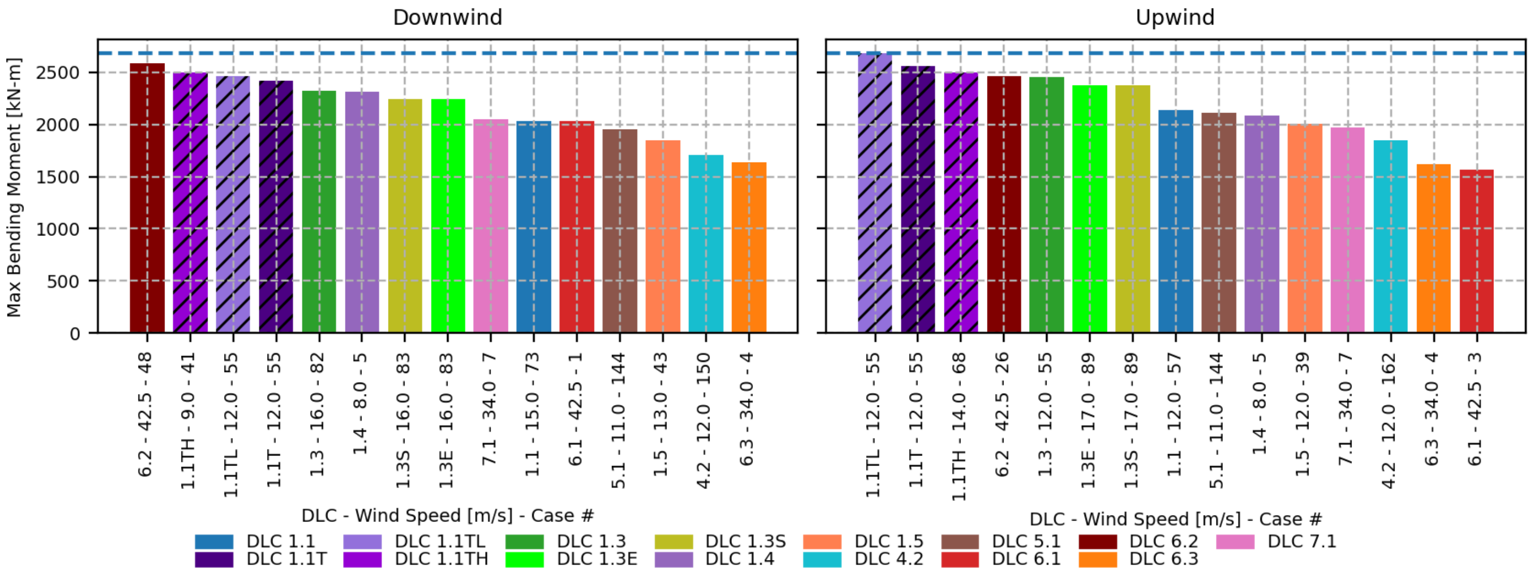
Model linearization performed at 0 RPM

Test data collected at 0 RPM after controlled shutdown

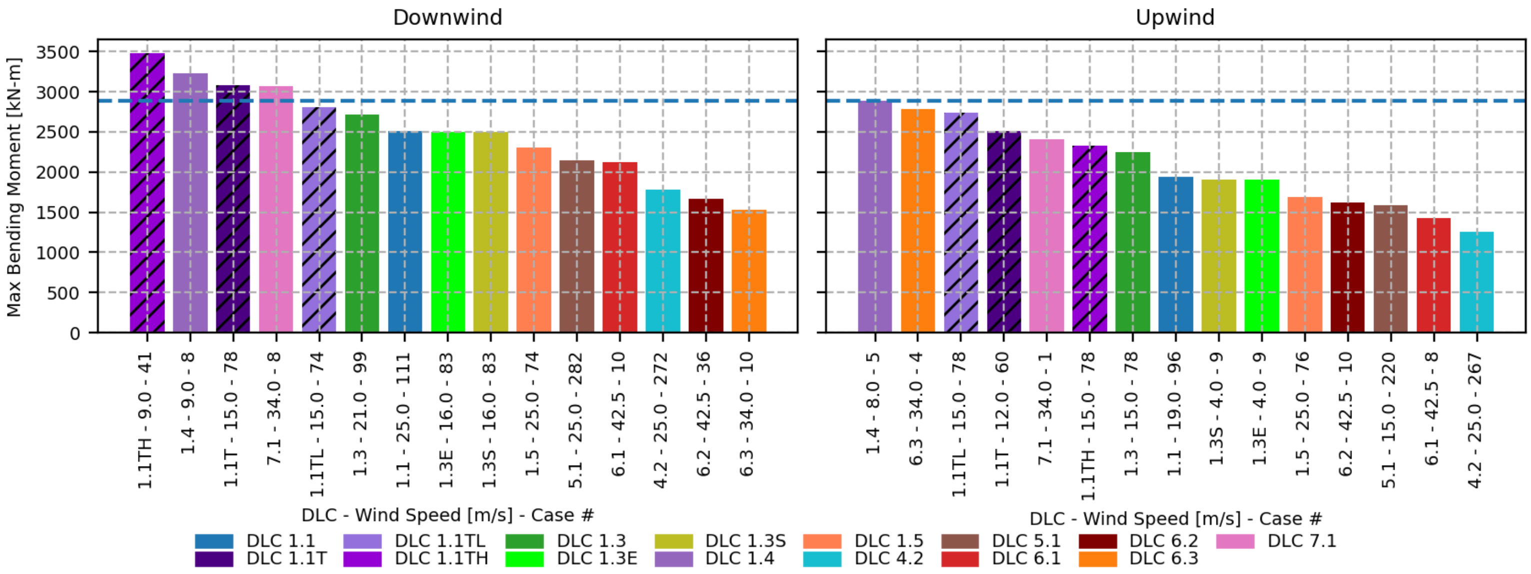
Model frequencies show good correlation with modes extracted from test data

