Global Blockage Effects in Offshore Wind Farms: Knowns, Unknowns and Opportunities

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SUPPORTED BY THE OFFSHORE WIND ACCELERATOR PARTNERS:

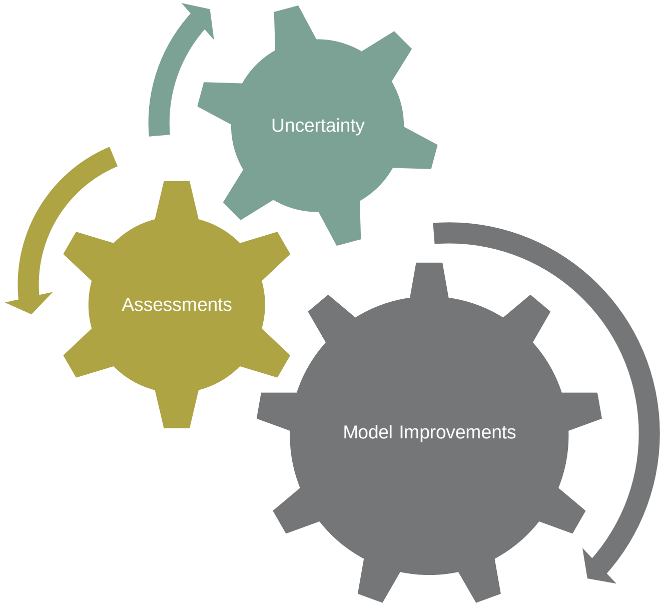
Context of this Study

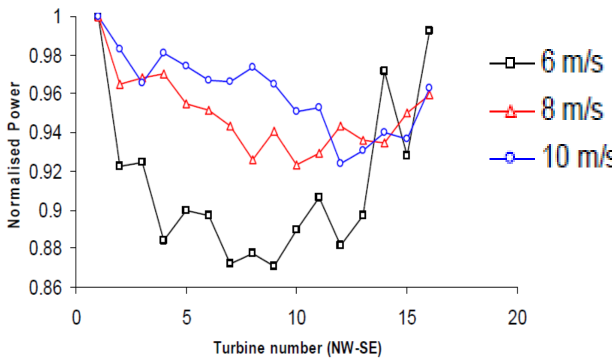
Uncertainty in wind turbine and wind farm performance drives a high cost of capital for offshore sites.

Focus on appraising the available site resource, understanding array wake effects and losses and also to enhance power curve assessments.

It is well known that a wind turbine decelerates the upwind flow. Conventional methods do not take account of how an array may create a global blockage effect.

Evidence for blockage effects has accumulated and there is a concern that the potential impact on wind farm energy yield is neither understood nor quantified





12% variation in power at Horns Rev

SYSTEMS AND ENGINEERING TECHNOLOGY

Carbon Trust has been working with government and industry to accelerate offshore wind for >10 years

The Offshore Wind Accelerator (OWA)

€100m+ Total programme spend	**60%** Industry funded
9 Leading developers	**11 yrs** Established 2008

- The GBE project is one of the priority focus areas within the OWA Wakes and Resource Research Area in this funding round.
- Objective:
  - To appraise the significance, evidence for and dependencies of GBE
  - To identify R&D activities needed to close gaps in understanding or prediction capability

Project Structure

Frazer-Nash and DTU

WP1: Literature Review

Sources of information:
- Wake effects y4 report
- A Meyer Forsting Thesis
- Other identified literature
- Rødsand II data
- OWA projects (power curves, LiDAR surveys, Boundary Layer profiling)

Approach:
- Claims, Arguments, Evidence

Questions to answer:
- Significance of GBE
- Origin of GBE
- Measurement options
- Options for resource correction
- Dataset interrogation

WP2: Research Scoping

WP2.1 – R&D Identification

Develop up to 6 R&D options at a high level:
- Technology and Resources,
- Costs and Timescales
- Risks, Opportunities and Constraints

Downselect 3 options with TWG

WP2.2 – R&D Scoping

Detailed development of up to 3 scopes:
- Measurement or Modelling?
- Stakeholder and supplier engagement
- Scope, Cost, Timescales

WP3: Further Analysis

- Data study for GBE effect on power curves
- Benchmarking study for VC, CSL and PF models.

