# Preliminary Results for The Aerodynamic Wind Turbine Design Optimization Case Study for the IEA Task 37 on Wind Energy Systems Engineering

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# Acknowledgments

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This work is a collaboration between many researchers and institutions. The following have contributed results for this presentation:

- Michael K. McWilliam, Frederik Zahle, DTU Wind Energy
- Pietro Bortolotti, Carlo Bottasso, Technische Universitat Munchen
- Birger Luhmann, Niklas Jores, University of Stuttgart
- Andrew Ning, Katherine Dykes, Rick Damiani, Brigham Young University/NREL
- Evan Gaertner, Matthew Lackner, University of Massachusetts, Amherst

The following researchers are also involved in this collaboration:

- Ozlem Ceyha, ECN
- Beatriz Mendez Lopez, CENER
- Rad Haghi, Curran Crawford, University of Victoria

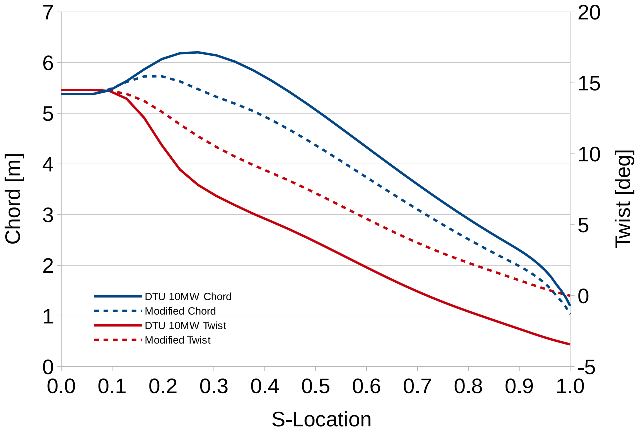
# Problem Description

# Research Objectives

- This IEA Task is meant to coordinate international research activities, towards the analysis of wind power plants as holistic systems
- Multi-disciplinary Design Analysis and Optimization (MDAO) is a valuable tool in systems engineering with all disciplines
- Starting with single discipline case studies because full turbine MDAO is complicated
- This will help us in the following ways:
  - Provides a baseline to help understand the differences in future studies
  - Allow more researchers to be involved by starting with simpler cases
  - Gives us experience in creating, managing and analyzing optimization case studies
- This is **less about validation and more about developing design techniques**

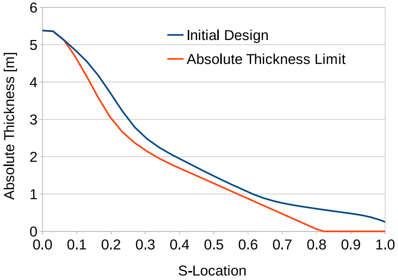
# Initial Design

- Based on the DTU 10MW reference wind turbine with the following modification:
  - Reduced chord, less aggressive twist, thicker blades
  - No coning or tilt



# Optimization Problem

- Load constraints based on initial design loads
- Structural considerations:
    - Minimum absolute thickness
    - Smaller center of thrust




Maximize Annual Energy Production

Varying

Chord

Twist

Relative Thickness

subject to

$$T \leq 1.14 \max T_0,$$

$$M \leq 1.11 \max M_0,$$

Absolute thickness $\geq$ limit

# Aerodynamic Analysis

- Design evaluated with steady, uniform wind without turbulence
- Turbine operates between $4$ and $25m/s$
- AEP based on Weibull distribution with scale and shape 8 and 2 respectively
- Must find optimal regulation based on:
    - Design Tip-Speed-Ratio: 7.8
    - Minimum RPM: 6
    - Maximum RPM: 9.6
    - Find optimal pitch to feather when in constant speed operation

# Survey of Tools

# Survey of Tools

- Typical set-up:
  - Steady-state BEM with angular moment and tip-loss functions
  - Spline parameterization with approximately 15 design variables
  - Sequential Quadratic Programming (SQP)
  - Finite-difference gradients
- Some exceptions:
  - Brigham Young University/NREL:
    - Analytic adjoint gradients mixed with automatic differentiation (Tapenade)
  - University of Massachusetts, Amherst
    - The NSGA genetic optimization algorithm
  - DTU Wind Energy
    - IPOPT optimization algorithm
  - University of Stuttgart
    - Sequential Least Squares Programming

