Power performance comparison of unmoored floating offshore wind turbines and energy ships

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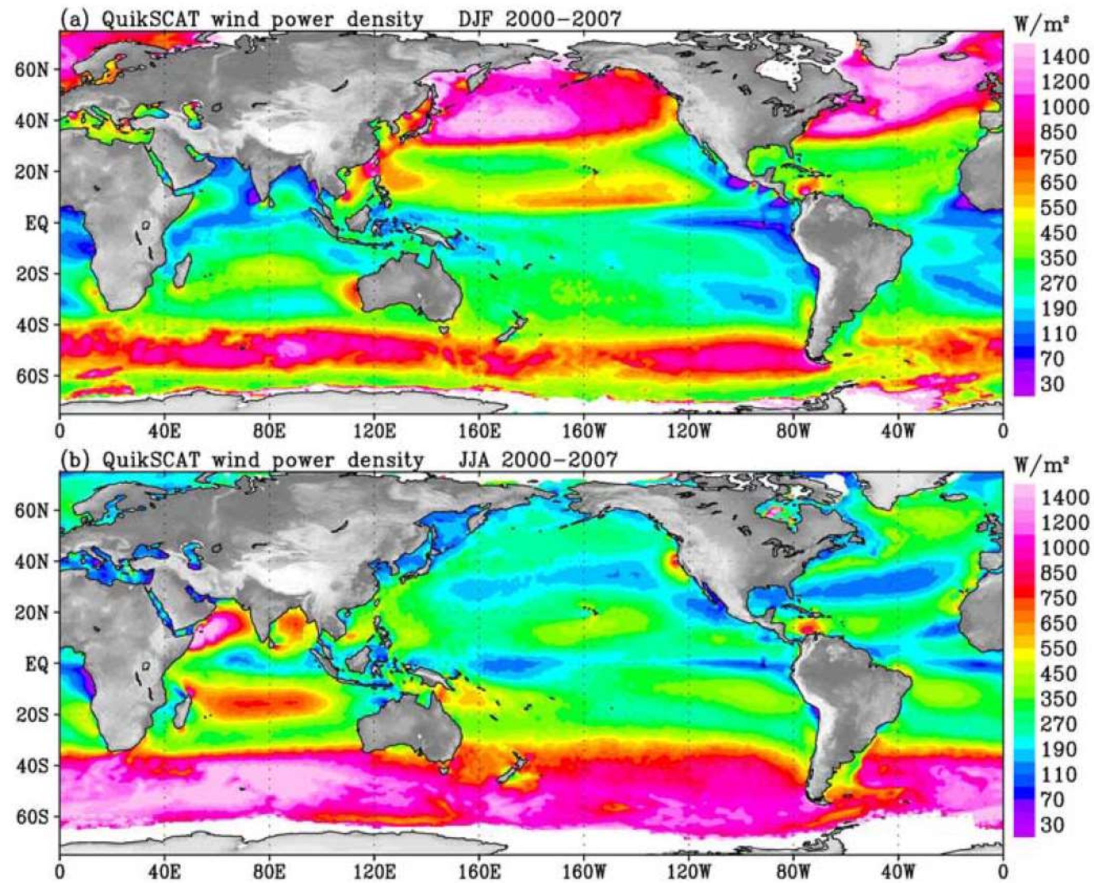
Overview

- Motivation and Background
- Research Questions
- Modelling Methodology
- Results and Discussion
- Conclusion

Motivation and Background

Far-offshore wind

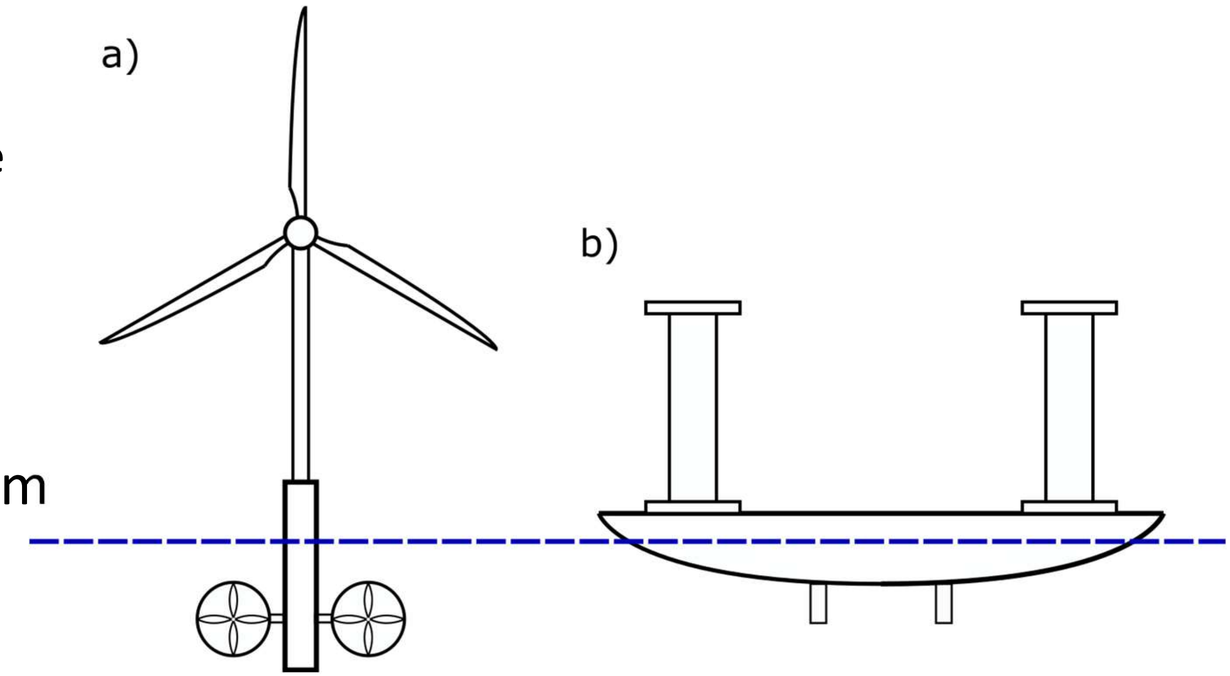
- Higher average wind speeds farther offshore
- Operating far-offshore means storing or using generated power
- Harsher met-ocean conditions
- Unknowns: O&M, Perception, legality



