The influence of wind farm control on optimal wind farm layout

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Outline

- Introduction
- Tools and wake control procedure
- Three wind turbine row
- The Lillgrund wind farm
- Conclusions

Introduction

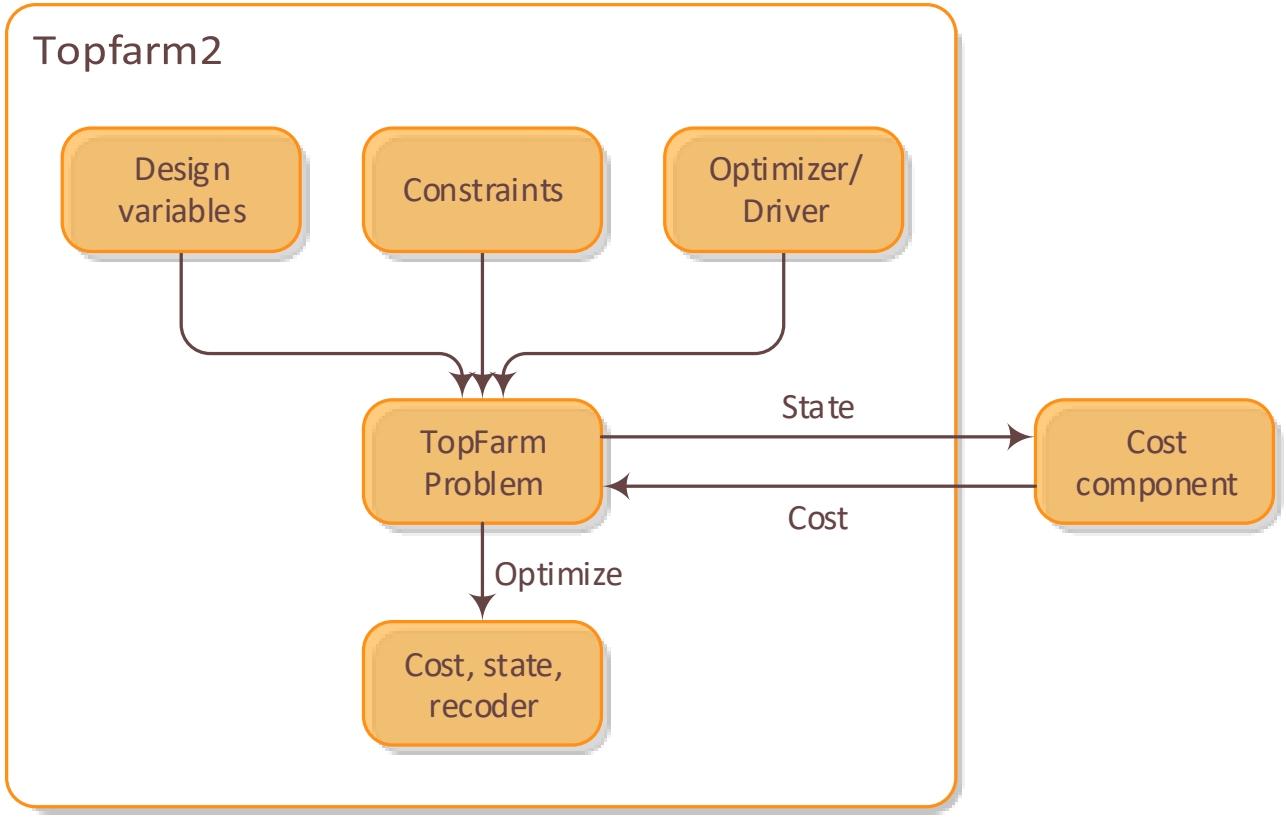
- Wind farm optimization
  - Increase the overall farm production
  - Lower costs

- Previous work:
  - Turbine layout optimization
  - Wake steering via wind farm yaw control
  - Combined layout and wake steering (Fleming et al 2016, Gebraad et al 2017)
  - Wake control via derating
  - Past work has had limited focus on other objectives like load reduction and grid services

- Research objective: Investigate effect of combined layout / derating optimization wrt. power production and load reductions

Topfarm - *DTU Wind Energy's wind-farm optimizer*

- Open source python package developed by DTU Wind Energy (gitlab.windenergy.dtu.dk/TOPFARM/TopFarm2)
- Intended to make windfarm optimization easier
- Based on the OpenMDAO framework (openmdao.org)



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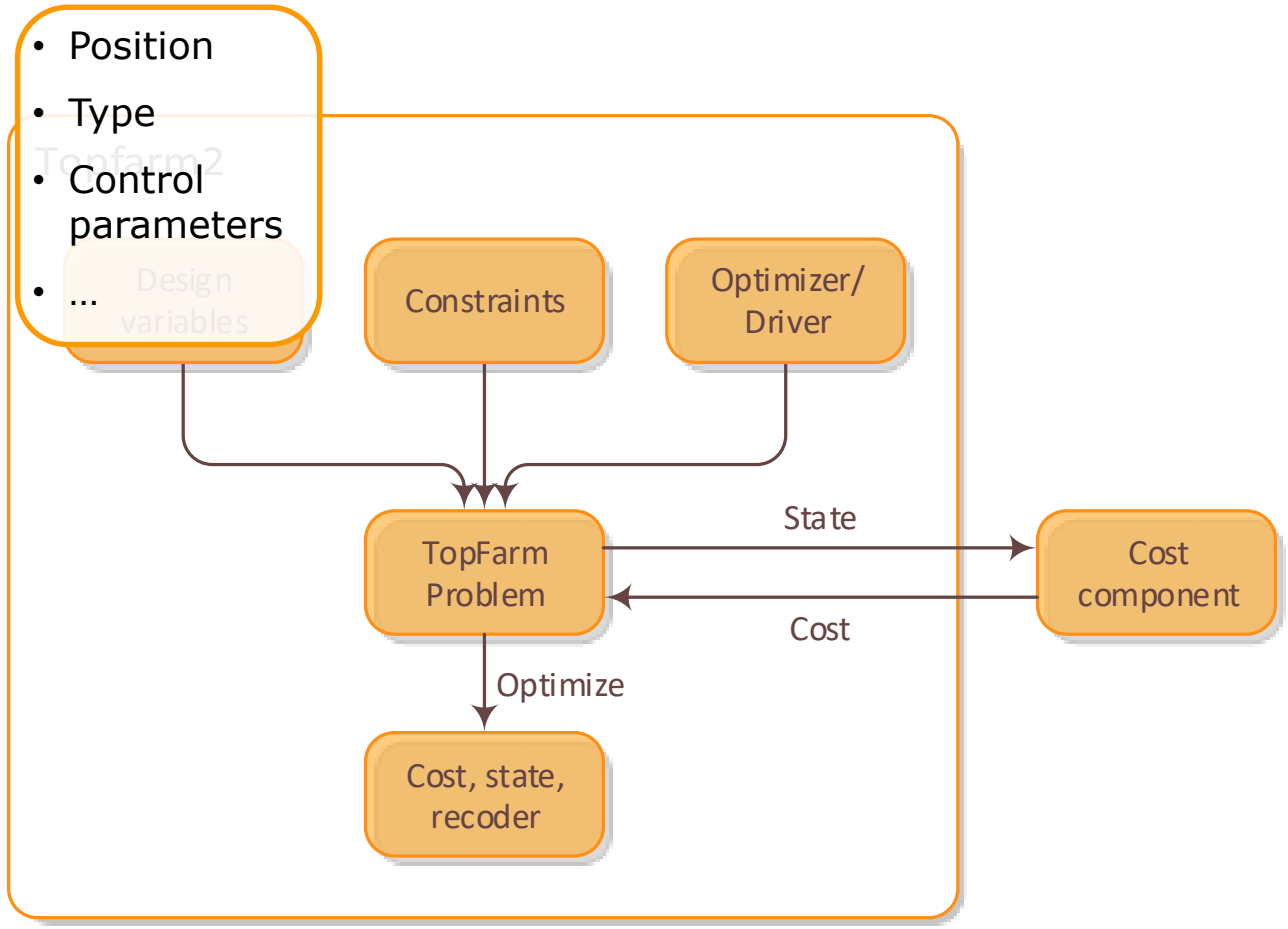

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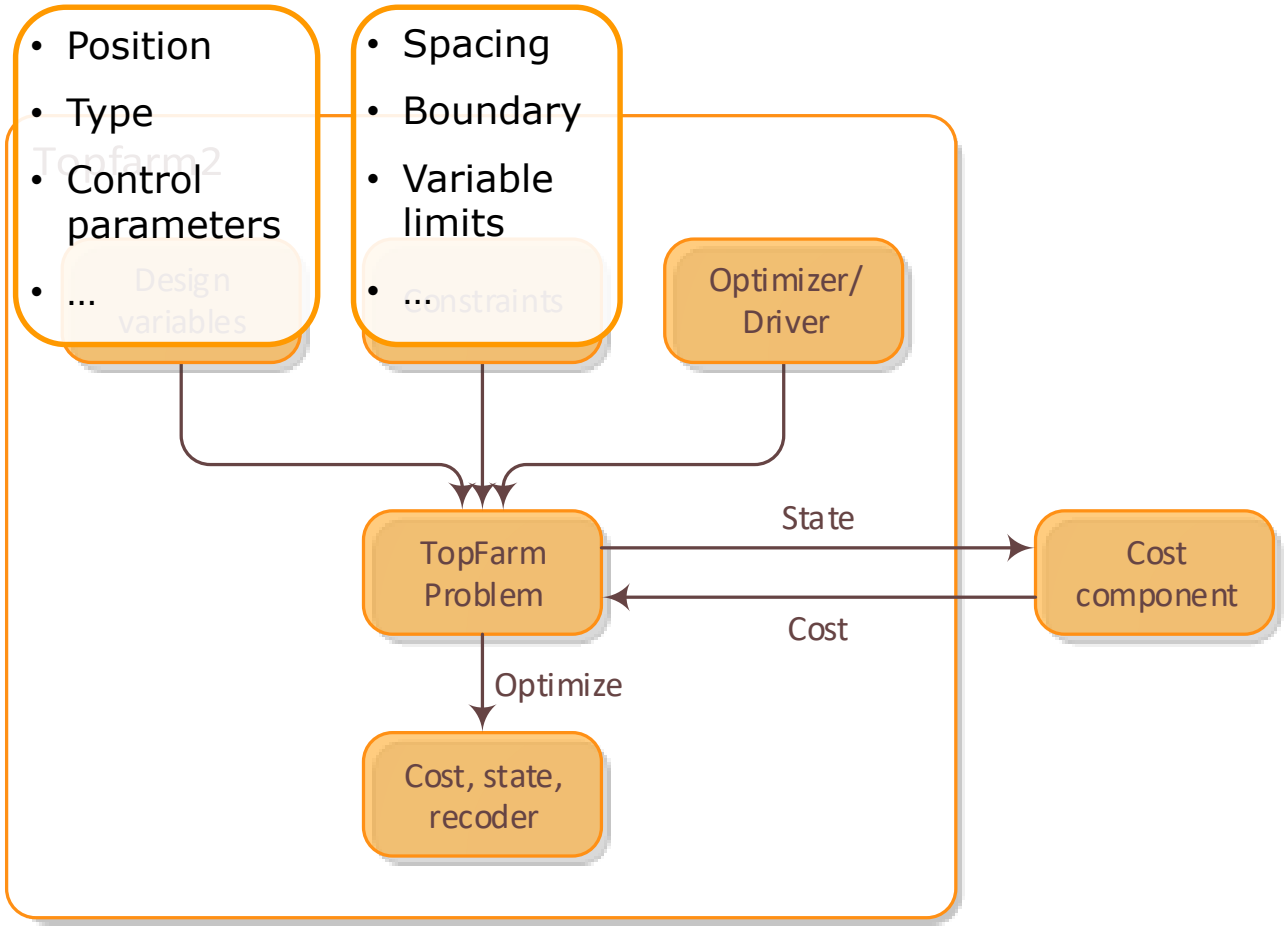

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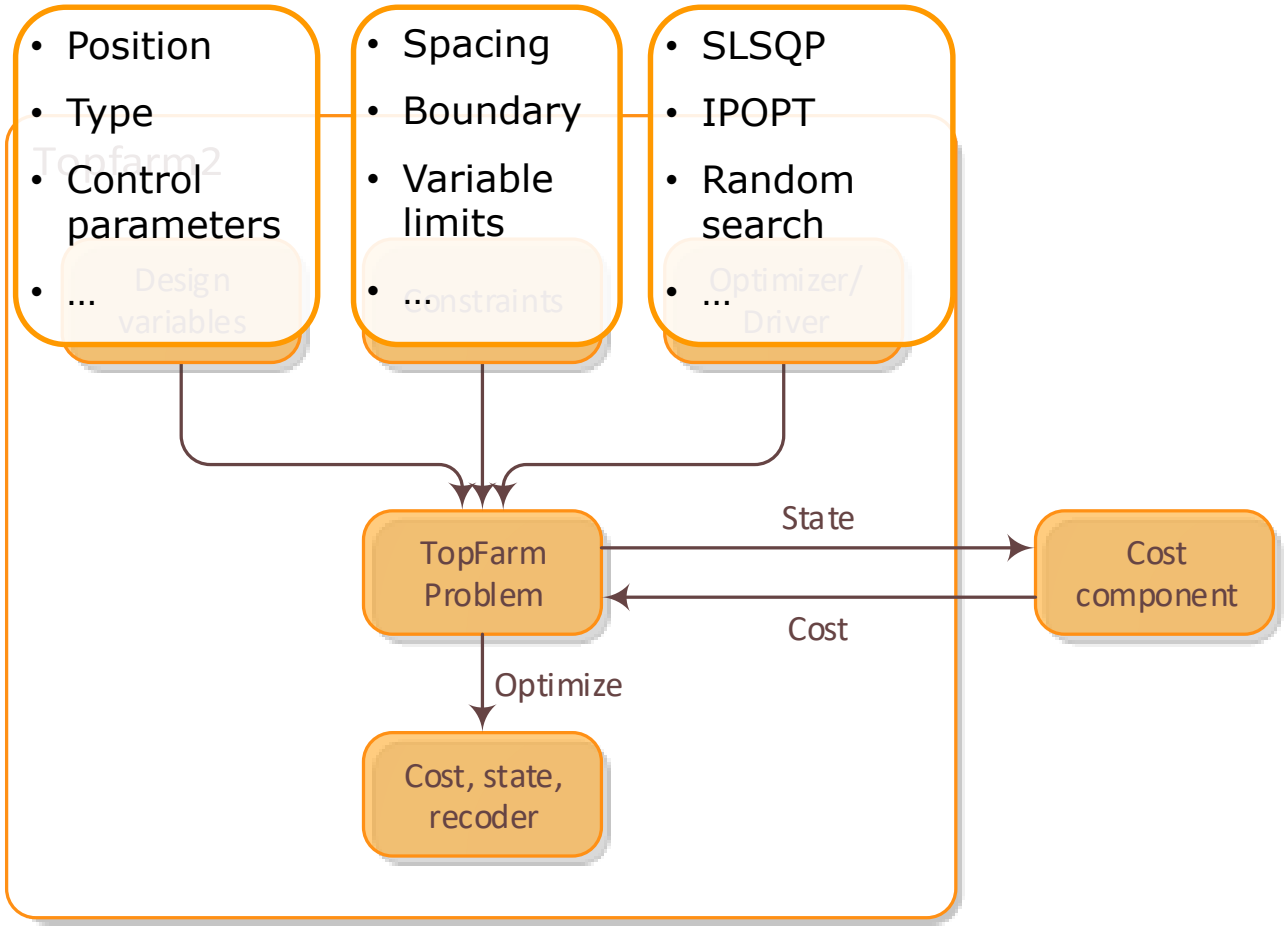

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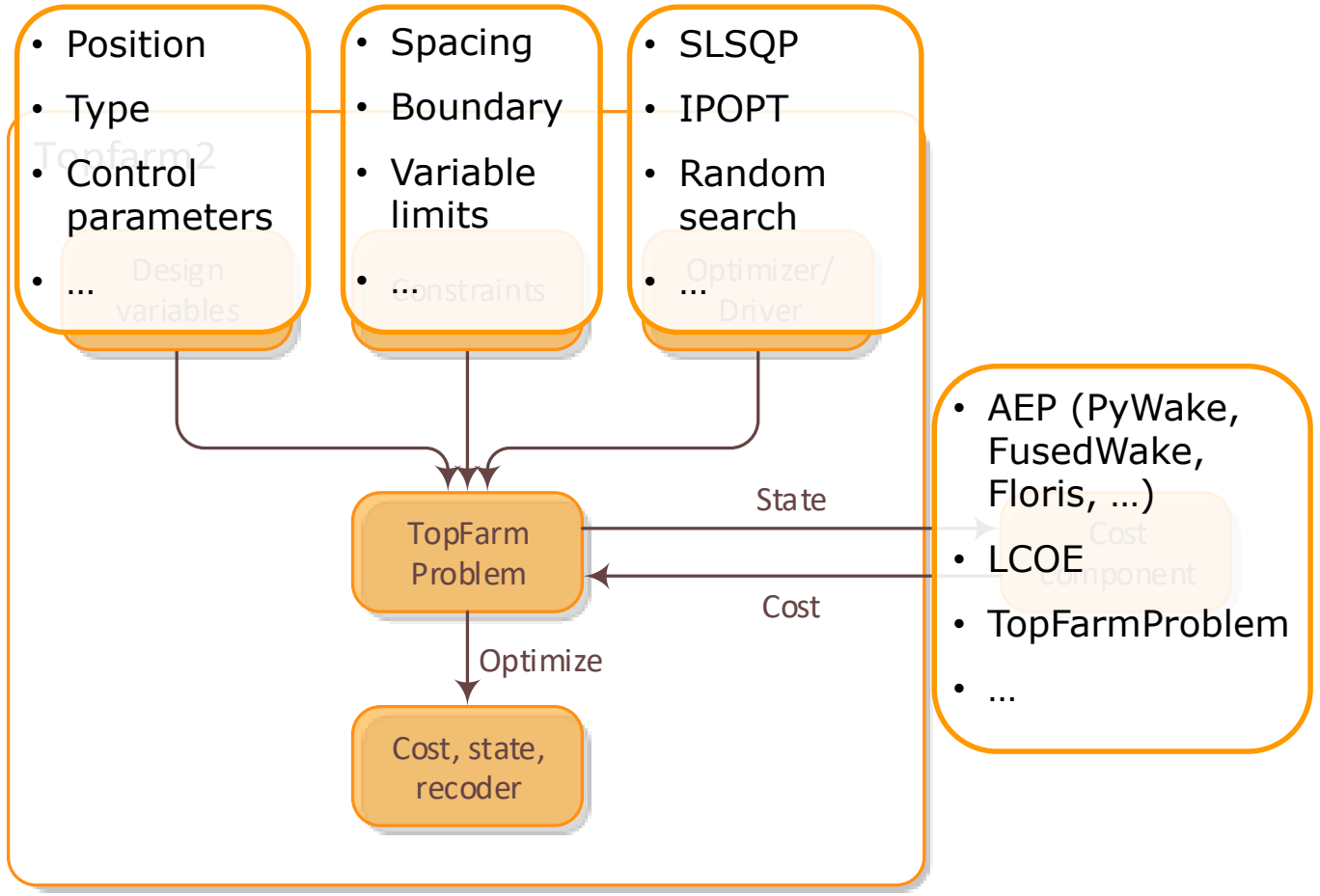
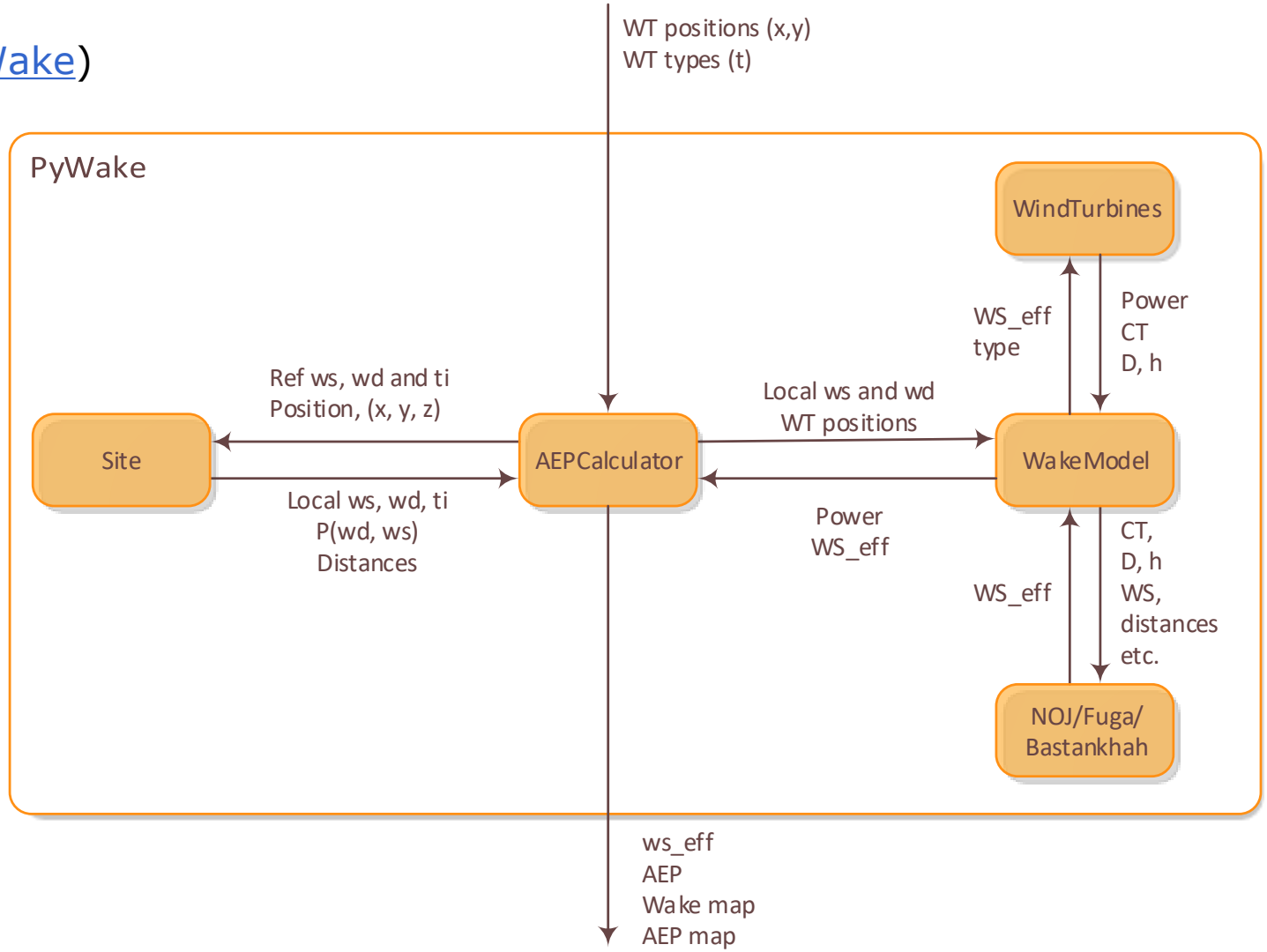