Decision Point

Future R&D Work

- More substantial modelling and/or measurement campaigns
- Opportunity for other parties to support

WP1: Literature Review

Systematic Approach

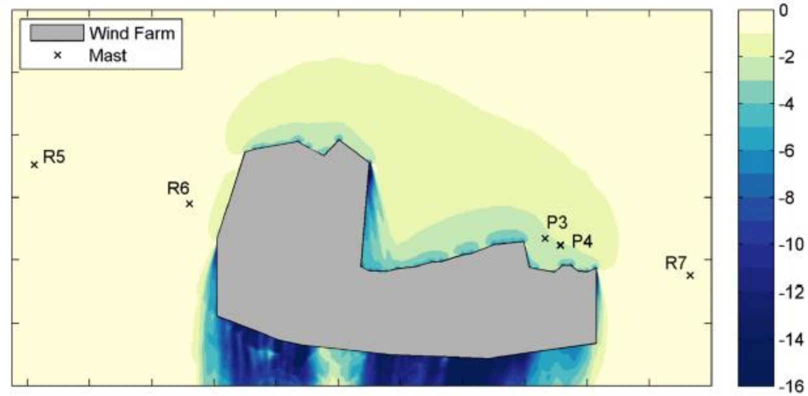
Develop hypotheses → Define “signatures” → Identify/Test evidence → Make conclusions → Plan future R&D

WP1: Literature Review

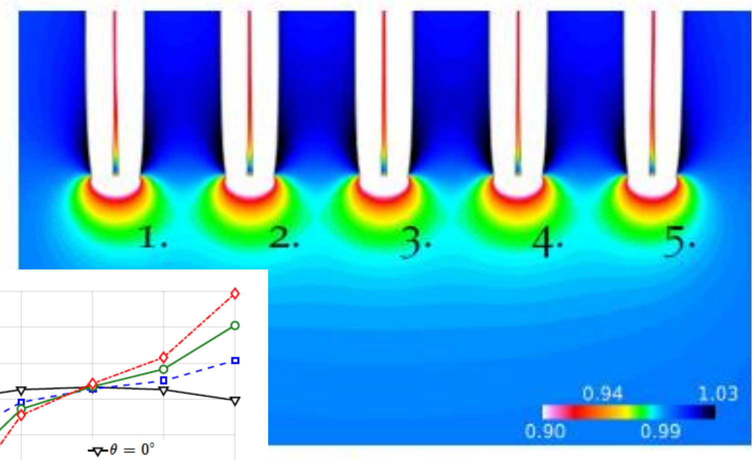
Hypothesis	Status	Next Steps
GBE are significant	Yes ✓	Needs more evidence to understand and quantify
Physical processes that are important:		
Inviscid	Yes ✓	Evaluate rapid models coupled to wakes
Viscous / turbulent	Probably ✓	See how far we can get with inviscid, and CFD
Stability	Possibly, combined with gravity waves ~	Get better field measurements
Coriolis	No ✗	
Gravity Waves	Possibly ~	Get better field measurements Don't be scared by the modelling results
Array Geometry	Yes ✓	
Causes Power Curve Bias	No ✗	
Can be modelled	Yes ✓	
Models Can be trusted	Not yet ✗	Pursue validation. Get better field measurements

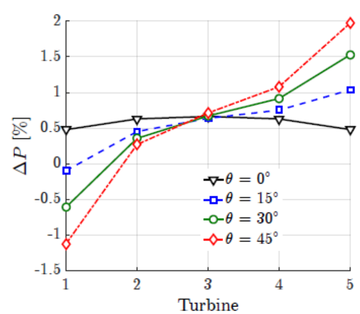
Global Blockage Effects are Significant

- Evidence from measurements offshore
  - Power and LIDAR data show significant variation from freestream can occur
  - Sometimes (under certain conditions?) the effect can be much greater (stability, gravity waves?)
- Evidence from measurements onshore
  - Bleeg et al 2018 (-3.1 to -5.2% bias in power)
- Evidence from modelling
  - Evidence of strong effect in several models
  - Some configurations yield a net benefit
- **Conclusion:**
  - ~-0.5% influence of single turbine on wind resource is lower bound
  - Lots of evidence of double this magnitude in general, even higher sometimes
  - Enough evidence that effect is to be taken seriously.
  - Not enough evidence to quantify the effect with confidence.



