Imperial College London

Wind Energy: Wakes and Wind Farm Layout

Rafael Palacios

Wind Turbine Wakes

Wake development seen as water-vapour formation at Horns Rev Windfarm.

There are two aspects: deceleration of the airflow and creation of vortices.

Imperial College London

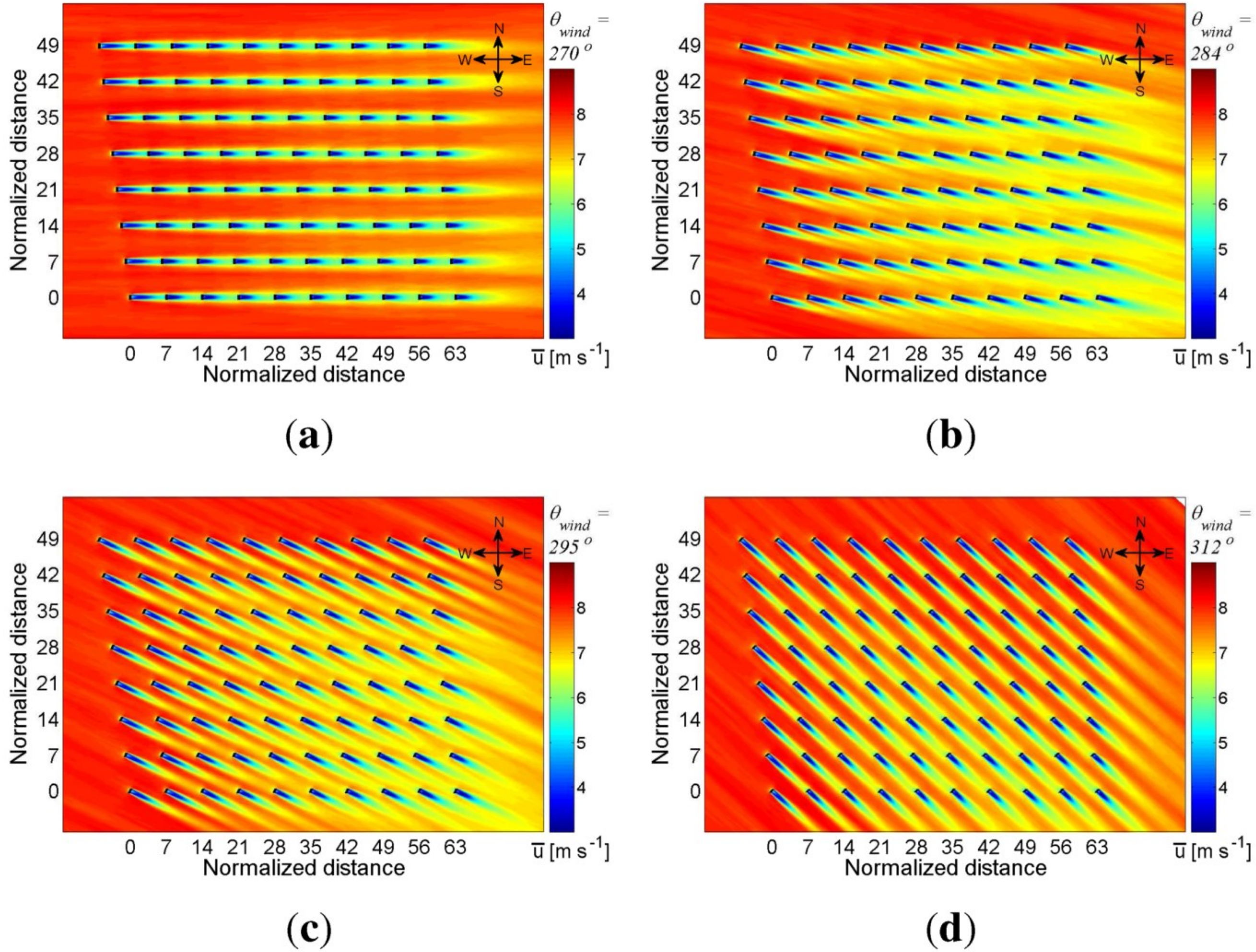
Wakes in a Square-Grid Windfarm

Speed reduction in the wake of a turbine will affect any turbine directly downstream giving rise to “wake losses’

Wakes stay relatively narrow

Turbines here space at $7 \times D$ (D is blade diameter). Distance to next turbine in the wind (stream) direction depends on the angle of the wind w.r.t. grid.