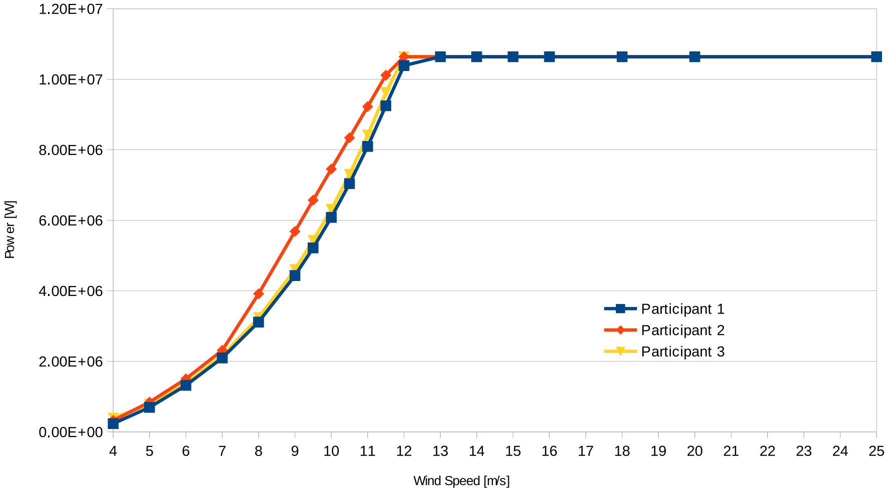
# Comparison of Preliminary Results

# Comparison of Preliminary Results

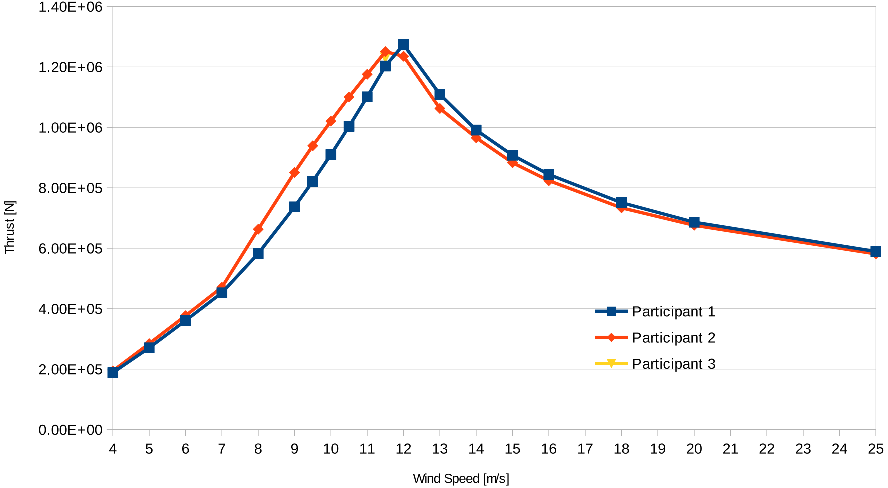
- The results are preliminary
    - Not all participants provided optimization results
    - There are differences in the problem set-ups
    - It appears that not all results are fully converged
    - Not all results were reported fully
- Further iterations are needed
- The source of the results is anonymous

