Design optimization of floating offshore wind farms using a steady state motion and flow model

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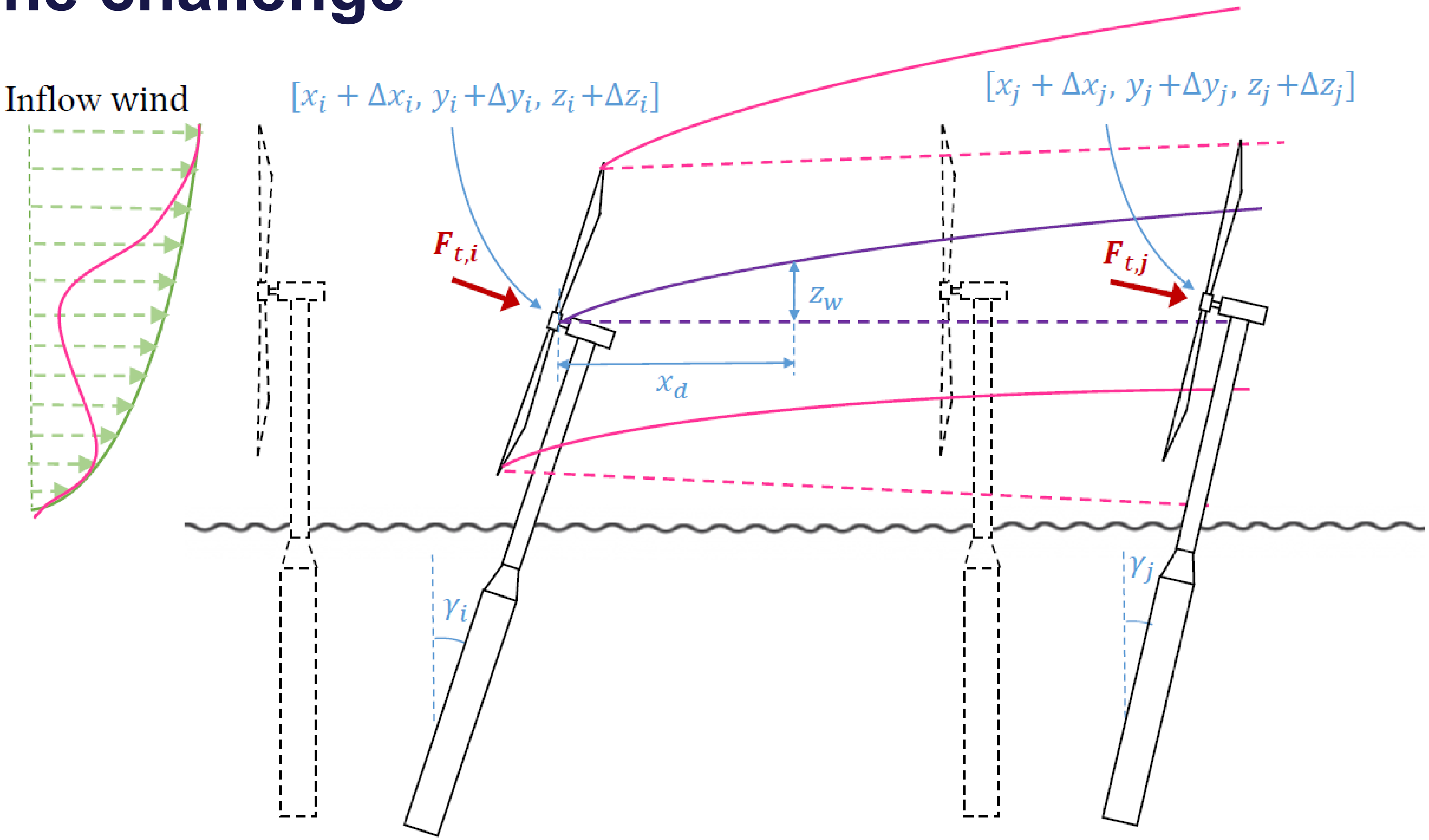
1. The background

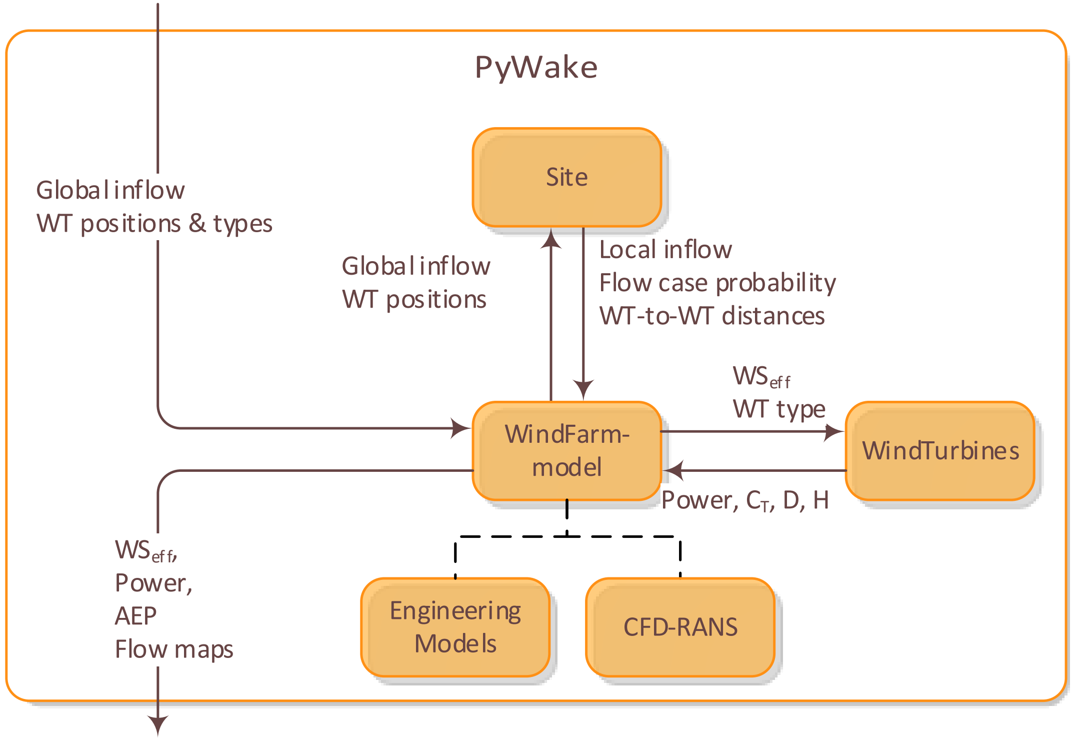
- Floating wind is set to grow tremendously in the near future.
- Large FOWFs will be designed and constructed.
- Design optimization of these FOWFs will be an important task.
- Most of the current studies on FOWF design ignore the motion of the FOWTs.
- A fast model that can capture the mean (and essential) effects introduced by platform motion will be needed for energy yield assessment of FOWFs.
- How much difference will floating cause for the power production and wake flow needs to be evaluated.

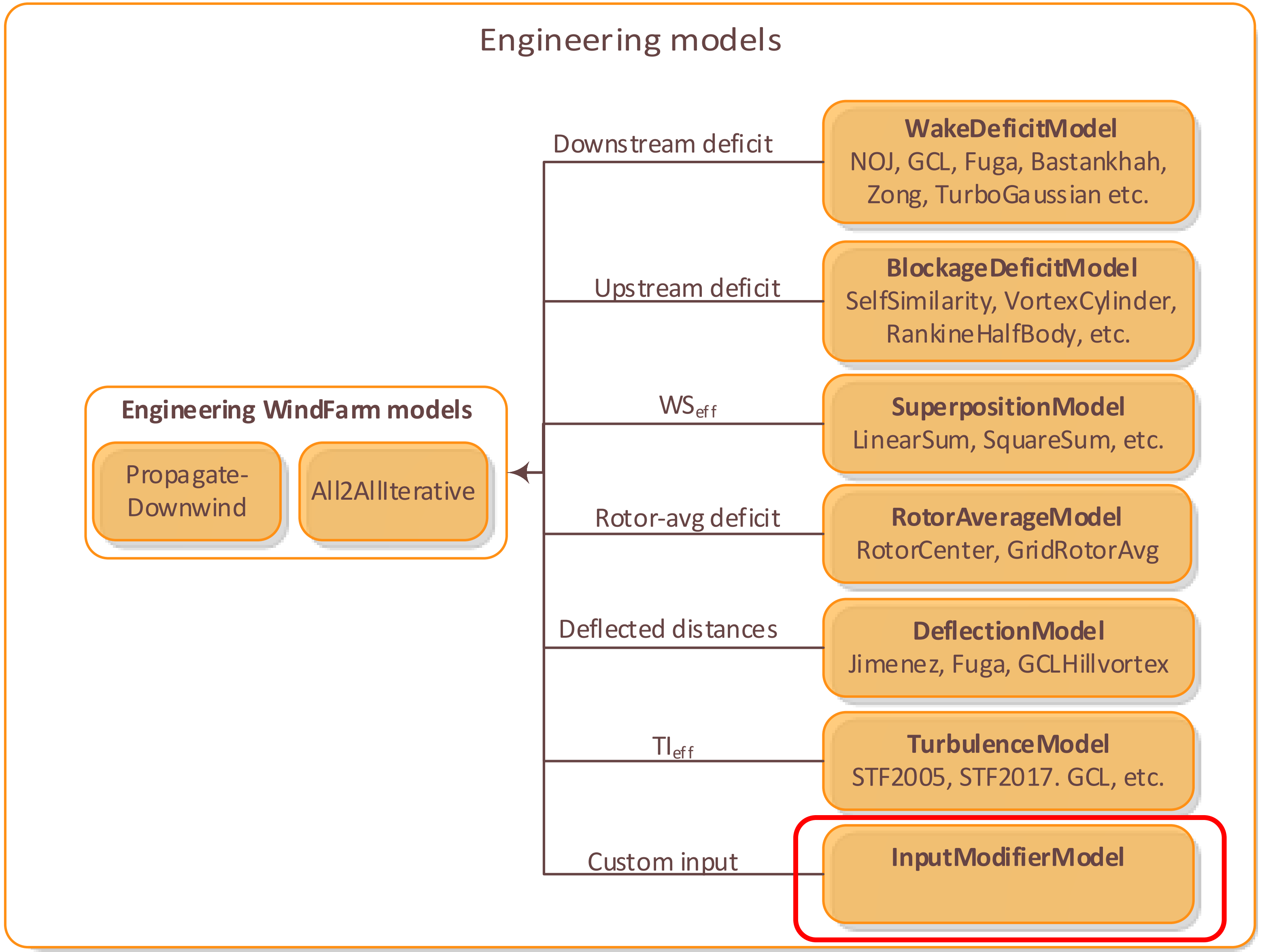
2. The challenge

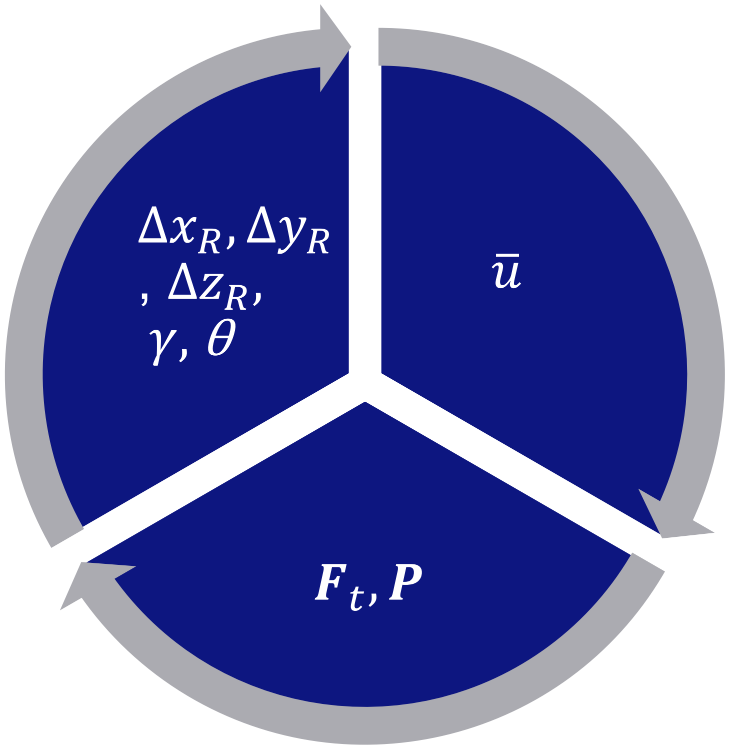


3. The modelling

- Python package developed by DTU Wind Energy
- Open source and available at PyPi and https://gitlab.windenergy.dtu.dk/TOPFARM/PyWake
- Simulates static flow in wind farms
- Calculate AEP and flow maps
- Modular, flexible and very fast
- Used by +35 companies