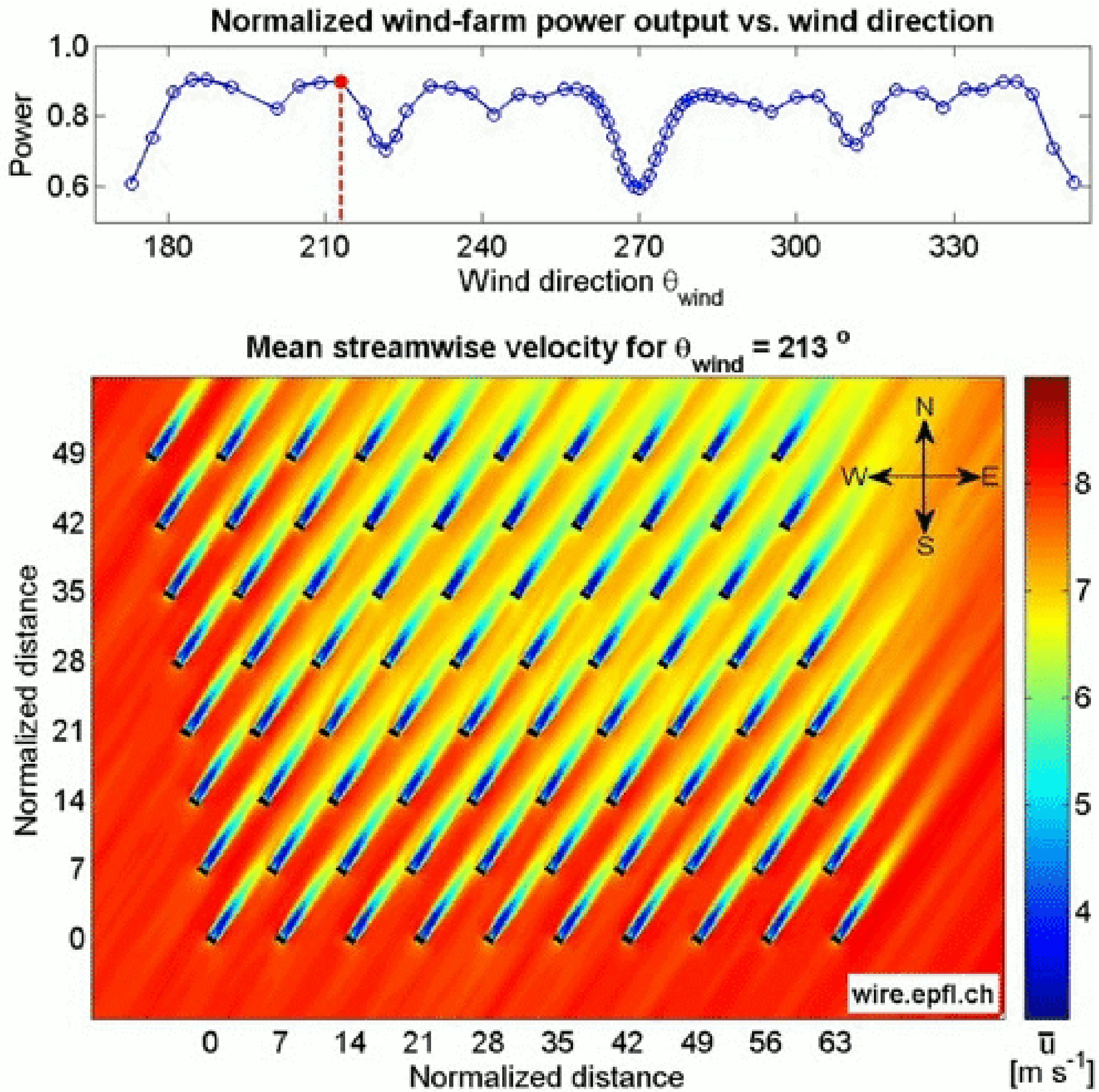
If down stream turbine is sufficiently far away, wind speed will have recovered by mixing with rest of stream and wake loss will be small.



