Comparison of yaw angle selection strategies for wake steering control of wind farms using FLORIS

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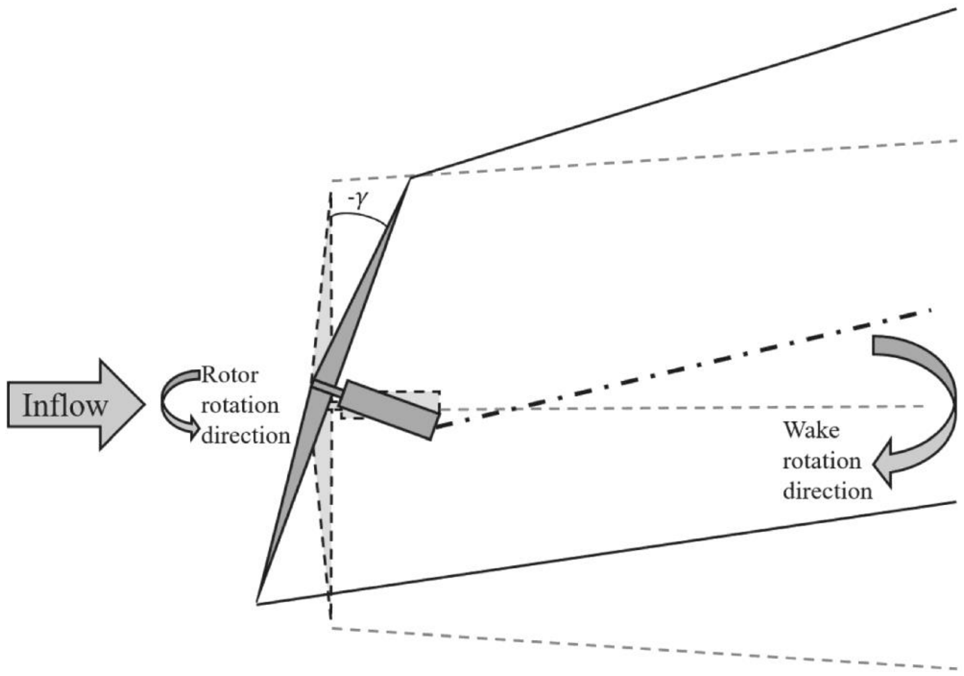
Background – Turbine Wakes

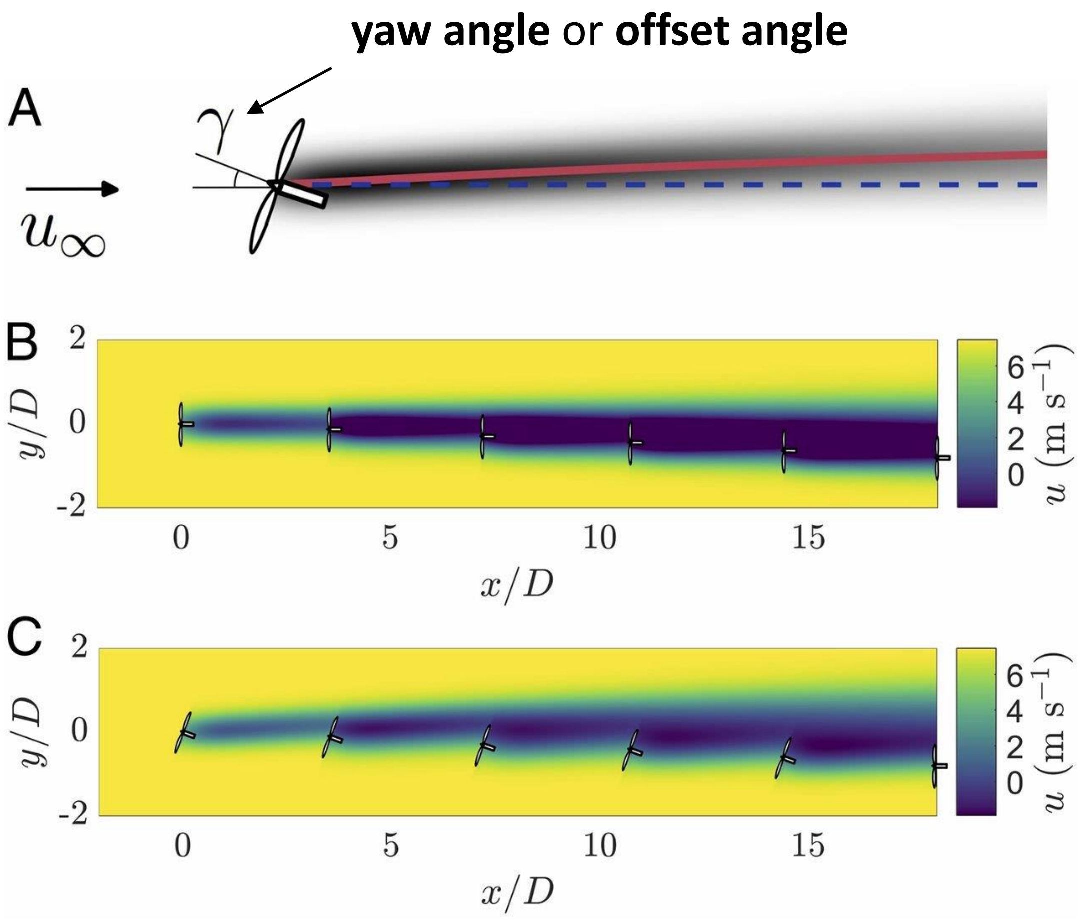
Source: Vattenfall (Flickr)

Fog makes it easy to see the wakes of wind turbines at the Horns Rev offshore wind farm.