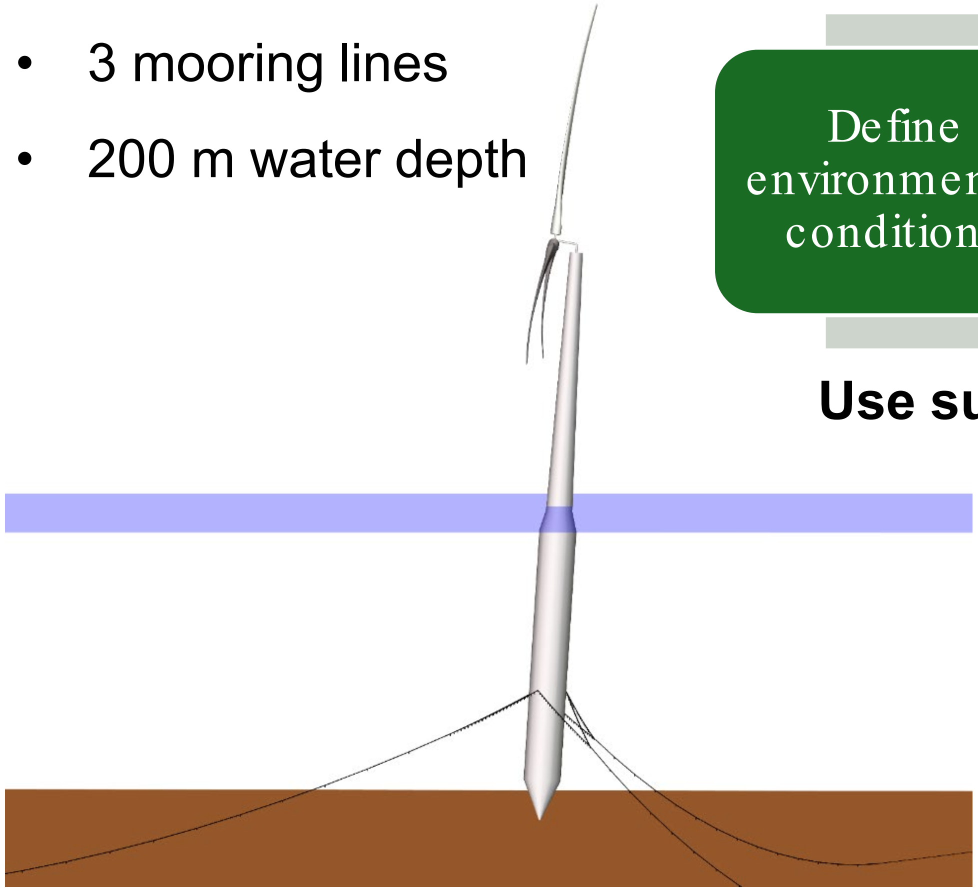


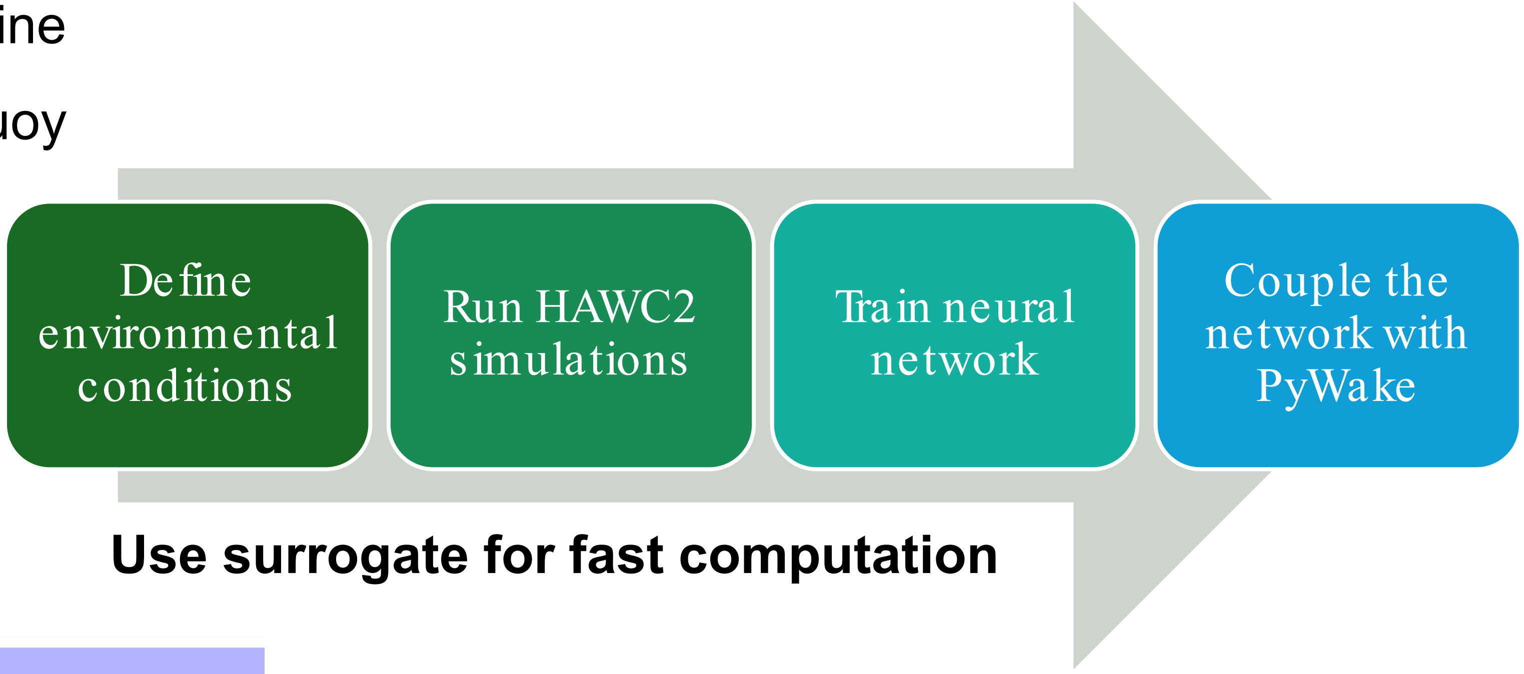


Iteratively solve for platform movements and power production

Turbine model

- IEA 15 MW reference turbine
- WindCrete floating spar buoy
- 3 mooring lines
- 200 m water depth