PyWake

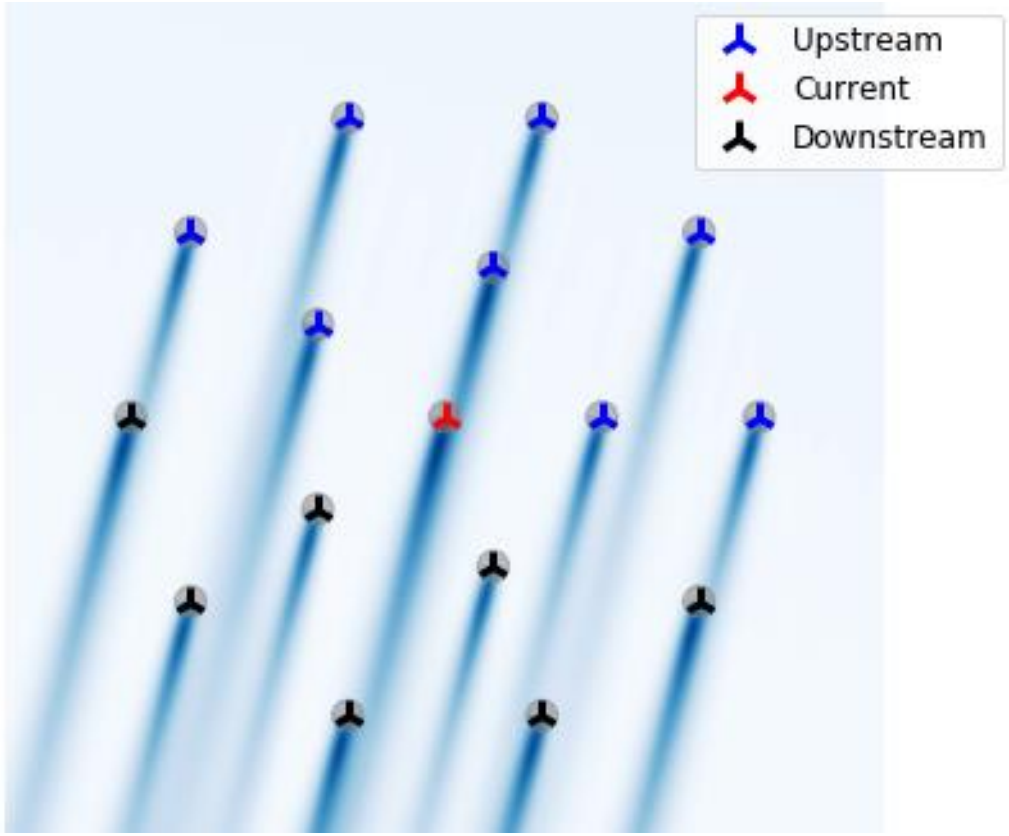
- Open source python package developed by DTU Wind Energy (gitlab.windenergy.dtu.dk/TOPFARM/PyWake)
- AEP calculator for wind farms
- Included wake models
  - NOJ
  - Bastankhah
  - Fuga (Commercial software required to generate input data)
- Flexible and customizable



PyWake - Fuga

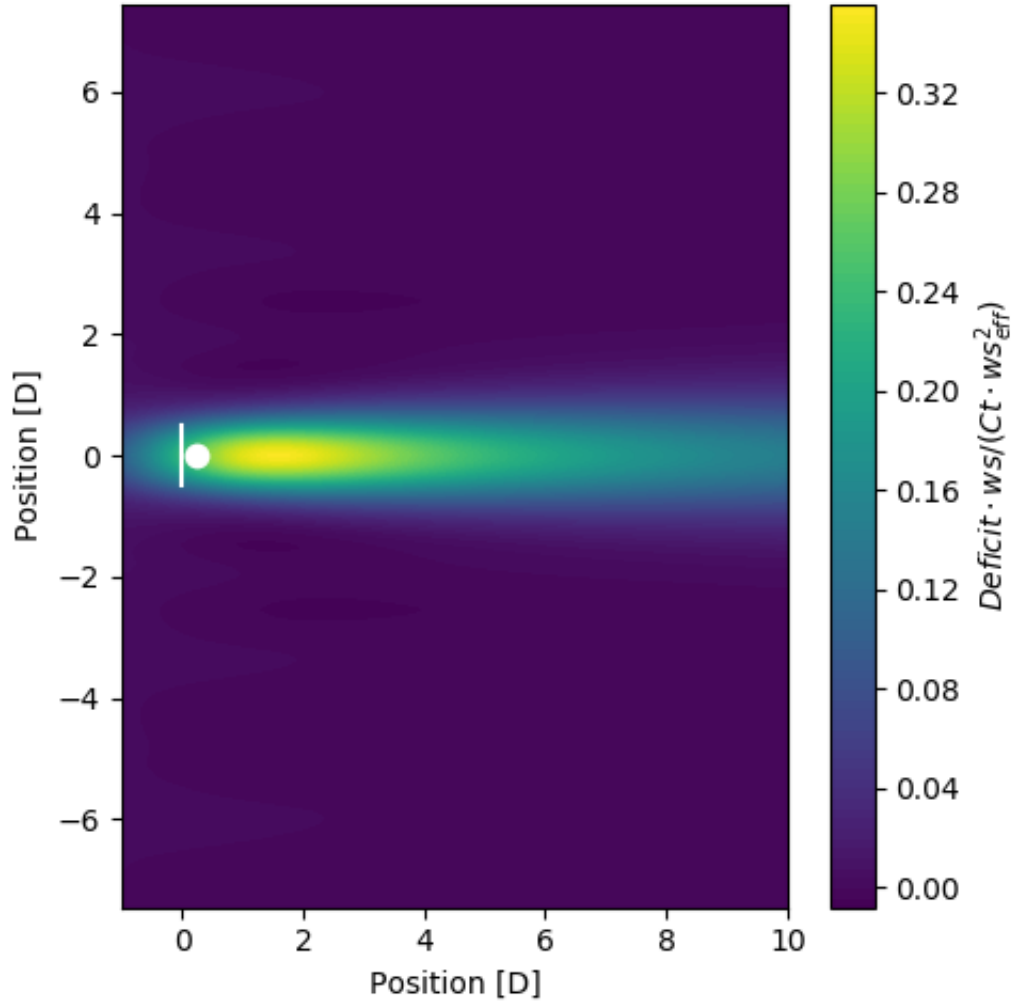
Simple engineering approach

```
For each wind direction
    For each wind speed
        For each turbine (down wind order)
            ws_eff = free_ws – sum(deficits)
            deficits = f(ws_eff, Ct, dw_dist, cw_dist)
```



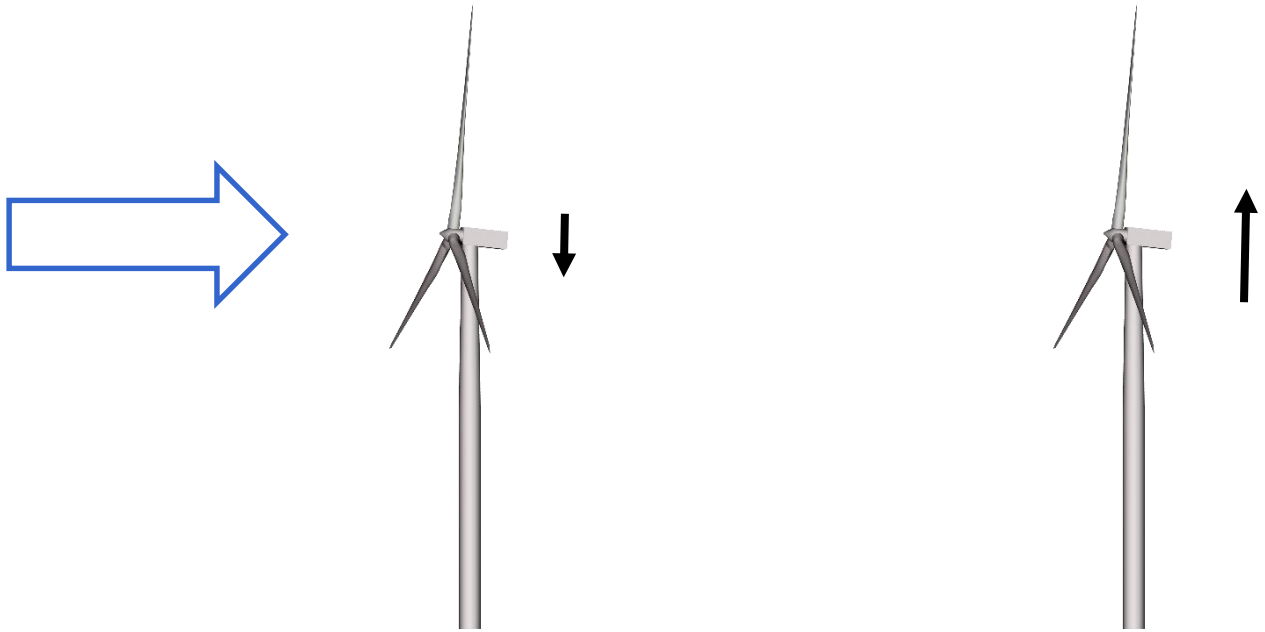
Fuga

- Commerical flow solver developed by DTU Wind Energy (wasp.dk/fuga)
- Linearized CFD RANS solver
- Mixed spectral domain and look-up tables
- Very fast compared to traditional RANS solvers (PyWake 48 wt, 360 wd, 23 ws: <0.5s)



Active wake control - derating

- Derating
  - Derate upstream turbines
    - Pitch angle: f(wt, wd, ws)
    - Rotor speed: g(wt, wd, ws)
  - Increase total wind farm power

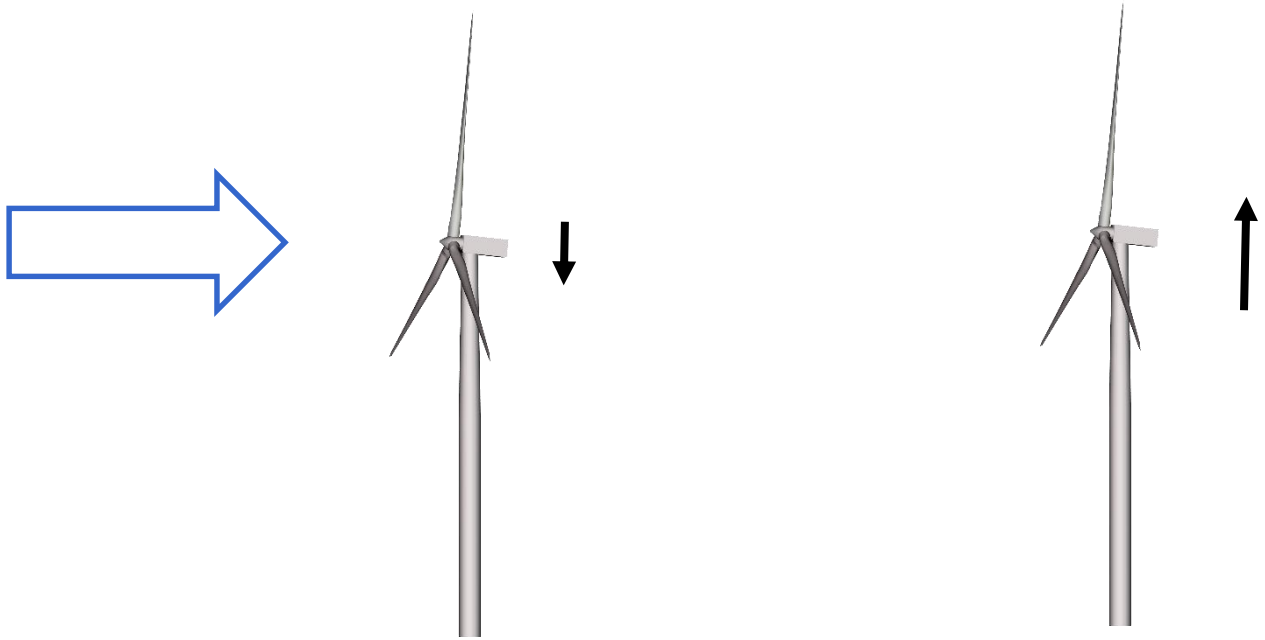


Active wake control - derating

- Derating
  - Derate upstream turbines
    - Pitch angle: f(wt, wd, ws)
    - Rotor speed: g(wt, wd, ws)
  - Increase total wind farm power

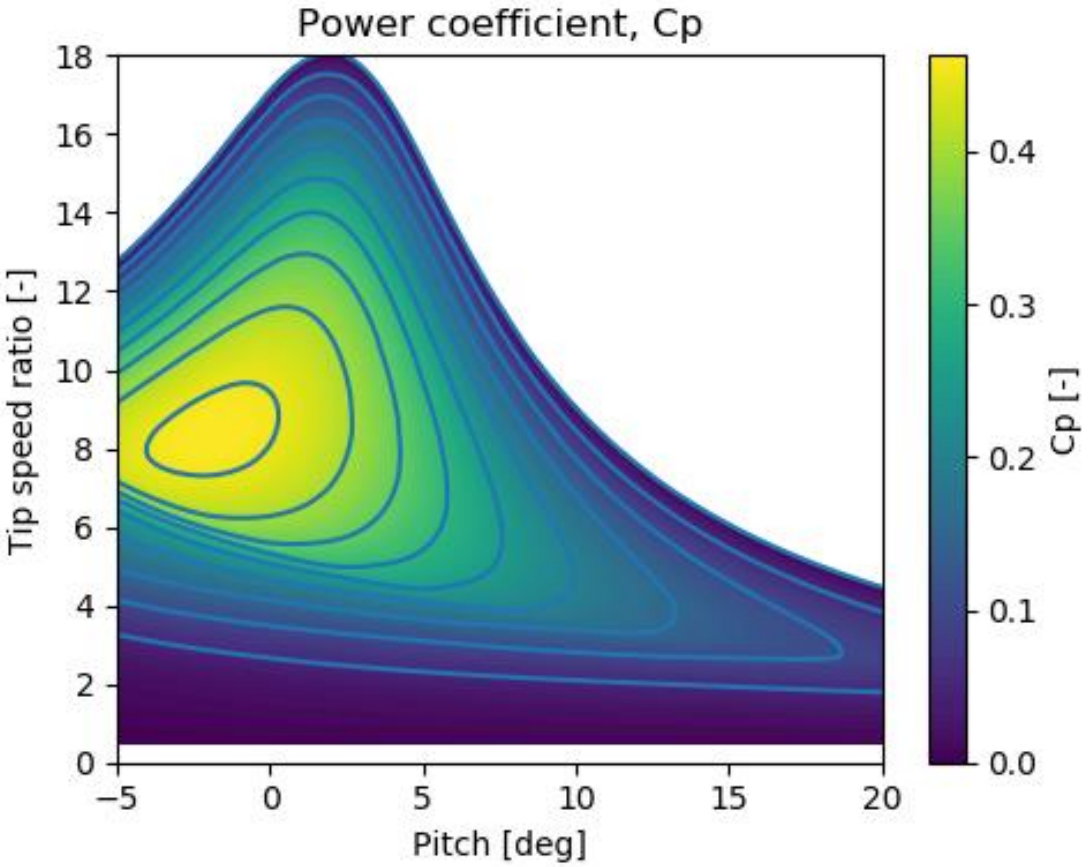
Assumption:

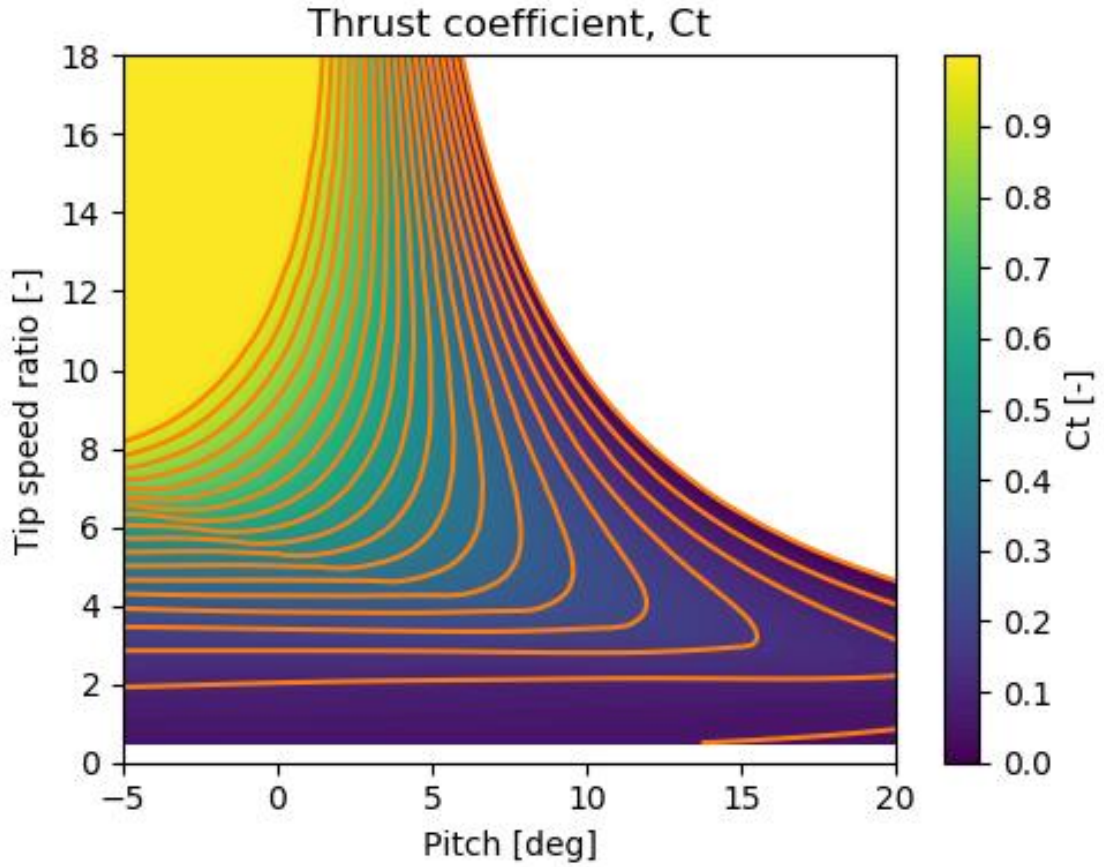
Wind direction and ambient wind speed known and constant over the wind farm area