Wind speed is reduced in the wake, this can cause up to 40% reduction in power output!

Background – Wake Steering

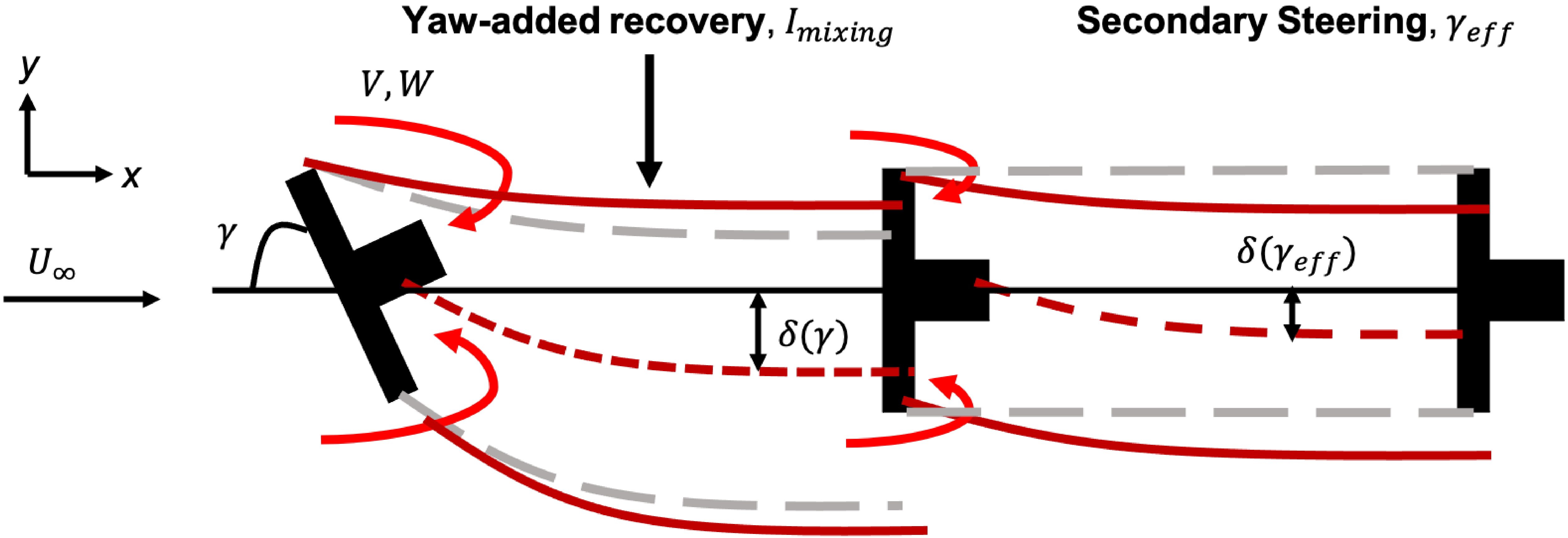




Source (left): D. R. Houck. “Review of Wake Management Techniques for Wind Turbines.” *Wind Energy*, vol. 25, no. 2, pp. 195–220., 2021.

Source (right): M. F. Howland, S. K. Lele and J. O. Dabiri. “Wind Farm Power Optimization through Wake Steering.” *Proceedings of the National Academy of Sciences*, vol. 116, no. 29, pp. 14495–14500., 2019.

Background – Secondary Steering



Source: J. King, P. Fleming, R. King, L. A. Martínez-Tossas, C. J. Bay, R. Mudafort and E. Simley. "Control-Oriented Model for Secondary Effects of Wake Steering." *Wind Energy Science*, vol. 6, no. 3, pp. 701–714., 2021.