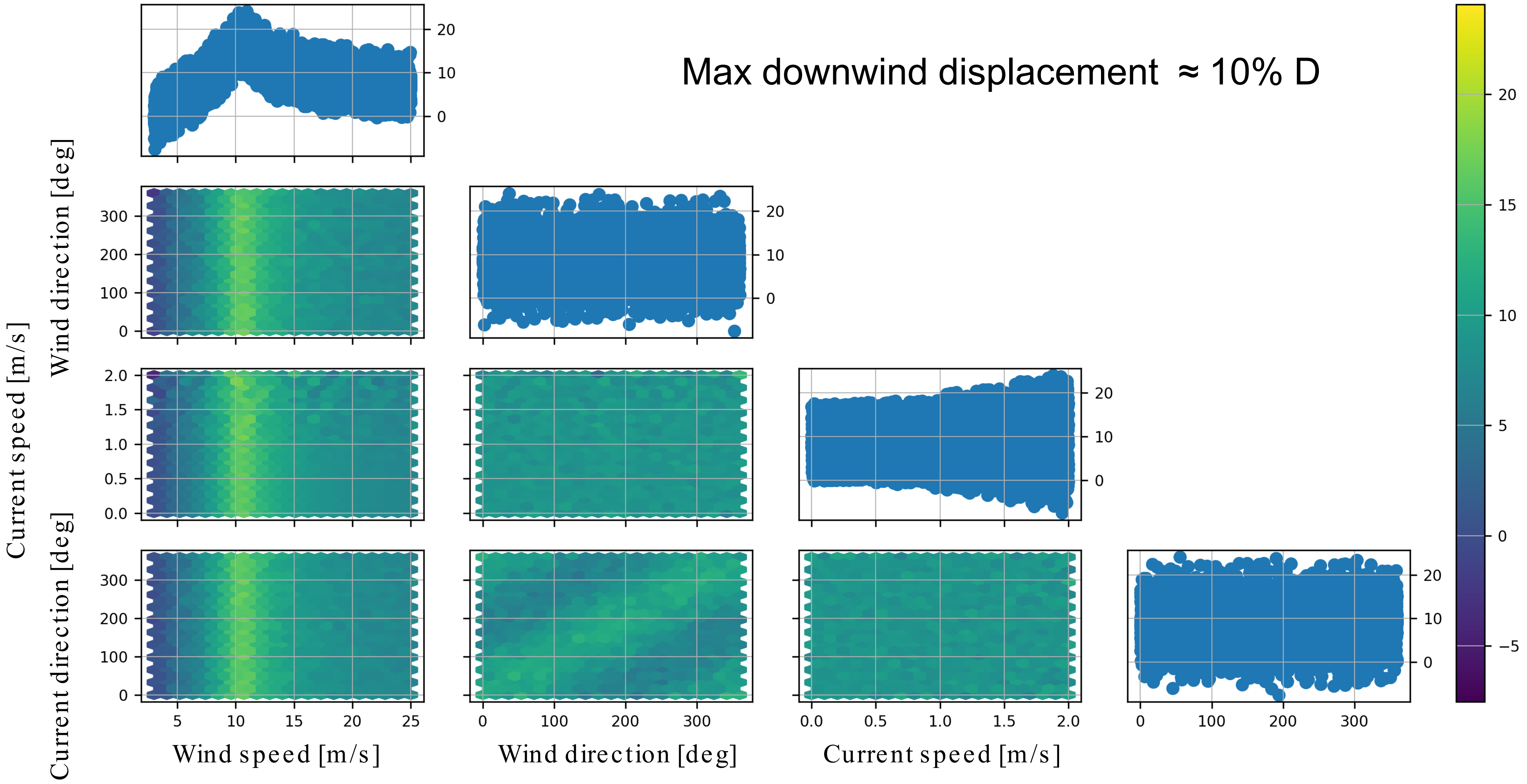




Use surrogate for fast computation

Database from HAWC2 Simulations

Max downwind displacement ≈ 10% D

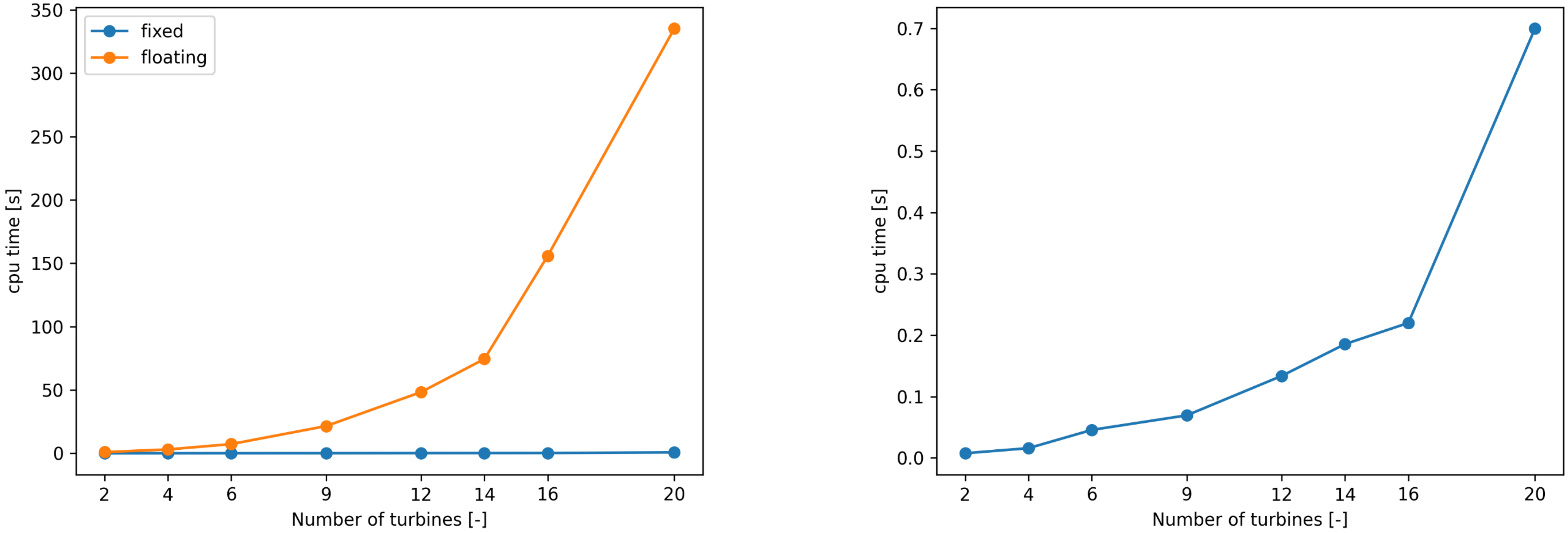


Surrogate inputs and outputs

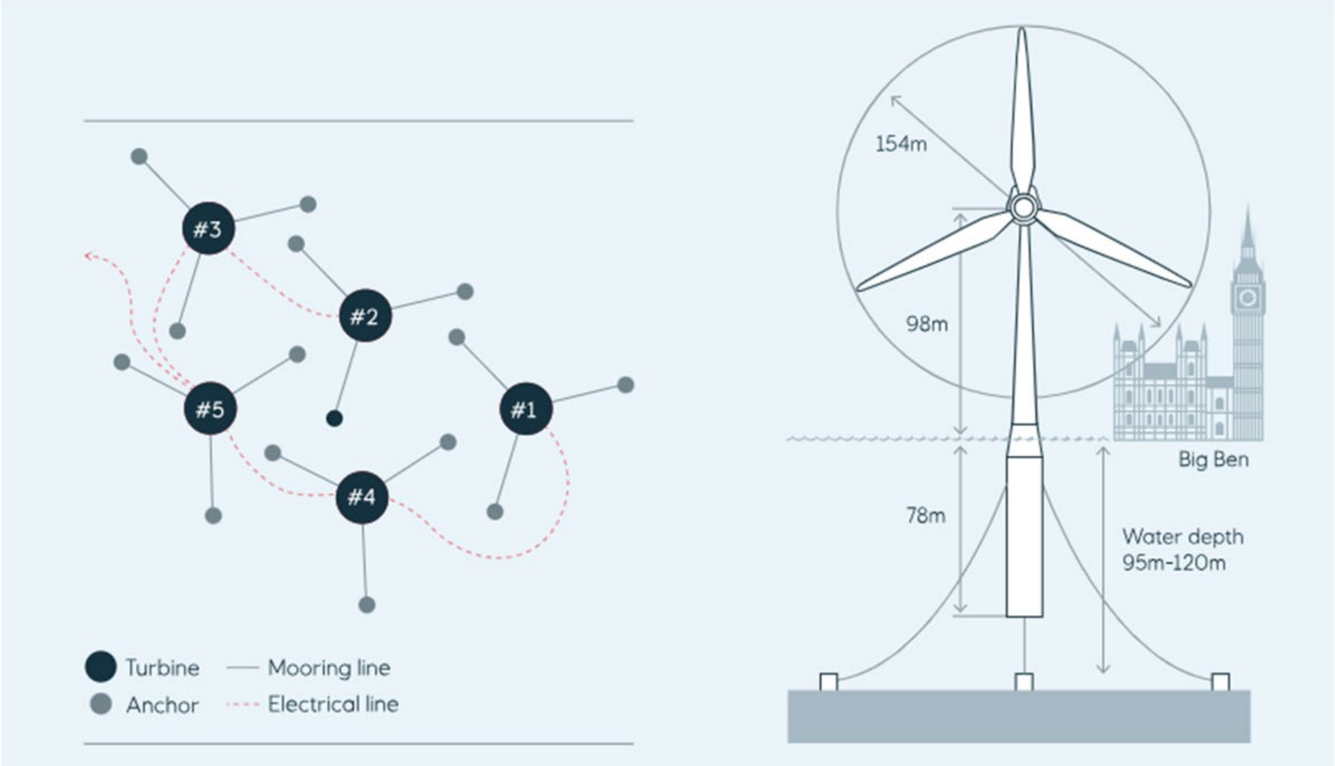
Inputs	Outputs
• Wind speed • Wind direction • Current speed • Current-wind misalignment	• Downwind/crosswind displacement • Tilt/yaw rotation • Power and thrust

Note: The procedure for modelling steady state motion and flow of floating wind farms using PyWake will be presented in TORQUE conference in May 2024, by Riccardo Riva with the title "**Incorporation of floater rotation and displacement in a static wind farm simulator**". Full paper will come out earlier.

Computational speed comparison



3. The optimization



Design of Hywind Scotland

(source: https://www.equinor.com/energy/hywind-scotland)

Problem formulation

Objective: $\max_{\boldsymbol{L}} AEP$

Design variable:

$$\boldsymbol{L} = [x_1, x_2, \dots, x_{N_{wt}}, y_1, y_2, \dots, y_{N_{wt}}]$$

Constraints:

Wind farm boundary:

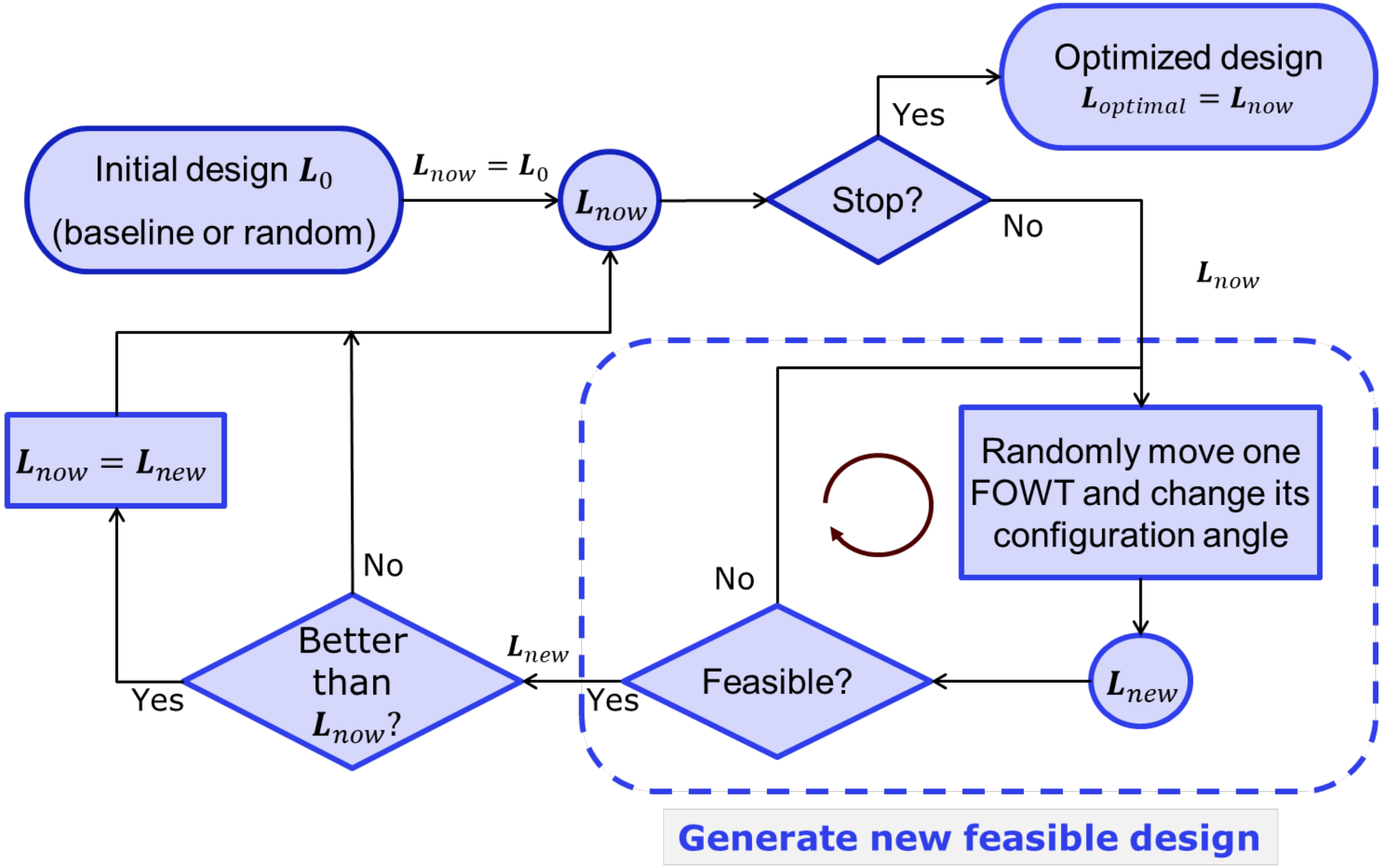
$$(x_i, y_i) \in S_{feasible}, \text{for } i = 1, 2, \dots, N_{wt}$$

Minimal distance between FOWTs:

$$\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \geq D_{min},$$

$$\text{for } i, j = 1, 2, \dots, N_{wt} \text{ and } i \neq j$$

Optimization algorithm: Random Search



- Random search is a wind farm layout optimization algorithm first proposed by Feng and Shen [1].
- Simple and easy to implement.
- Great performance in various wind farm optimization applications [3, 4].

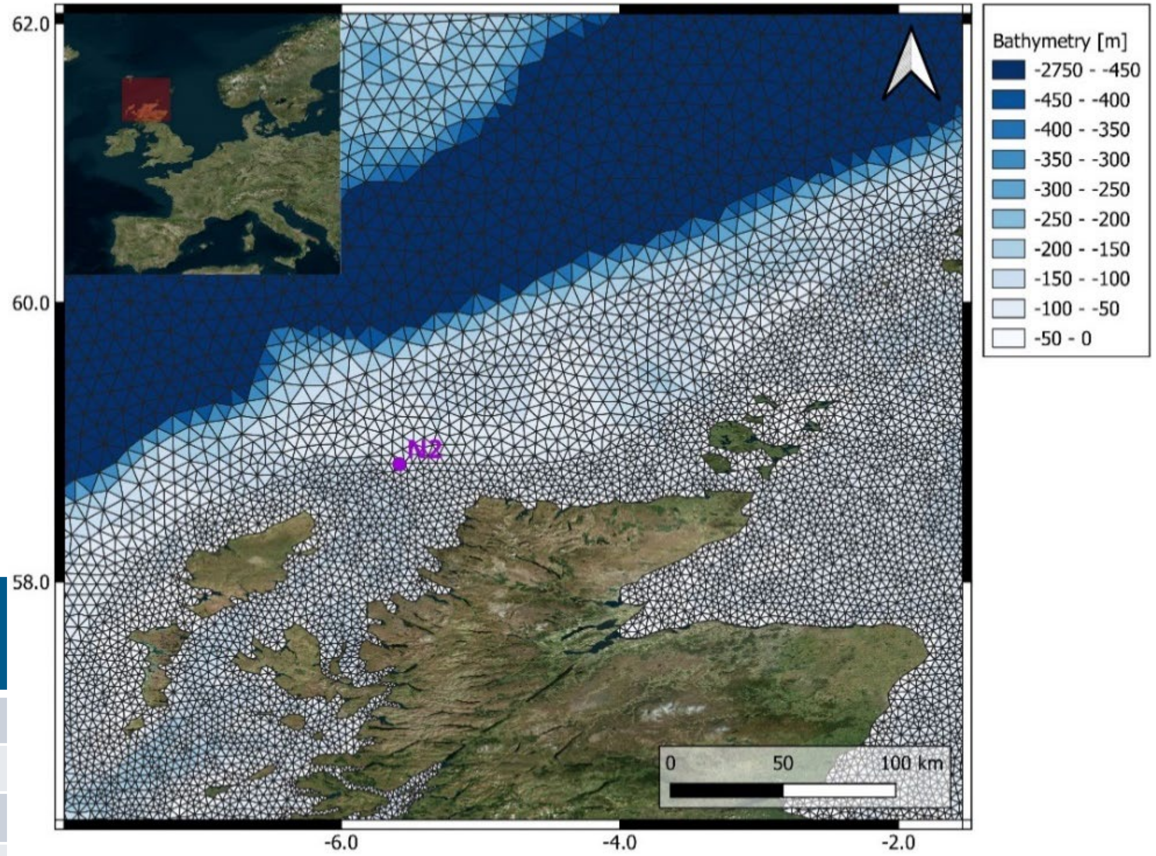
[1] Feng, J., & Shen, W.Z. (2015). Solving the wind farm layout optimization problem using random search algorithm. Renewable Energy, 78, 182-192.
[2] Feng, J., & Shen, W.Z. (2017). Design optimization of offshore wind farms with multiple types of wind turbines. Applied Energy, 205, 1283–1297.
[3] Brogna, R., Feng, J., Sørensen, J. N., Shen, W. Z., & Porté-Agel, F. (2020). A new wake model and comparison of eight algorithms for layout optimization of wind farms in complex terrain. Applied Energy, 259, 114189.

4. The metocean condition

Havbredey FOWF site in Scotland

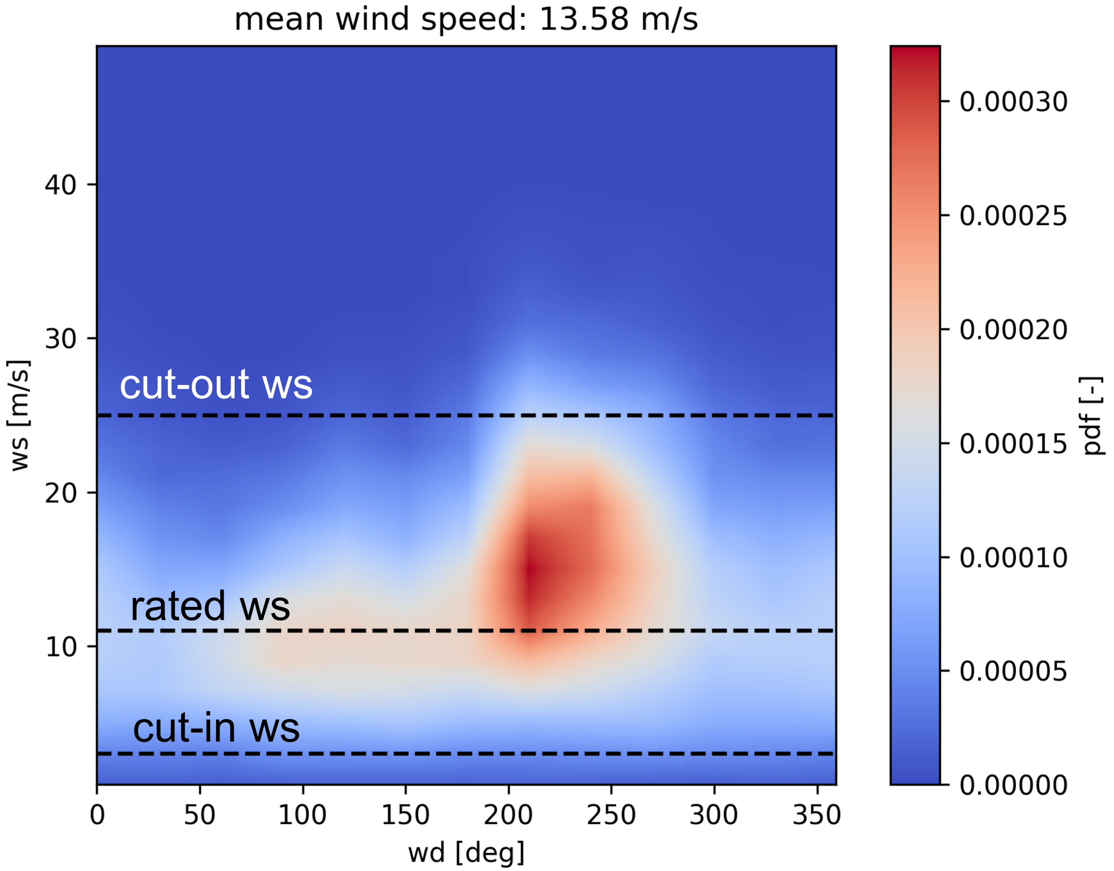
- Climate Forecasting System Reanalysis
- DHI North Europe Spectral Wave model
- DHI 3D Hydrodynamic UK/North Sea model