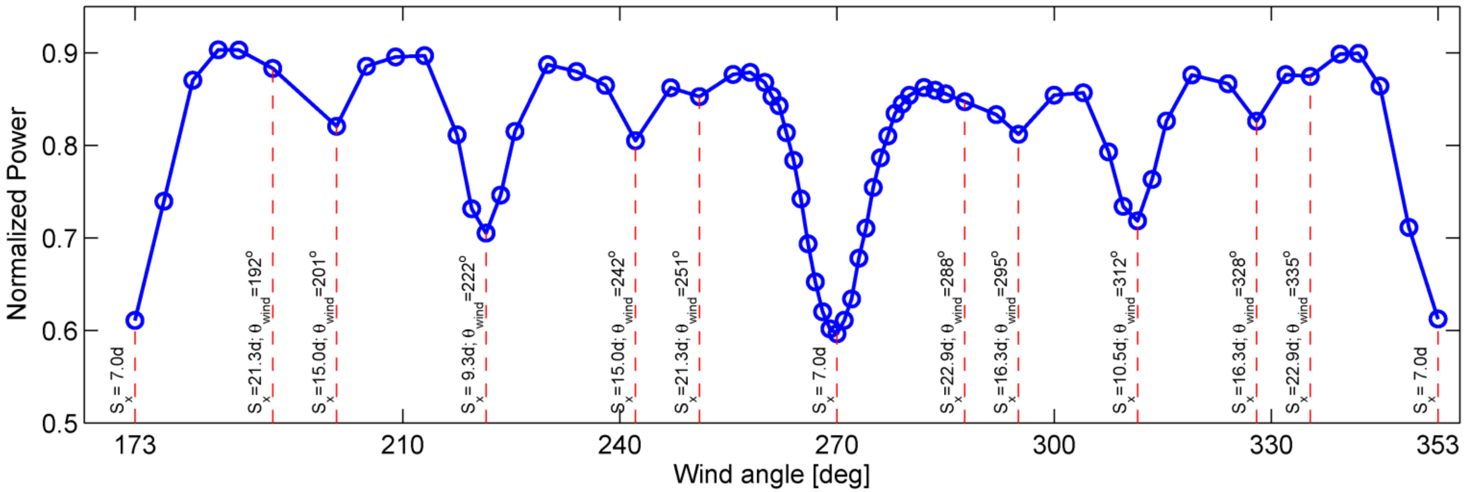
“Heat-map” plot of the time-averaged streamwise velocity on a horizontal plane at hub level for different incoming wind directions of (**a**) 270°; (**b**) 284°; (**c**) 295°; and (**d**) 312°. Distances are normalized by the turbine rotor diameter d = 80 m.

Fernando Porté-Agel, Yu-Ting Wu and Chang-Hung Chen, “A Numerical Study of the Effects of Wind Direction on Turbine Wakes and Power Losses in a Large Wind Farm”, Energies 2013, 6(10), 5297-5313, DOI: 10.3390/en6105297

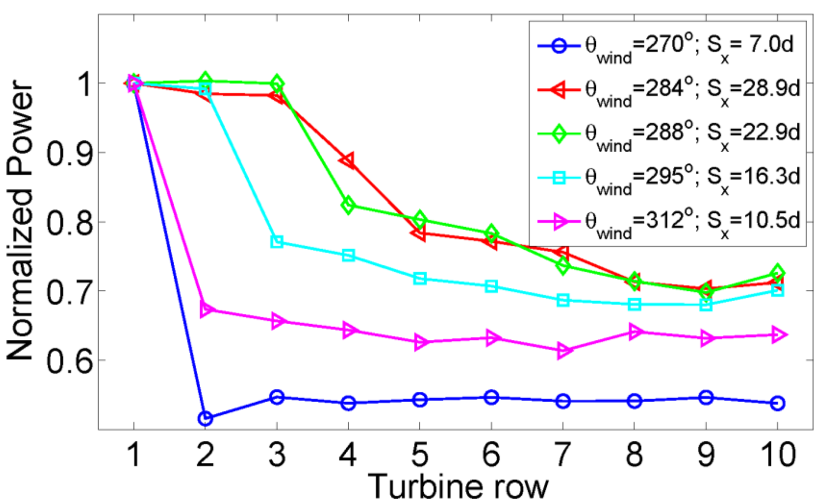
Wake Interactions as a Function of Incident Angle of Wind