Research Motivation + Process

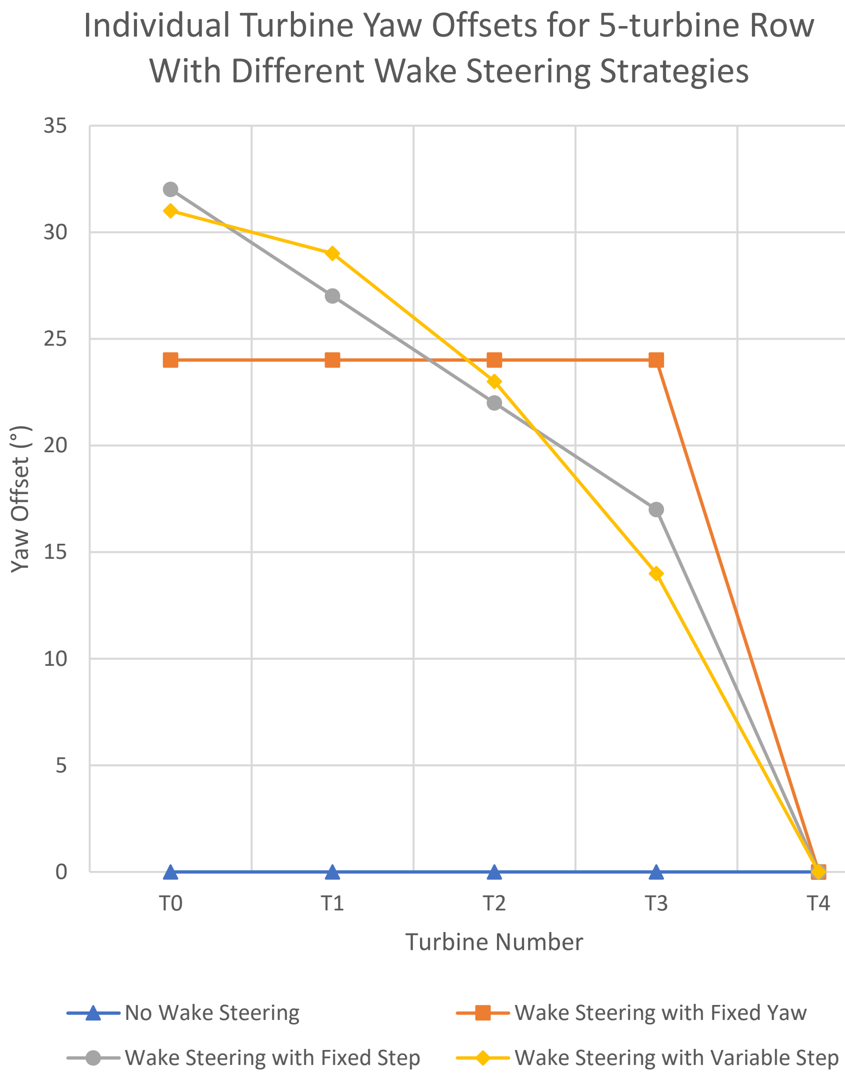
1. Optimize for power maximization
2. Compare different control strategies
   1. Some wind farms have global control
   2. Is it worth designing for local control?
3. Every wind farm is different!
   1. Controlled parametric experiments
   2. Find: optimal angles, max power output