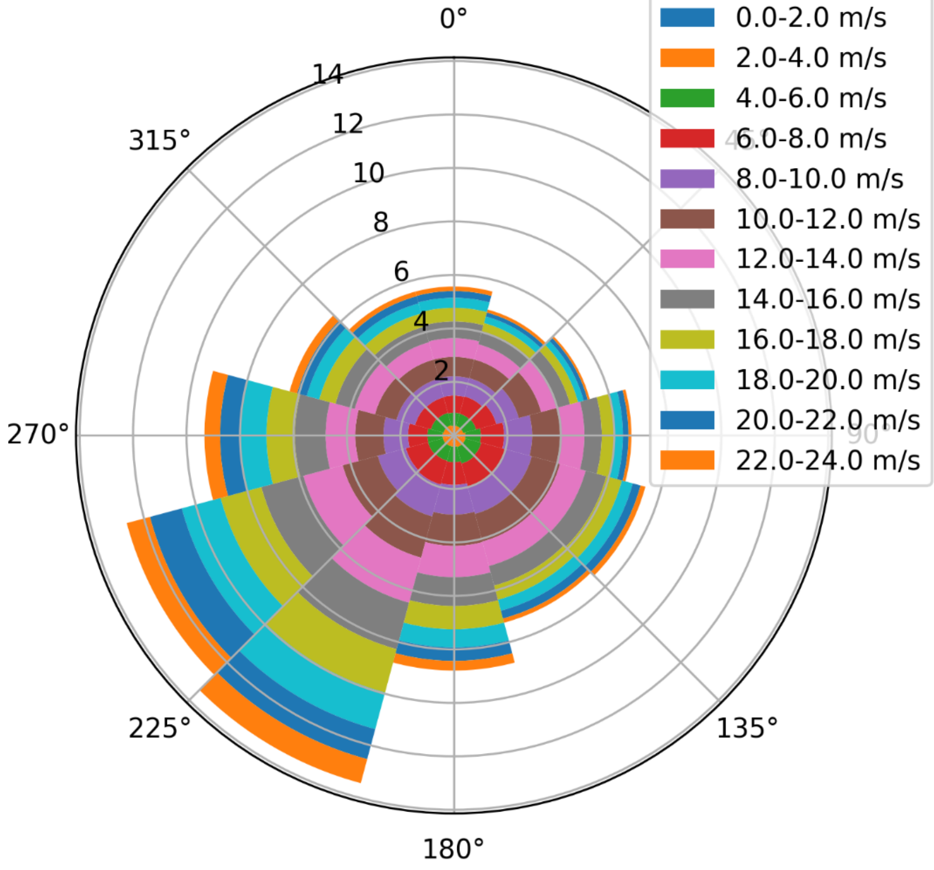
Dataset	Source	Grid cell size	Temporal res.	Temporal extent
Winds	CFSR	~23 km	Hourly	2001-2021
Waves	SW_{NE}	~3-30 km	Hourly	2001-2021
Water level	HD_{UKNS}	~2-12 km	30 min	2001-2021
Depth-averaged	HD_{UKNS}	~2-12 km	30 min	2001-2021
Current profiles	HD_{UKNS}	~2-12 km	30 min	2018

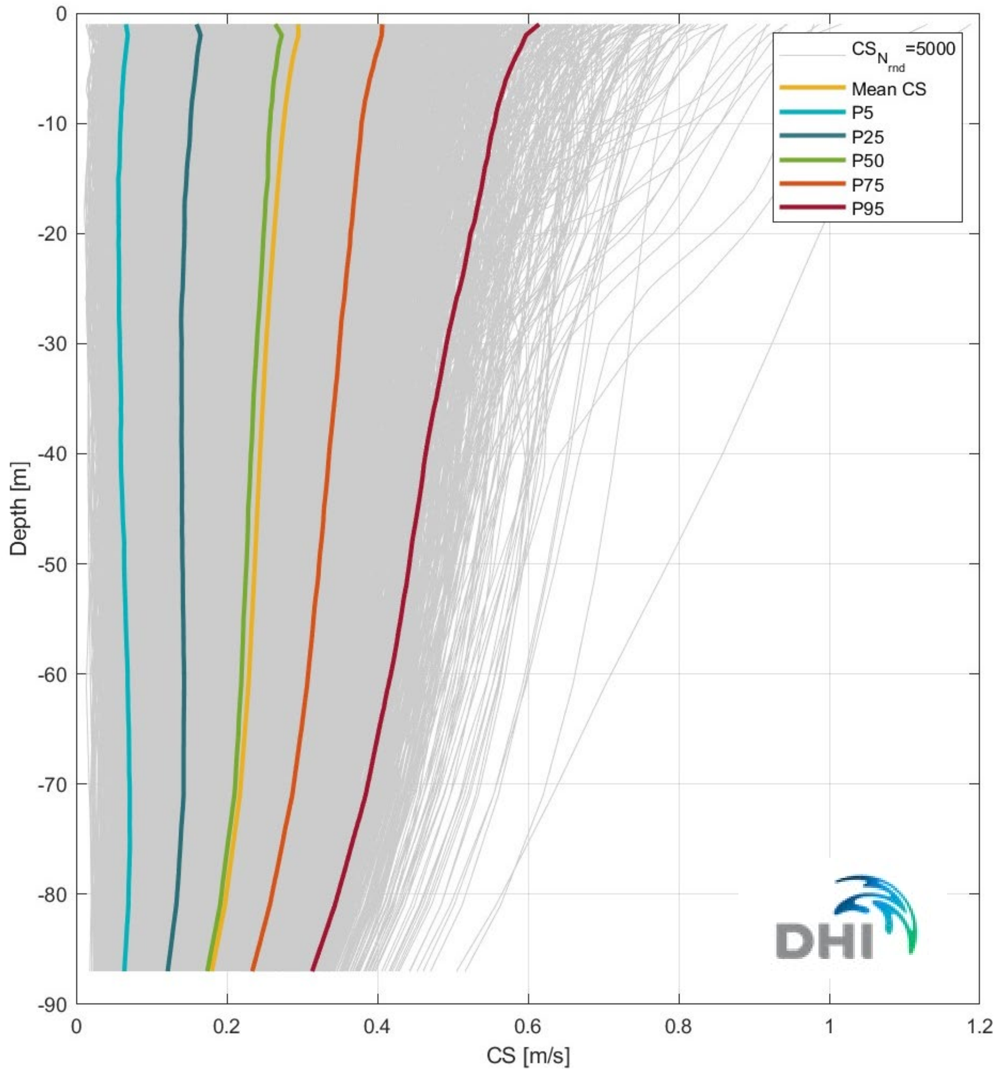


Lon	Lat	Depth	Grid cell size HD_{UKNS}	Grid cell size SW_{NE}
-5.58093°	58.84328°	85.5 m	~ 6 km	~13 km

Original wind condition (u_{mean} = 13.58 m/s)



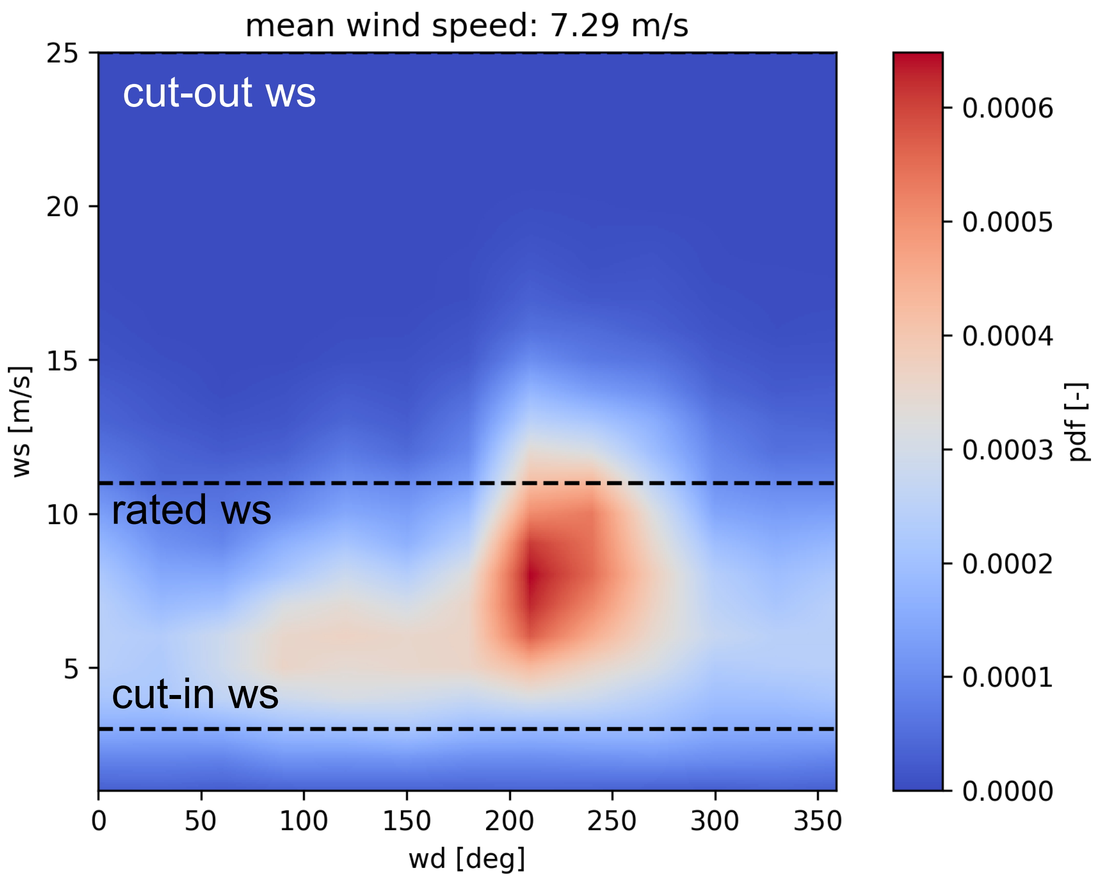


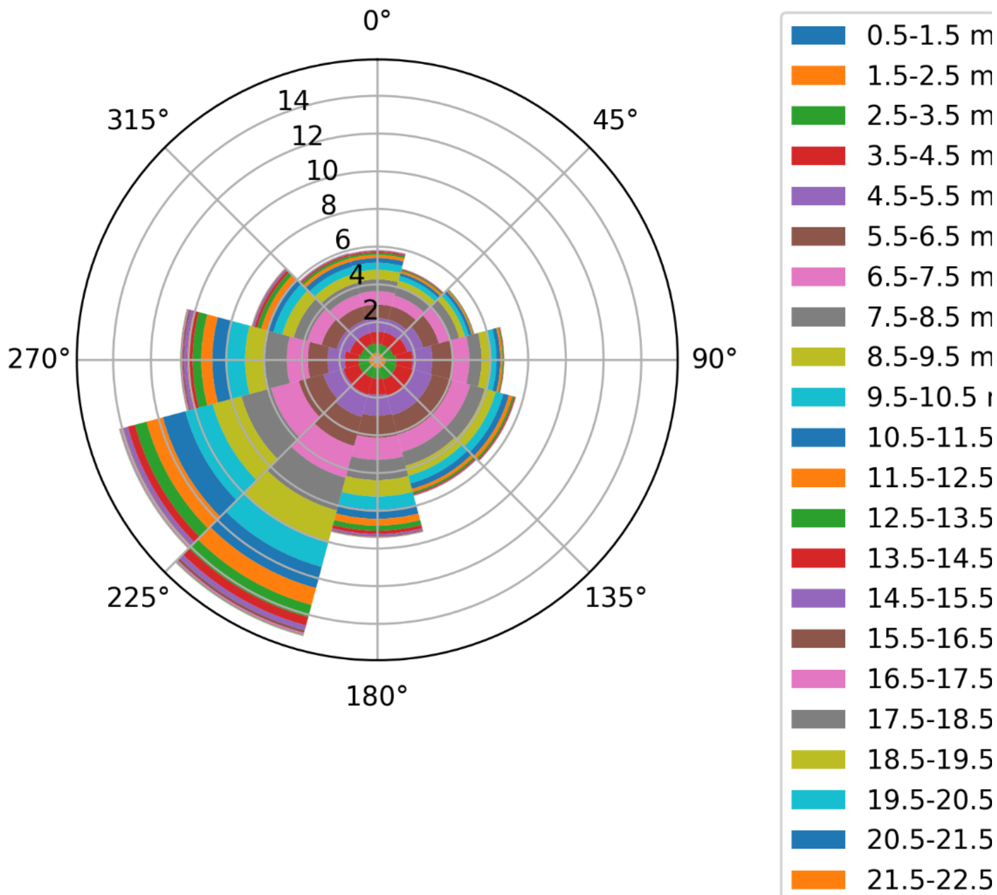


Current profiles from 3D HD_{UKNS} for year 2018

- A representative current condition is selected.
- Current speed: 0.25 m/s
- Current direction: 60 deg
- Wind shear exponent: 0.14
- Turbulence intensity: 0.07