Global wind power density, [1] (Liu et al. 2008)

Technology concepts

- Two concepts:
  a) Unmoored floating offshore wind turbine (UFOWT)
  b) Energy ship
- Expressly designed for far-offshore operation
- Mobile, leads to problem of weather-routing
- Energy is used for synthesizing e-fuel or used directly (i.e DAC)



Research Questions

Questions

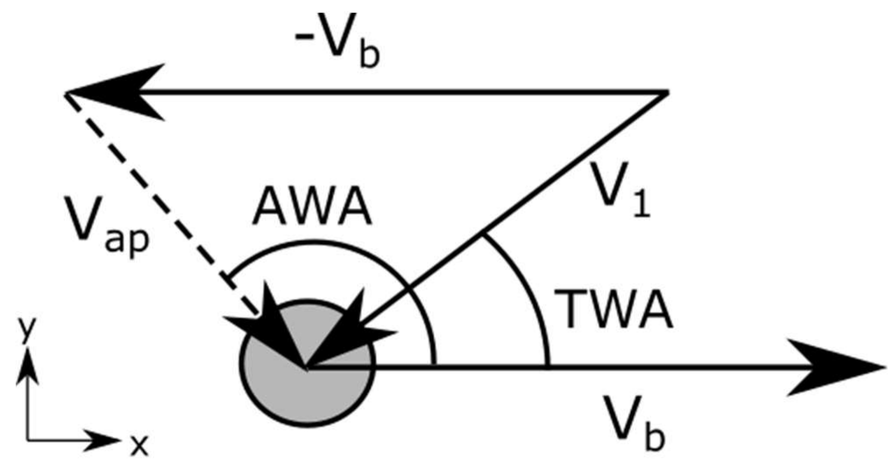
1. How does each concept (for a given design) perform at producing power under various environmental conditions?

2. How do the performance maps compare?

Modelling Methodology

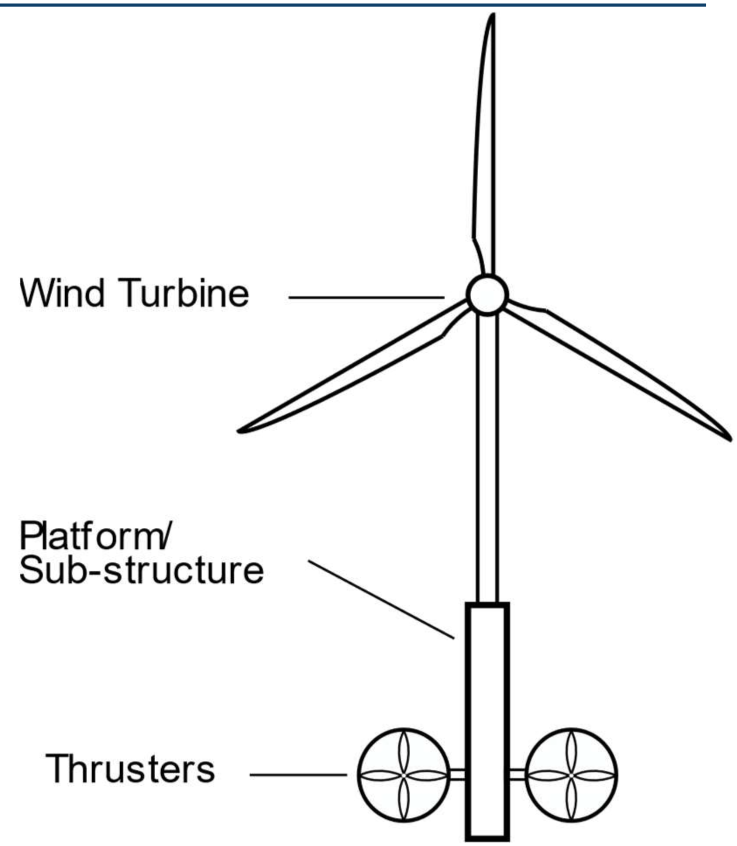
Conventions

- V_1 - True wind velocity
- V_b – vessel/body velocity
- V_{ap} – Apparent wind velocity
- TWA – True wind angle
- AWA – Apparent wind angle