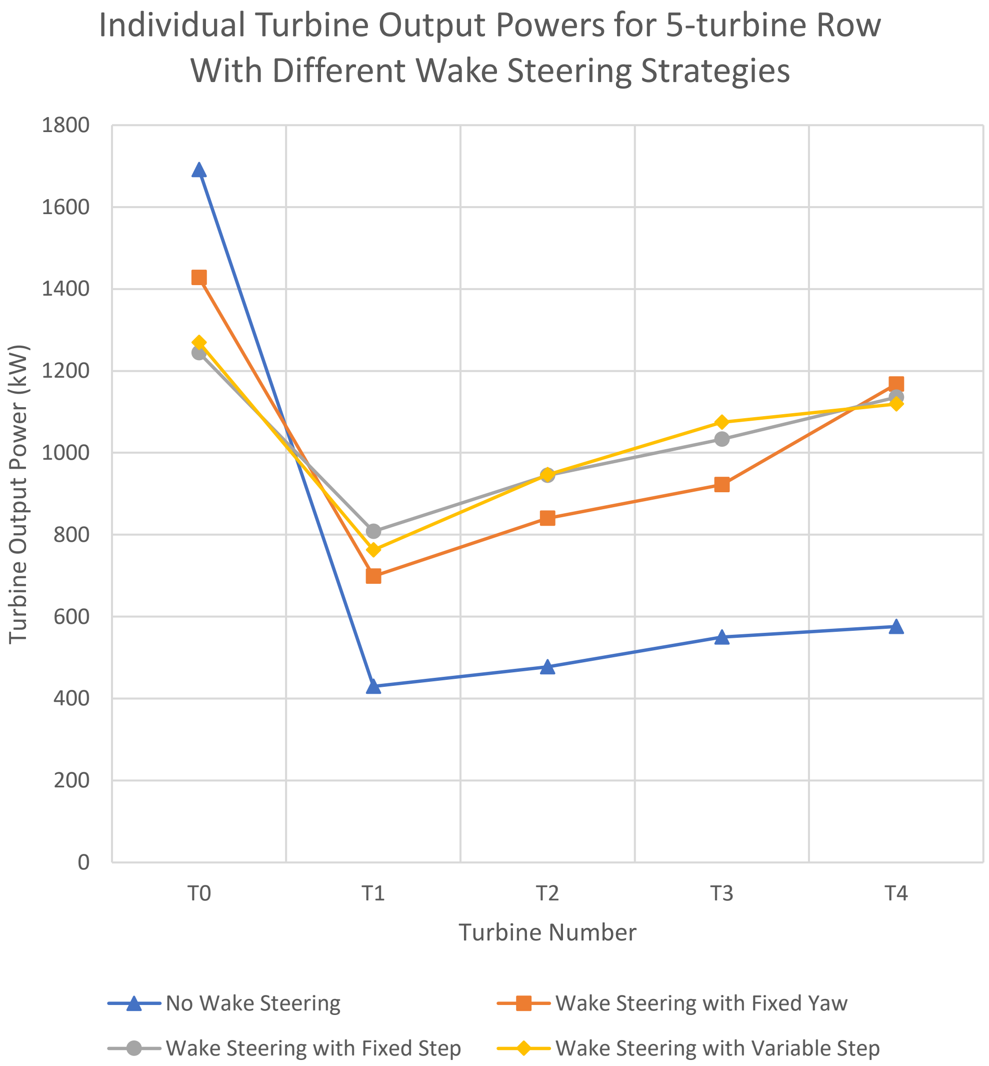
Fixed offset strategy

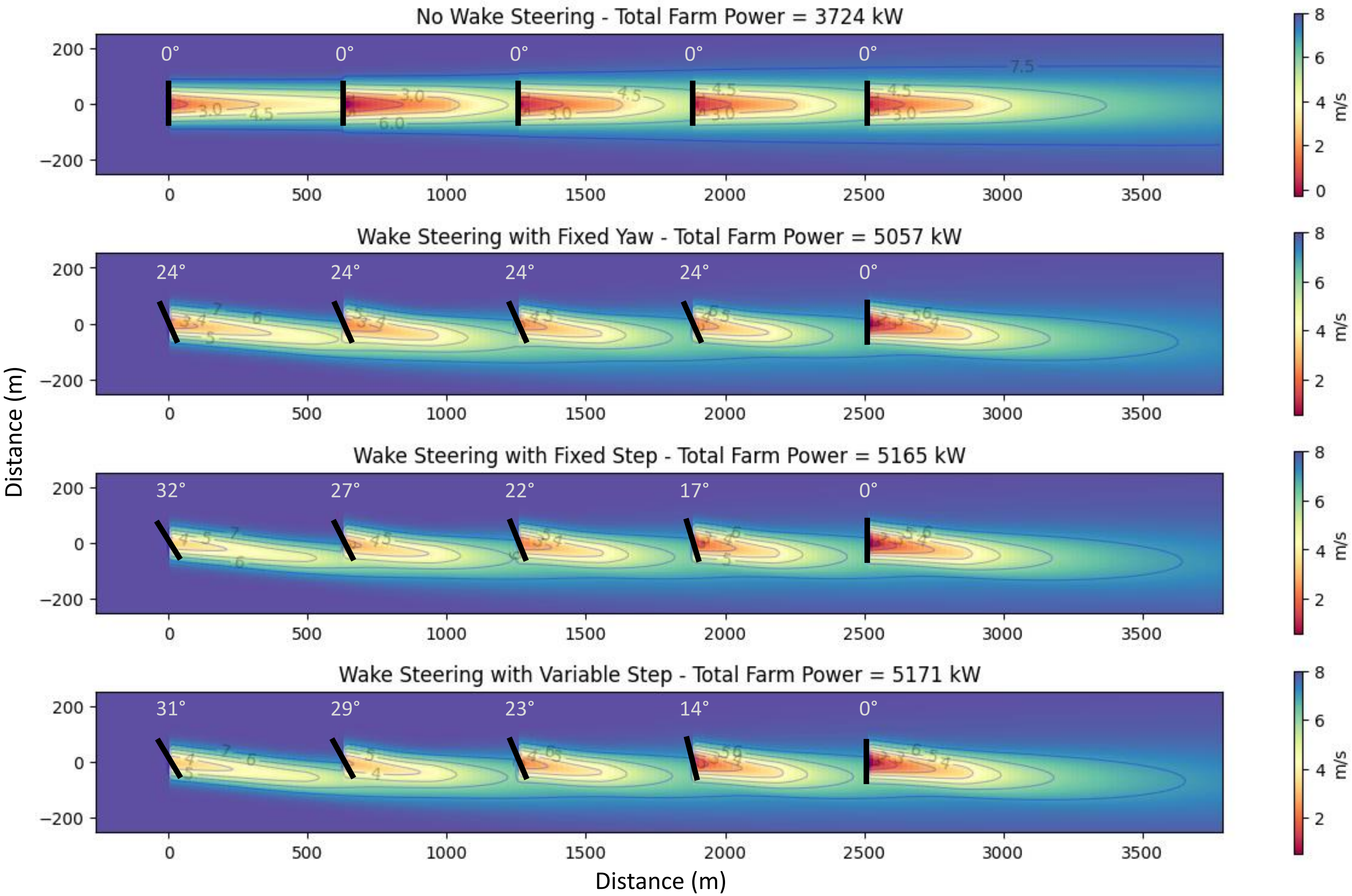
- Global control
- All turbines except for last one get the same misalignment
- Last turbine does not yaw