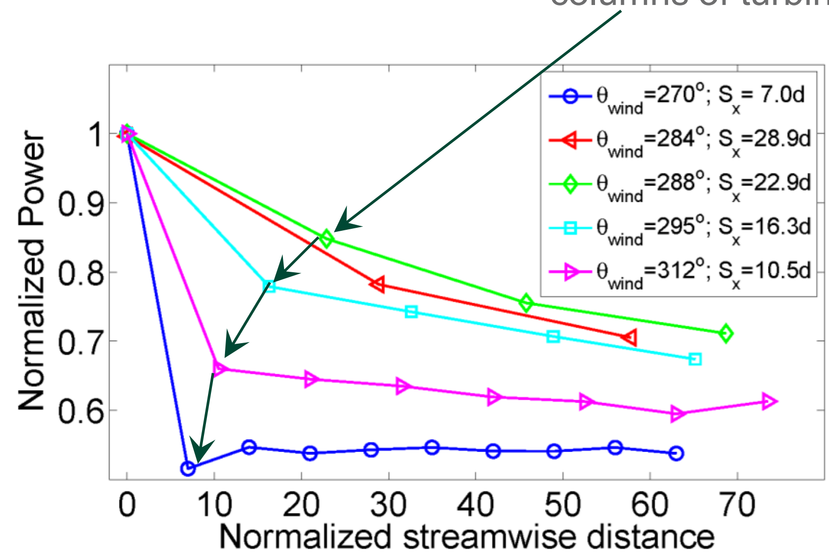
Windfarm Power Reduction due to Wake for Various Incident Angles



Distance to next turbine in the stream direction depends on the angle of the wind w.r.t. rows and columns of turbines.

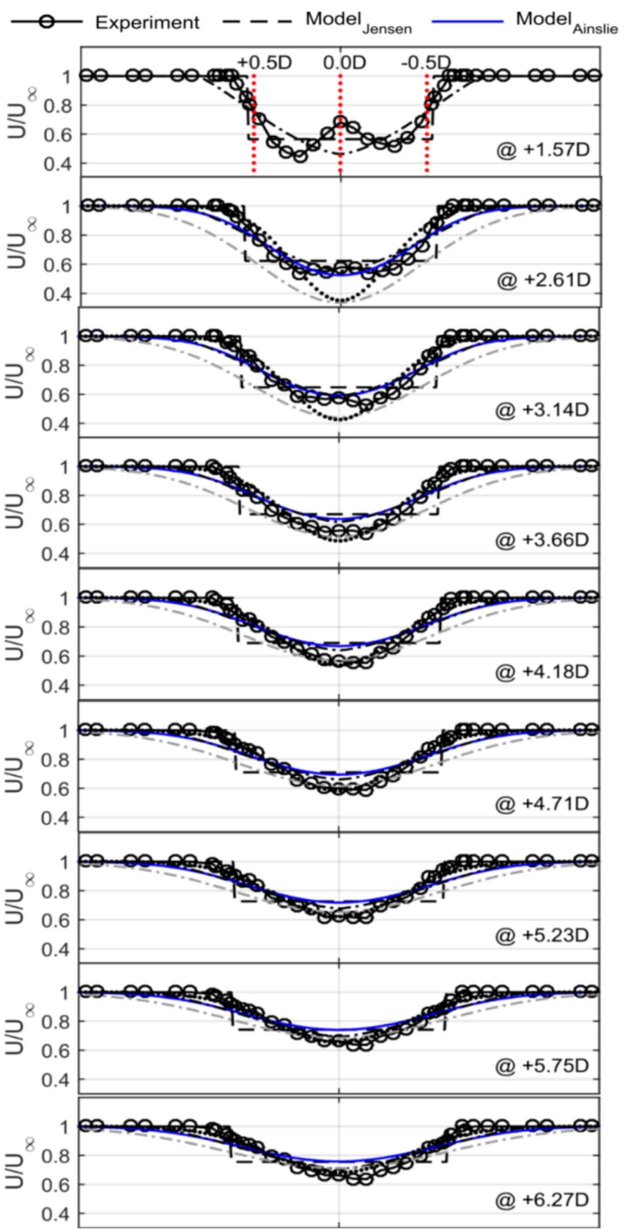


Power output as a function of turbine row (averaged over columns C2, C3 and C4)



Power output distribution along the wind direction lines (distance in multiples of D and rows spaced at 7 D)

Wind Profile Variation with the Downstream Distance



Wake is $\pm 0.5\ D$ wide at $1.5\ D$ downstream . Flow is approximately 50% of undisturbed flow near the centre.