Mode	OpenFAST Frequency (Hz)	Experimental Frequency (Hz)
1^{st} Tower FA	0.37	0.34
1^{st} Tower SS	0.36	0.35
1^{st} Blade Flap (Collective)	1.06	1.03
1^{st} Blade Edge (w/o Drive Train)	1.63	1.7

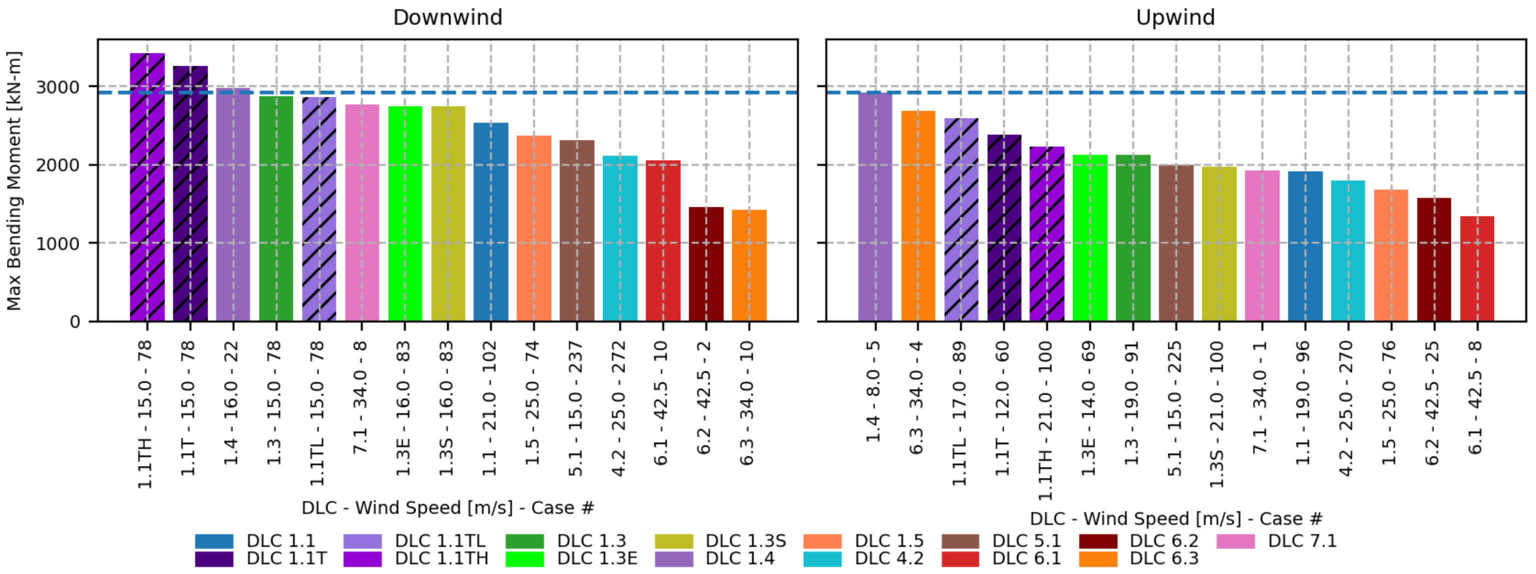
Blade Root Total Bending Moment