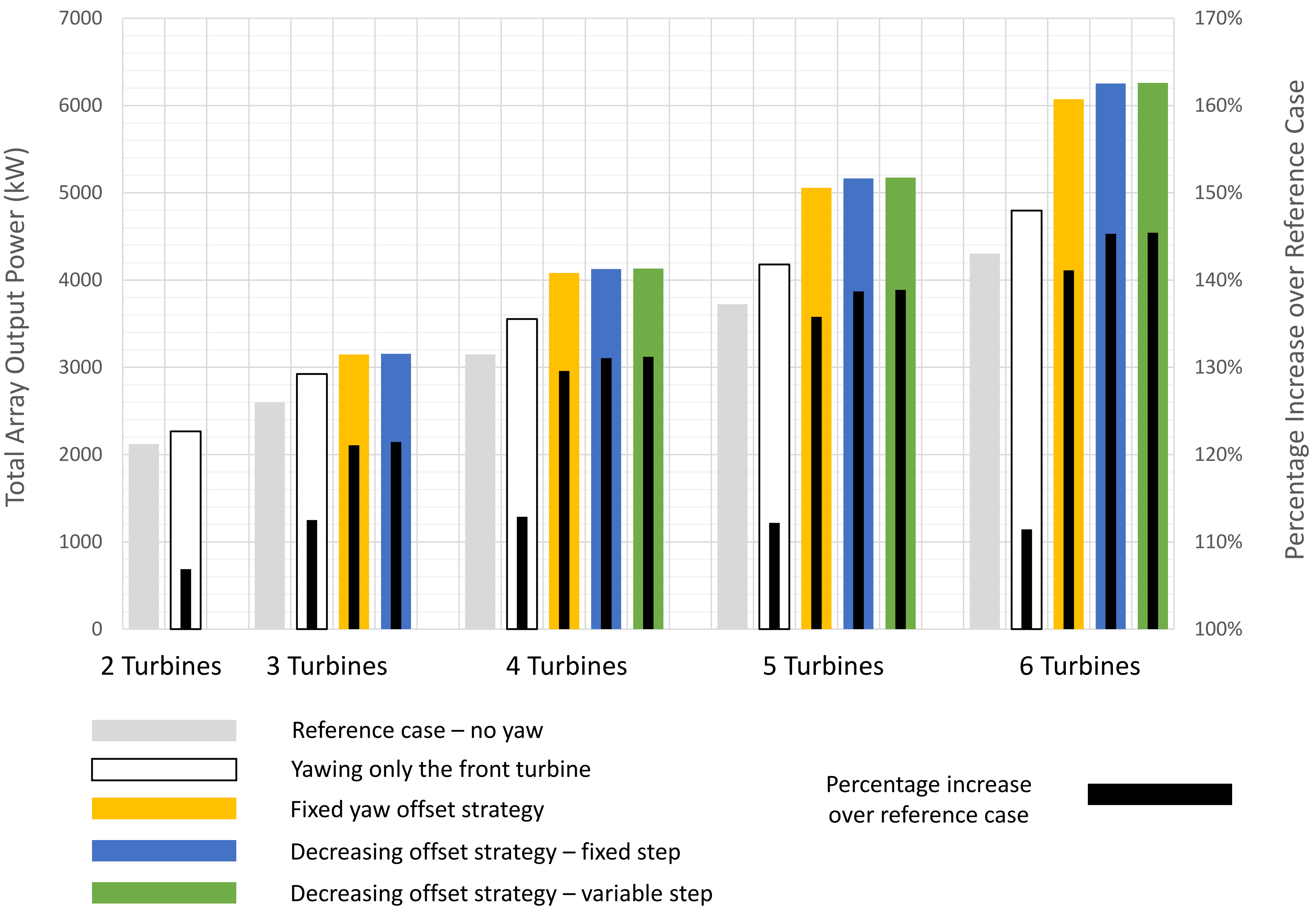
Decreasing offset strategy

- Local control
- Linearly decreasing offset
- Last turbine does not yaw

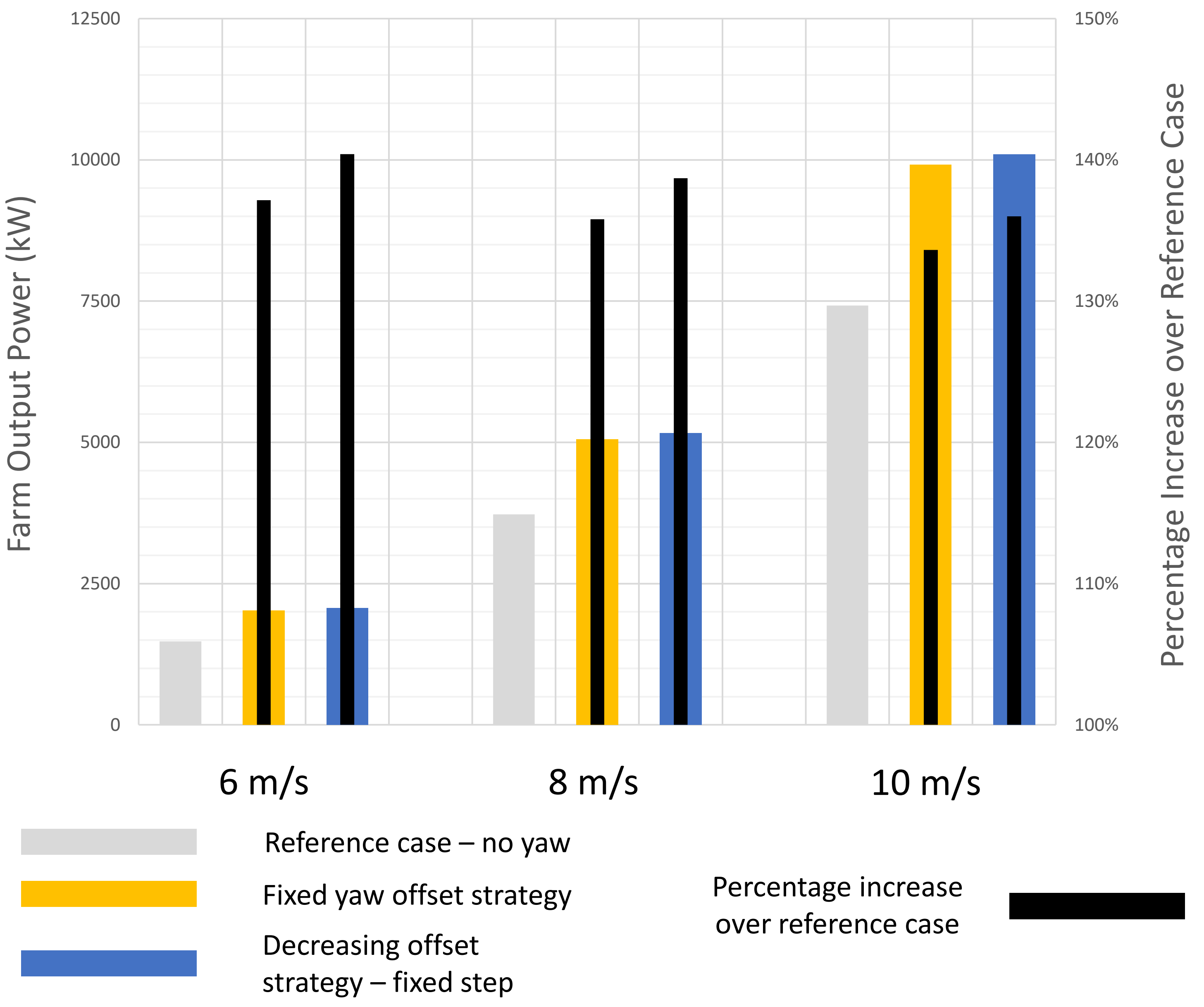

Individual Turbine Yaw Offsets for 5-turbine Row
With Different Wake Steering Strategies
35
30
25
20
15
10
5
0
Yaw Offset (°)
T0
T1
T2
T3
T4
Turbine Number
No Wake Steering
Wake Steering with Fixed Yaw
Wake Steering with Fixed Step
Wake Steering with Variable Step


Individual Turbine Output Powers for 5-turbine Row
With Different Wake Steering Strategies
1800
1600
1400
1200
1000
800
600
400
200
0
Turbine Output Power (kW)
T0
T1
T2
T3
T4
Turbine Number
No Wake Steering
Wake Steering with Fixed Yaw
Wake Steering with Fixed Step
Wake Steering with Variable Step