Active wake control - derating

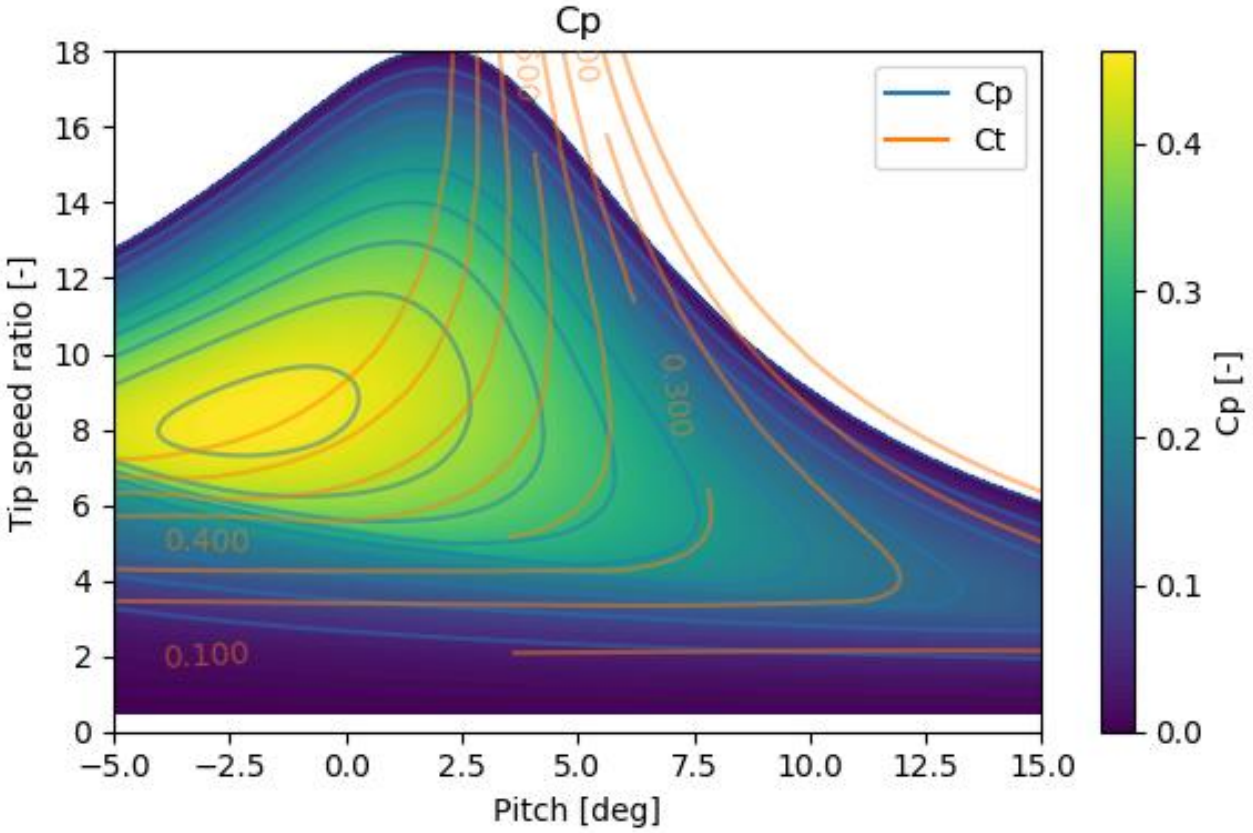
- Power and thrust coefficients for range of rotor speeds and pitch angles
- Calculated using HAWCSTAB2 (steady-state aeroelastic code http://www.hawcstab2.vindenergi.dtu.dk/)





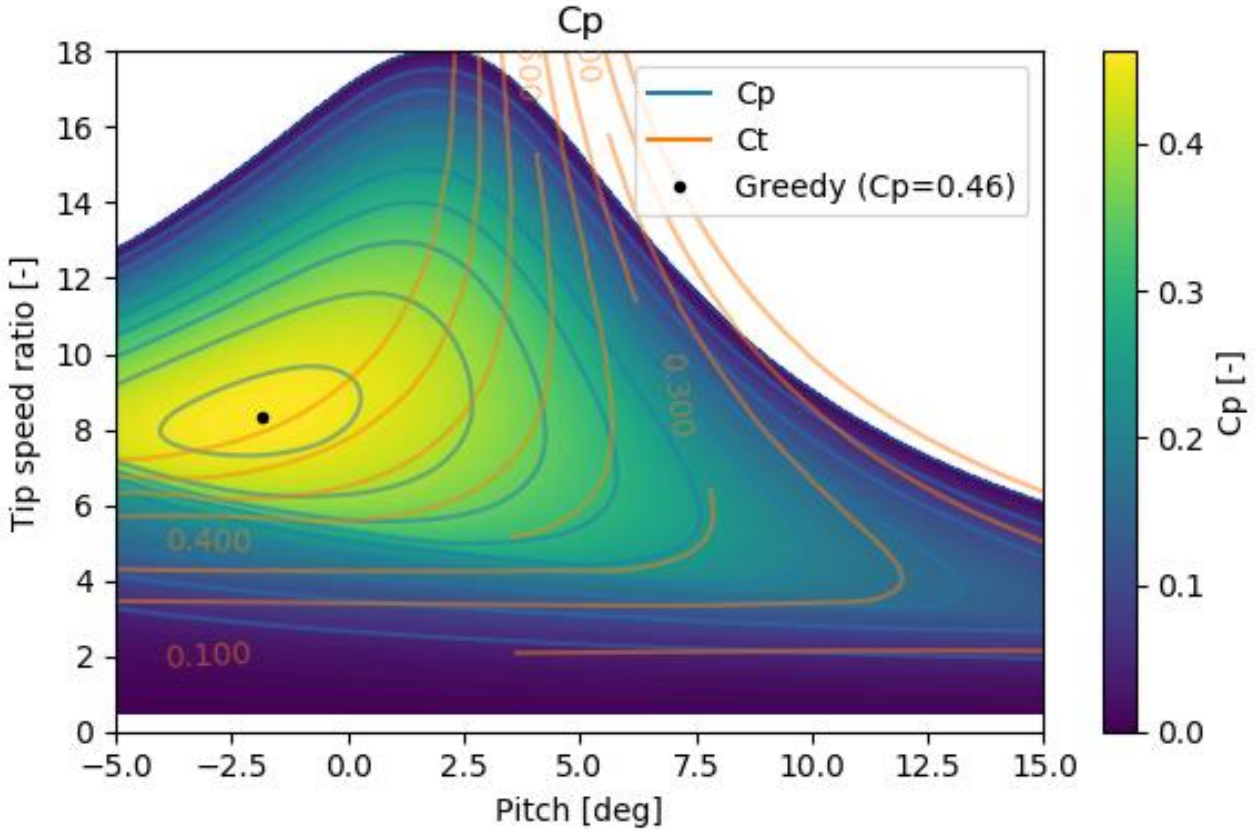
Active wake control - derating

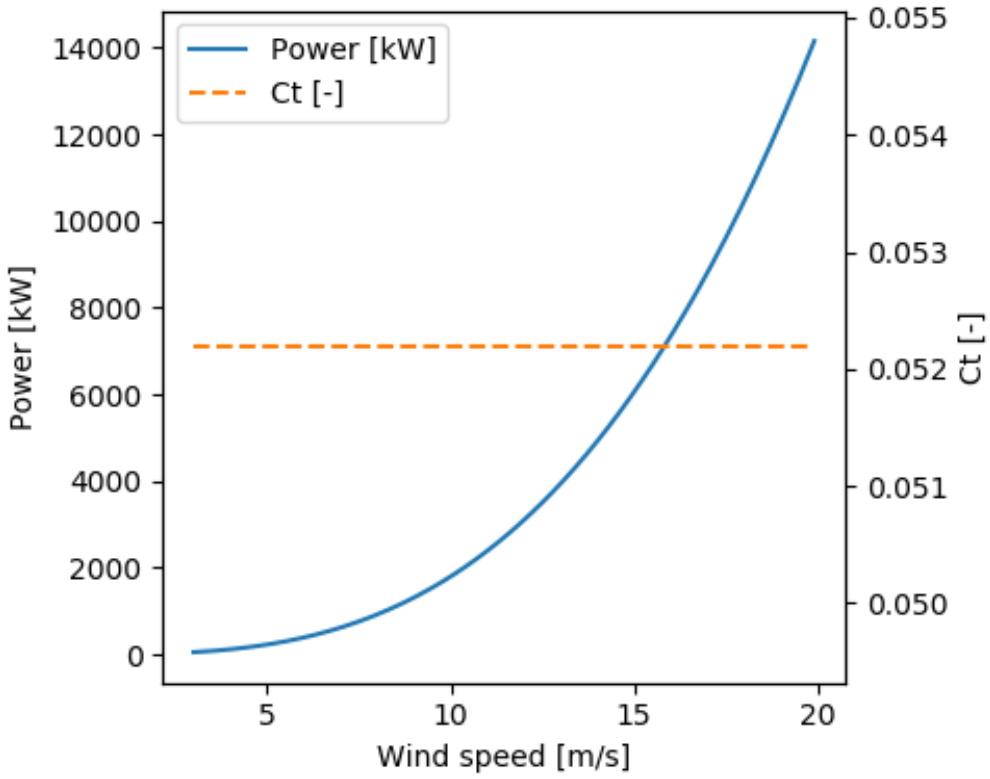
- Power and thrust coefficients for range of rotor speeds and pitch angles
- Calculated using linear steady-state aeroelastic code (HAWCSTAB2)



Active wake control - derating

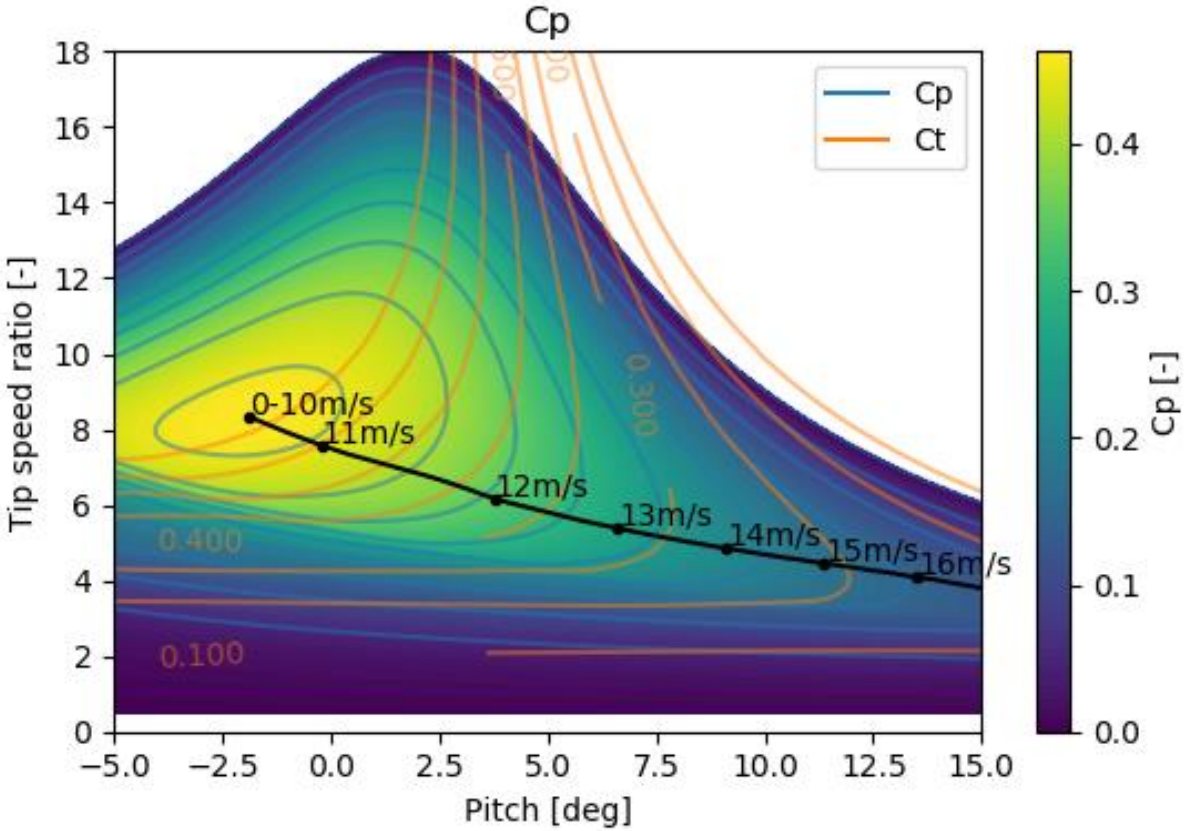
- Greedy operation
- Max Cp
- Constant Ct

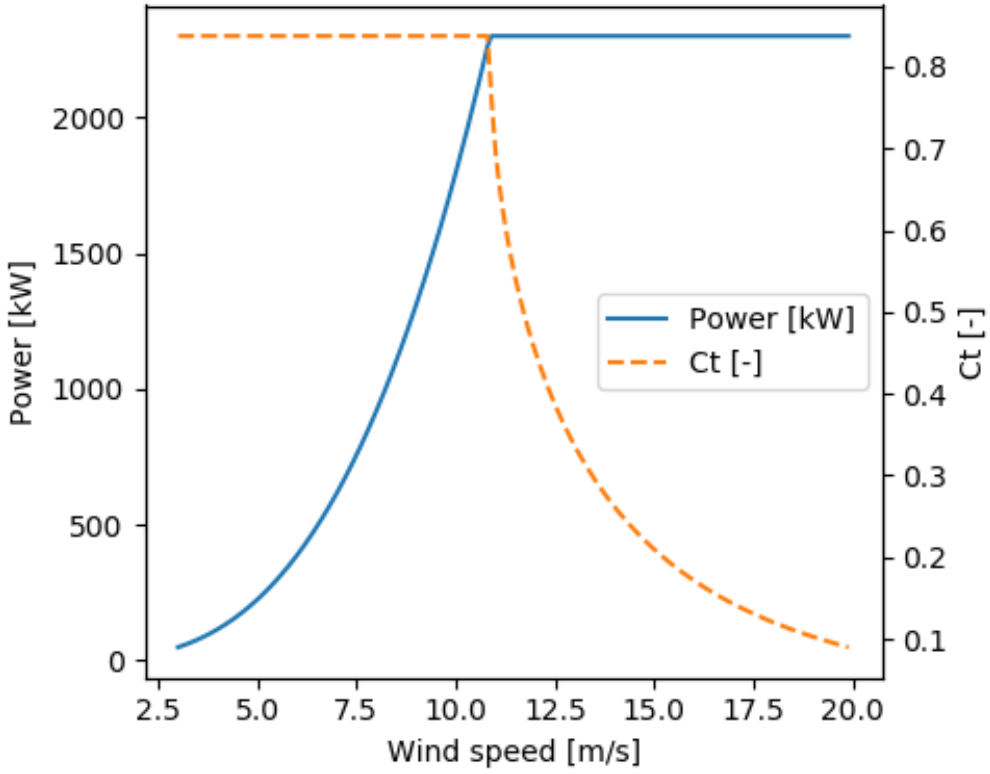




Active wake control - derating

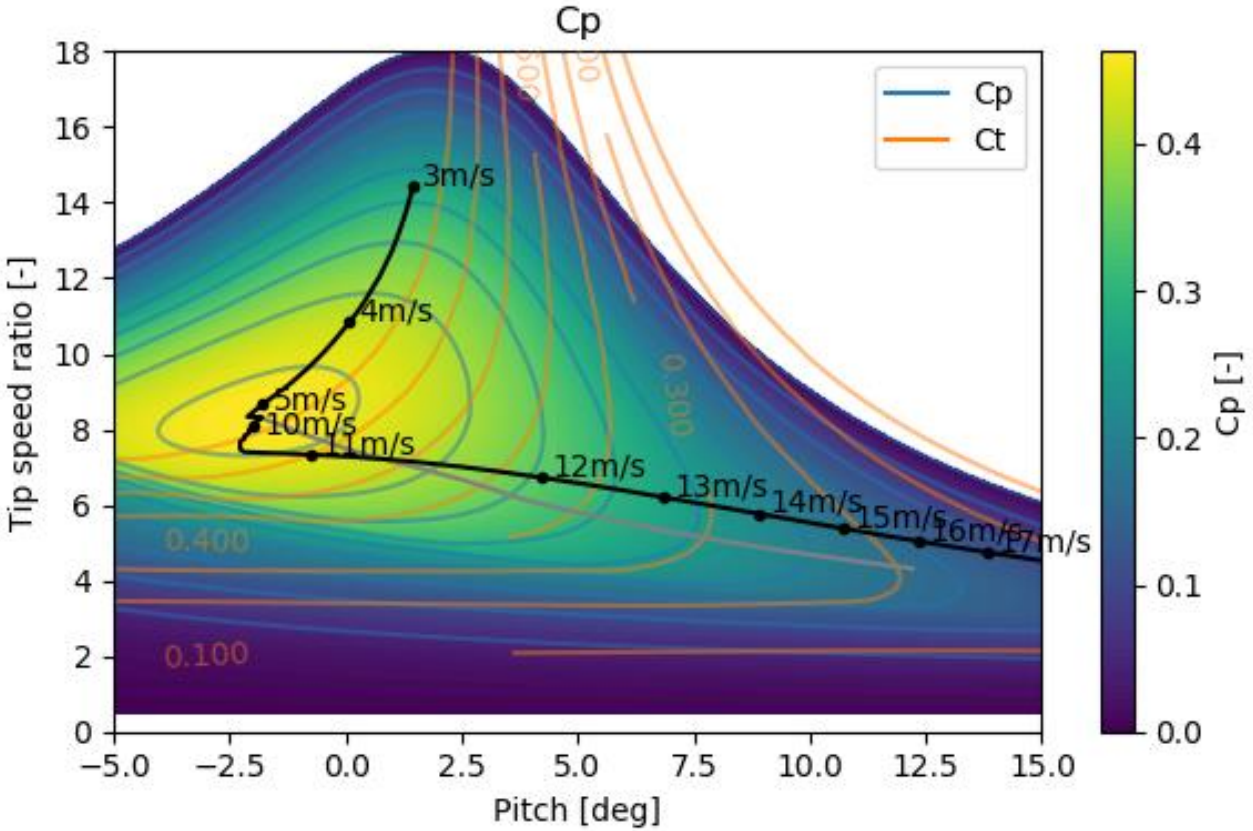
- Power limit
- Decrease Cp
- Minimize Ct