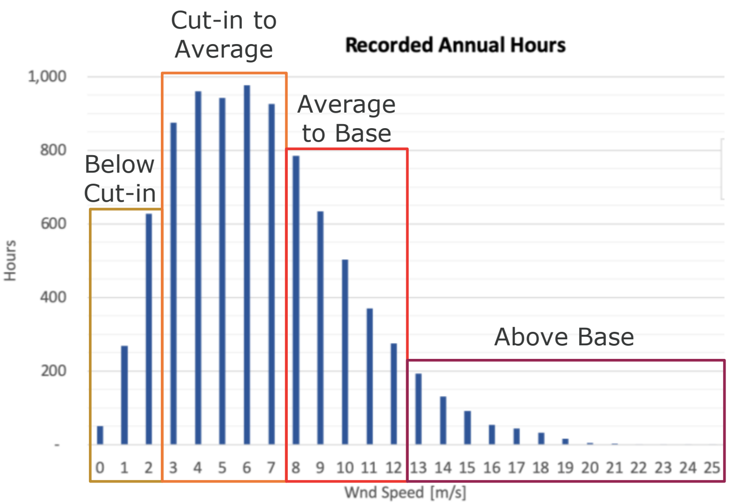
Wake is $\pm 0.75\ D$ wide at $5.25\ D$ downstream. Flow is approximately 65% of undisturbed flow in the centre.

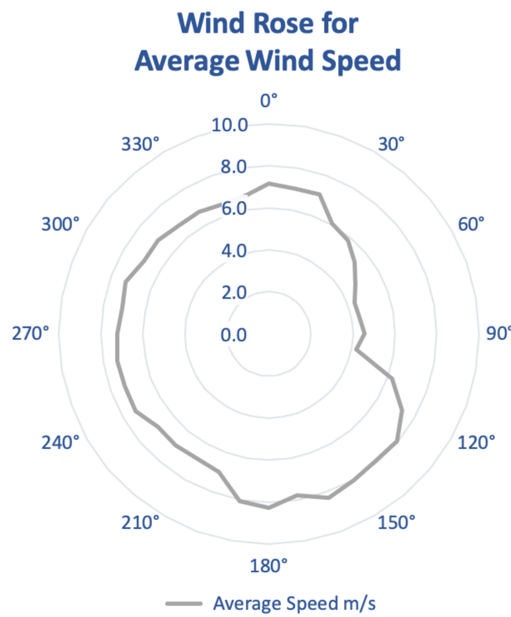
Hyungyu Kim, Kwansu Kim, Carlo Luigi Bottasso, Filippo Campagnolo and Insu Paek , "Wind Turbine Wake Characterization for Improvement of the Ainslie Eddy Viscosity Wake Model", Energies, Vol. 11 https://doi.org/10.3390/en11102823, 2018

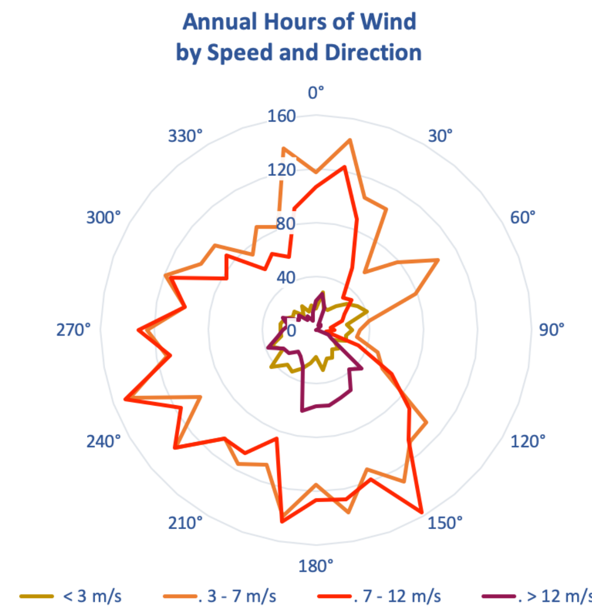
Assessing Prevailing Wind Direction

A “wind rose” is a plot of wind speed on a polar plot according to the wind direction

Shown here are plots for the same site on the West Coast of Scotland used for the wind speed assessment.







The **wind rose of wind speed** shows that wind speeds average is approximately 7 m/s for most wind directions but that wind from the East and North-East has a lower speed.

The **wind rose of occurrence** (hours) shows that wind comes mostly from the South and South-West and North-by-North-East but rarely from the East.