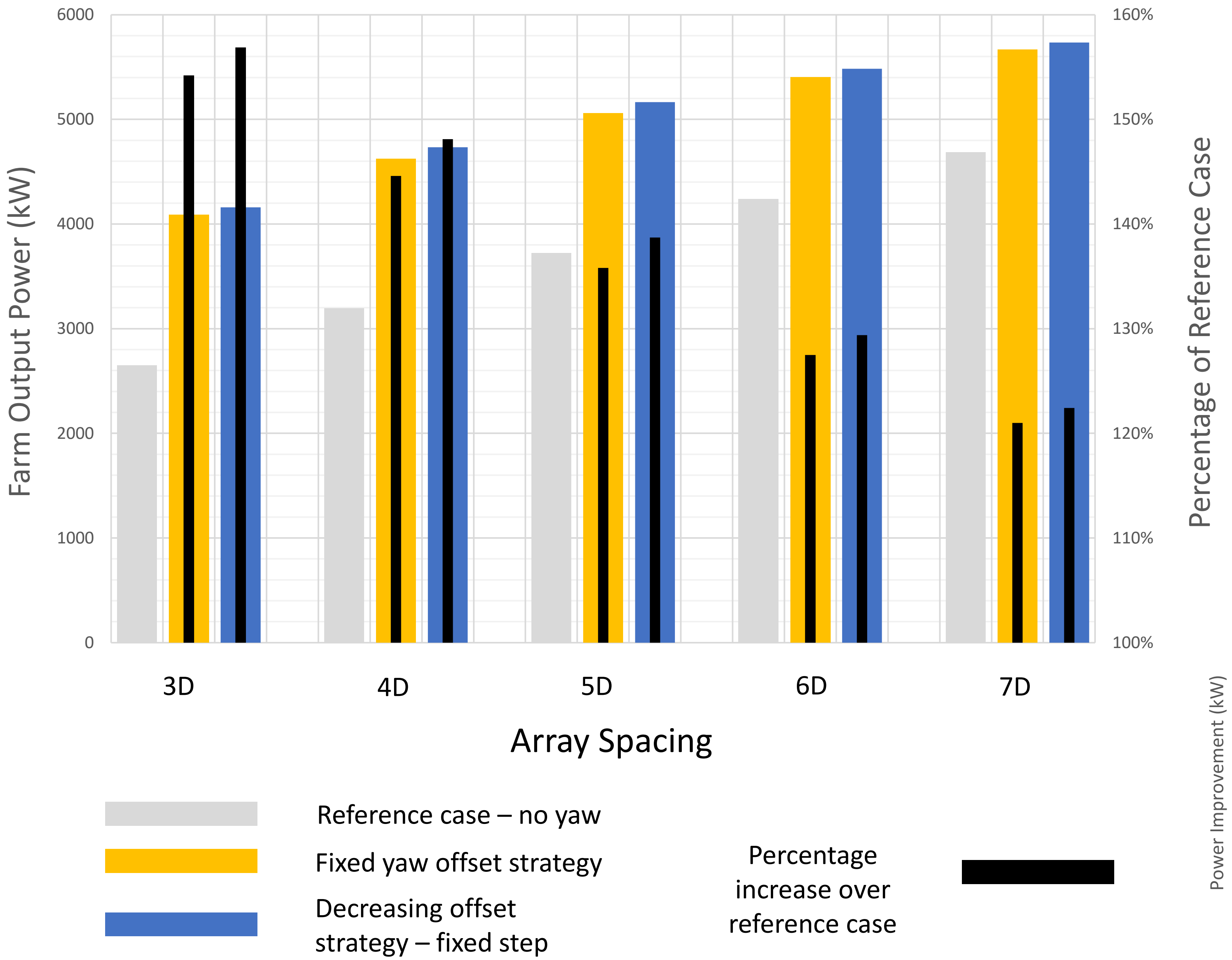

No Wake Steering - Total Farm Power = 3724 kW
0°
0°
0°
0°
0°
Wake Steering with Fixed Yaw - Total Farm Power = 5057 kW
24°
24°
24°
24°
0°
Wake Steering with Fixed Step - Total Farm Power = 5165 kW
32°
27°
22°
17°
0°
Wake Steering with Variable Step - Total Farm Power = 5171 kW
31°
29°
23°
14°
0°
Distance (m)
Distance (m)
m/s
200
0
−200
0
500
1000
1500
2000
2500
3000
3500



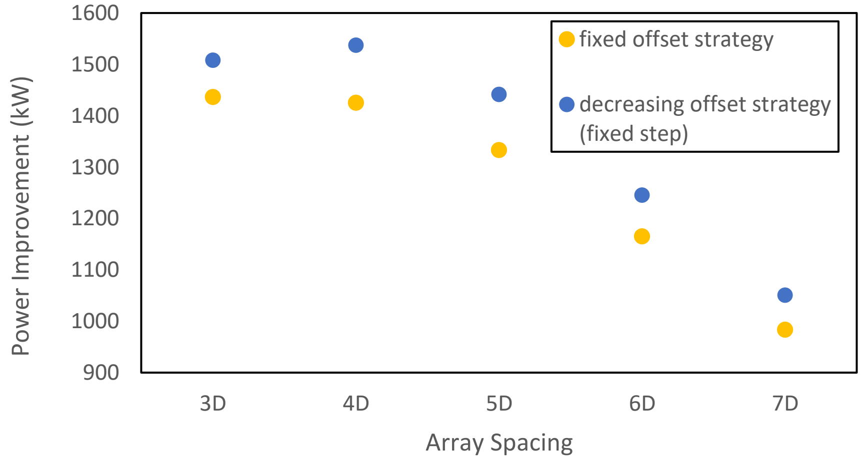
7000
6000
5000
4000
3000
2000
1000
0
Total Array Output Power (kW)
170%
160%
150%
140%
130%
120%
110%
100%
Percentage Increase over Reference Case
2 Turbines
3 Turbines
4 Turbines
5 Turbines
6 Turbines
Reference case – no yaw
Yawing only the front turbine
Fixed yaw offset strategy
Decreasing offset strategy – fixed step
Decreasing offset strategy – variable step
Percentage increase over reference case