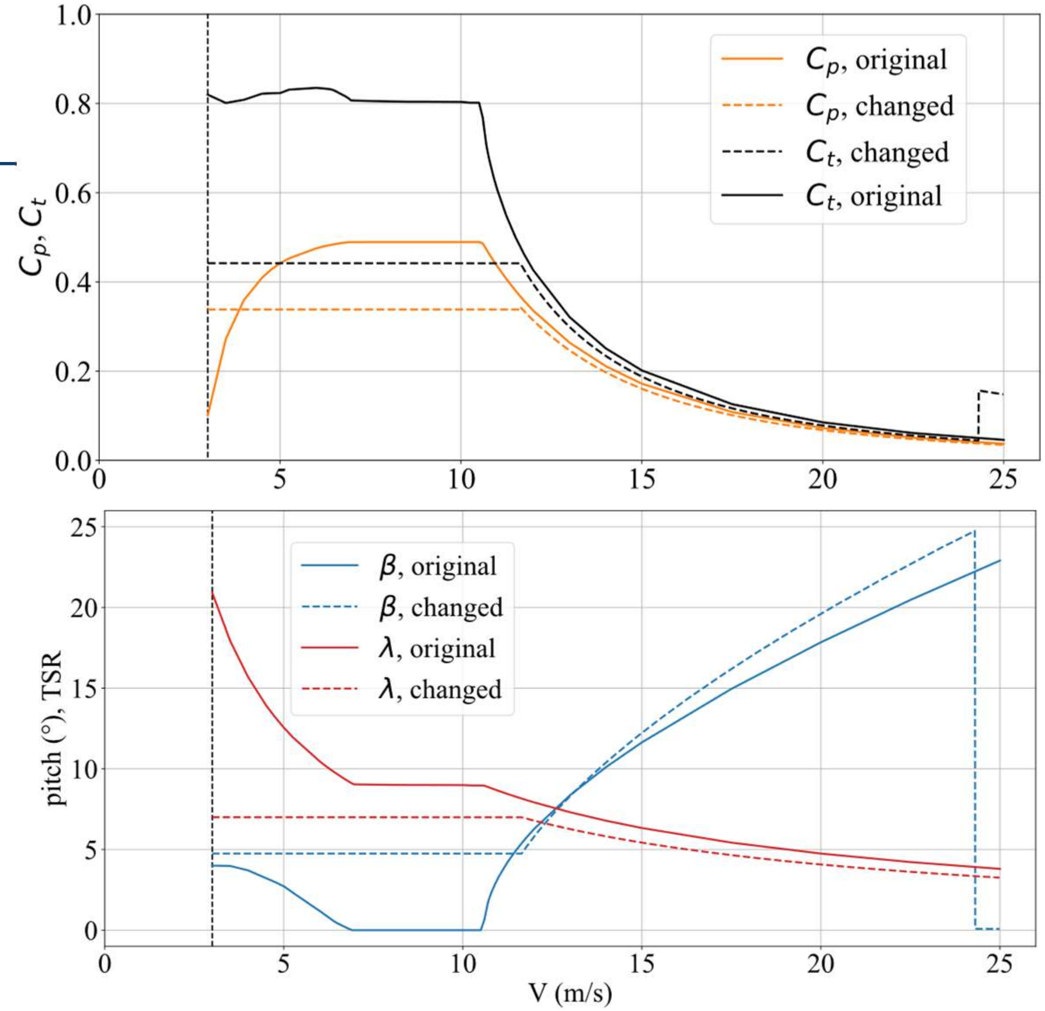
UFOWT (1)

- 2D waterplane Steady-state model ($\sum \vec{F} = \vec{0}$)
  - $\overrightarrow{F_g} = \left[\frac{1}{2}\rho_1 A_1 |V_{ap}|^2 C_{t1}(\beta,\lambda) - m_{rotor} g \sin(\theta_{tilt})\right] [\cos(AWA)\,\hat{x}, \sin(AWA)\,\hat{y}]$
  - $\overrightarrow{F_p} = -n_{wt}\rho_2 D_2^4 f^2 K_{t2}(J)[\cos(\theta)\,\hat{x}, \sin(\theta)\,\hat{y}]$
  - $\overrightarrow{F_{d2}} = -\frac{1}{2}\rho_2 A_{d2} V_b |V_b| C_{d2}[1\hat{x}, 0\hat{y}]$
- Power
  - $P_g = \frac{1}{2}\rho_1 A_1 V_{ap}^3 C_{p1}(\beta,\lambda)$
  - $P_p = -2\pi n_{wt}\rho_2 D_2^5 f^3 K_{q2}(J)$
  - $C_{p,net} = \frac{P_g + P_p}{P_1}$
- Note: No accounting for wave forces



UFOWT (2)

- Several control variables
  - β - Wind turbine blade pitch
  - λ – Wind turbine tip-speed ratio
  - θ – Thruster yaw angle
  - J – Thruster advance ratio
- Choose a new schedule (i.e $\beta(V_1)$)of (β, λ) to maximize $\frac{C_p}{C_t}$
- Solve for other variables analytically
- Design based on
  - IEA 15 MW reference turbine [2]
  - UMaine Volturn platform [3]
  - Wageningen B-series, 7 bladed propeller [4]



Data from IEA 15 MW reference turbine [2] (Gaertner et al. 2020), denoted as “original”

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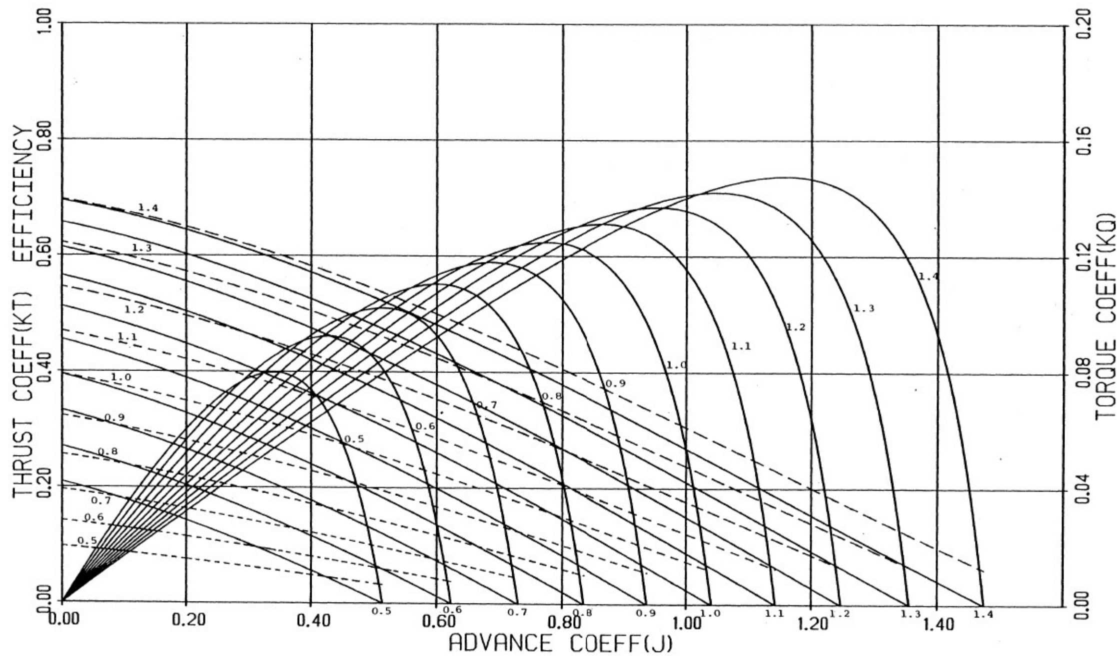
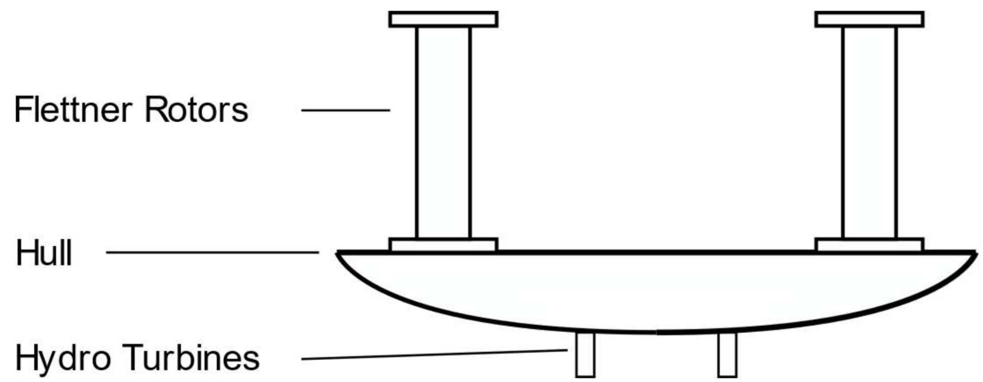
UFOWT (3)