Together, these plots indicate that the layout of a windfarm at this site should be optimised for winds from the South and South-West

Turbine Spacing in Wind Farms

A rough guide is that

- Rows should face prevailing wind
- Rows should be spaced at $\geq 7\,D$ if not staggered $\geq 4\,D$ or staggered
- Turbines should be spaced at $\geq\ 5\,D$ within each row

Rampion Wind Farm

116 × 3.45 MW turbines

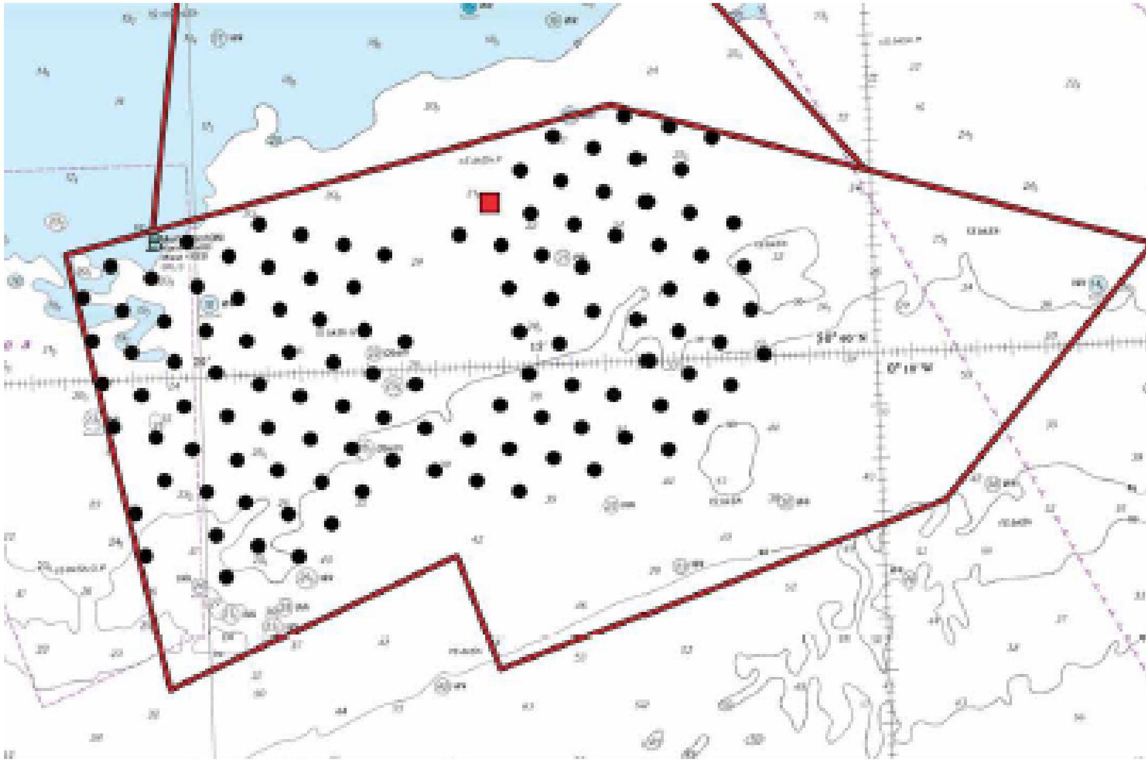
Blade diameter D = 122 m

Turbines here are in rows.

Within rows, turbines are spaced at 750 m which is about $5.75 \times D$.