# Performance of the initial design

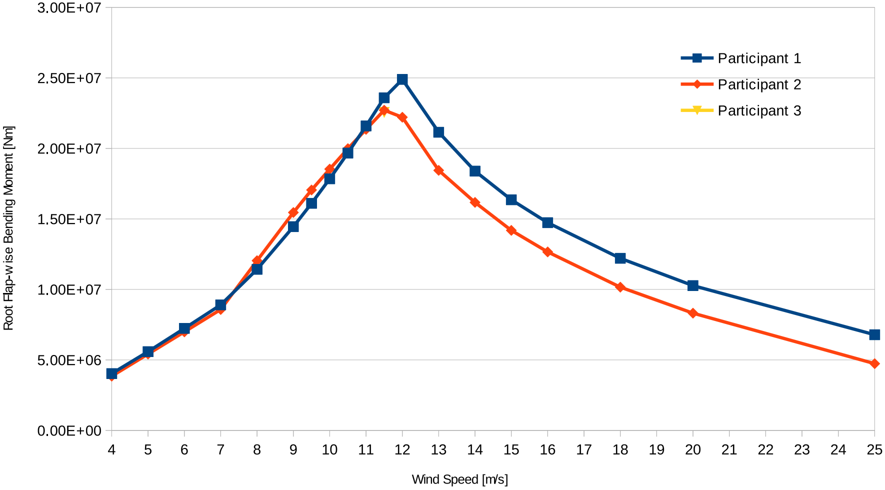
# Initial Power



# Initial Thrust

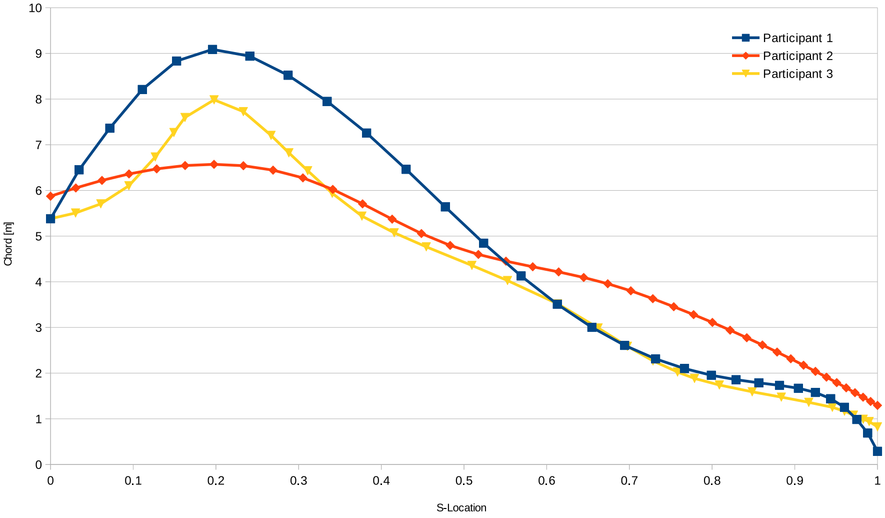


# Initial Blade Root Flap-wise Bending Moment

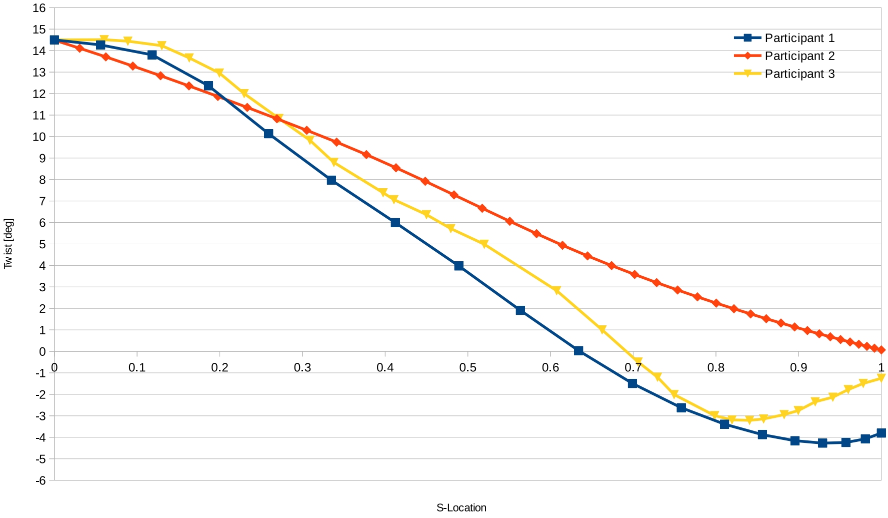


# Optimal design

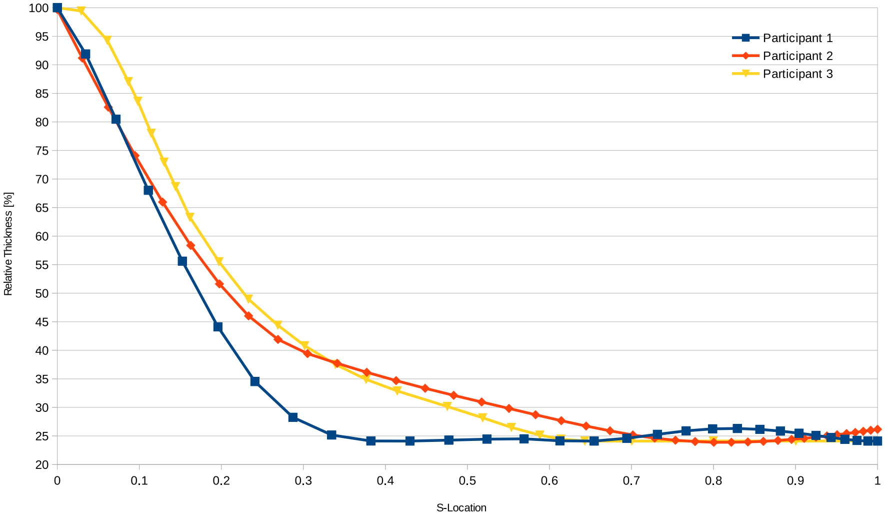
# Optimal Chord



# Optimal Twist



# Optimal Relative Thickness



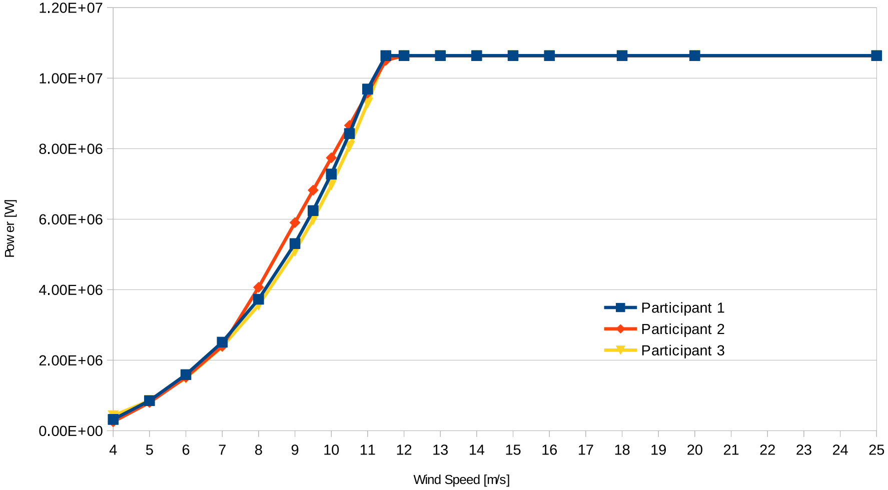
# Performance of the optimal design

# Improvement in AEP

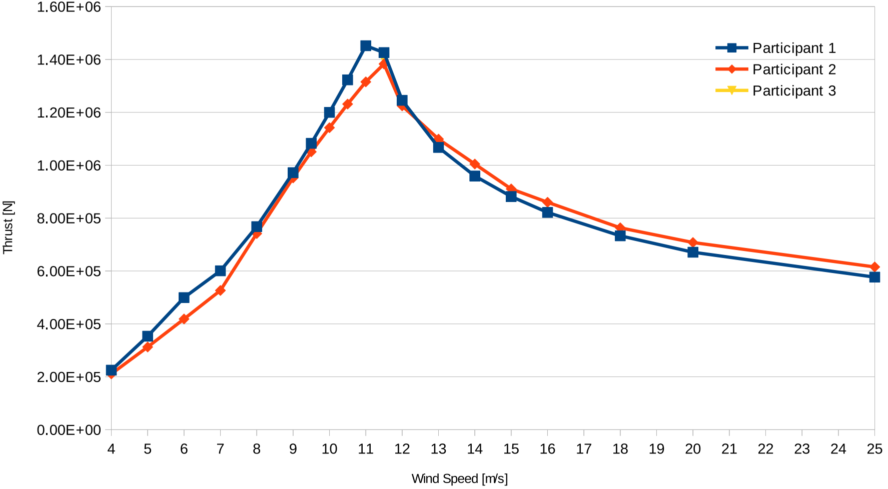
| Participant | Initial AEP | Optimal AEP | Relative Improvement |
|---|---|---|---|
| Participant 1 | 28.4 GWh | 31.9 GWh | 12.44% |
| Participant 2 | 31.9 GWh | 32.6 GWh | 1.96% |
| Participant 3 | 29.3 GWh | 31.2 GWh | 6.42% |

- Participant 1 demonstrated the greatest improvement
- Wide variation in the relative improvement
- Questions on whether optimization is fully converged:
  - Thrust constraint not active for participant 2
  - Moment constraint violated for participant 2