- Design based on
  - IEA 15 MW reference turbine [2]
  - Umaine Volturn platform [3]
  - Wageningen B-series, 7 bladed propeller [4]
- Design choices made for data availability, NOT optimality



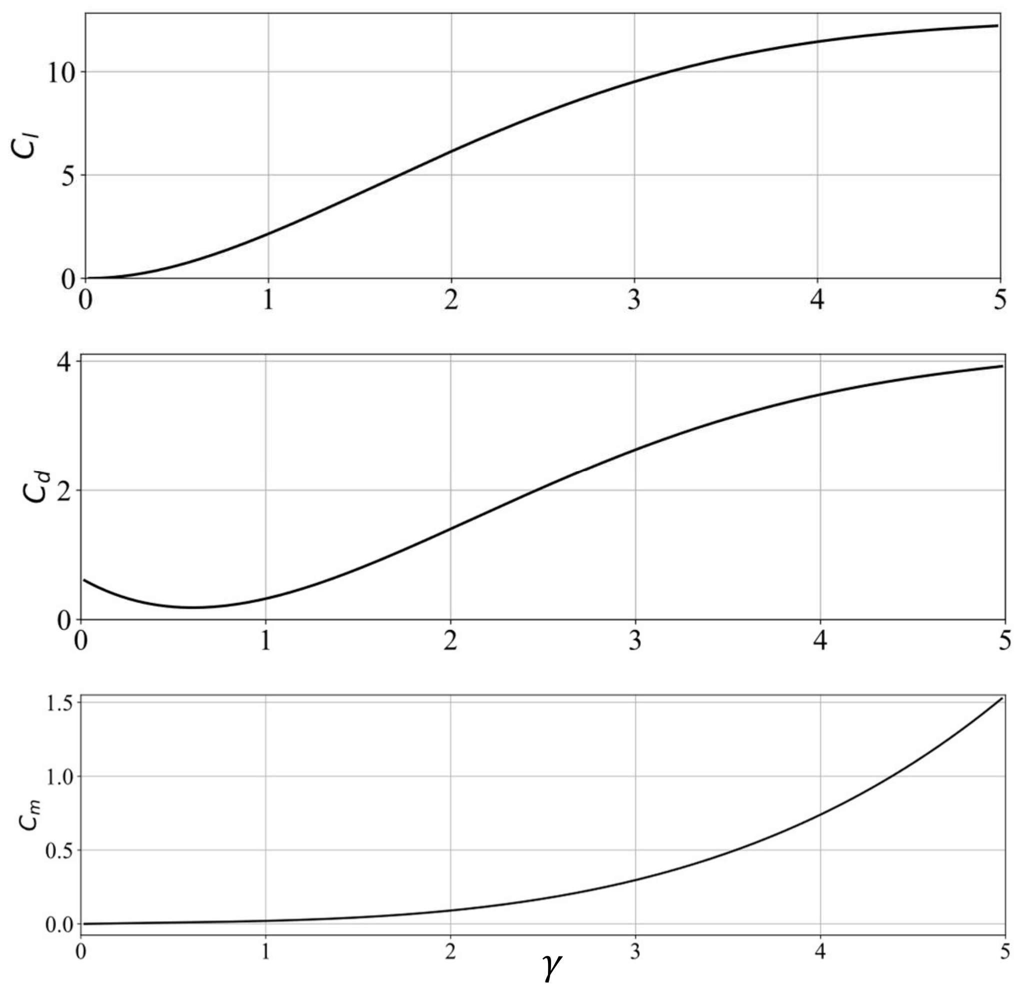
Energy Ship (1)