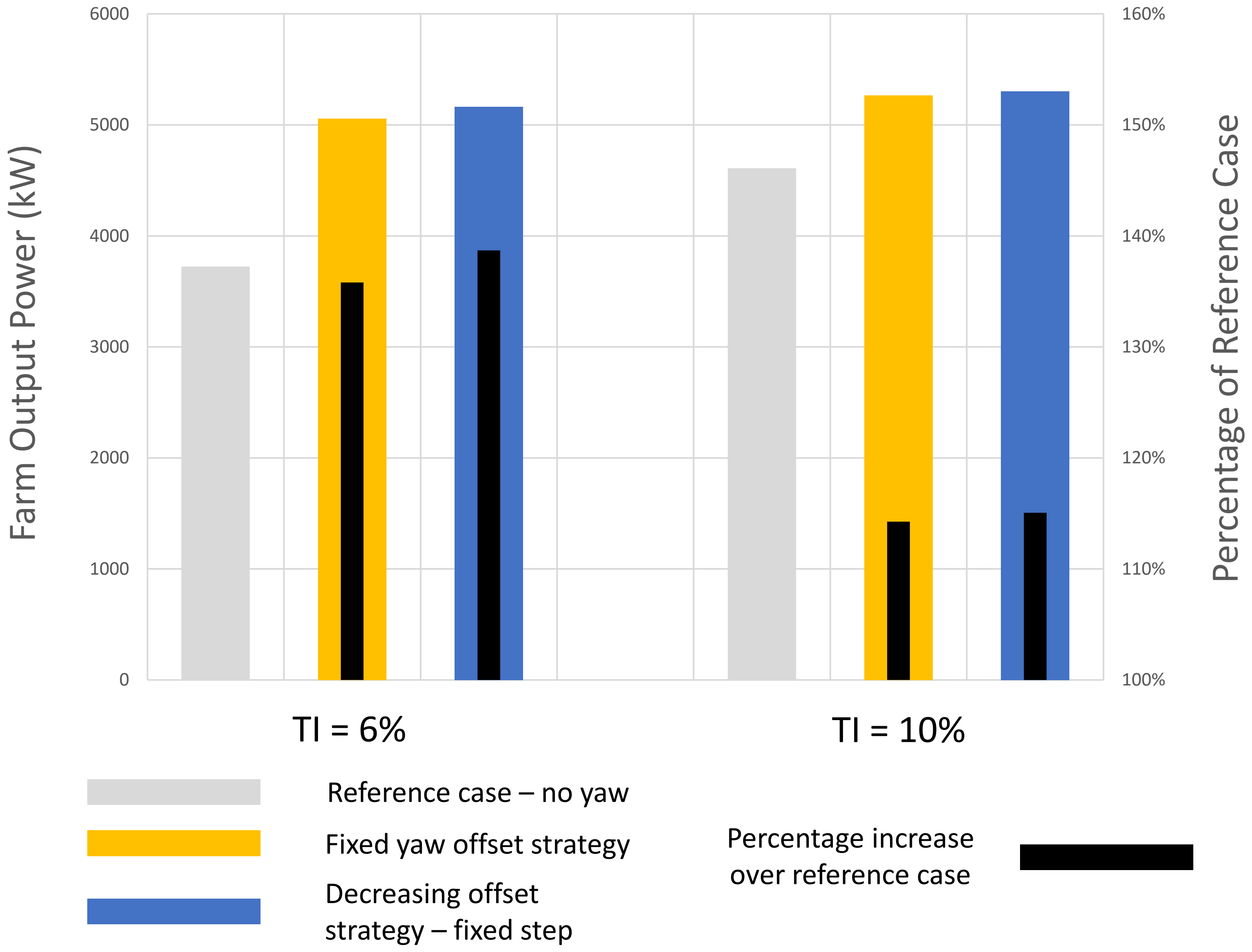


1. Tested wind speeds are above cut-in speed and below rated speed of turbine
2. Wind speed affects power significantly more than yaw control
3. Decreasing offset strategy increases power by a greater percentage for lower wind speeds, but power gains are more noticeable at higher wind speeds



1. Wake steering control on par with 3D increase in array spacing
2. Wider spacing allows for greater wake recovery in between turbines
3. “Sweet spot” around 4D where marginal spacing increase pays off most





1. Higher turbulence intensity aids wake recovery
2. Turbulence intensity roughly correlated to terrain variability

Summary

Parameter	Power improvement over unyawed case due to wake steering	Relative improvement over unyawed case
Array depth ↑	↑	↑
Wind speed ↑	↑	↓
Array spacing ↑	↑ ↓	↓
Turbulence intensity ↑	↓	↓

1. Farm layouts that stand to benefit most from wake steering control will benefit more from decreasing offset than fixed offset strategy!
2. Decreasing strategy up to 4% better in these cases
3. Power improvements on the order of 100 kW compared to fixed offset

Opportunity for Further Investigation

- Time-varying wind direction
  - Wake steering application is most impactful for slow, consistent winds
- Consider turbine loading
  - Increase in power output during certain wind conditions may not necessarily be worth a reduced lifetime

References

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2. FLORIS. Version 3.3 (2023). Available at https://github.com/NREL/floris.
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