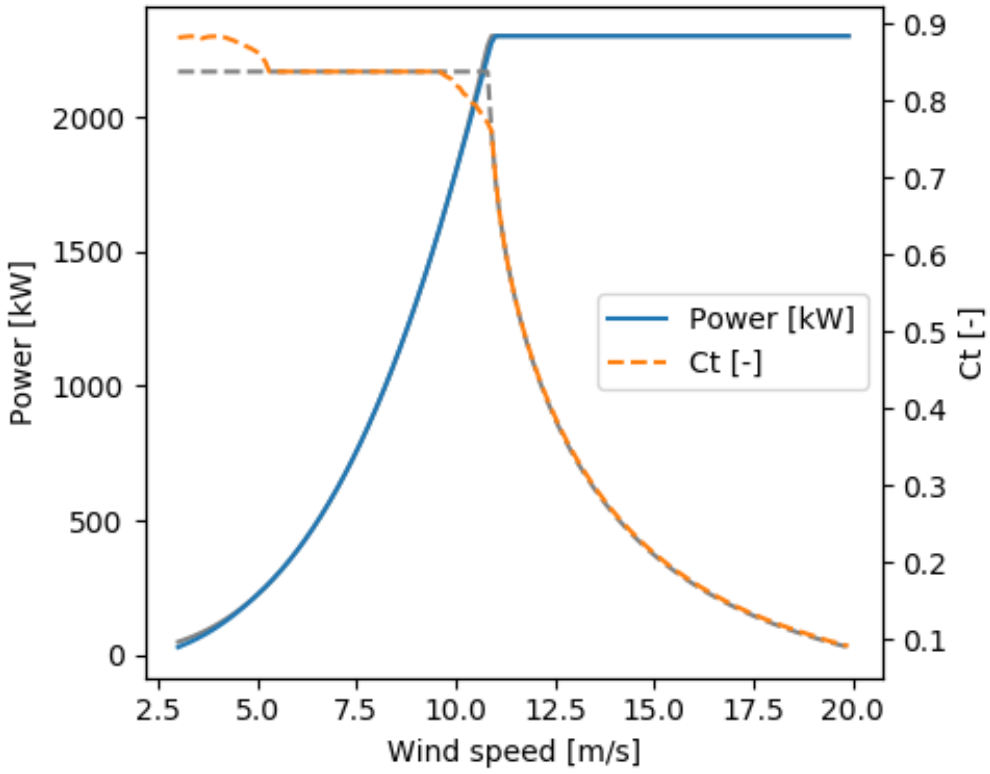




Active wake control - derating

- Power and Rotor speed limits
- Decrease Cp
- Minimize Ct





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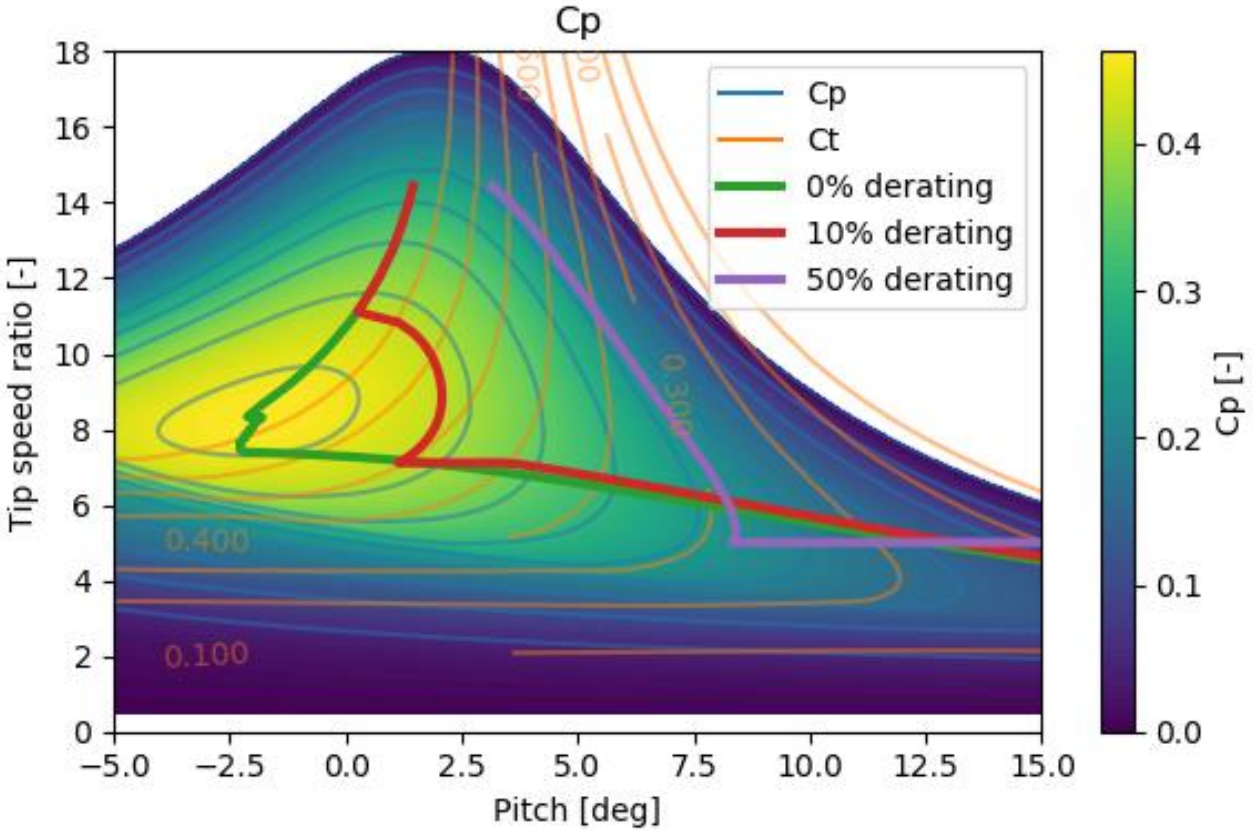
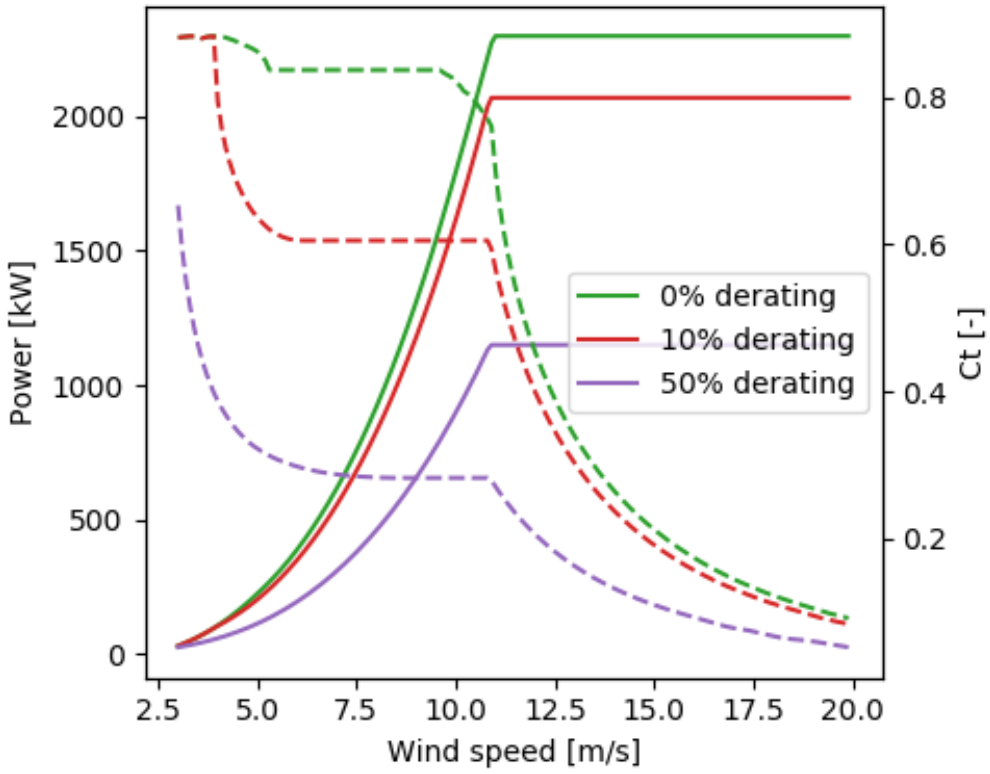
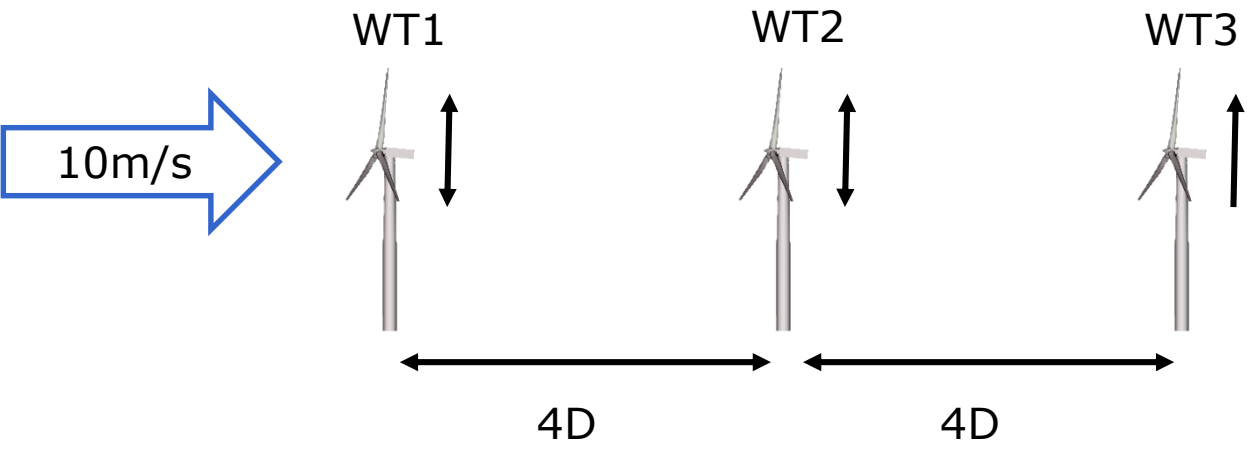
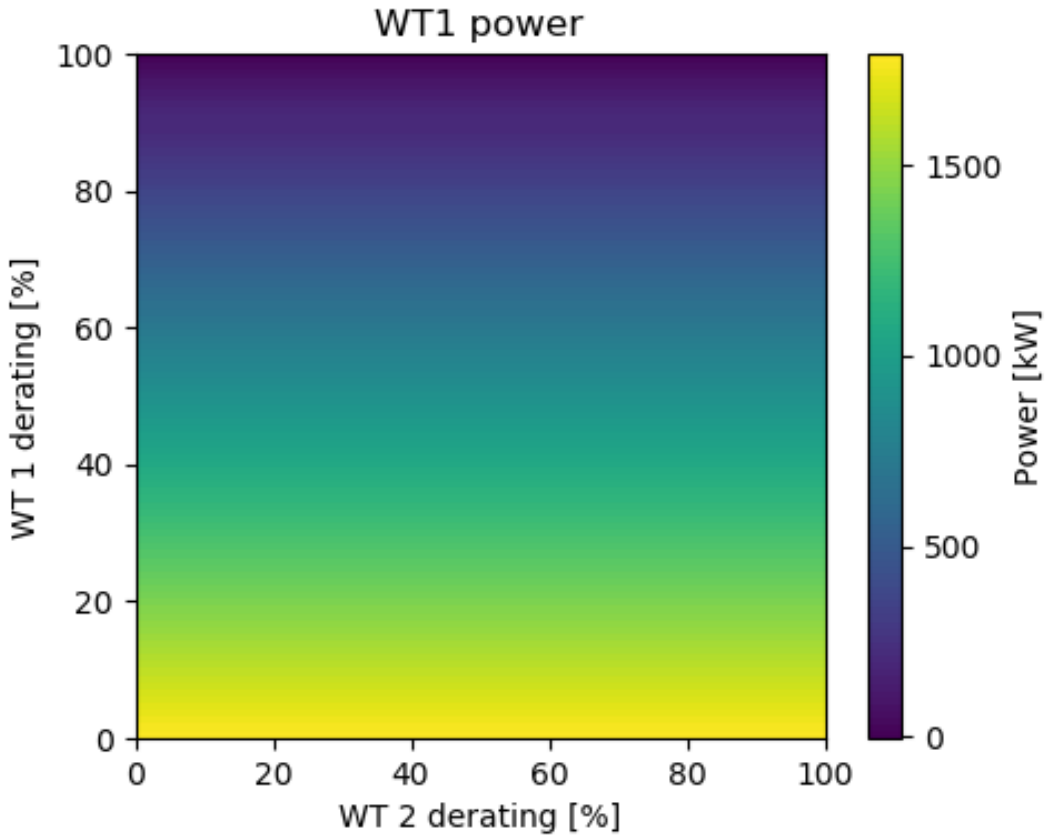




Single row, 3 wind turbines





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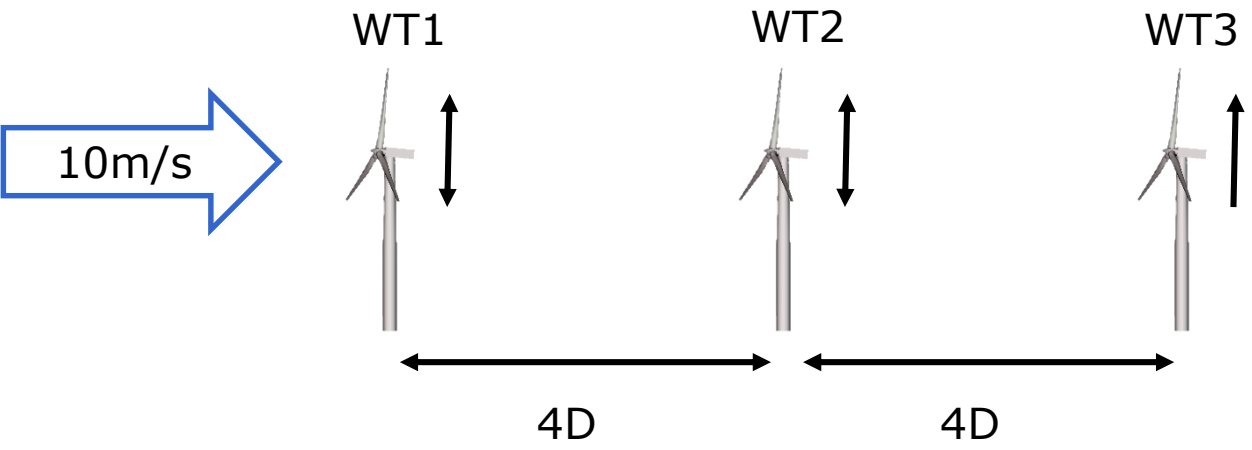

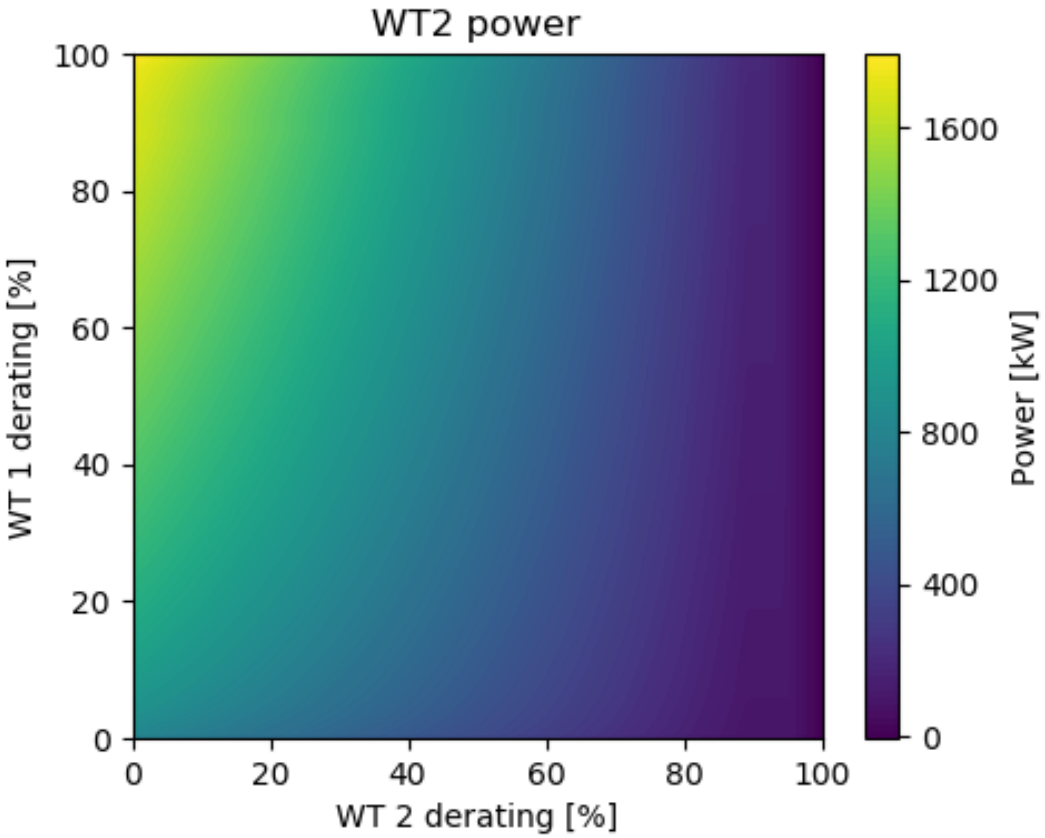

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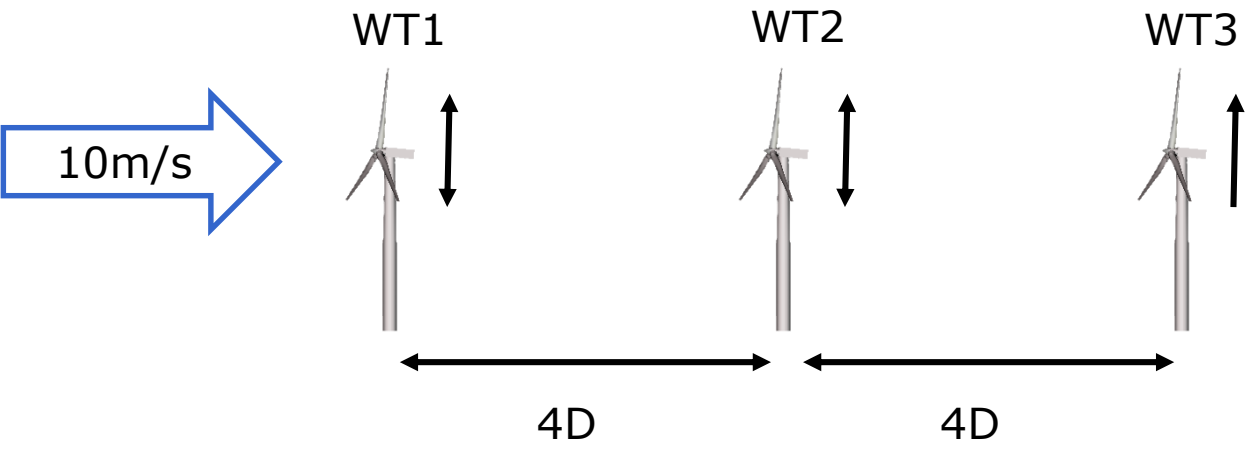

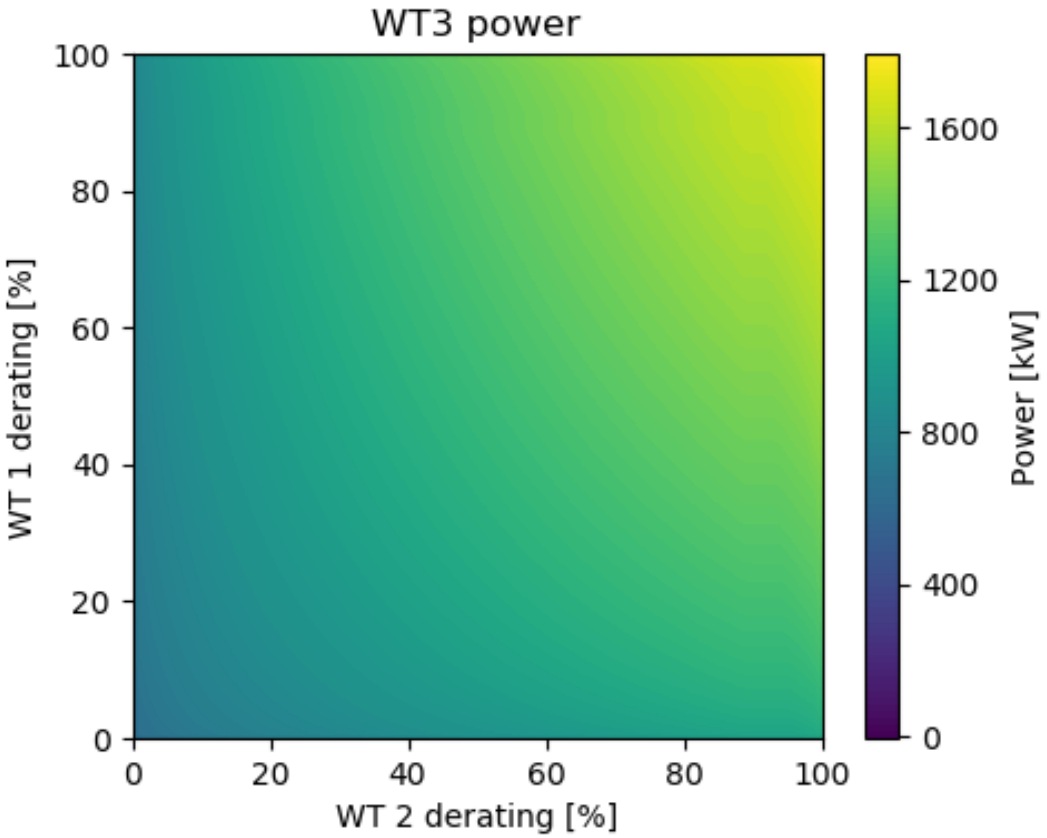

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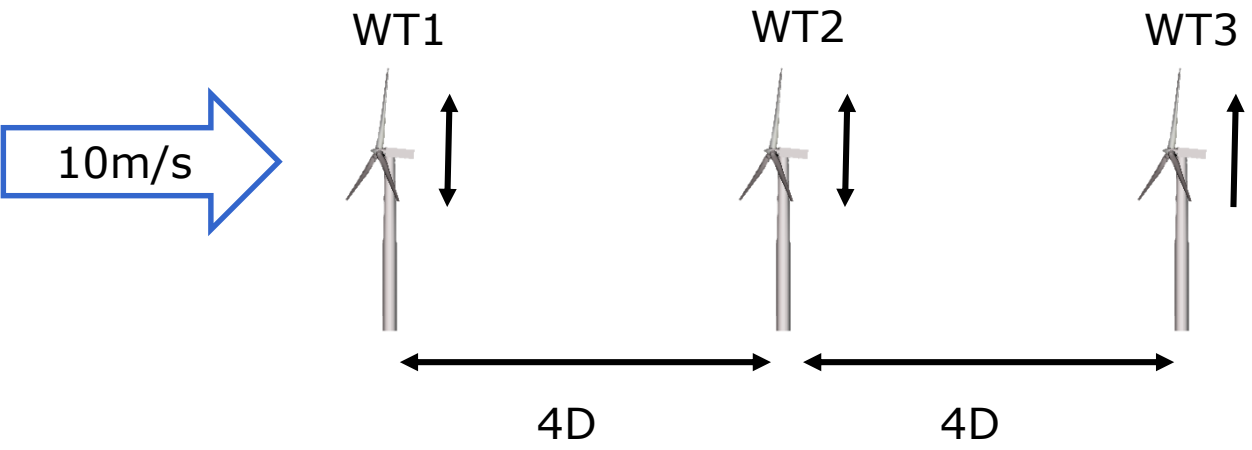