- Forces
  - $\overrightarrow{F_g} = -2\rho_2 A_2 V_b |V_b| a(1-a)[1\hat{x}, 0\hat{y}]$
  - $\vec{L} = \frac{1}{2}\rho_1 A_1 |V_{ap}^2| C_{lp}(\gamma)[\sin(AWA), \cos(AWA)]$
  - $\vec{D} = \frac{1}{2}\rho_1 A_1 |V_{ap}^2| C_{dp}(\gamma)[-\cos(AWA), \sin(AWA)]$
  - $\overrightarrow{F_p} = (\vec{L} + \vec{D}) C_{t,int}$
  - $\overrightarrow{F_{d2}} = -\frac{1}{2}\rho_2 A_{d2} V_b |V_b| C_{d2}(V_b)[1\hat{x}, 0\hat{y}]$
- Power
  - $P_g = 2\rho_2 A_2 V_b^3 a(1-a)^2 \eta_g$
  - $P_p = -\frac{1}{2}\rho_1 A_1 V_{ap}^3 C_m(\gamma)$
  - $C_{p,net} = \frac{P_g + P_p}{P_1}$



Energy Ship (2)

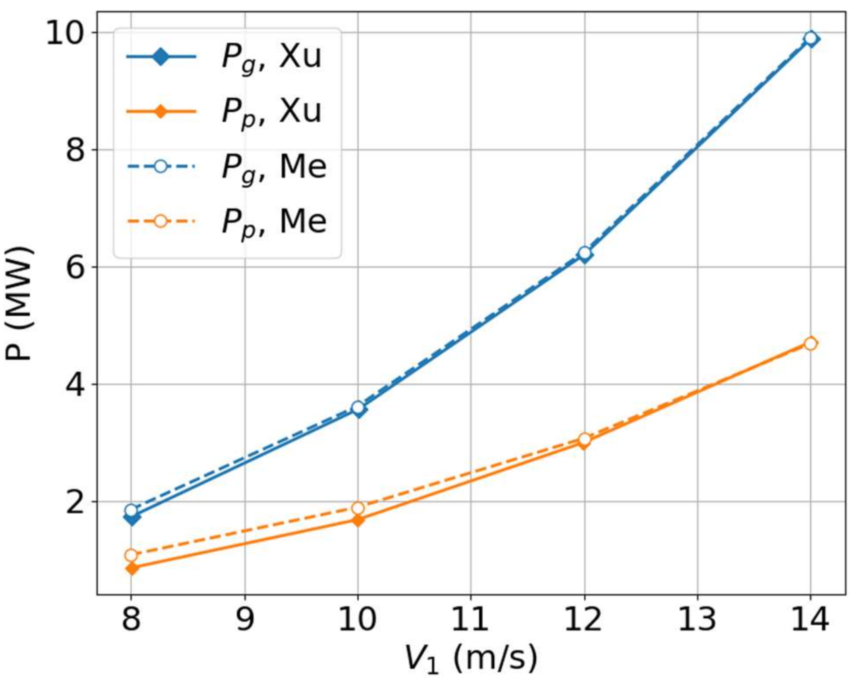
- Energy Ship Design based on FARWIND design [5]
  - 4x 35m tall Flettner rotors
  - 80m long catamaran hull
  - 2x 4m diameter water turbines
- Flettner rotor performance from empirical formulas [6]
- Use optimizer to choose control variables (γ, a, V_b)



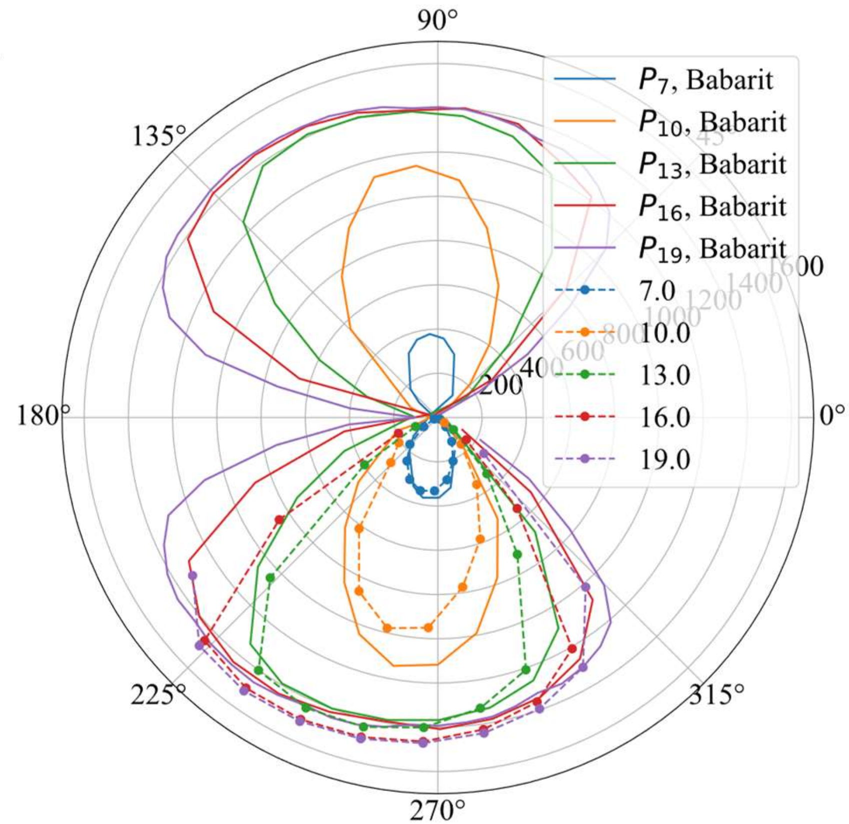
Flettner rotor performance curves [6]

Results and Discussion

Model Verification



UFOWT Verification against [7] (Xu et al. 2021)



Energy Ship Verification against [5] (Babarit et al. 2021)