Turbines are staggered between rows

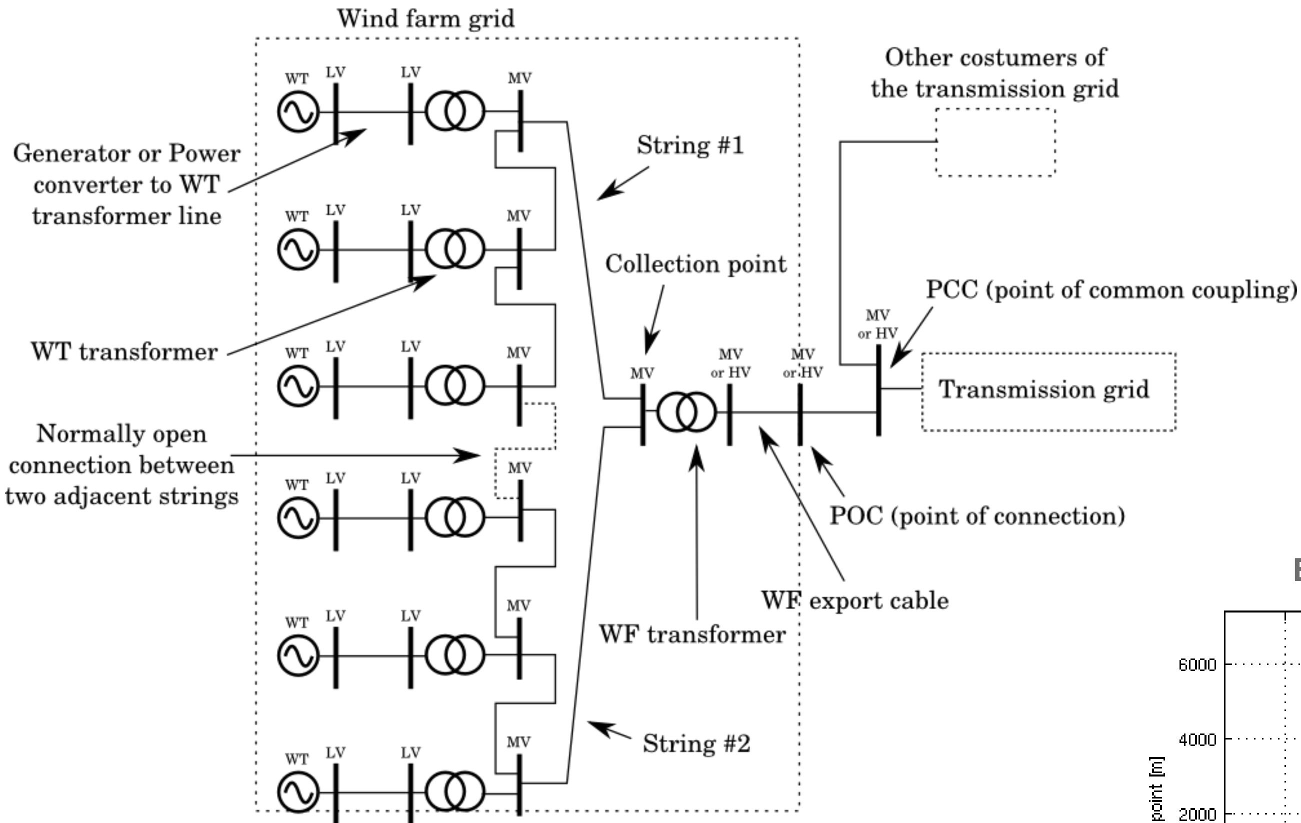
Rows are approximately 550m apart which is $4.5 \times D$



Rows face approximately 240° (West-by-South-West) which is the direction of prevailing wind

Imperial College London

Wind Farm Layout



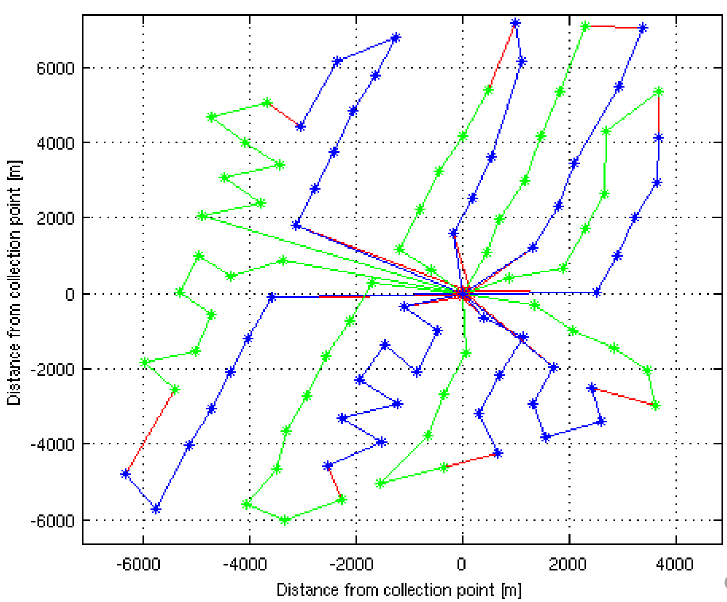
Common voltage levels:

- Wind turbine generator output: 690 V
- Wind turbine step-up transformer: 0.69 to 33kV for collection grid
- Wind farm step-up transformer(s): 33 to 133kV for transmission

The collection grid layout depends on:

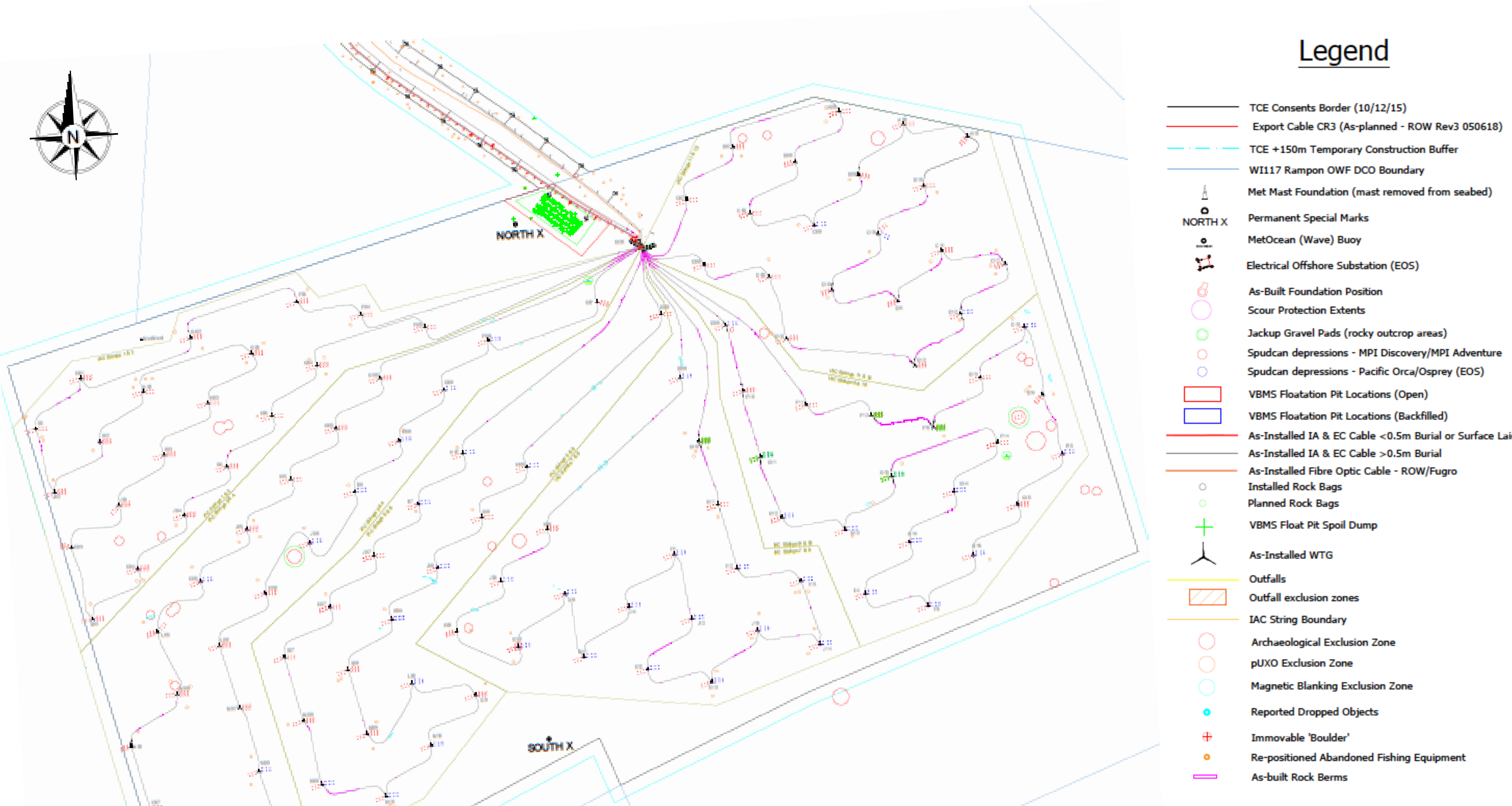
- WT locations which depend, in turn, on available space and wakes.
- Loss minimization.
- Reliability (how many turbines can we lose).
- Redundancy and re-configurability of connections.

Example of collection grid layout



Imperial College London

Electrical Layout of Rampion Wind Farm



116 × 3.45 MW turbines
12 × 33 kV array cables with 9 or 10 turbines per array
An offshore substation with 150 kV cables to shore

Summary of Wake Impact on Windfarm

- Wakes are relatively narrow and the adverse effects of wakes from upstream turbines on downstream turbines can be mitigated by suitable turbine spacing and orientation.

- The spacing allows decay of the vortices and a blending of undisturbed and decelerated flows back into a consistent flow.

- However, a reduction in power yield of downstream turbines is expected and it depends on the incident angle of the wind with respect to the turbine grid.

- With spacing of $7D$, velocity reduction due to wakes is in the region 10% to 20%

- The corresponding loss of power production is 2% to 7%