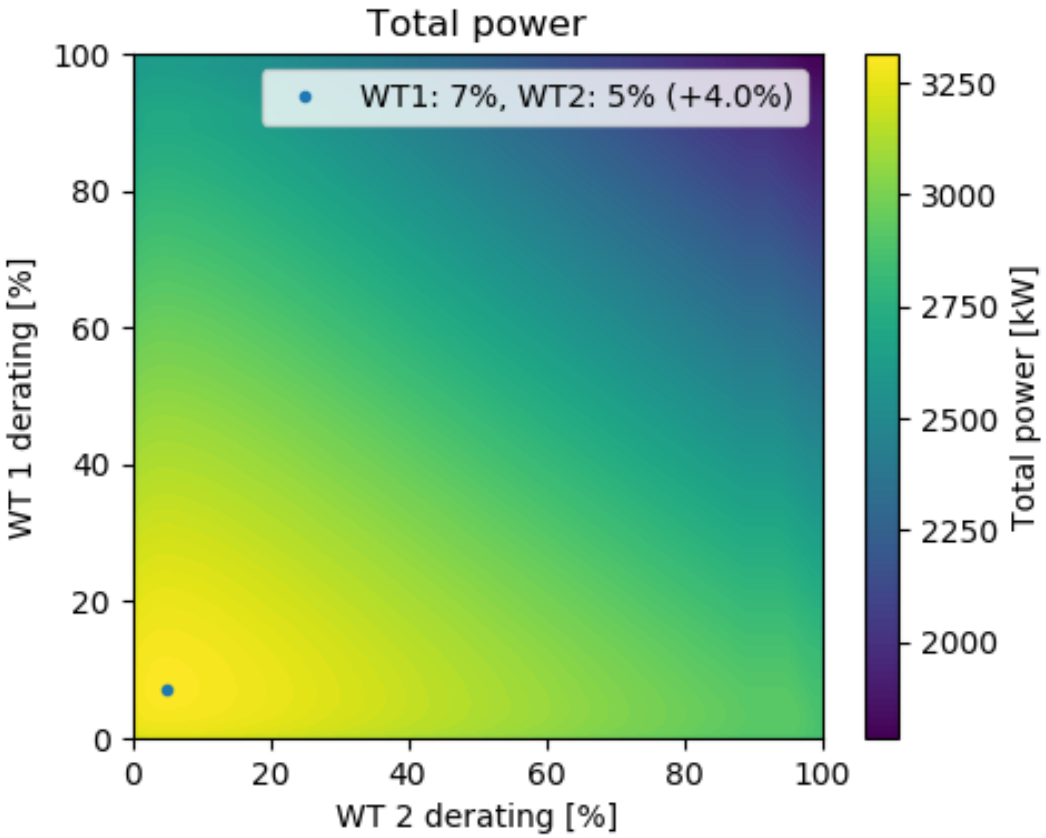

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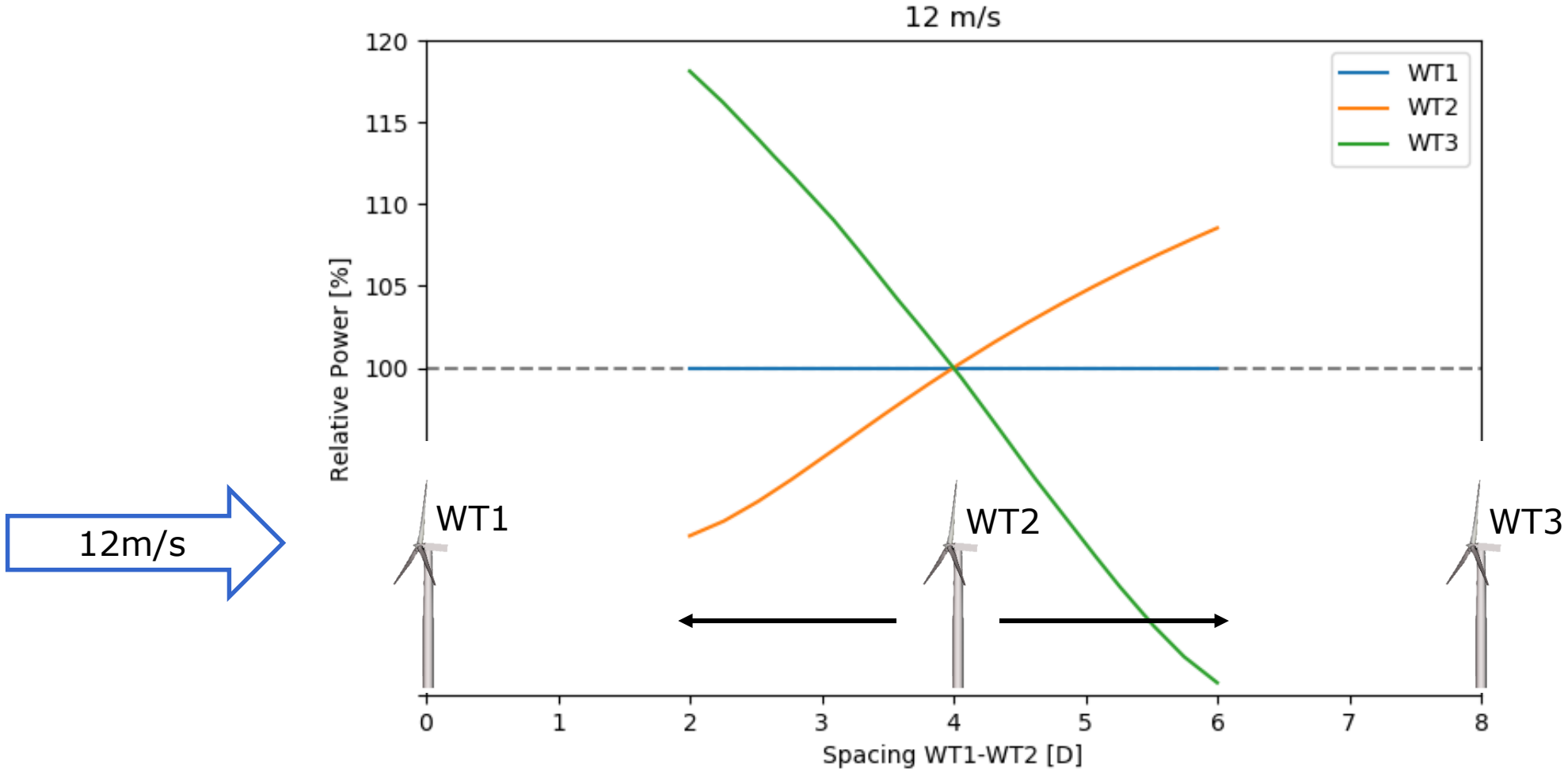

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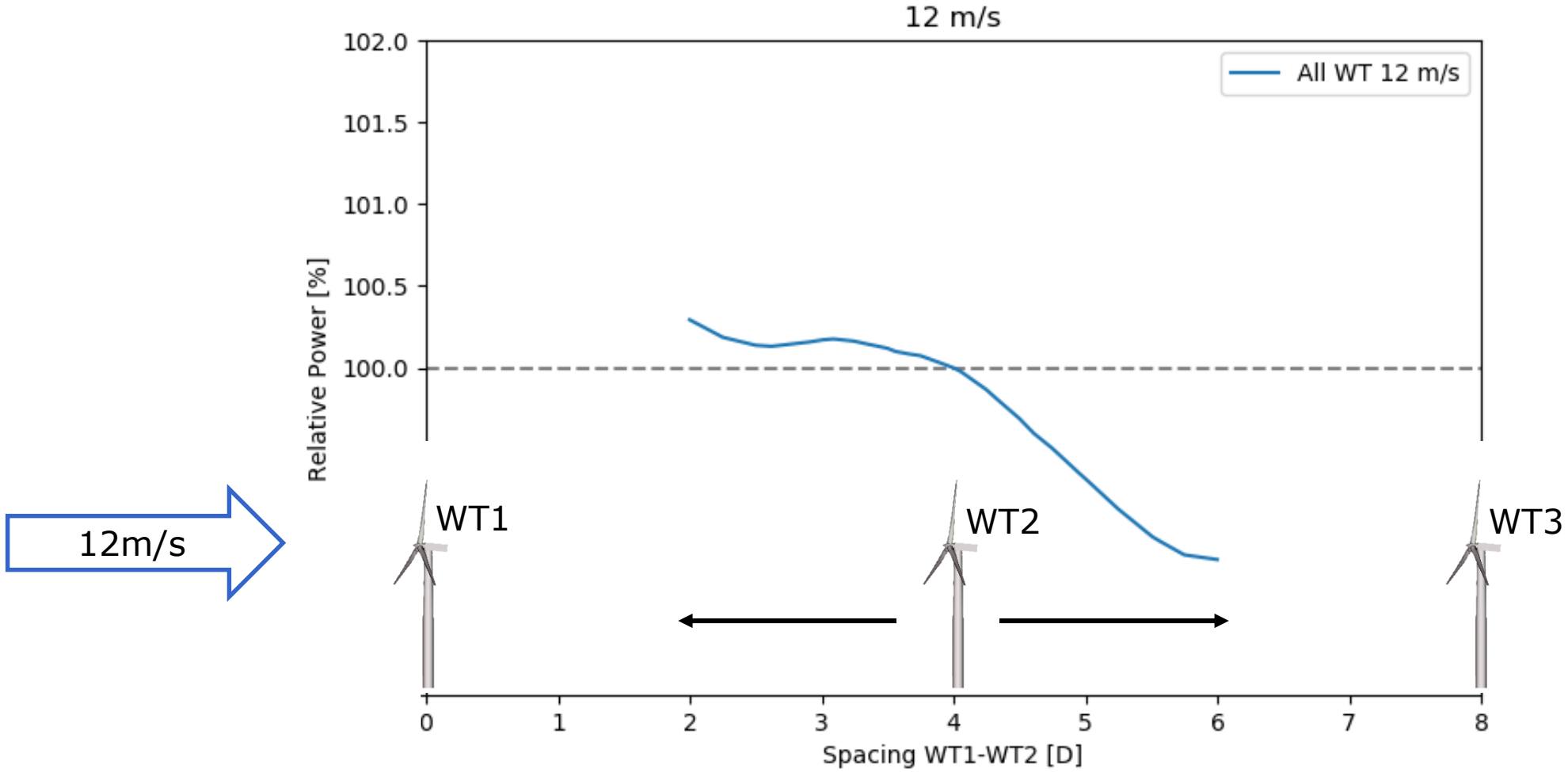

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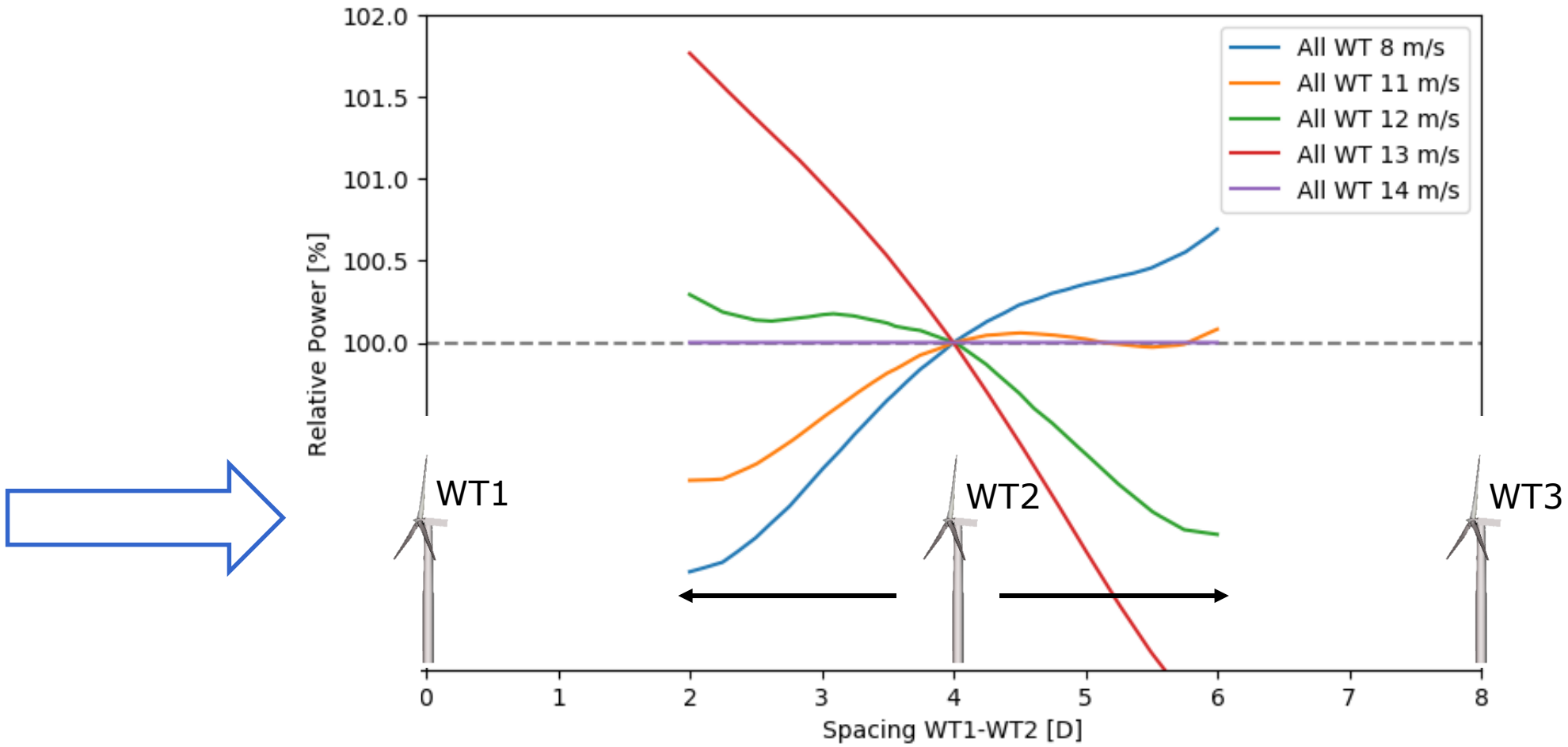

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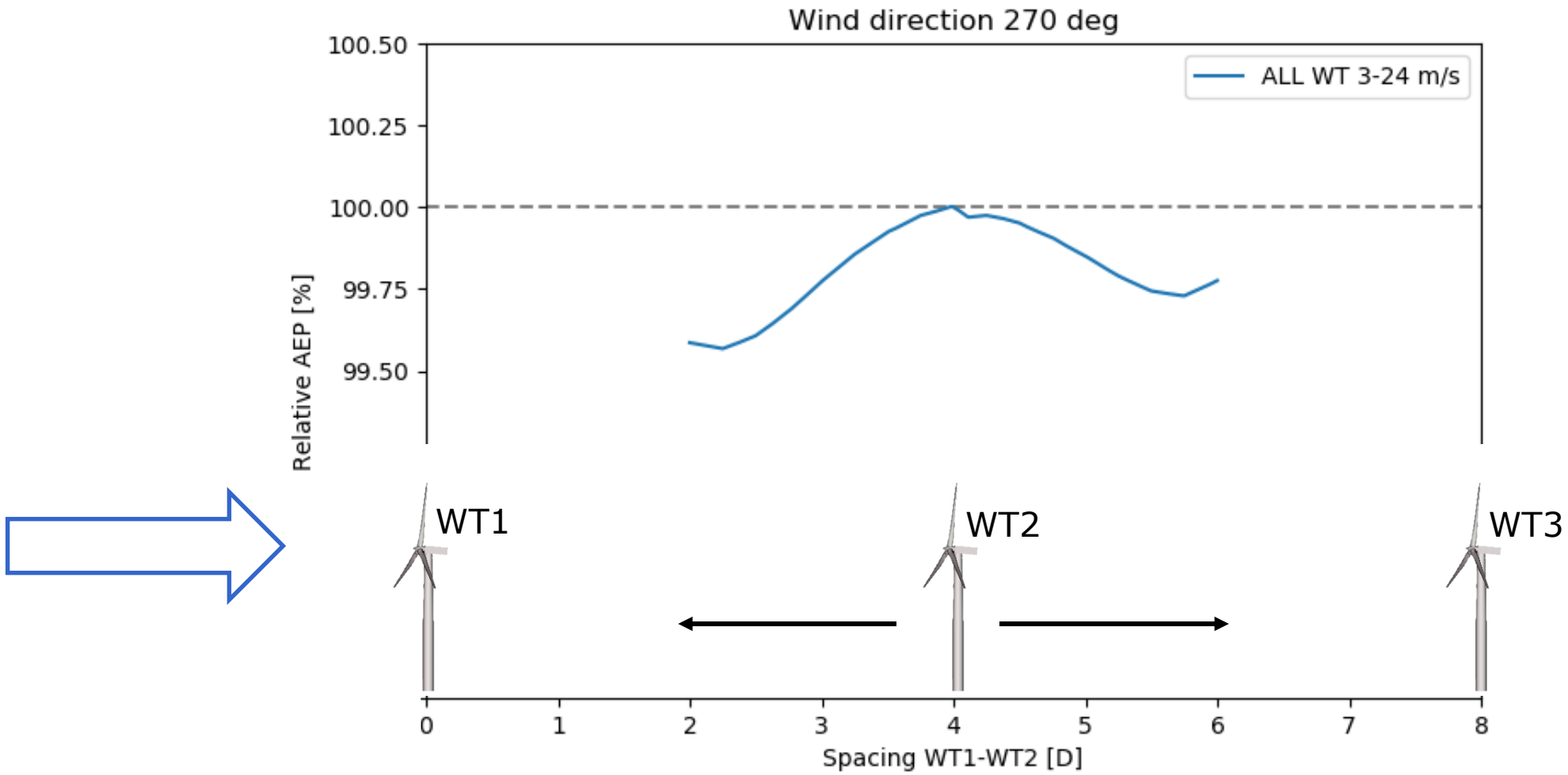

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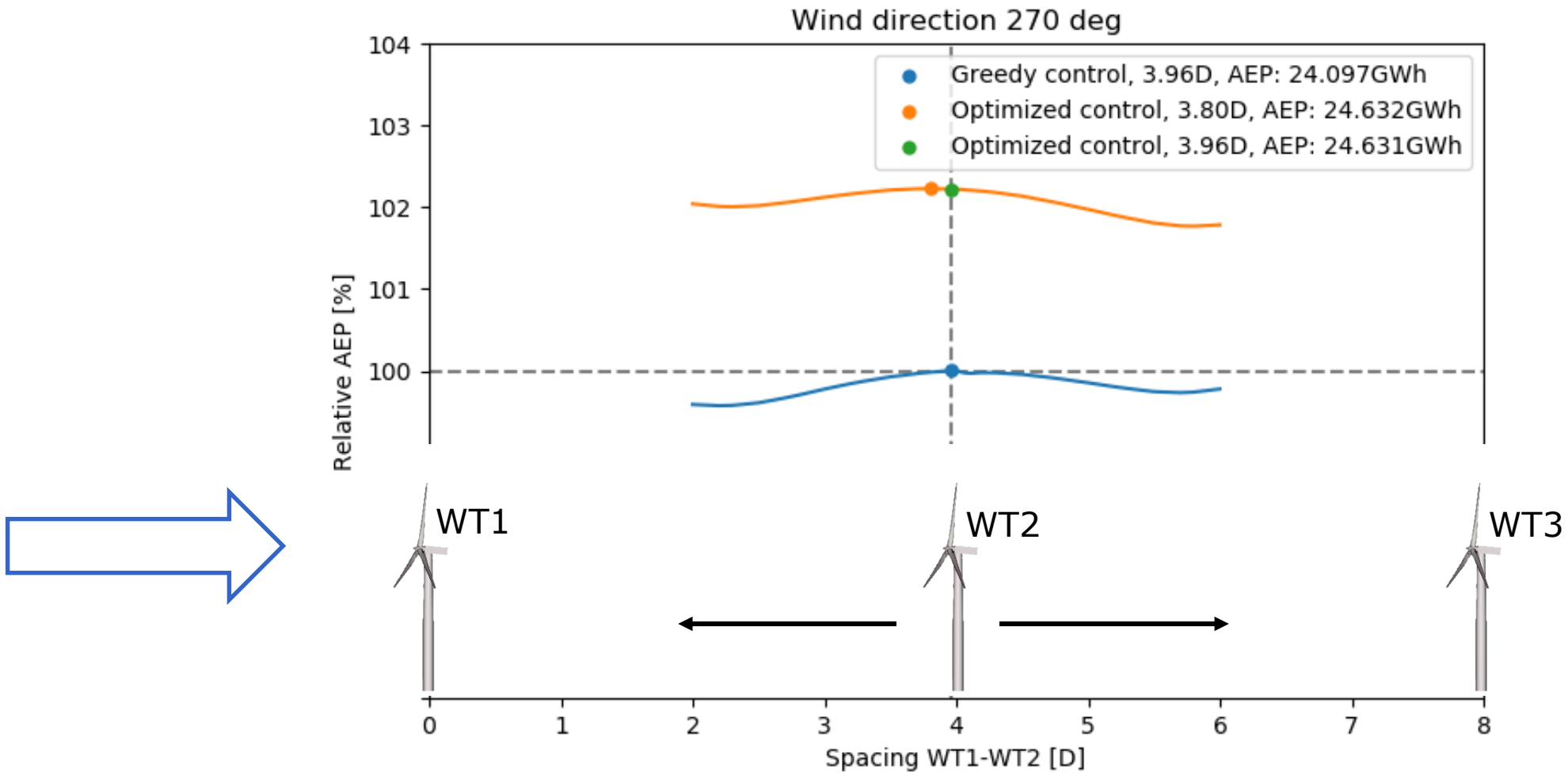