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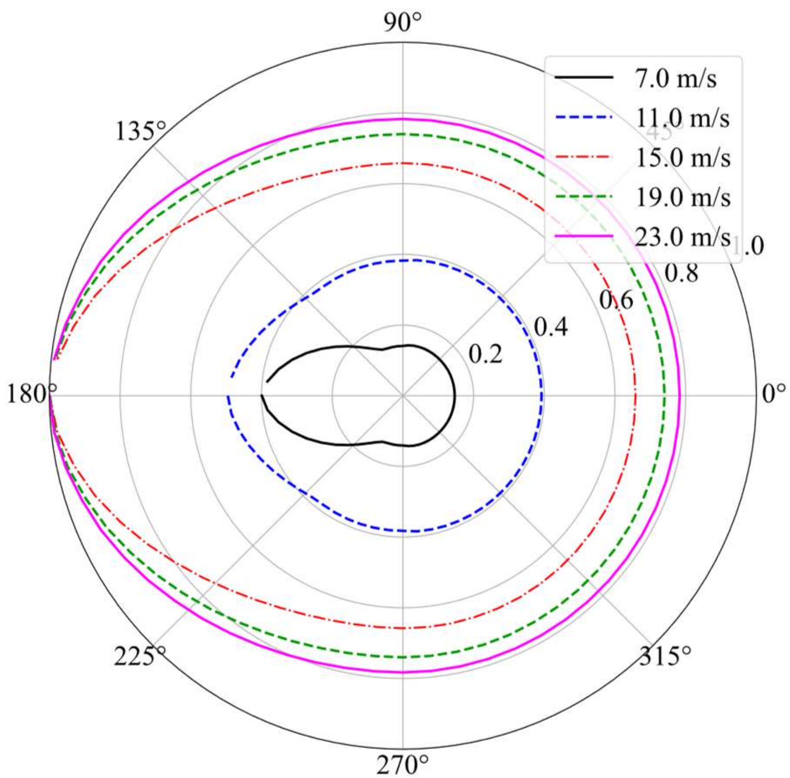
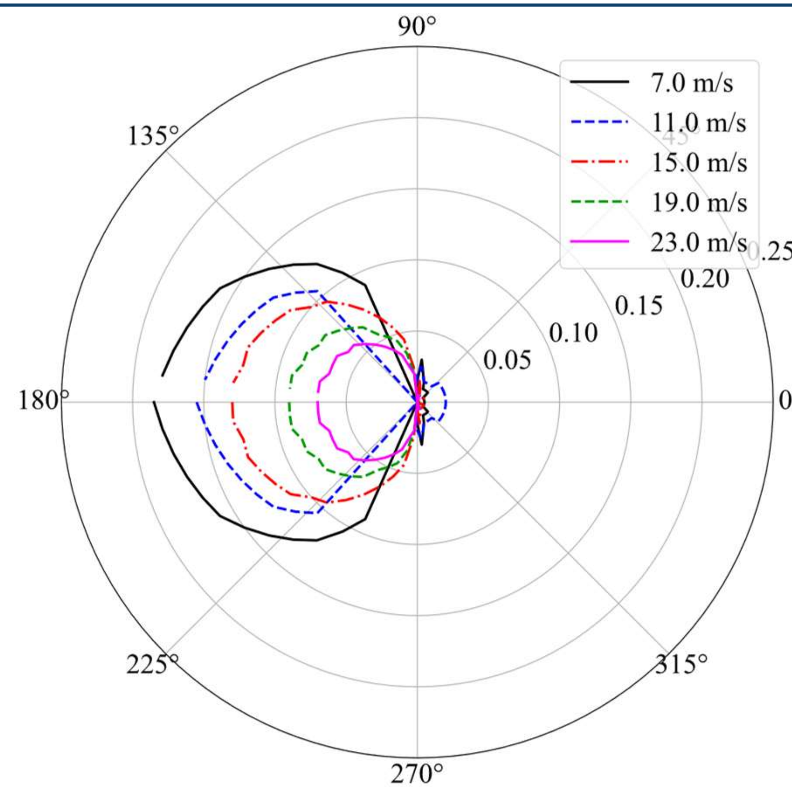
UFOWT Performance