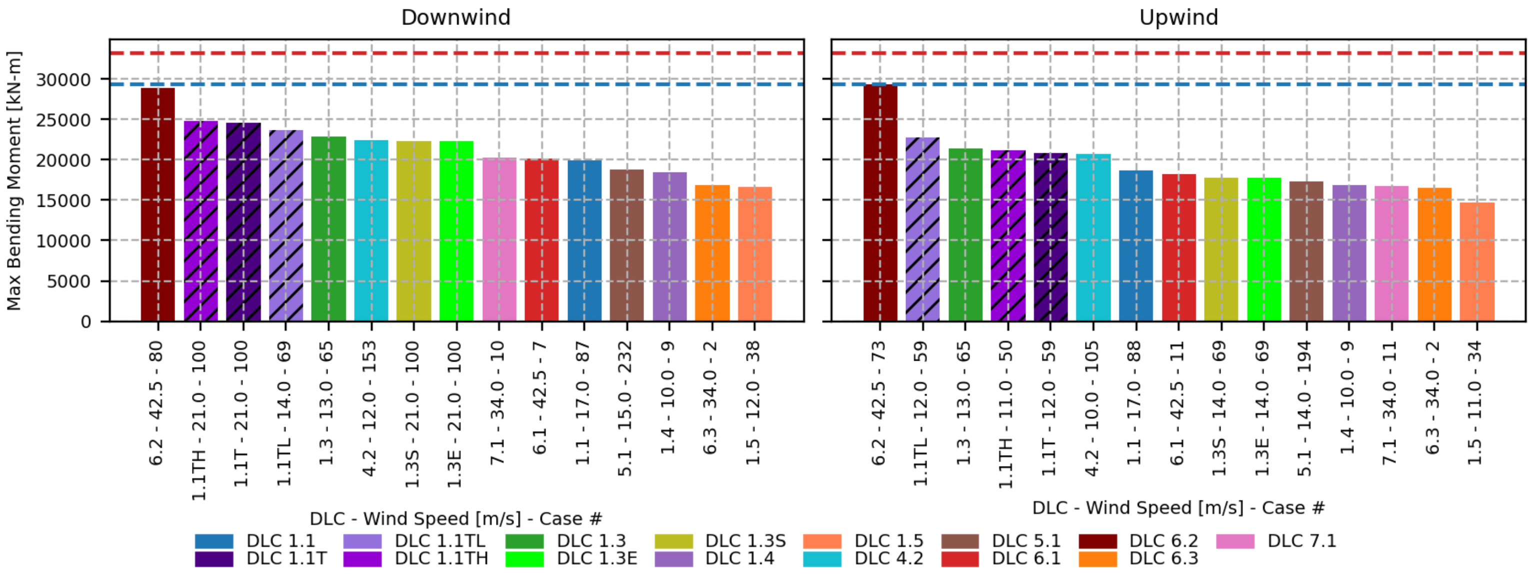
Low-Speed Shaft Total Bending Moment



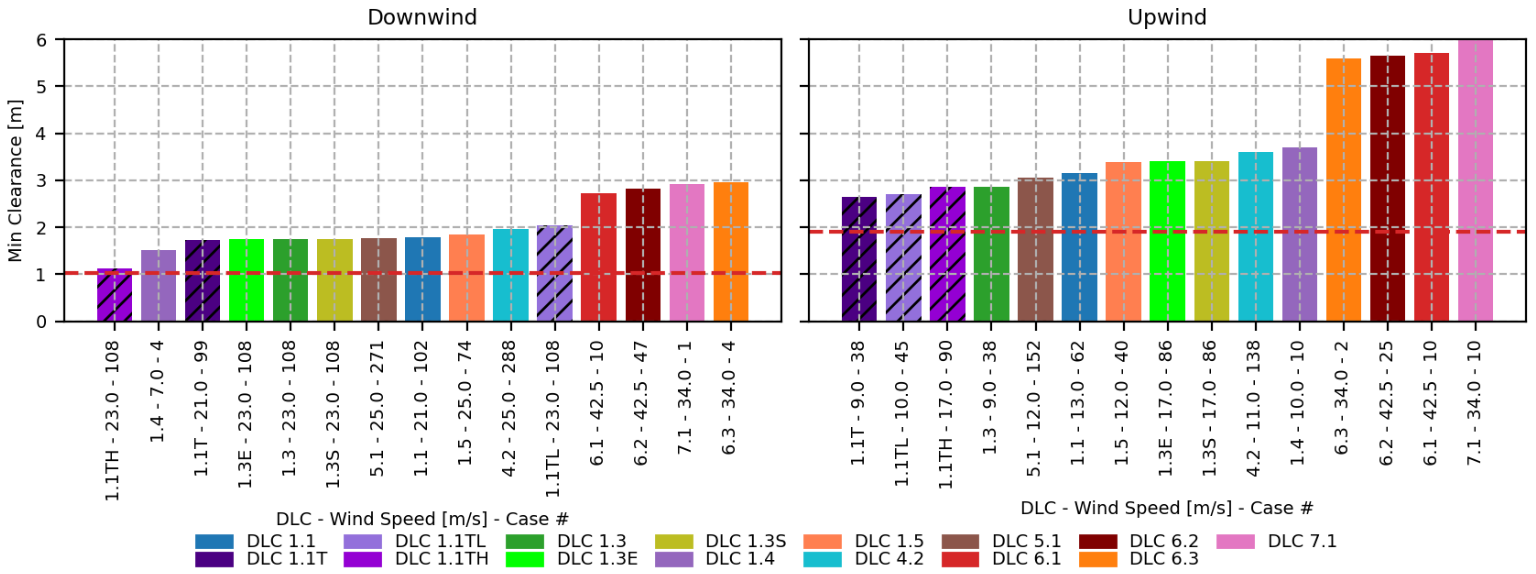
Tower Top Total Bending Moment



Tower Base Total Bending Moment



Blade Tip – Tower Clearance



Blade Tip – Tower Clearance