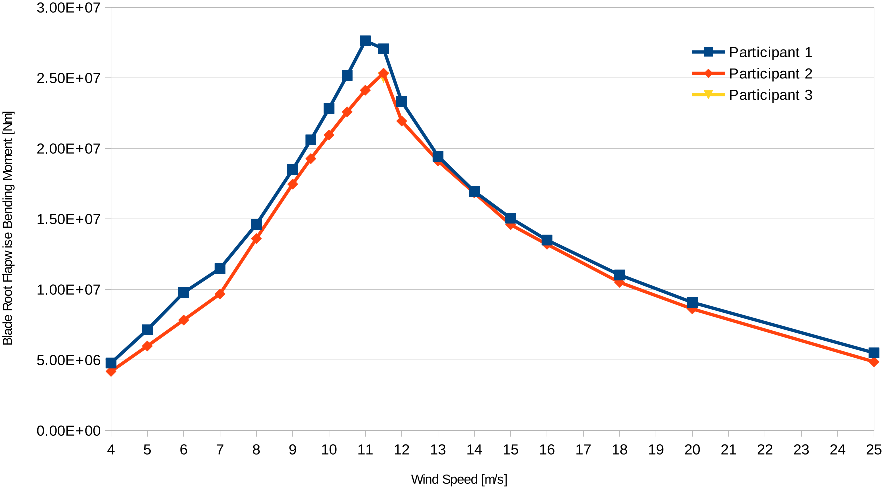
# Optimal Power



# Optimal Thrust

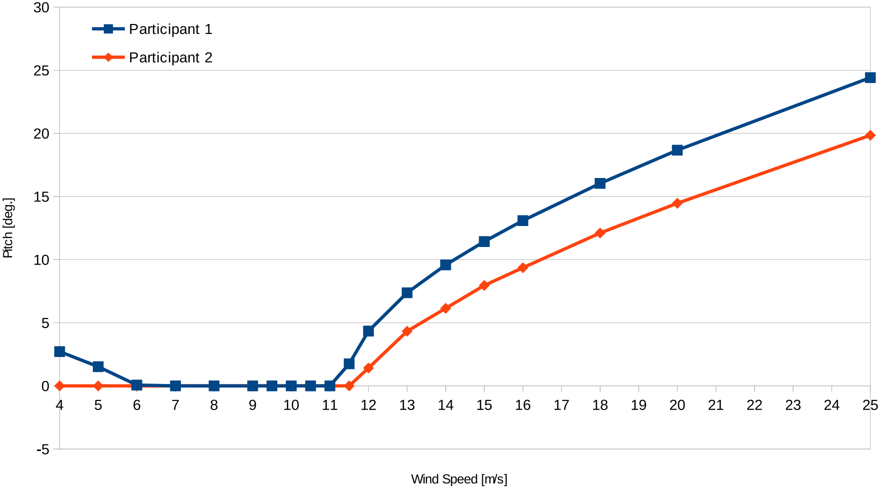


# Optimal Blade Root Flap-wise Bending Moment



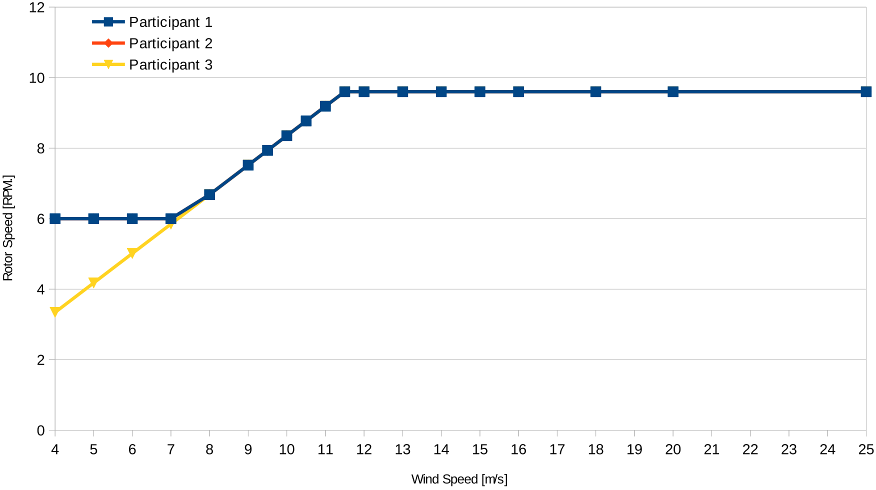
# Optimal Pitch

- Participant 2 does not optimization pitch at lower speeds



# Optimal Rotor Speed

- Participant 3 violates the lower speed constraint



# Closing Statements

# Conclusions

- IEA Task 37 is meant to explore MDAO of wind turbines
- Simple aerodynamic case study is developed
    - Based on a modified DTU 10MW Reference Turbine
    - Maximize AEP by varying chord, twist and thickness
    - Subject to thrust, moment and some geometric constraints
    - Some artificial structural considerations
    - Must solve optimal regulation strategy
    - Analysis based on steady uniform wind
- Many researchers are applying their tools to this problem
    - Most set-ups based on splines for the design variables, BEM aerodynamics with SQP optimization and finite difference gradients
    - There are differences in the optimization algorithms and gradient algorithms
- Current optimization results are preliminary
    - Not all participants have contributed results
    - Similar performance for the initial design
    - Large variation in the optimal design and performance
    - The current results showed differences in the regulation
    - It appears not all results are fully converged

## Thank-you for your interest

Comments or Questions?

Please approach me after if you want to participate