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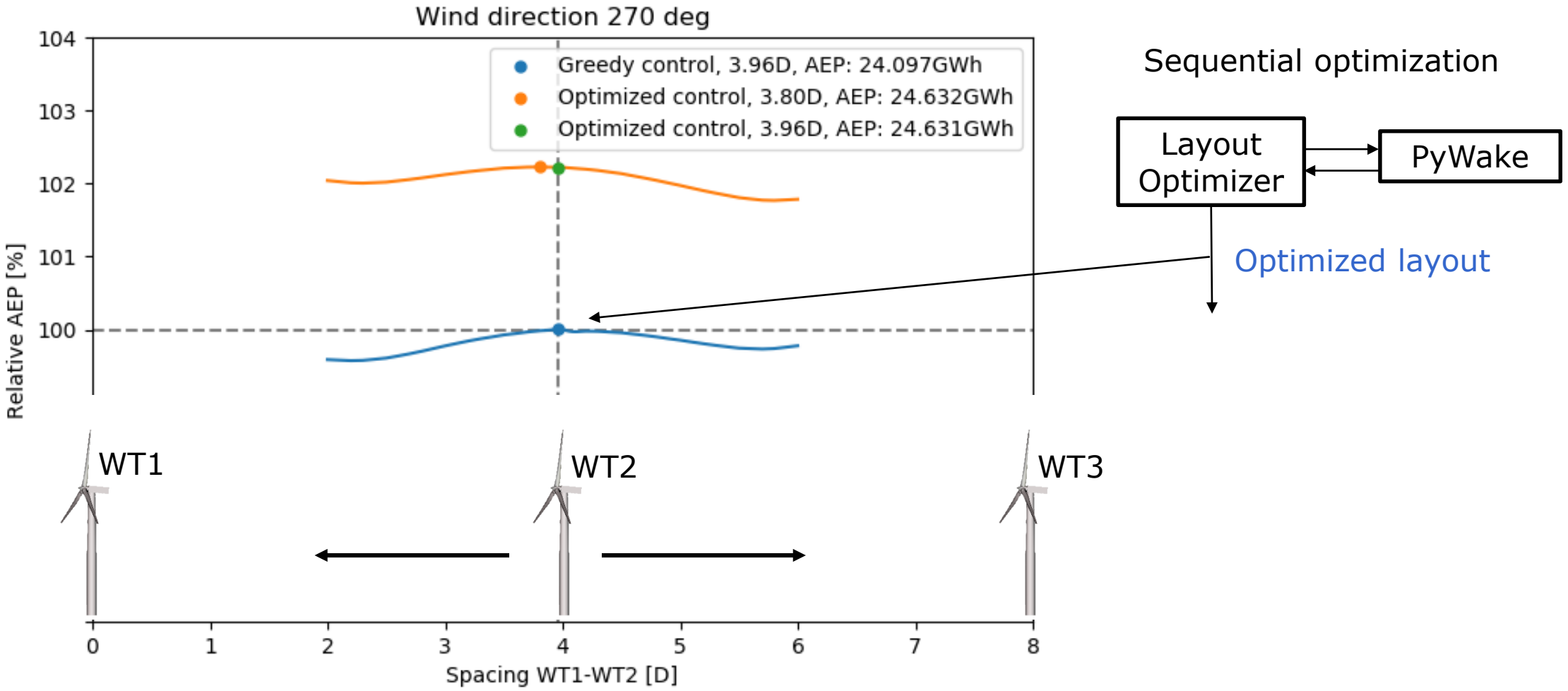
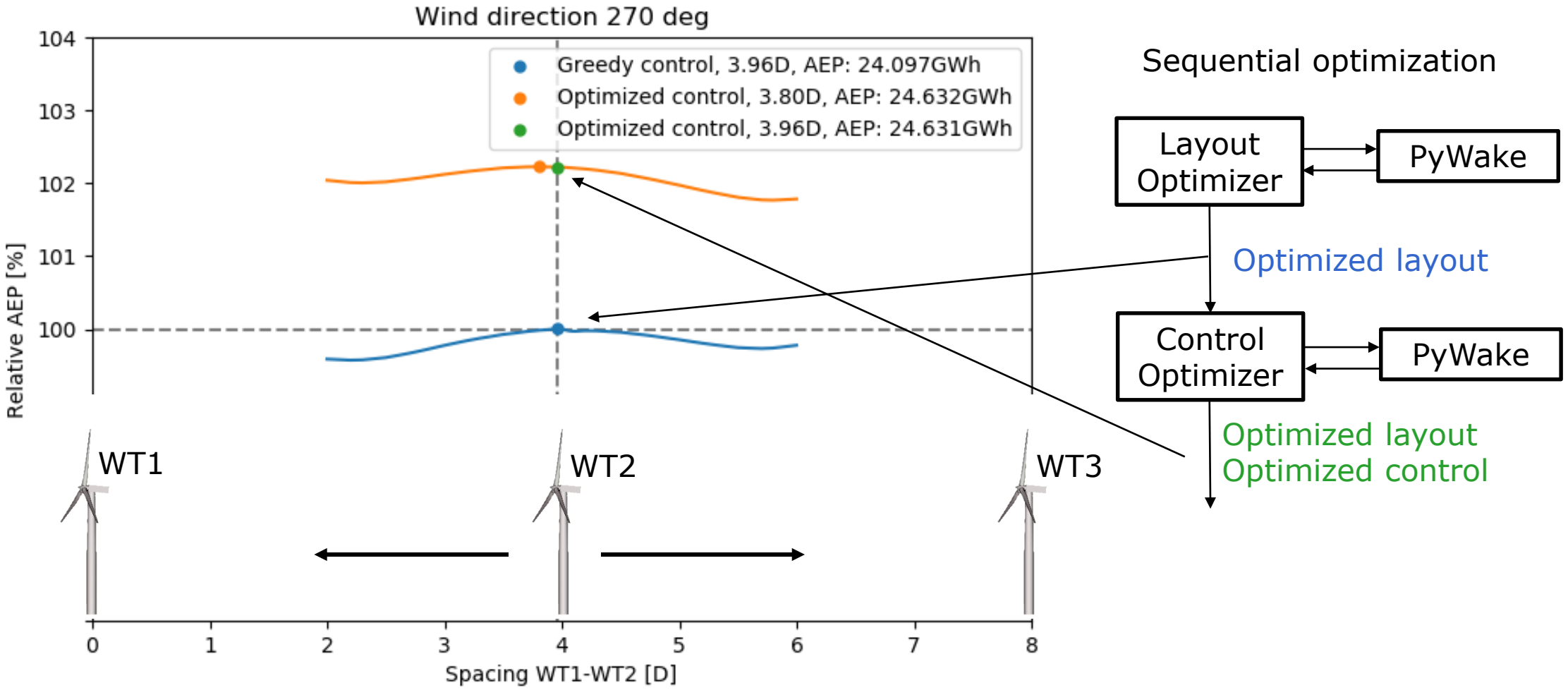
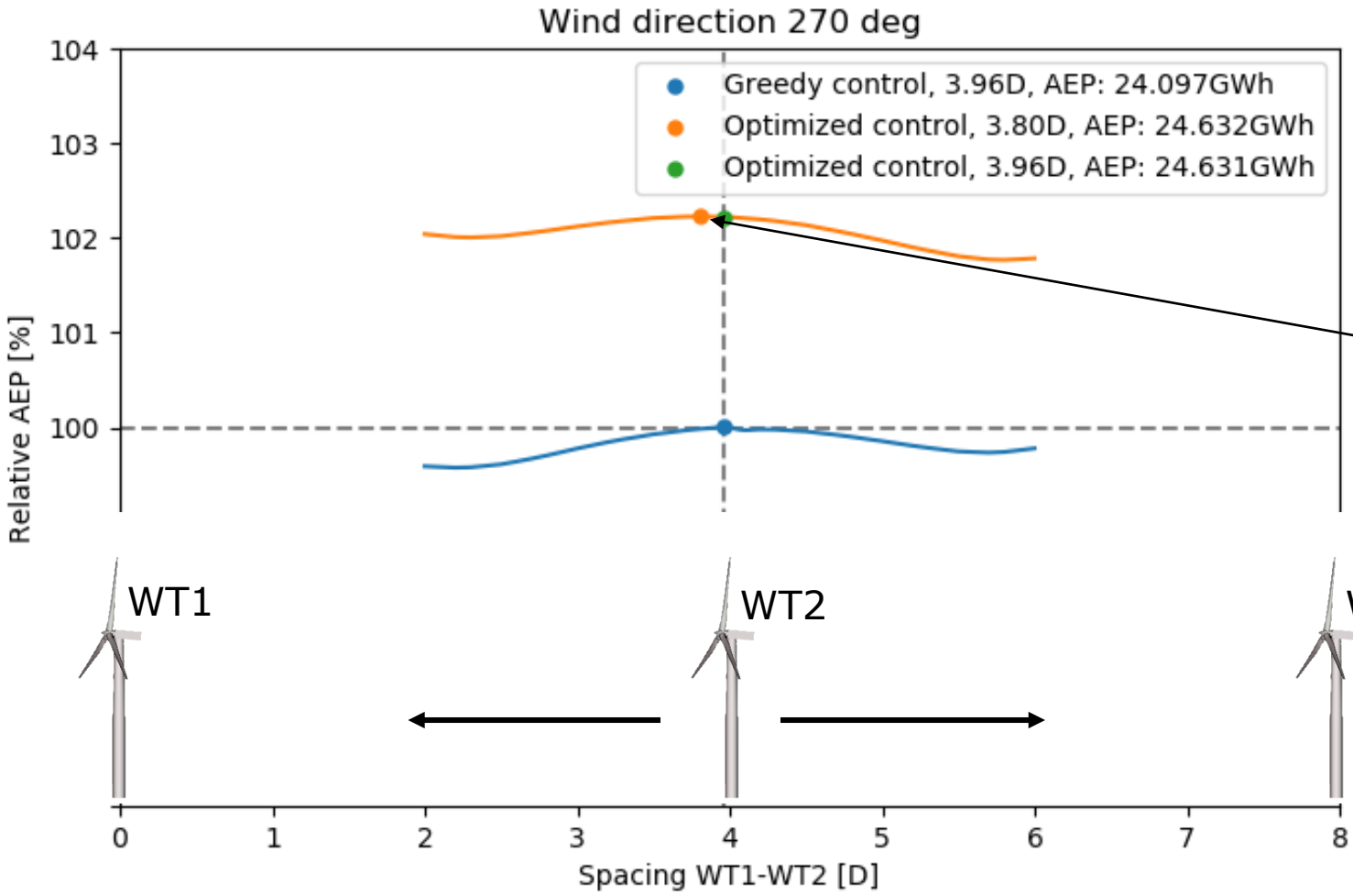


Sequential optimization

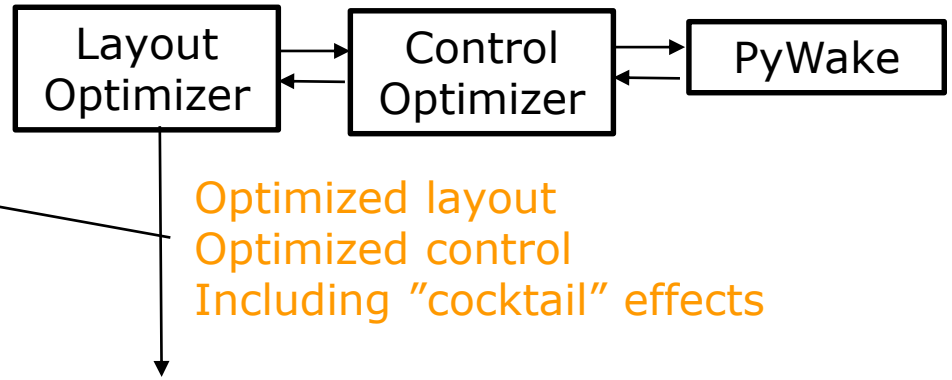
Single row, 3 wind turbines



Single row, 3 wind turbines

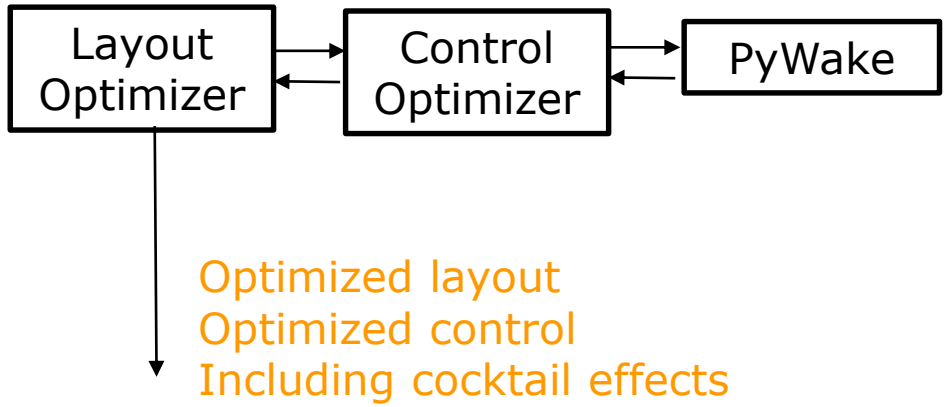


Nested optimization



Optimized layout
Optimized control
Including "cocktail" effects

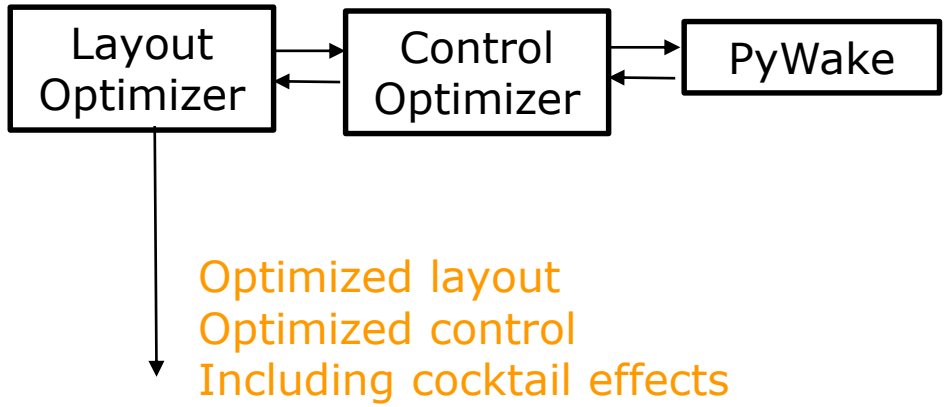
Nested optimization



Nested optimization

Layout optimizer:

- Random search
- Gradient based (finite difference)



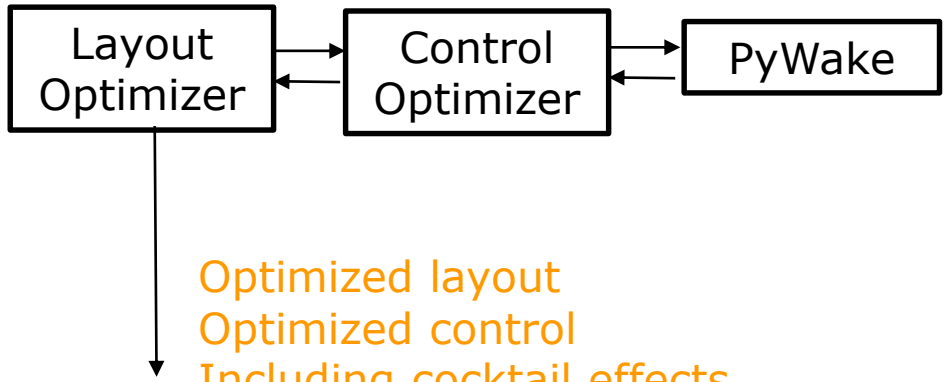
Nested optimization

Layout optimizer:

- Random search
- Gradient based (finite difference)

Control optimizer:

- Gradient based (finite difference)



Nested optimization

Layout optimizer:

- Random search
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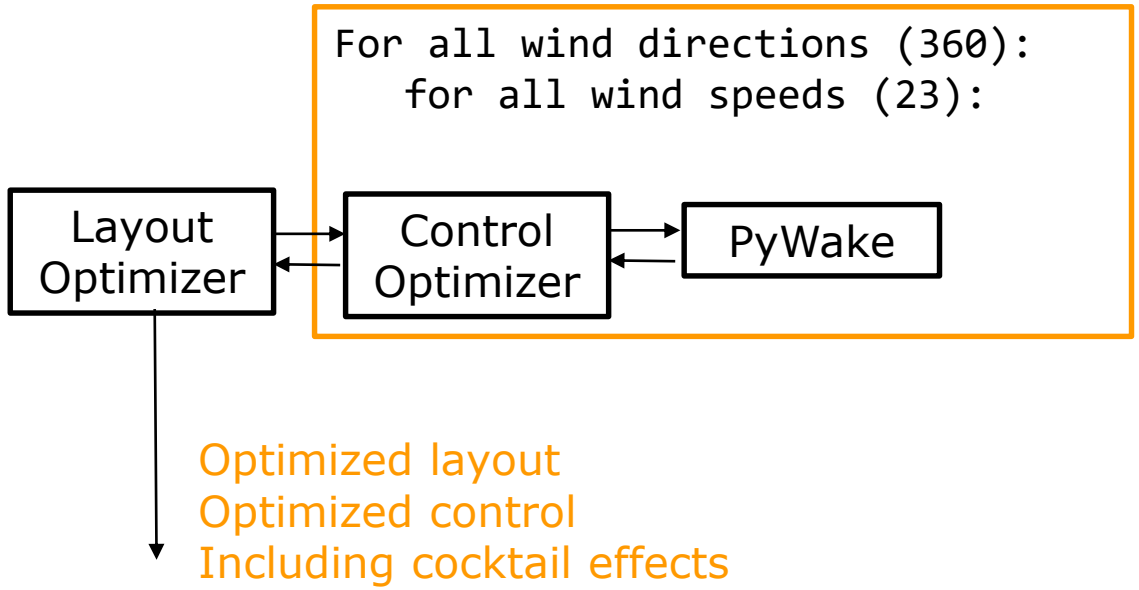
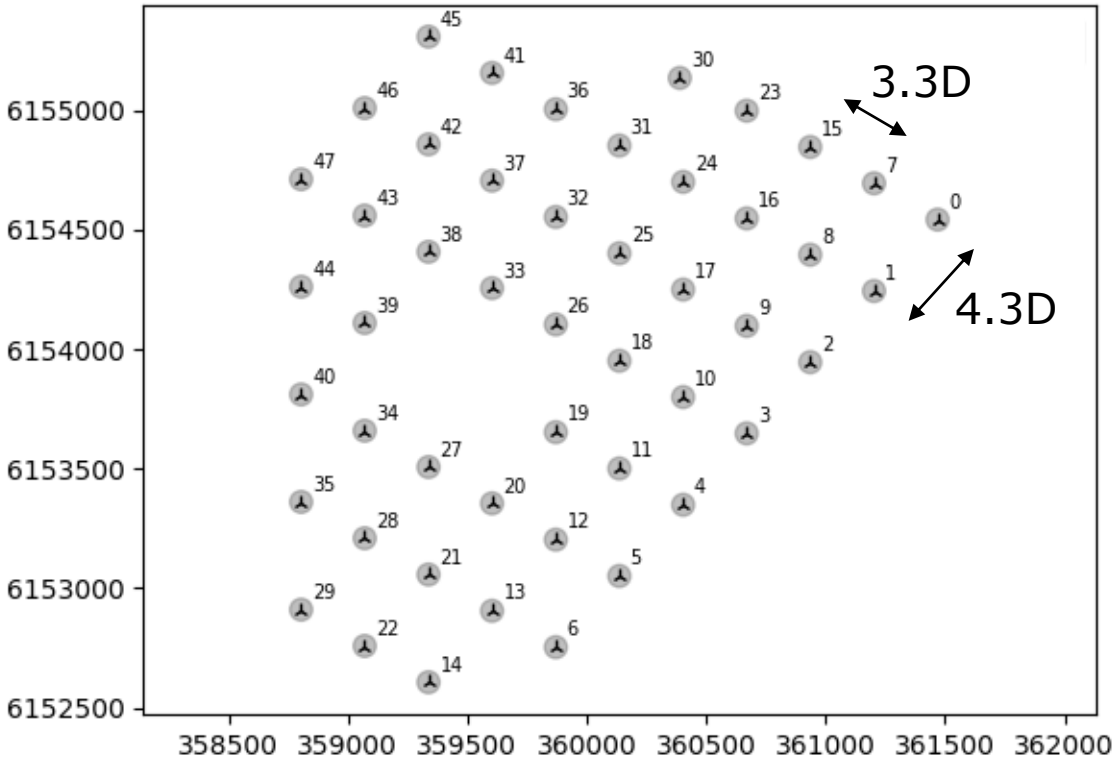
Control optimizer:

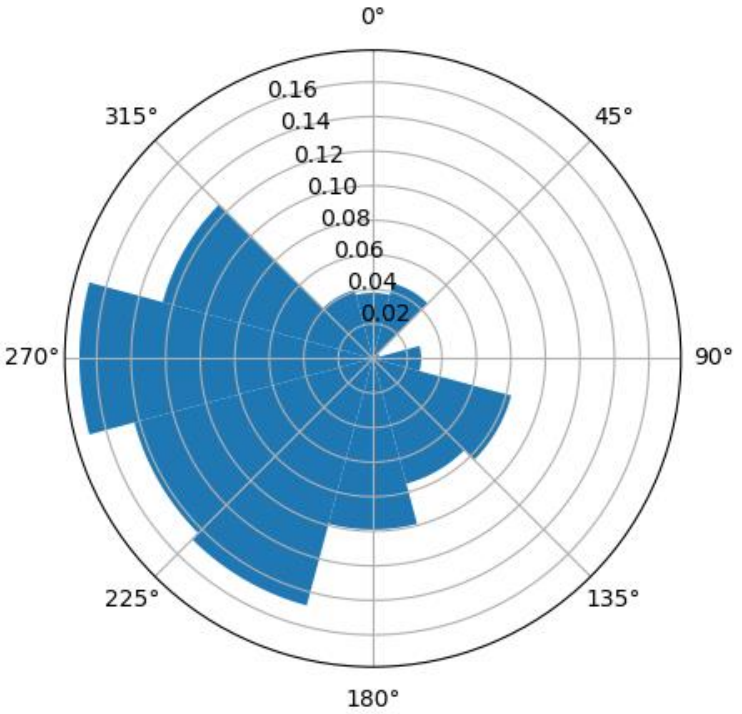
- Gradient based (finite difference)



LillGrund

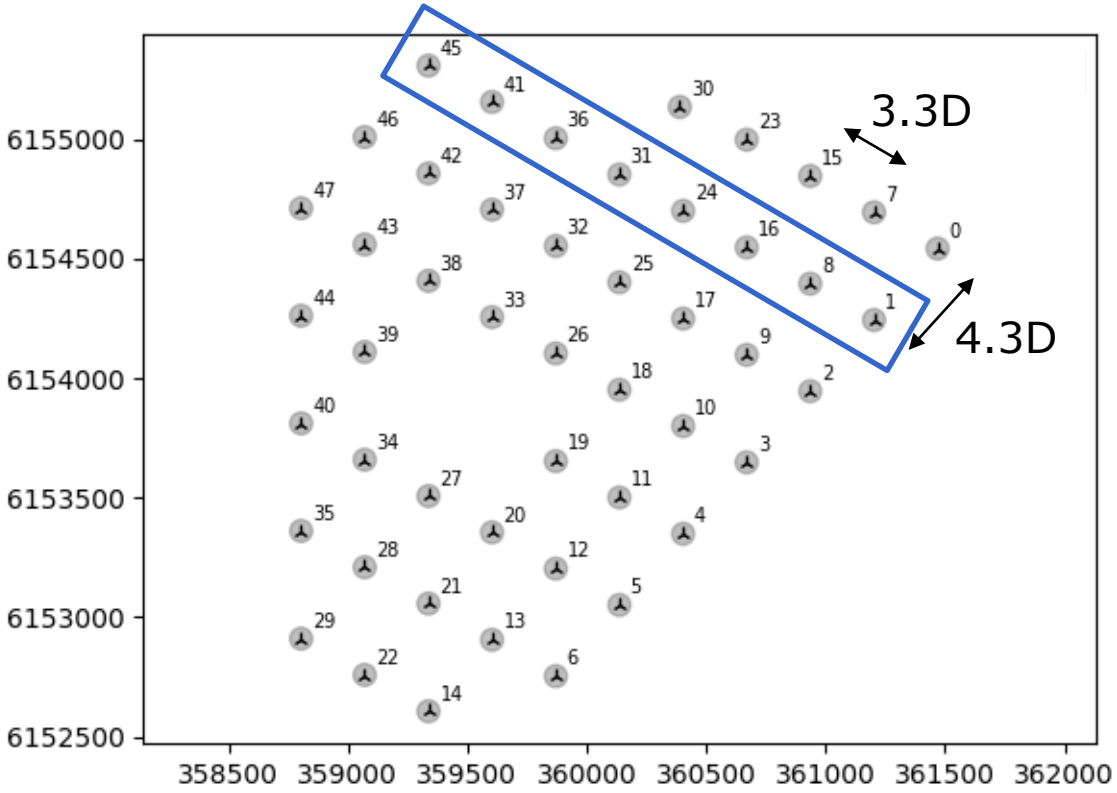
- 48 Siemens wind turbines
- 2.3MW
- 93m rotor

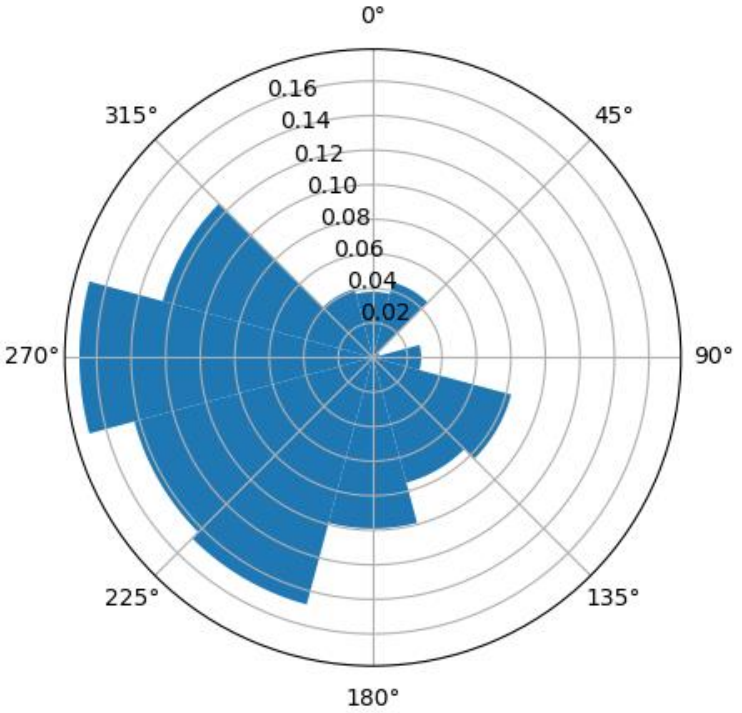




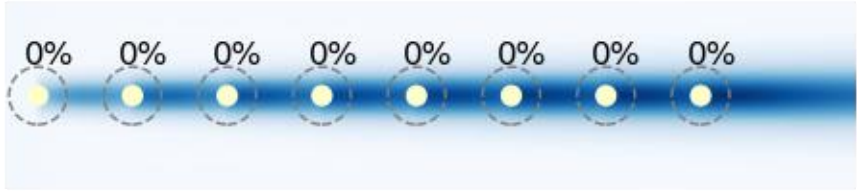
LillGrund

- 8 wind turbines
- 3.3D spacing



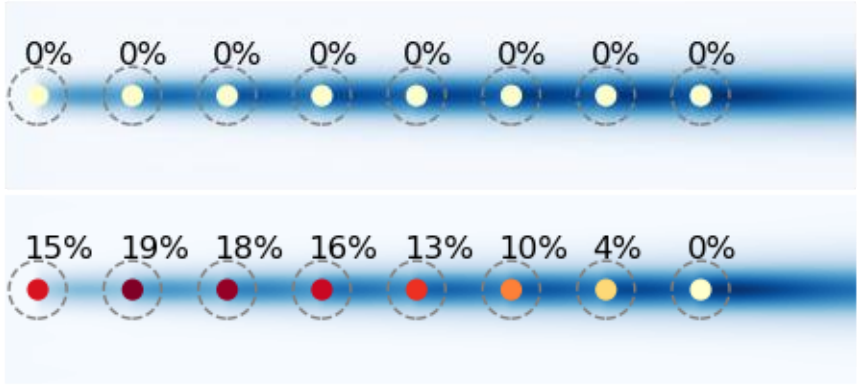


LillGrund row



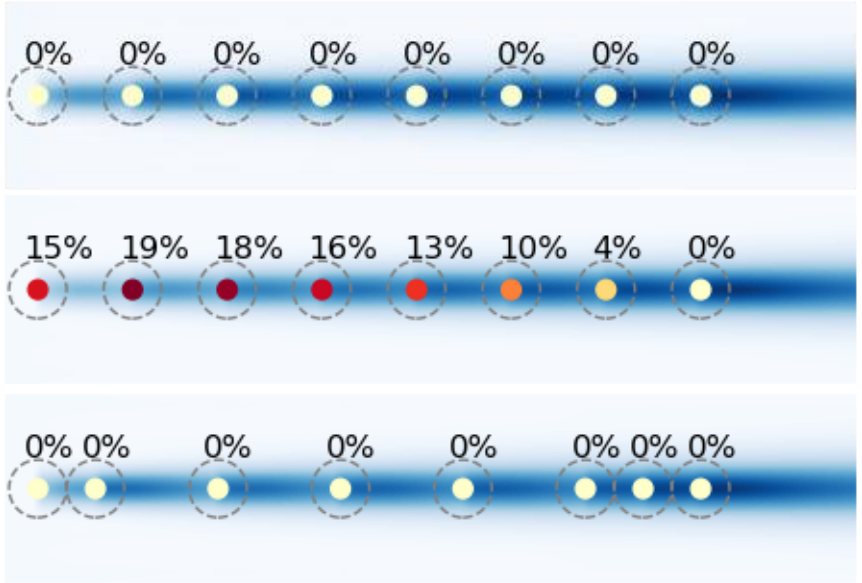
	AEP [Gwh]
Initial layout, greedy control	40.85

LillGrund row



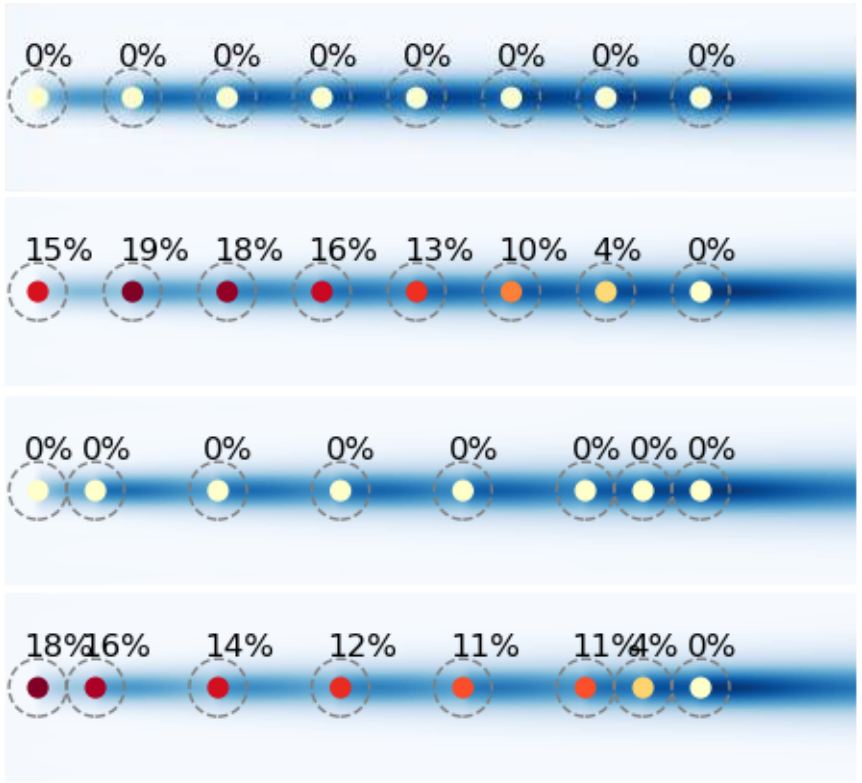
	AEP [Gwh]
Initial layout, greedy control	40.85
Initial layout, optimized control	44.10 (+8.0%)

LillGrund row



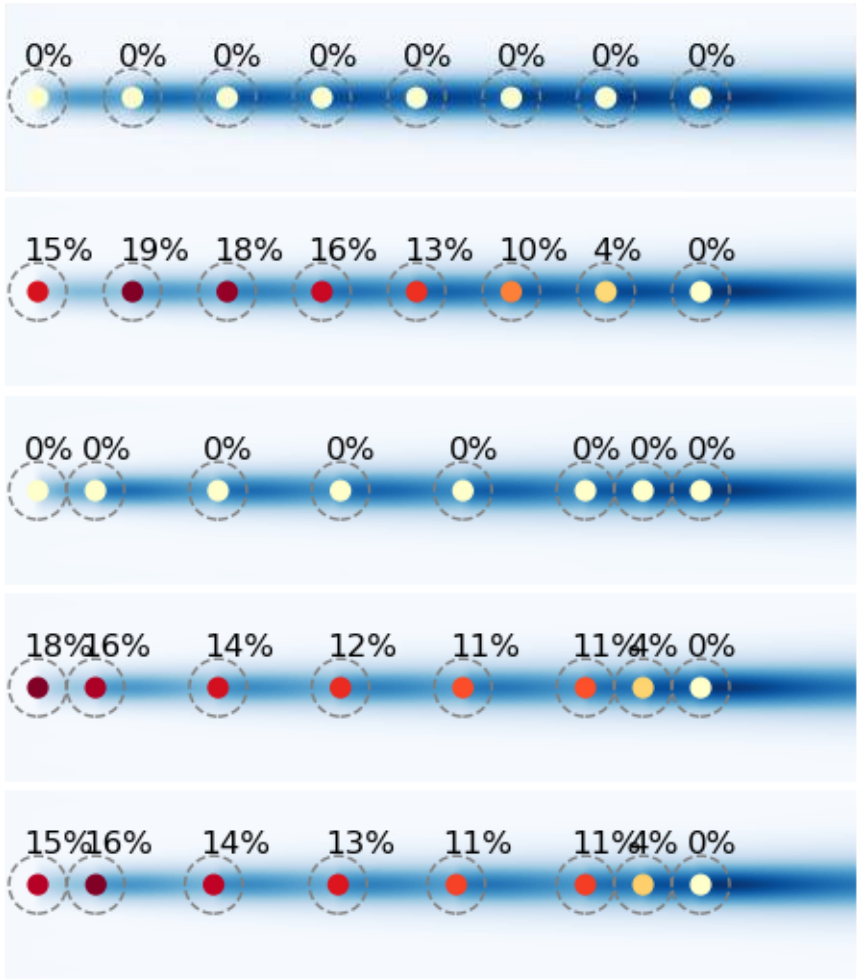
	AEP [Gwh]
Initial layout, greedy control	40.85
Initial layout, optimized control	44.10 (+8.0%)
Optimized layout, greedy control	41.44 (+1.4%)

LillGrund row



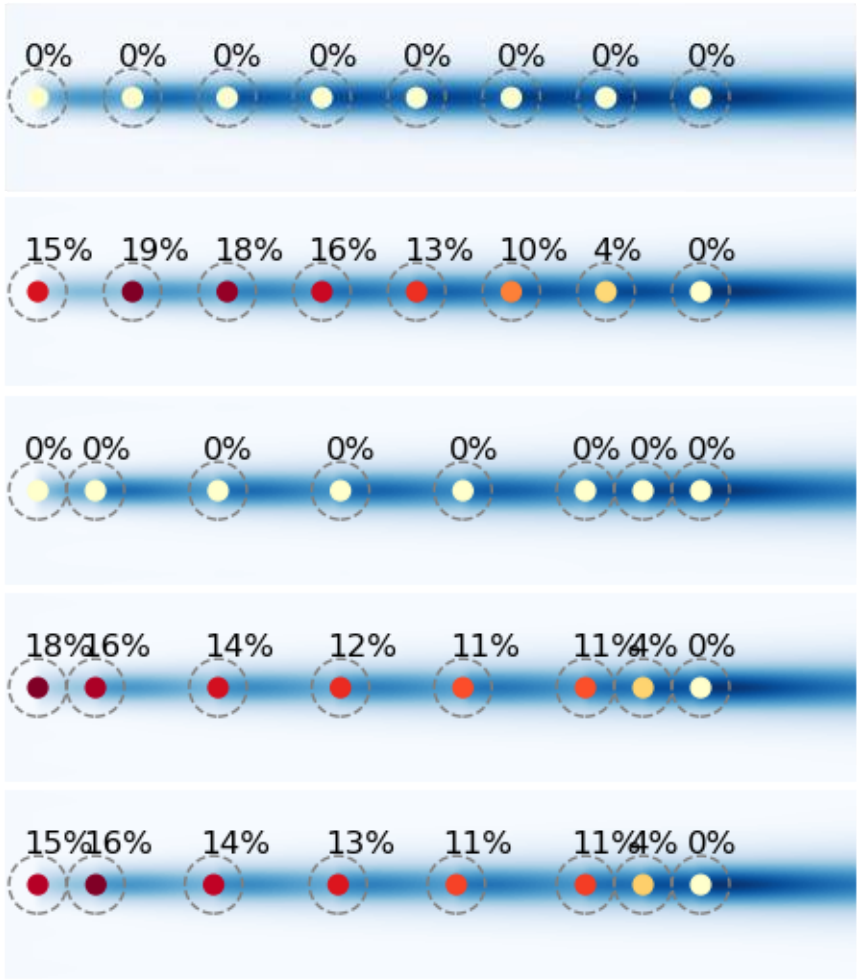
	AEP [Gwh]
Initial layout, greedy control	40.85
Initial layout, optimized control	44.10 (+8.0%)
Optimized layout, greedy control	41.44 (+1.4%)
Optimized layout, optimized control (sequential)	44.558 (+9.1%)

LillGrund row



	AEP [Gwh]
Initial layout, greedy control	40.85
Initial layout, optimized control	44.10 (+8.0%)
Optimized layout, greedy control	41.44 (+1.4%)
Optimized layout, optimized control (sequential)	44.558 (+9.1%)
Optimized layout and control (nested)	44.560 (+9.1%)