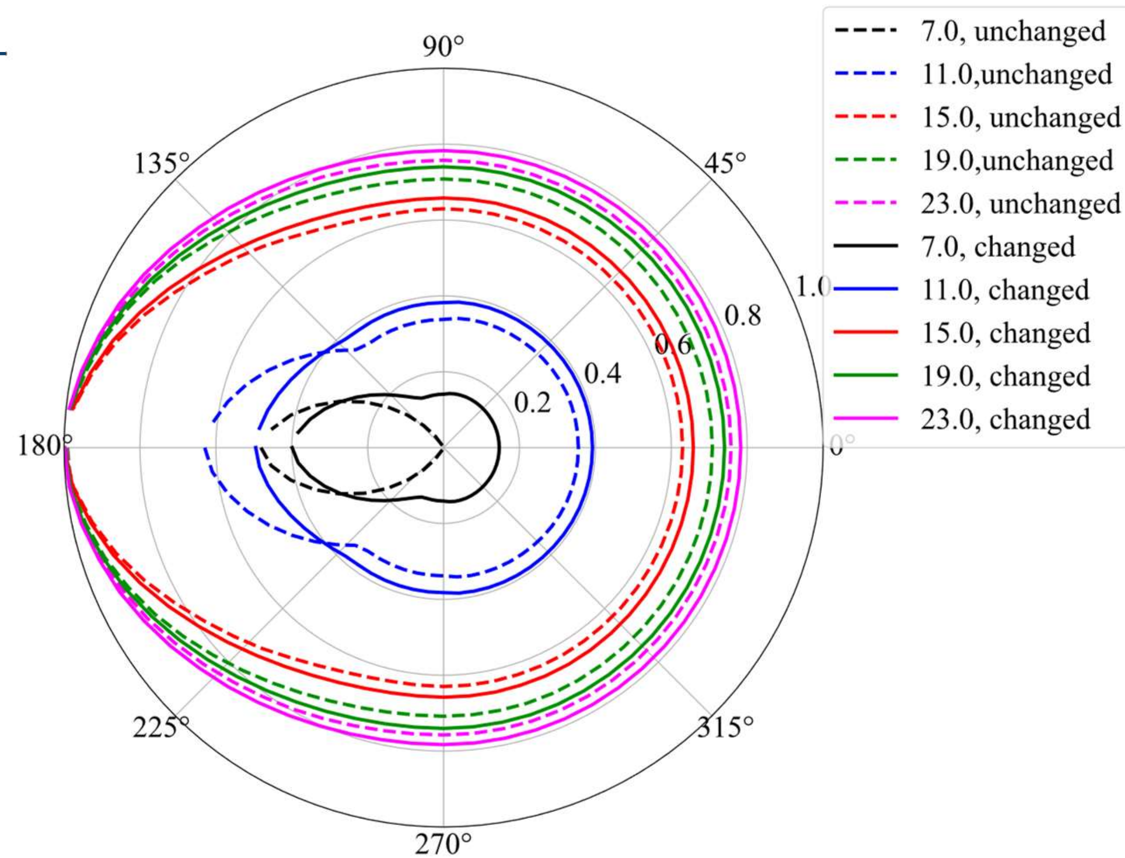
$C_{p,net}$ vs. TWA and V_1



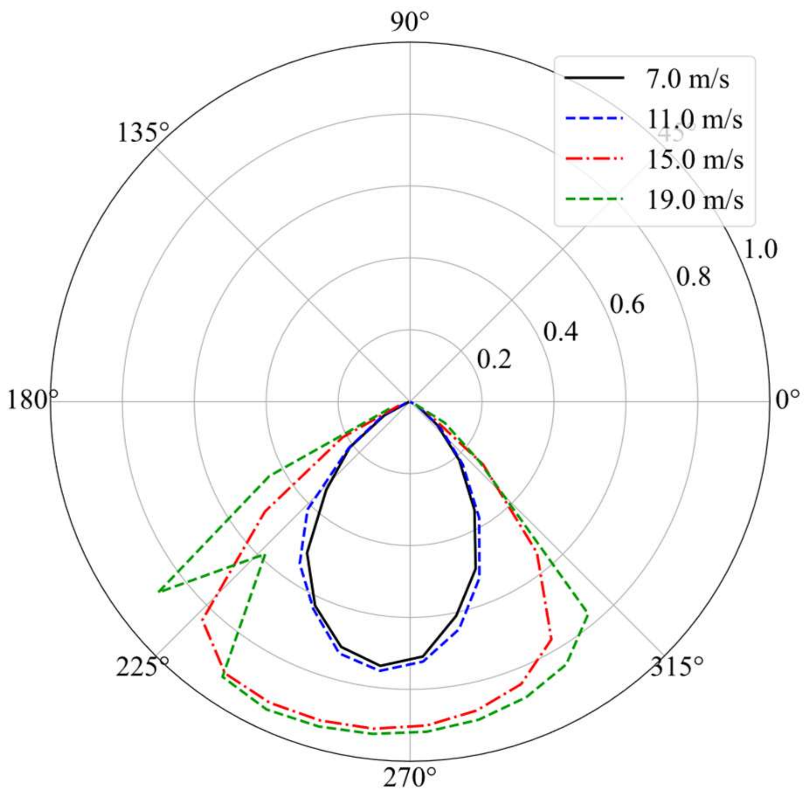
$V_{b,opt}$(m/s) vs. TWA and V_1

UFOWT Control

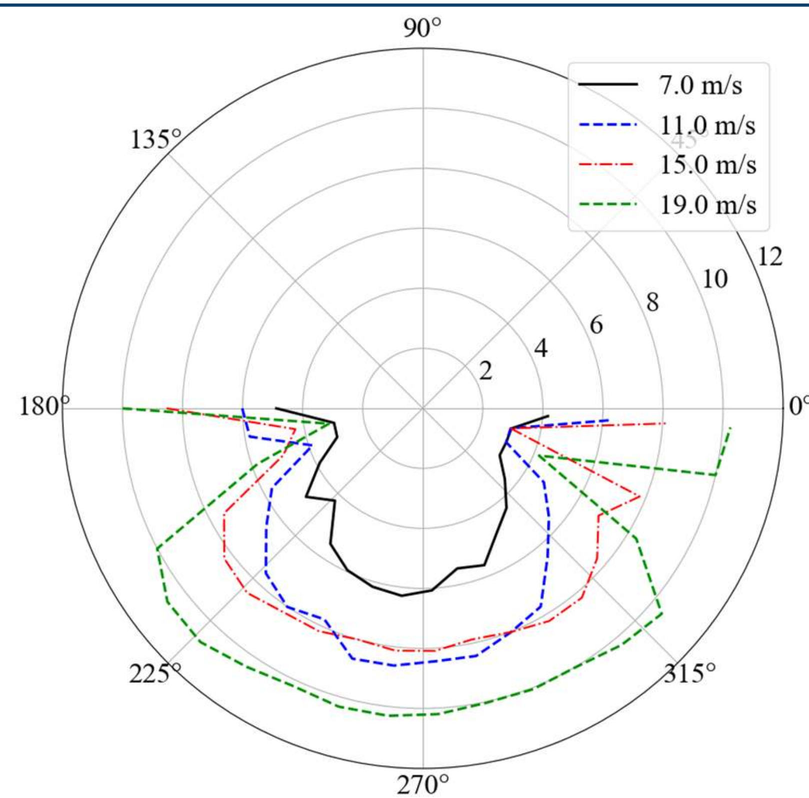
- Changing the C_p and the C_t map improves power performance for many cases
- However, better to use an optimization to find the best operating points