Reduced wind condition ($u_{mean} = 7.29$ m/s)



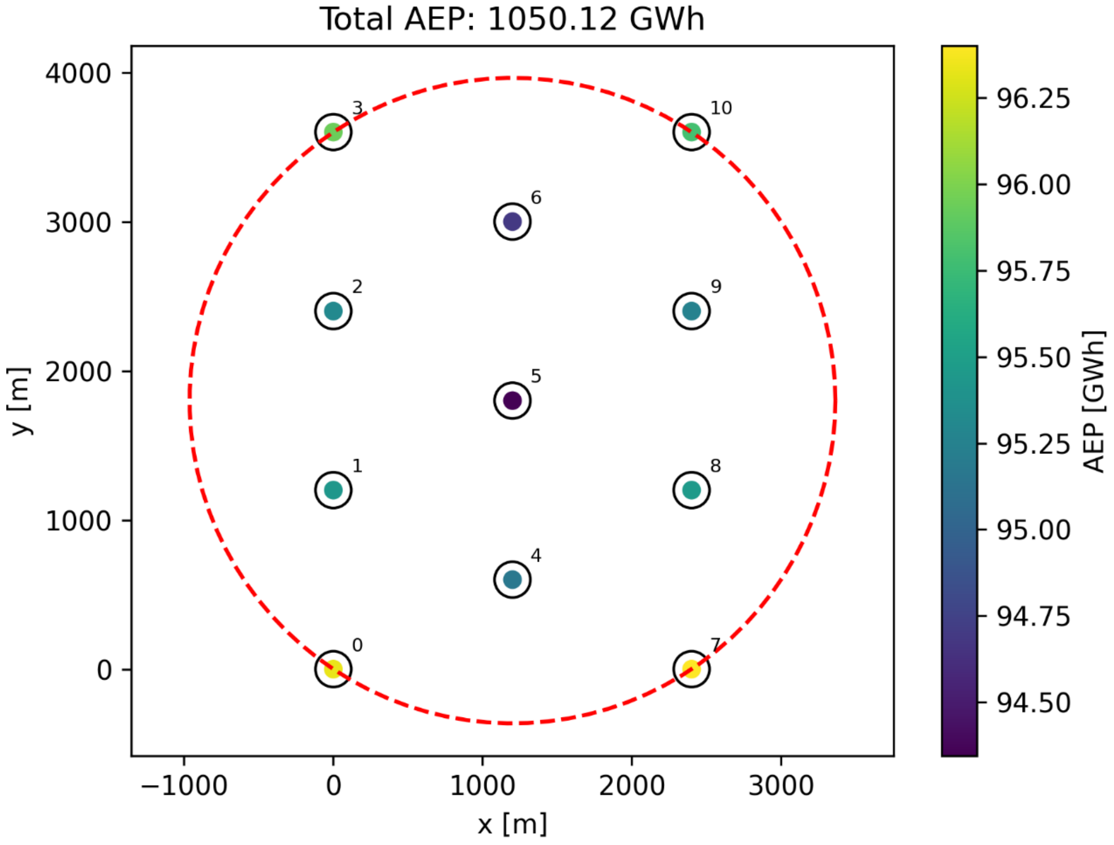


5. The Results

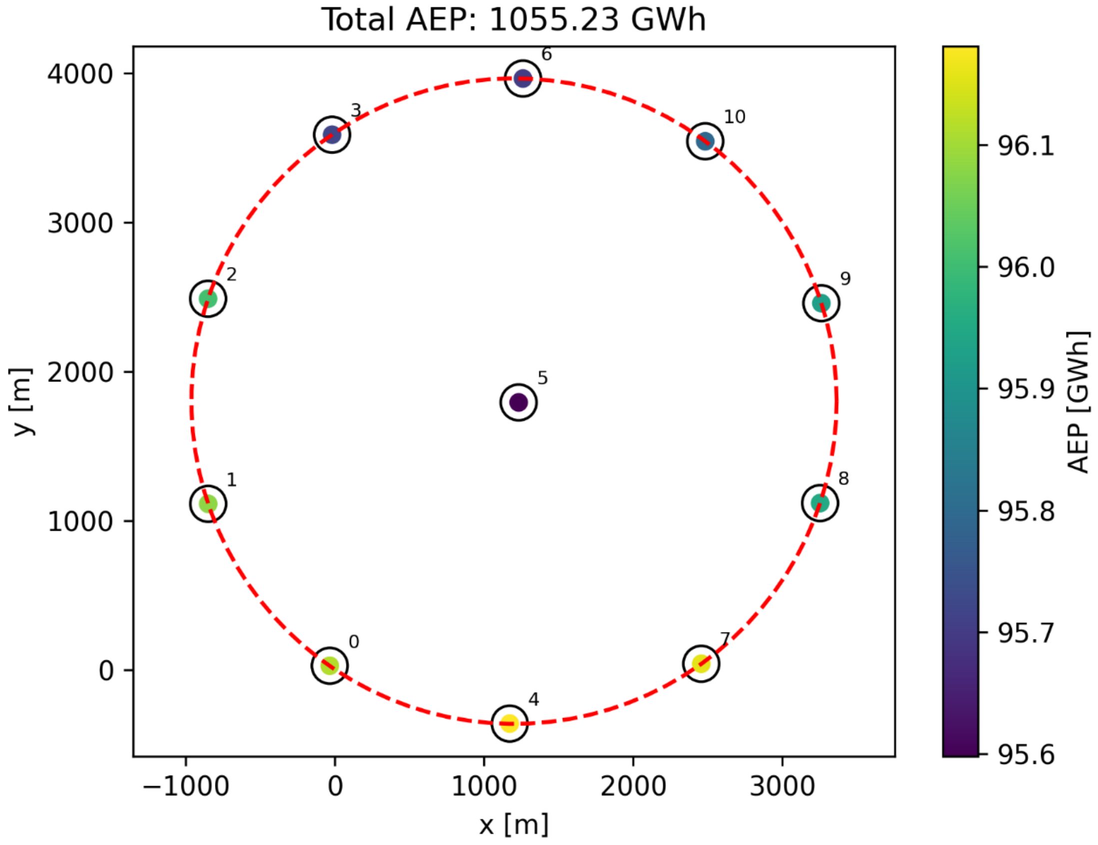
Original wind condition

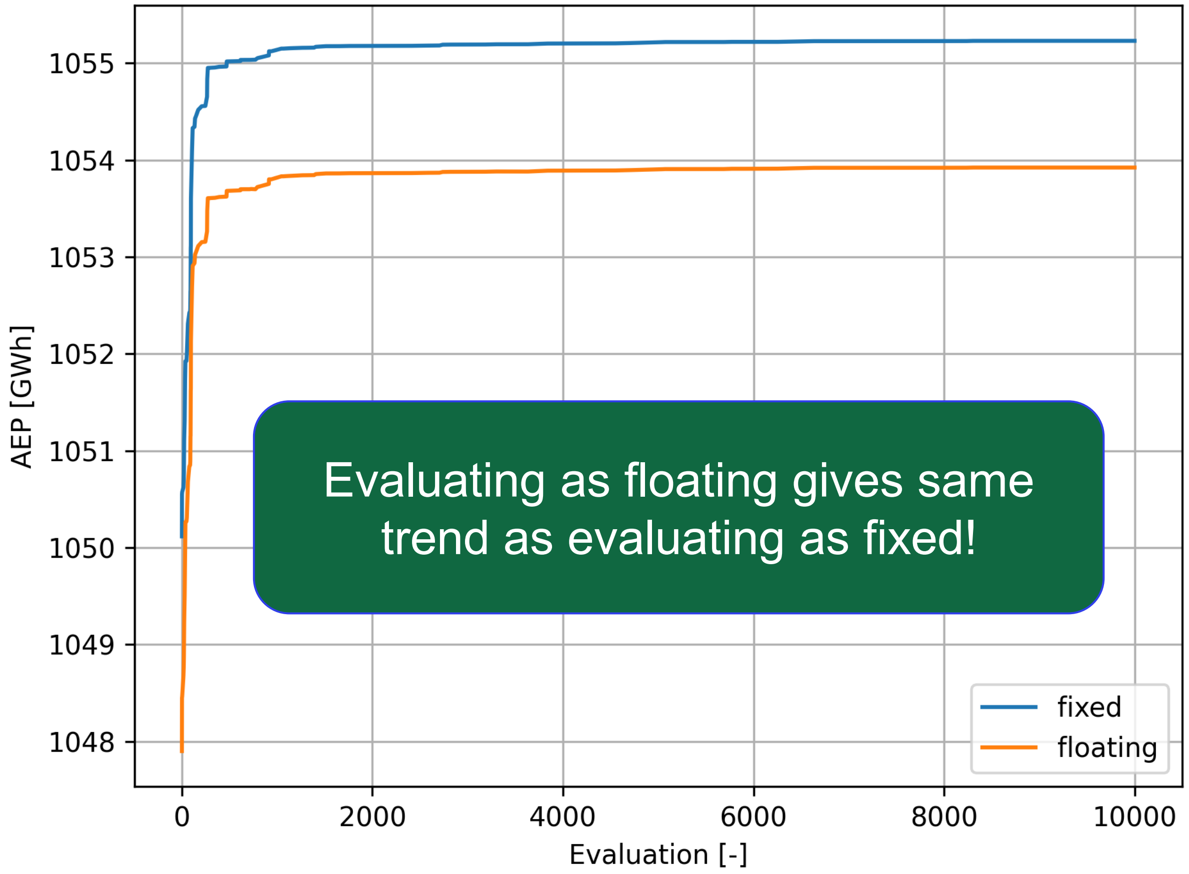
(u_{mean} = 13.58 m/s)

Floating: 1047.90 GWh



Floating: 1053.92 GWh





AEP_gross = 1073.7503 GWh

Consider as fixed:

AEP_initi = 1050.1161 GWh, CF = 72.65 %

AEP_optim = 1055.2304 GWh, CF = 73.01 %

wake_loss_initi = 2.2011 %

wake_loss_optim = 1.7248 %

AEP increase percentage = **0.4870 %**

Consider as floating:

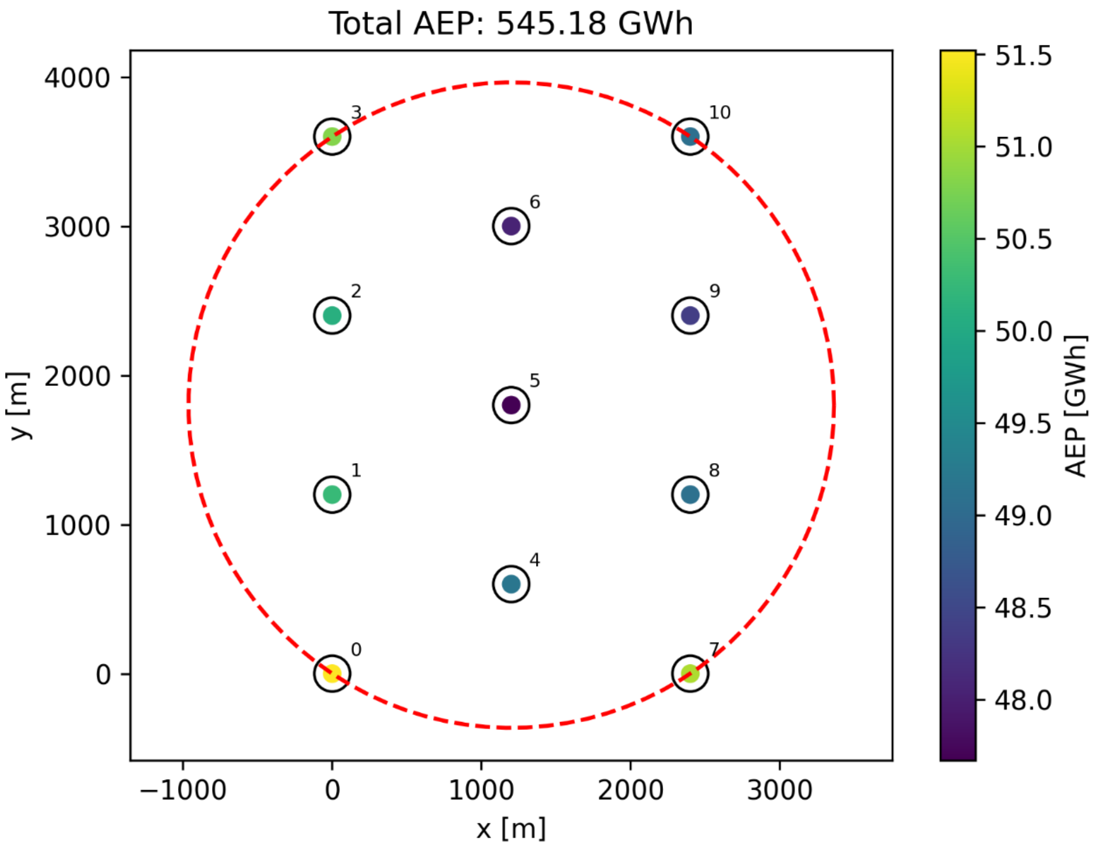
AEP_initi = 1047.9004 GWh

AEP_optim = 1053.9225 GWh

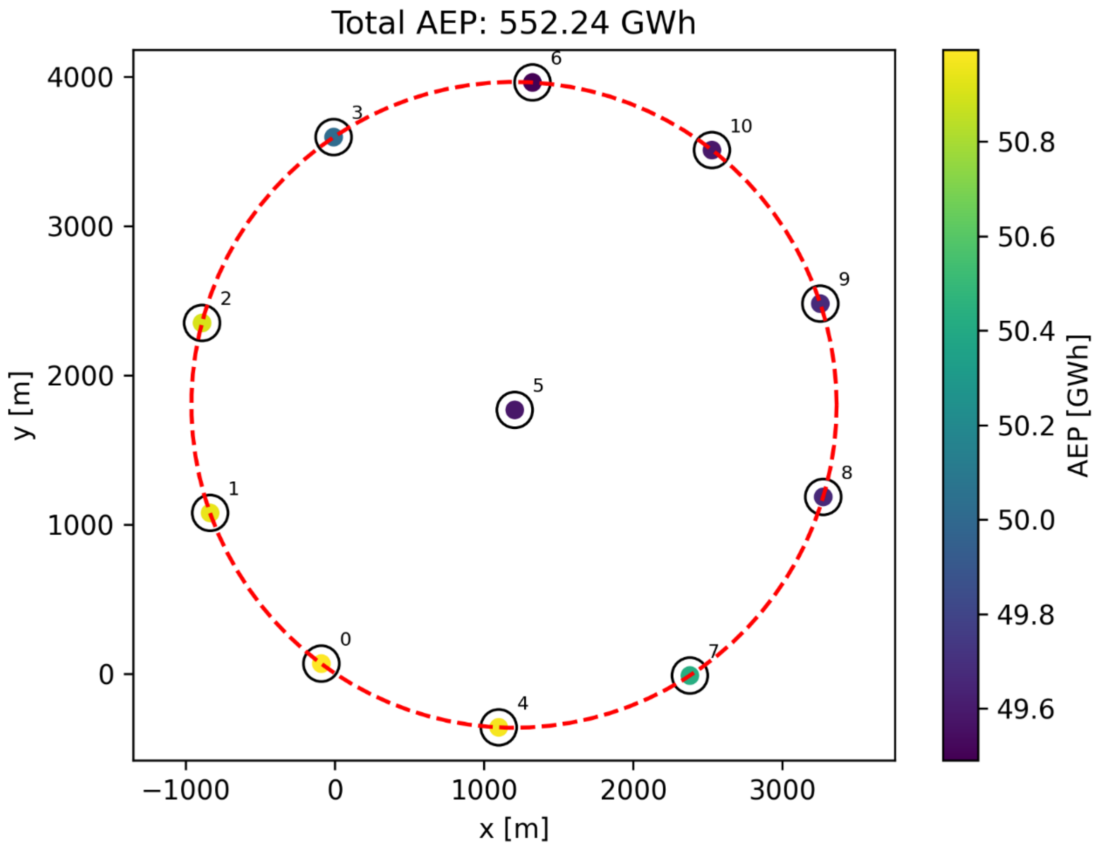
AEP increase percentage = **0.5747 %**

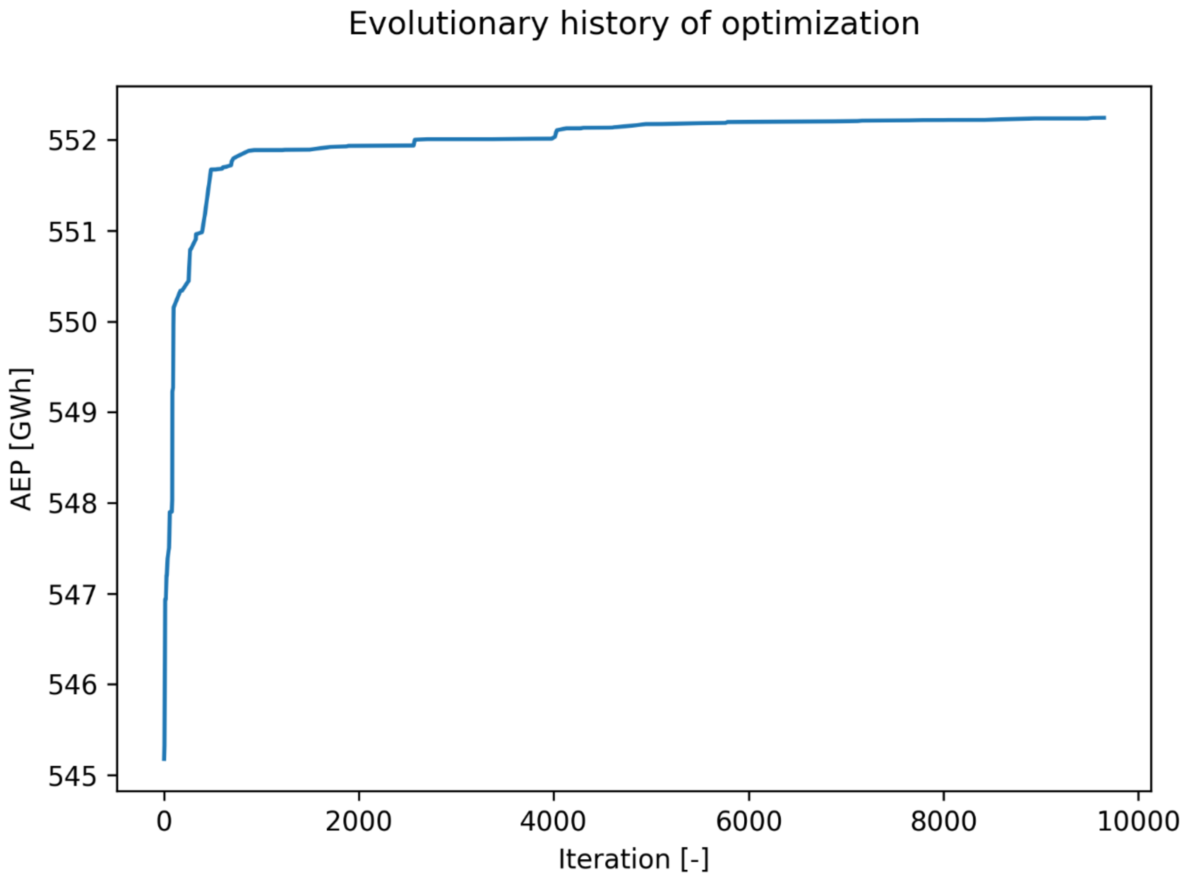
Reduced wind condition
($u_{mean} = 7.29$ m/s)

Floating: 543.57 GWh



Floating: 551.84 GWh





AEP_gross = 582.0226 GWh

Consider as fixed:

AEP_initi = 545.1751 GWh, CF = 37.72 %

AEP_optim = 552.2446 GWh, CF = 38.21 %

wake_loss_initi = 6.3309 %

wake_loss_optim = 5.1163 %

AEP increase percentage = **1.2967 %**

Consider as floating:

AEP_initi = 543.5741 GWh

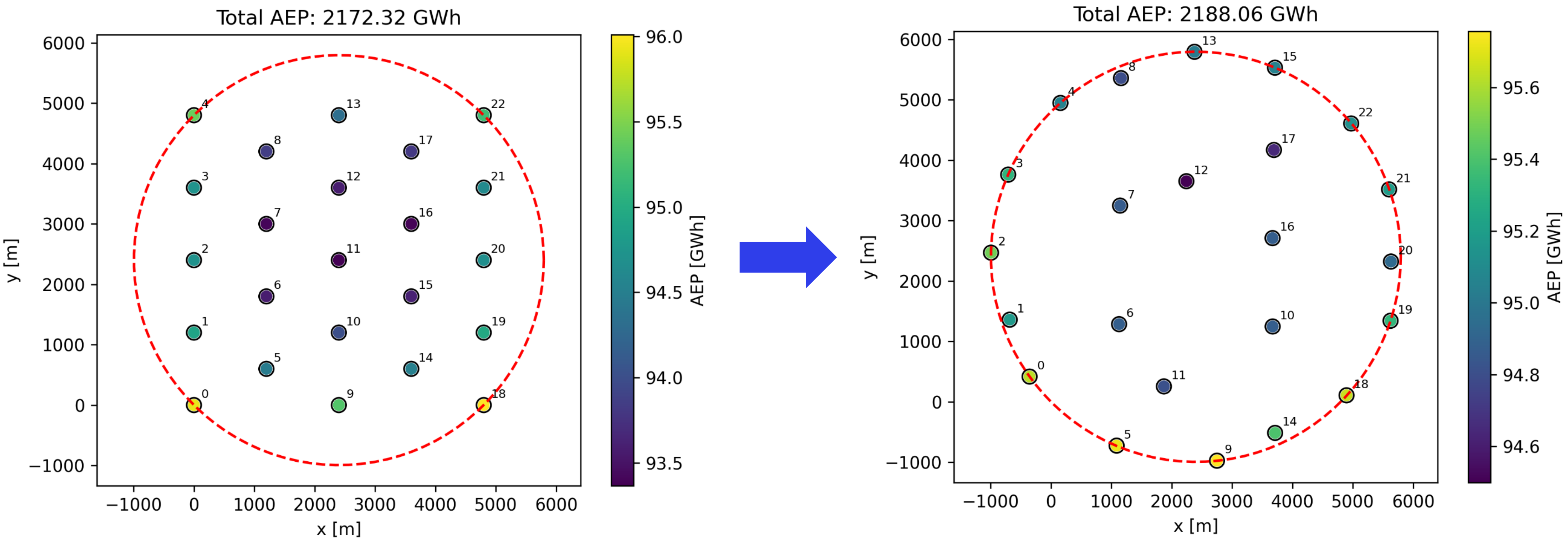
AEP_optim = 551.8396 GWh

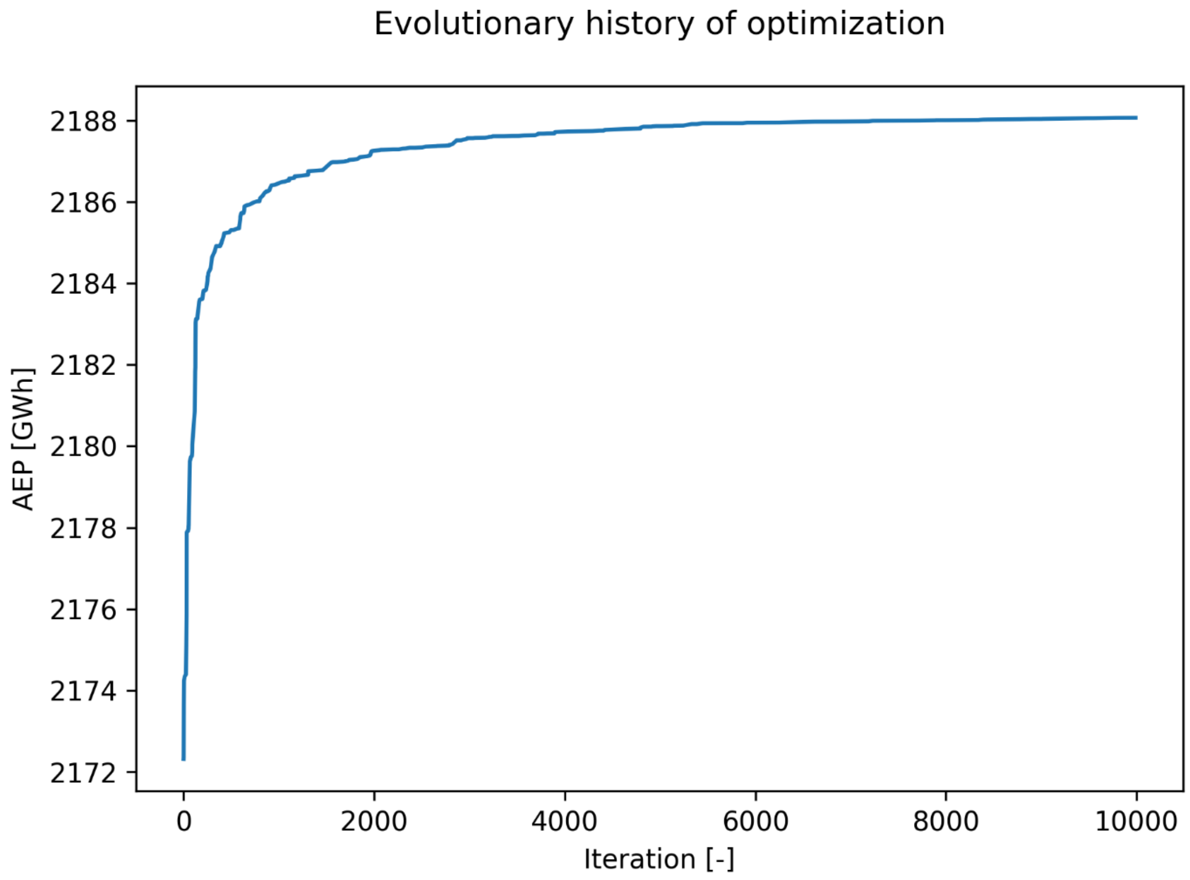
AEP increase percentage = **1.5206 %**

23 turbines under original wind condition

Floating: 2167.33 GWh

Floating: 2185.24 GWh





AEP_gross = 2245.1143 GWh

Consider as fixed:

AEP_initi = 2172.3154 GWh, CF = 71.88 %

AEP_optim = 2188.0640 GWh, CF = 72.40 %

wake_loss_initi = 3.2426 %

wake_loss_optim = 2.5411 %

AEP increase percentage = **0.7250 %**

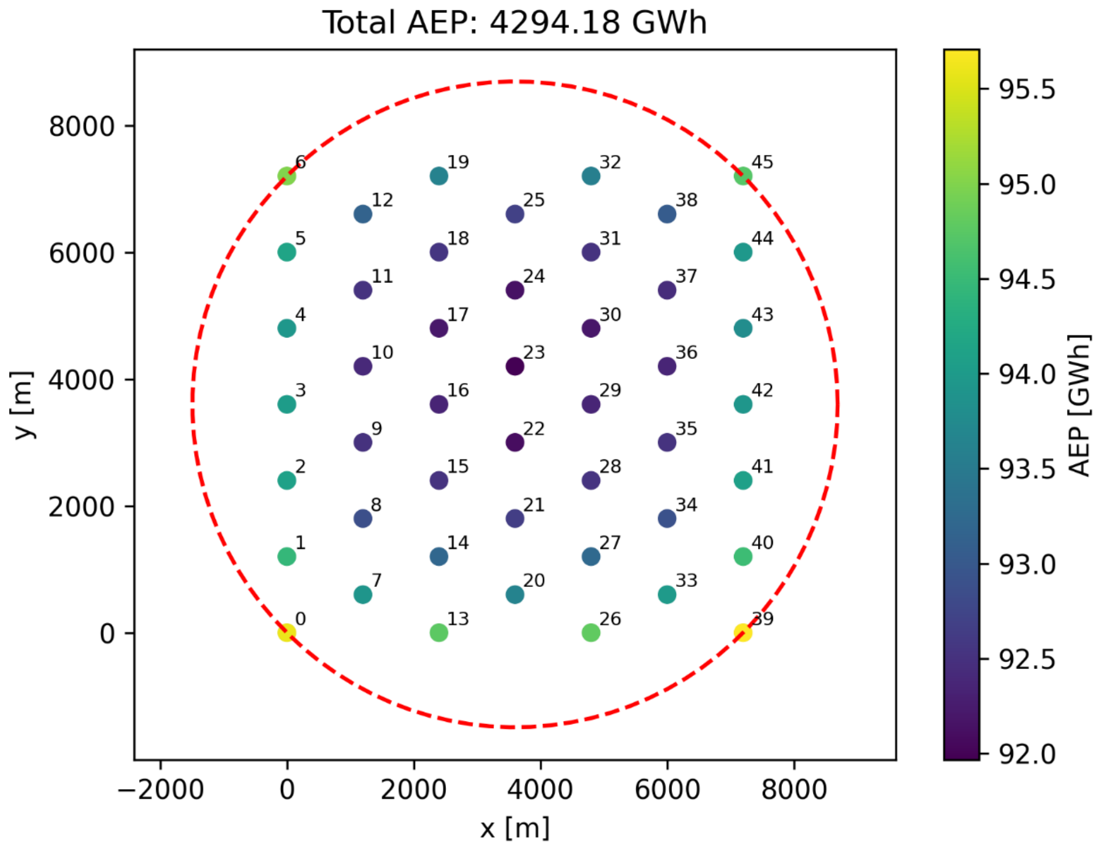
Consider as floating:

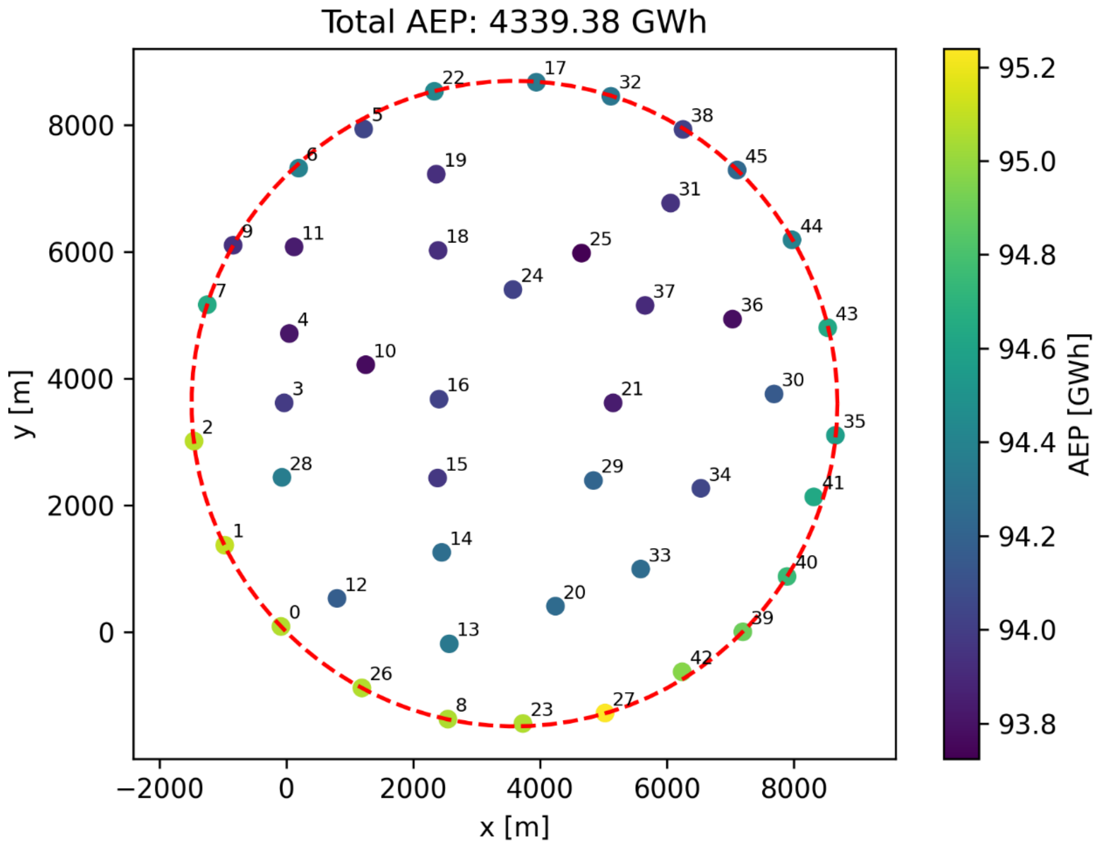
AEP_initi = 2167.3324 GWh

AEP_optim = 2185.2427 GWh

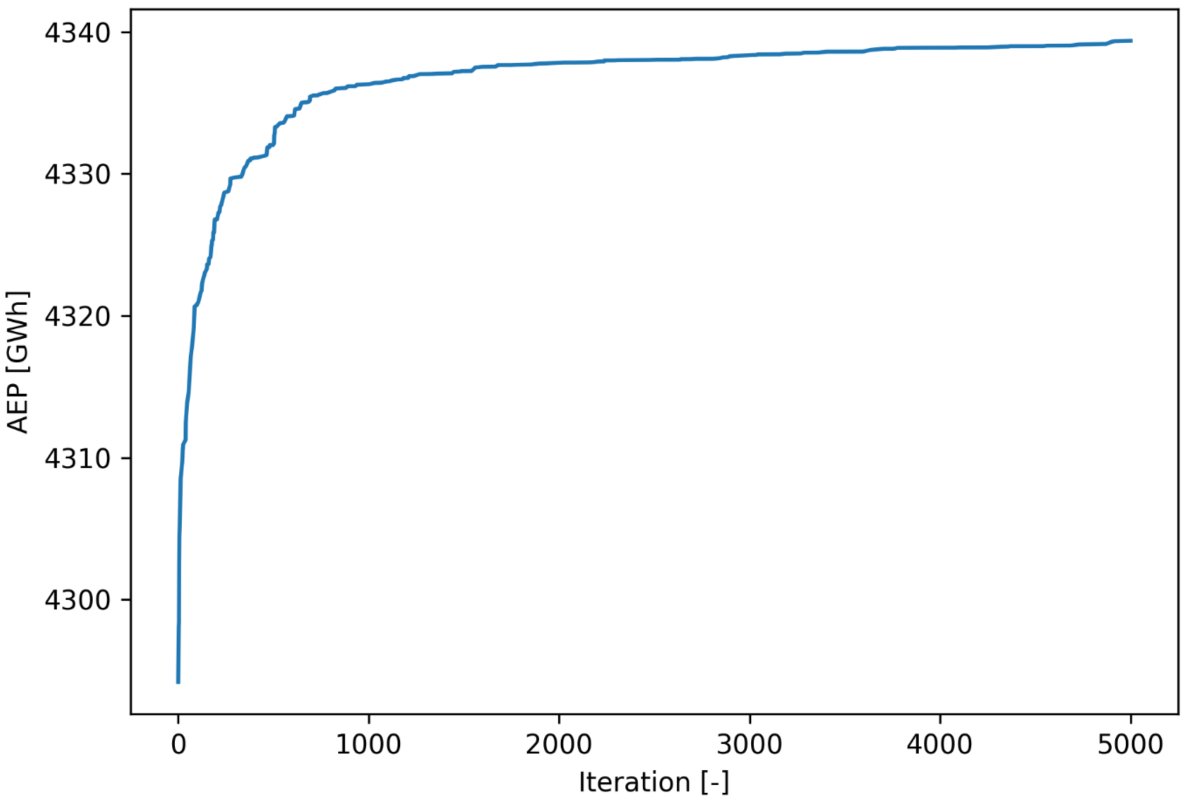
AEP increase percentage = **0.8264 %**

46 turbines under original wind condition





Evolutionary history of optimization



AEP_gross = 4490.2287 GWh

Consider as fixed:

AEP_initi = 4294.1789 GWh, CF = 71.04 %

AEP_optim = 4339.3799 GWh, CF = 71.79 %

wake_loss_initi = 4.3661 %

wake_loss_optim = 3.3595 %

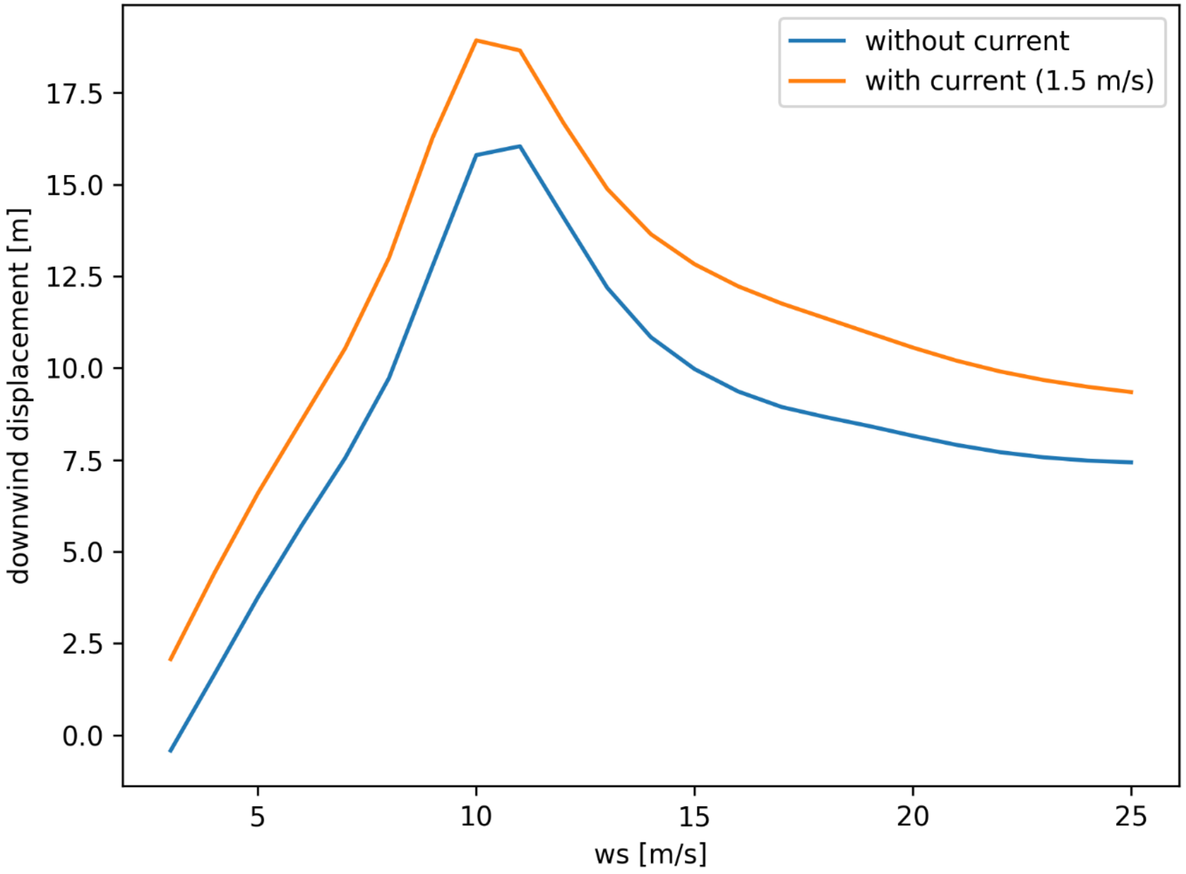
AEP increase percentage = **1.0526 %**

6. Conclusions

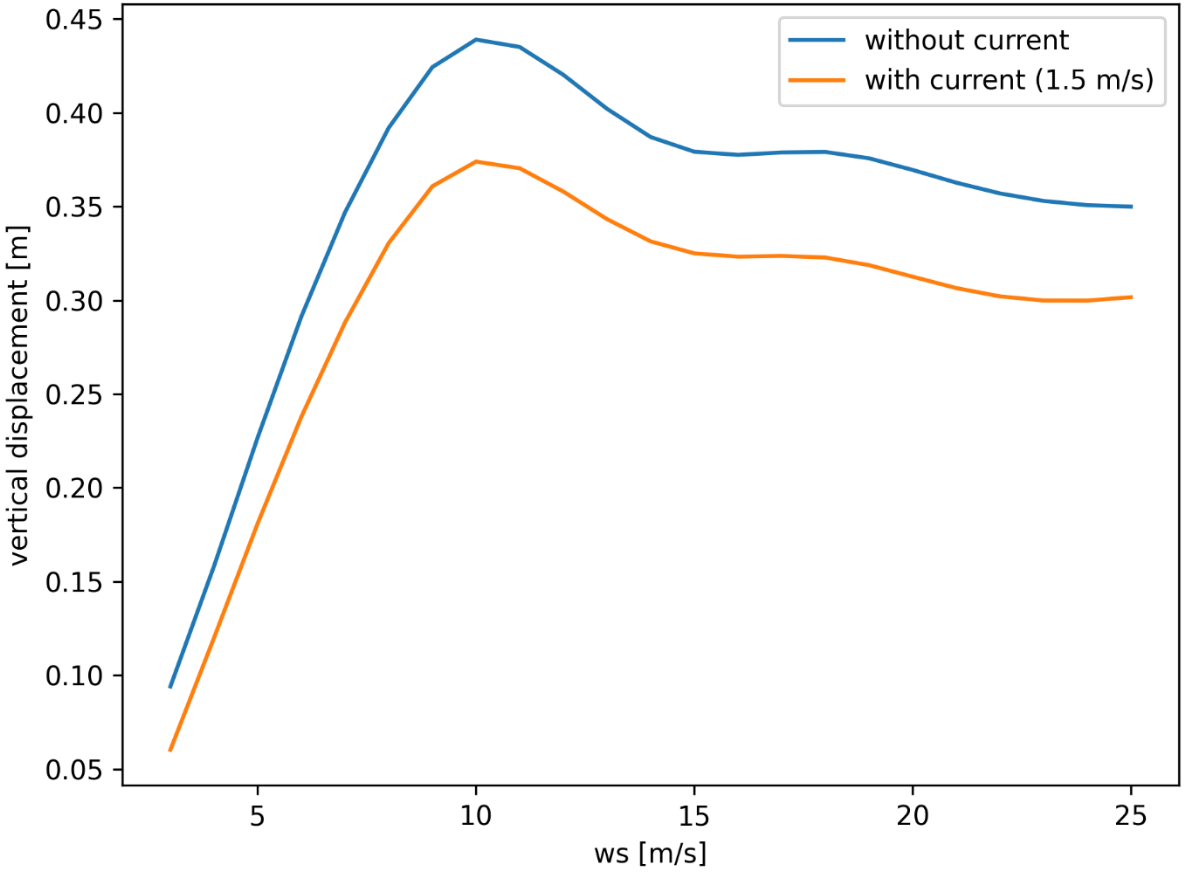
- A methodology to account for platform motion is developed with surrogate model.
- Fast calculation of FOWF static flow and AEP can be achieved using PyWake.
- For the considered scenarios, optimization based on fixed version of modelling is feasible, since the floater displacements and motion are limited.
- With better wind condition, the relative wake loss is lower, thus, the potential of AEP improvement through layout optimization is also lower.
- For the high wind site, the relative importance of optimization of the other aspects, such as mooring systems, cables, etc. will become higher.
- More research is needed.

Acknowledgments

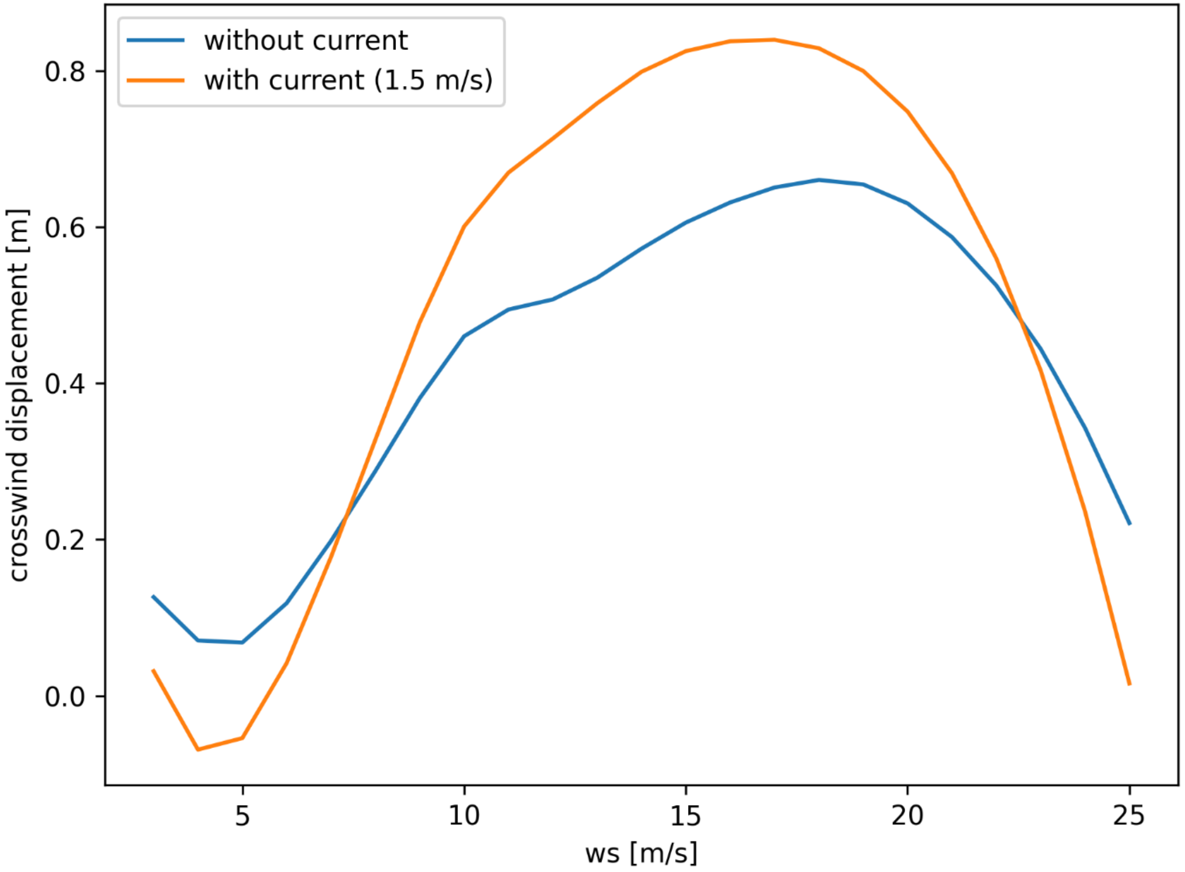
This research is supported by the IDEA project funded by the Danish Energy Technology Development and Demonstration Program (EUDP) under project number 134-21029. Discussions with many colleague in the IEA Wind Task 49 are also much appreciated.

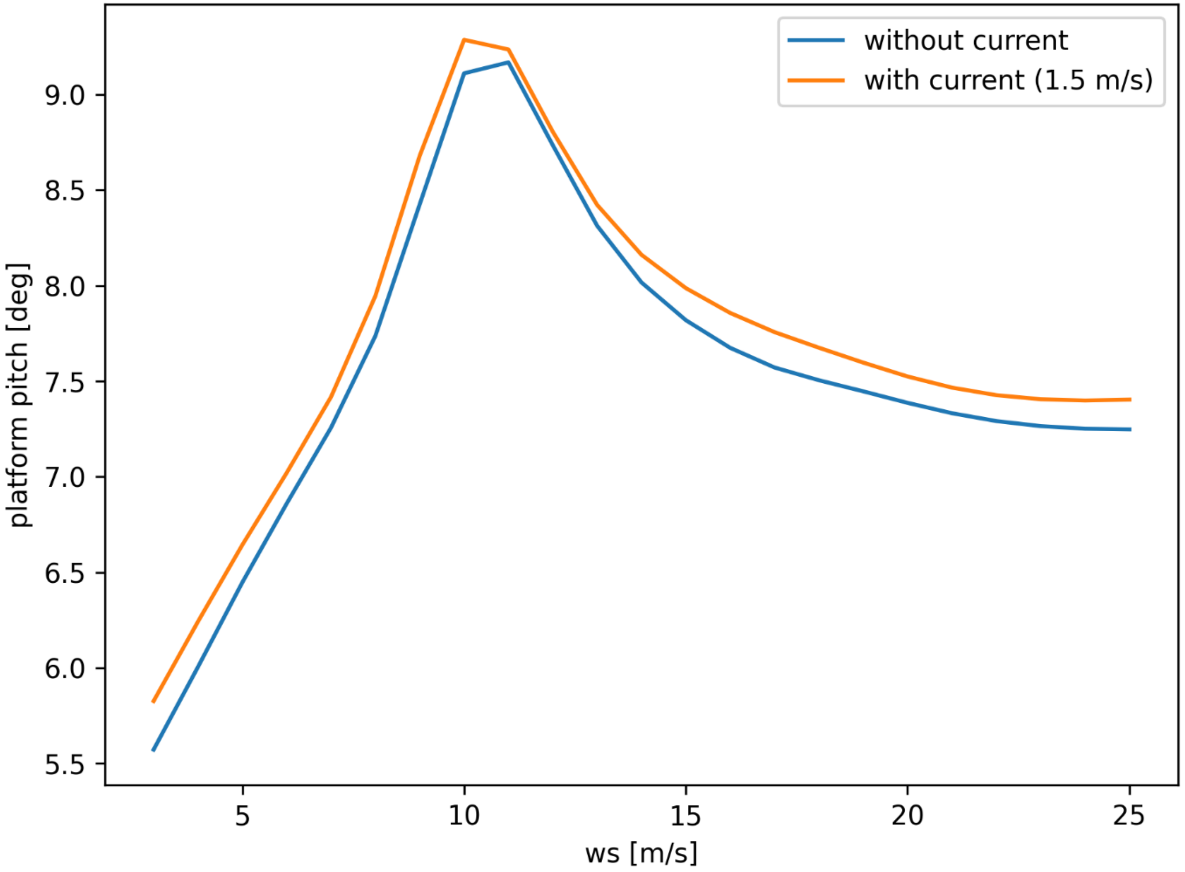


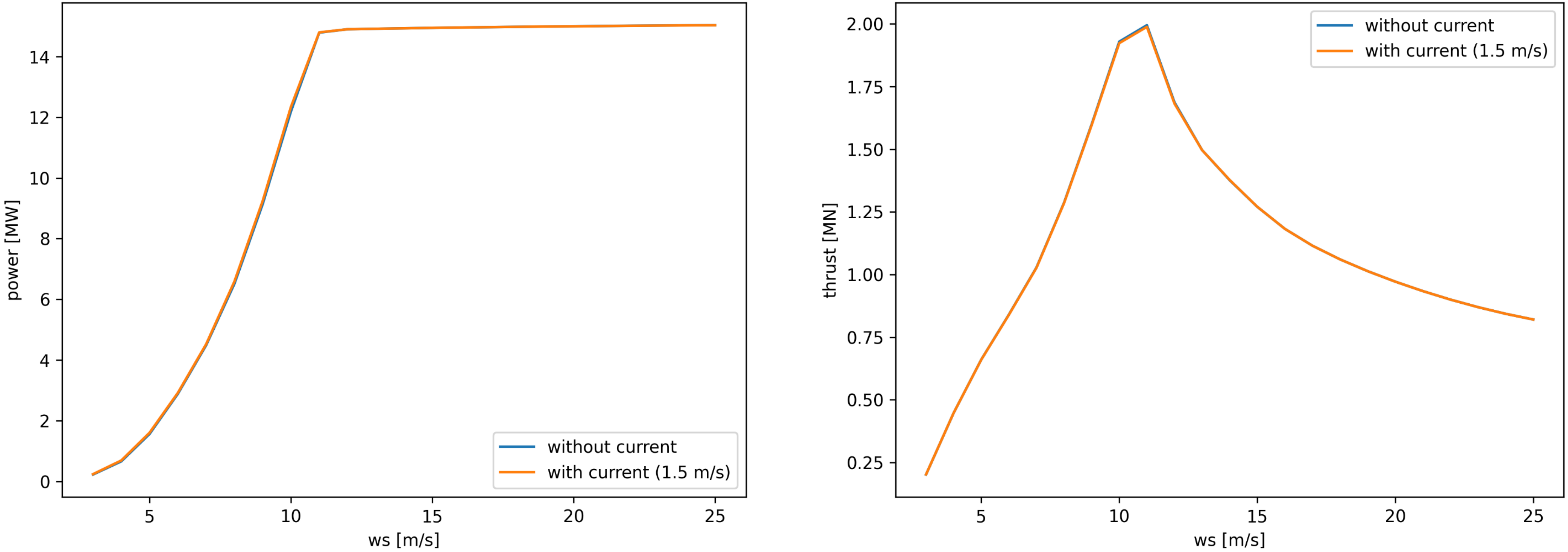
without current
with current (1.5 m/s)
downwind displacement [m]
ws [m/s]
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
5
10
15
20
25



without current
with current (1.5 m/s)
vertical displacement [m]
ws [m/s]
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
5
10
15
20
25


without current
with current (1.5 m/s)
crosswind displacement [m]
0.8
0.6
0.4
0.2
0.0
5
10
15
20
25
ws [m/s]


without current
with current (1.5 m/s)
platform pitch [deg]
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5
10
15
20
25
ws [m/s]



power [MW]
0
2
4
6
8
10
12
14
5
10
15
20
25
ws [m/s]
without current
with current (1.5 m/s)
thrust [MN]
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
5
10
15
20
25
ws [m/s]
without current
with current (1.5 m/s)