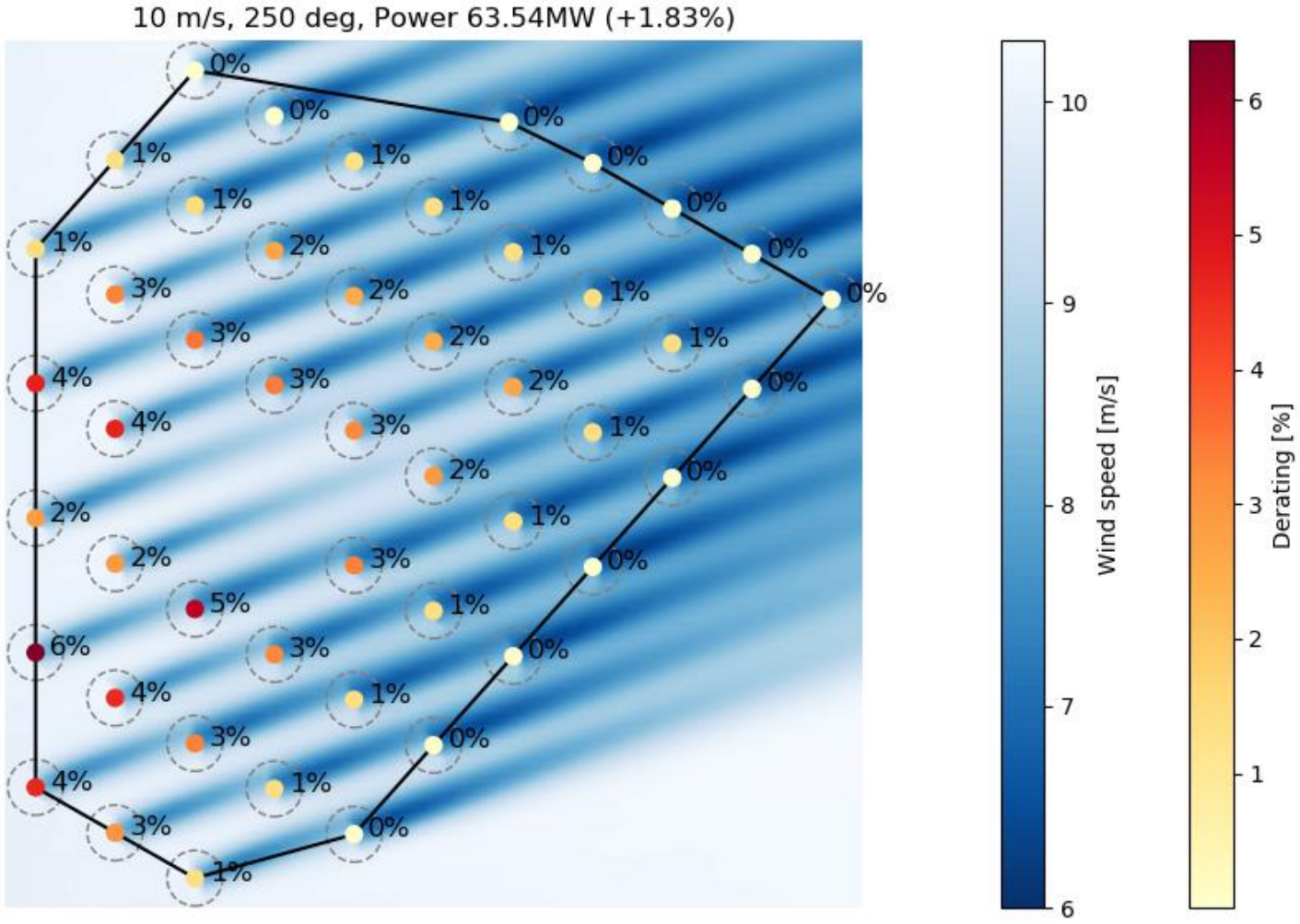
LillGrund row



	AEP [Gwh]
Initial layout, greedy control	40.85
Initial layout, optimized control	44.10 (+8.0%)
Optimized layout, greedy control	41.44 (+1.4%)
Optimized layout, optimized control (sequential)	44.558 (+9.1%)

Infeasible for full wind farm with current setup/models

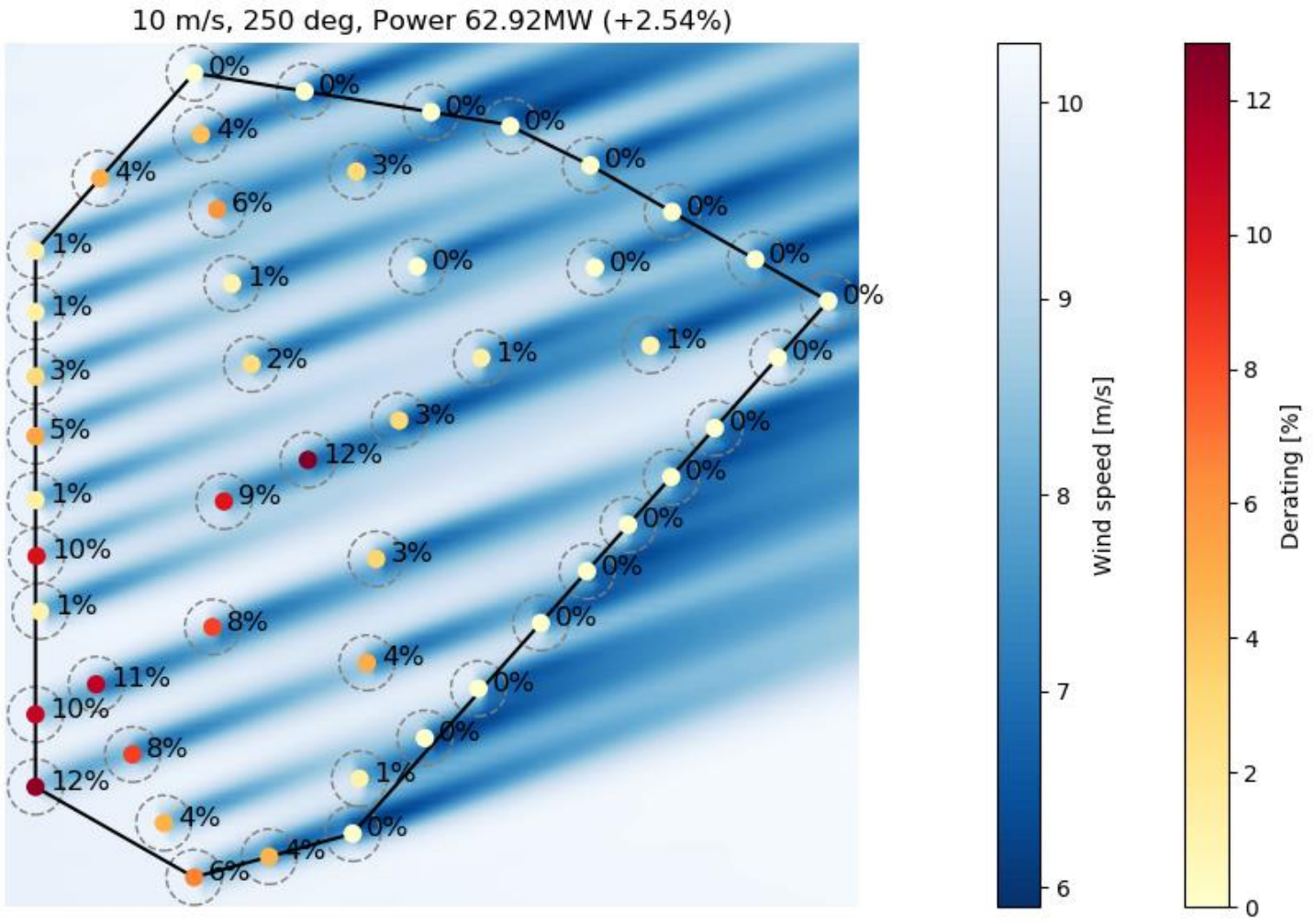
Lillgrund, initial layout



Initial layout

Control	AEP [GWh]
Greedy	345.2
Optimized	349.5 (+1.3%)

Lillgrund optimized layout



Initial layout

Control	AEP [GWh]
Greedy	345.2
Optimized	349.5 (+1.3%)

Optimized layout (sequential)

Control	AEP [GWh]
Greedy	354.9 (+2.8%)
Optimized	358.7 (+4.0%)

Conclusions

- Production gains found
  - Layout optimization (+2.8% for Lillgrund)
  - Control optimization (+1.3% for Lillgrund)
  - Sequential layout and control optimization (+4.0% for Lillgrund)
- Nested layout and control optimization of full wind farm infeasible with current setup/model
- Cocktail effects observed for 8-WT row, but insignificant

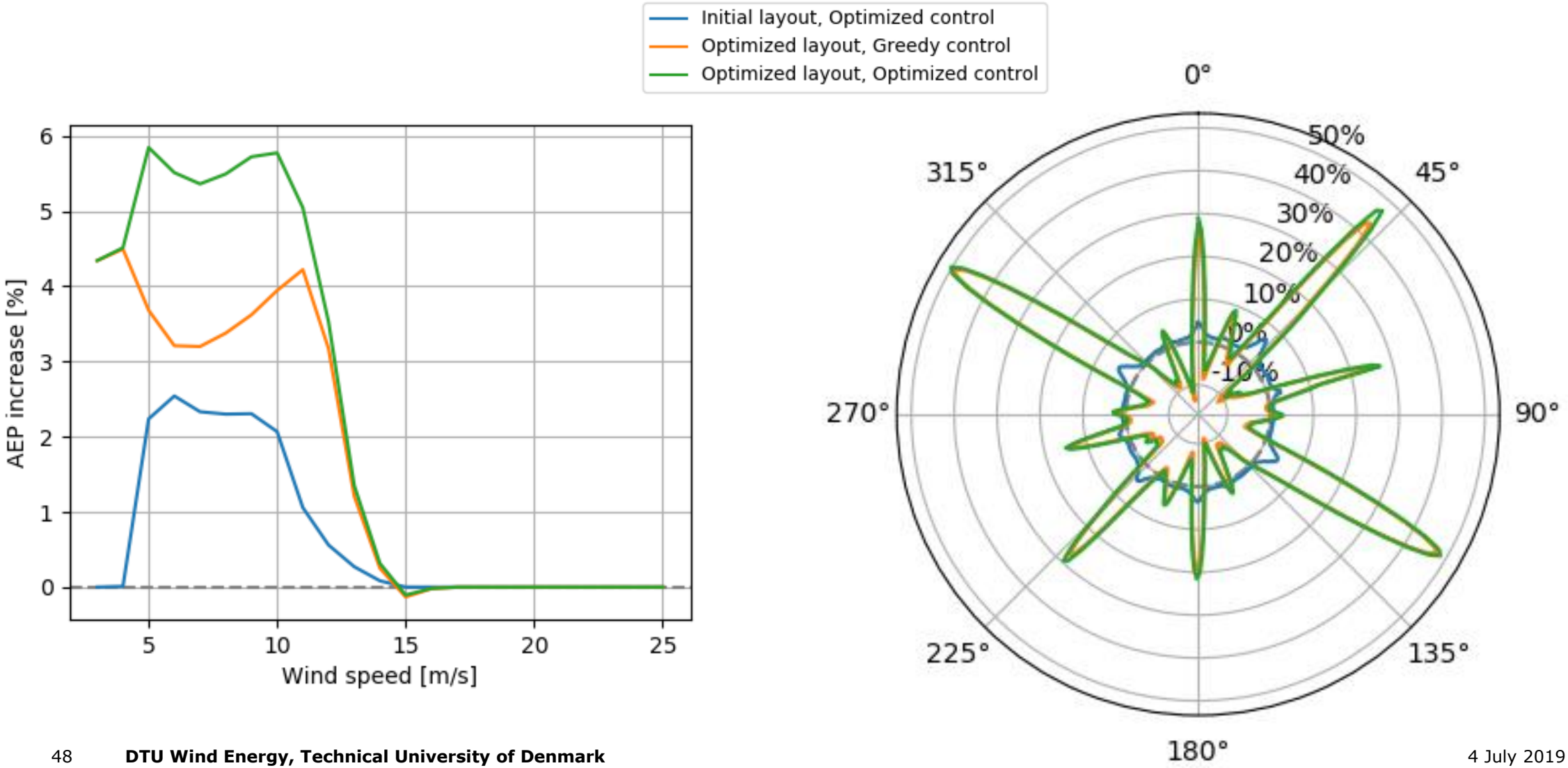
- Future work:
  - Include uncertainty of wind direction and wind speed
  - Include yaw control and wake steering
  - Integrate loads surrogates to address reliability and overall LCOE

Thank you for your attention

This study is funded by

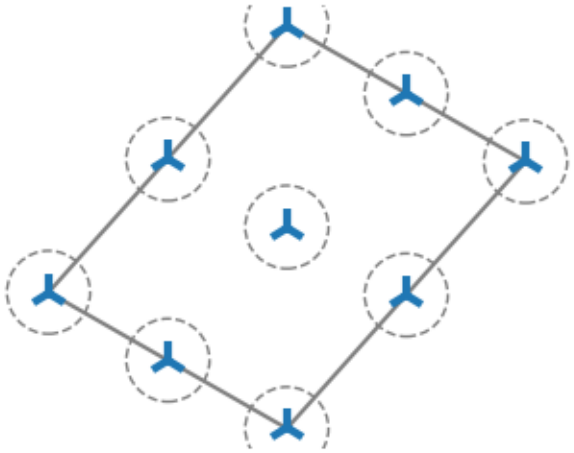
TotalControl is an EU Horizon2020 funded project running from 2018-2021.

Lillgrund – AEP increase



LillGrund 3x3

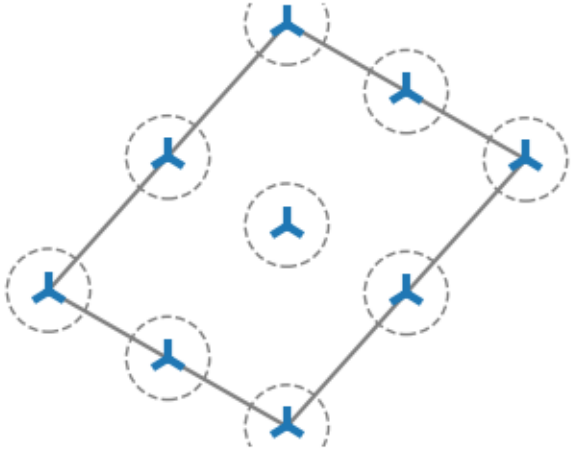
Initial layout



Control	AEP [GWh]
Greedy	73.28
Optimized	73.61 (+0.5%)

LillGrund 3x3

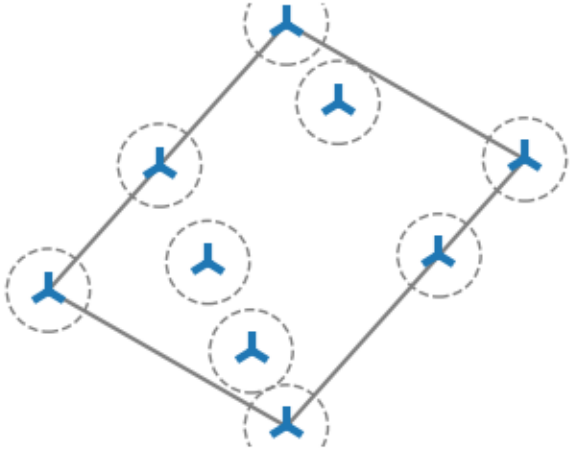
Initial layout



Control	AEP [GWh]
Greedy	73.28
Optimized	73.61 (+0.5%)

Optimized layout

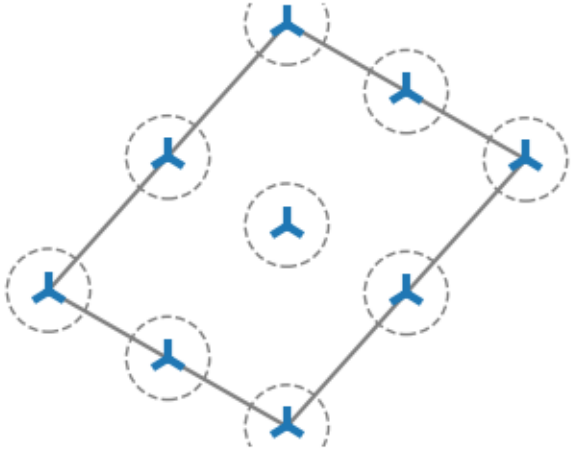
(First layout then control)



Control	AEP [GWh]
Greedy	73.86 (+0.8%)
Optimized	74.18 (+1.2%)

LillGrund 3x3

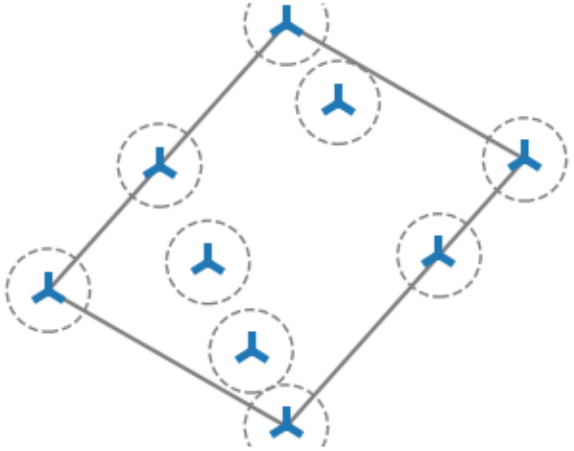
Initial layout



Control	AEP [GWh]
Greedy	73.28
Optimized	73.61 (+0.5%)

Optimized layout

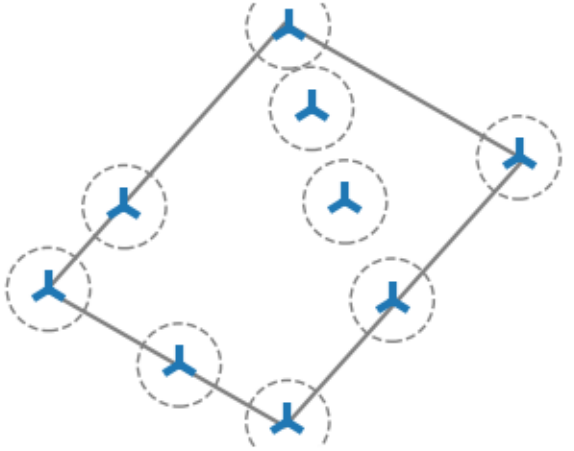
(Sequential)



Control	AEP [GWh]
Greedy	73.86 (+0.8%)
Optimized	74.18 (+1.23%)

Optimized layout

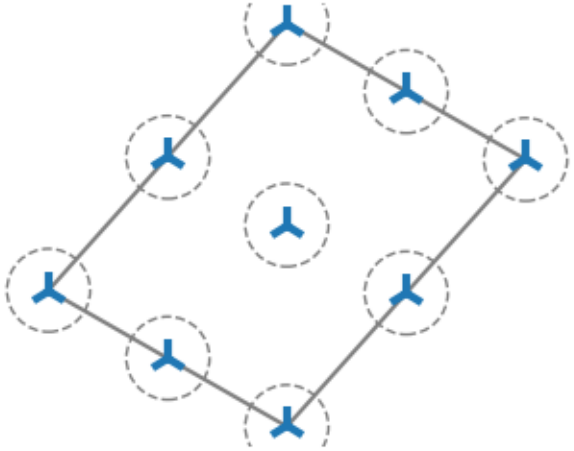
(Nested layout and control)



Control	AEP [GWh]
Optimized	74.15 (+1.18%)

LillGrund 3x3

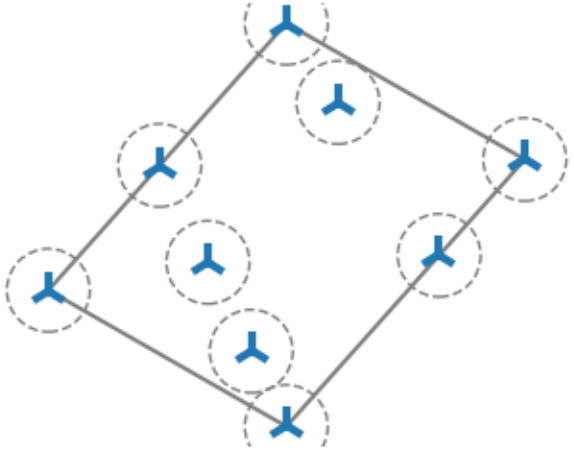
Initial layout



Control	AEP [GWh]
Greedy	73.28
Optimized	73.61 (+0.5%)

Optimized layout

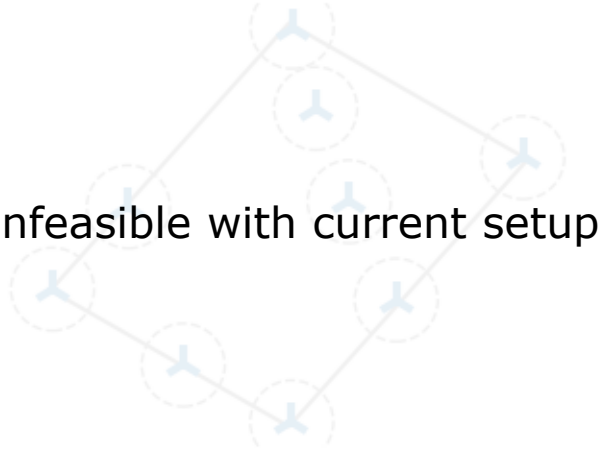
(First layout then control)



Control	AEP [GWh]
Greedy	73.86 (+0.8%)
Optimized	74.18 (+1.23%)

Optimized layout

(Combined layout and control)



Infeasible with current setup

Control	AEP [GWh]
Optimized	74.15 (+1.18%)