Energy Ship performance



$C_{p,net}$ vs. TWA and V_1



$V_{b,opt}$ vs. TWA and V_1

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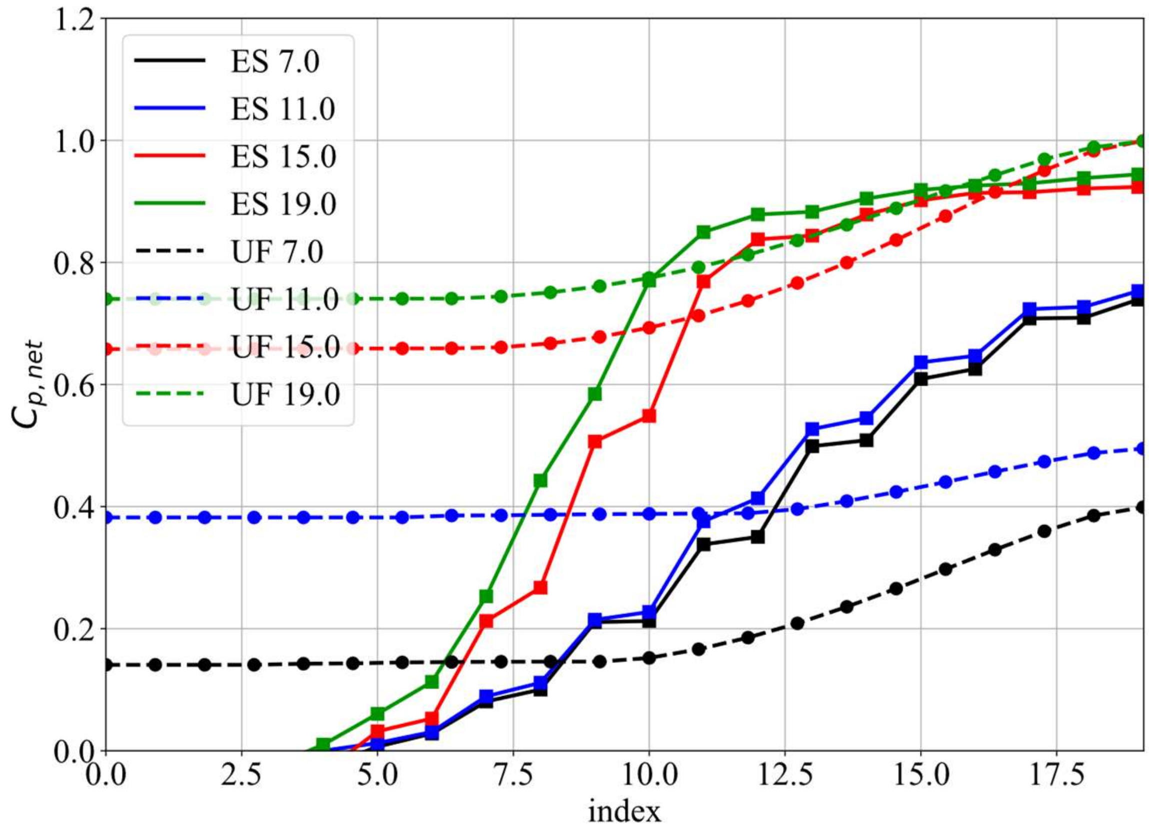
Note: performance is symmetric, one half plotted

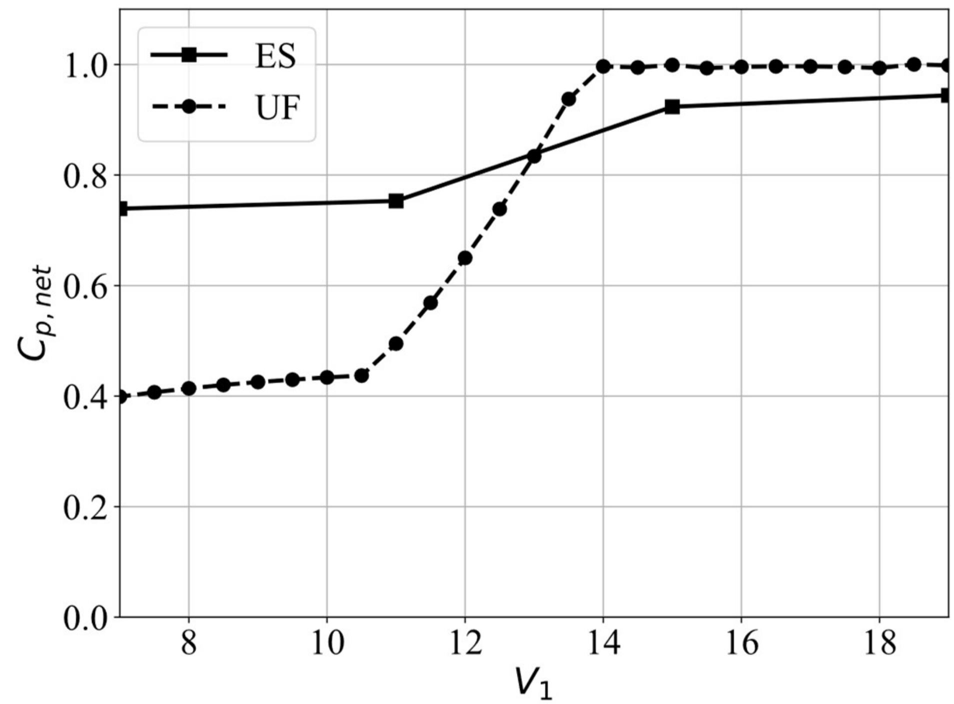
Comparison

- Power polars sorted for ascending $C_{p,net}$
- UFOWT performs better in best and worst cases
- Energy ship performs better in between



Comparison

- UFOWTs may perform better at very high wind speeds, but worse at low ones



Conclusion

Conclusions

- Developed models of two far-offshore wind energy systems
- These models can serve as the basis for further investigations
- More robust comparison is required, this requires design optimization and routing optimization
- Biggest differences are in optimal operating speeds. UFOWTs move slowly, energy ships move quickly

Future work

- Use the model for Design optimization and Optimization of control/operation
- Capital Cost estimates
- Routing → LCOE
- Account for other losses (i.e conversion efficiency, loading/unloading time, etc.)
- Dynamics
- Wind shear difference
- UFOWT hull design choices

References

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Questions

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Extra slides