% change in wind re. freestream – north wind (Bleeg et al, 2018)





(a) $\theta = 0°$

Meyer Forsting (2017)

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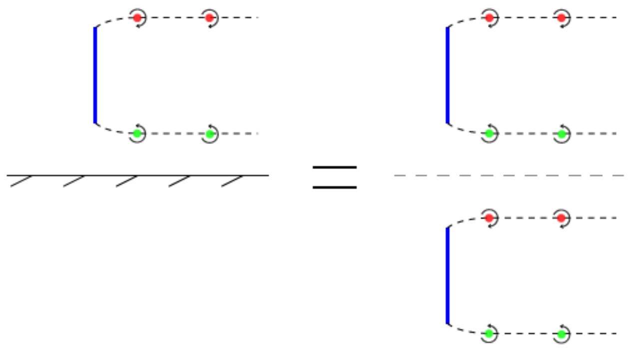
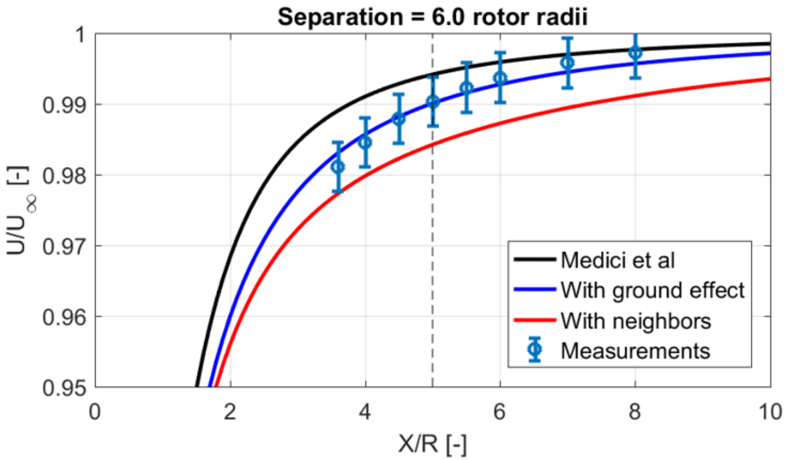
Inviscid & Array Effects Are Important

- Branlard and Gaunaa (2014) explain an inviscid model of a wind turbine:
  - Root vortex, bound vortex disk, semi-infinite vortex cylinder (or sheet thereof)
  - Basic model has zero wake expansion
  - Latter assumption revised in Øye model
- Nygaard and Brink (2017) ran this model against LiDAR measurements:
  - Single WTG model, + ground mirror
  - With neighbours (span and depth)
  - Good agreement on trends
  - (Not yet coupled to wakes calculation)
- **Conclusion:**
  - Cascading inviscid descriptions of the upstream zone could characterise blockage



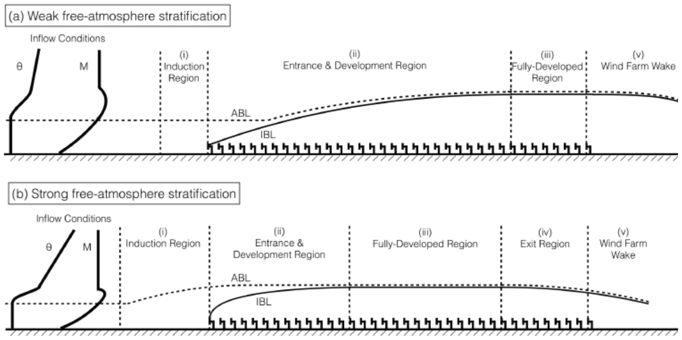
Mirror image for ground effect (Meyer Forsting, 2017)



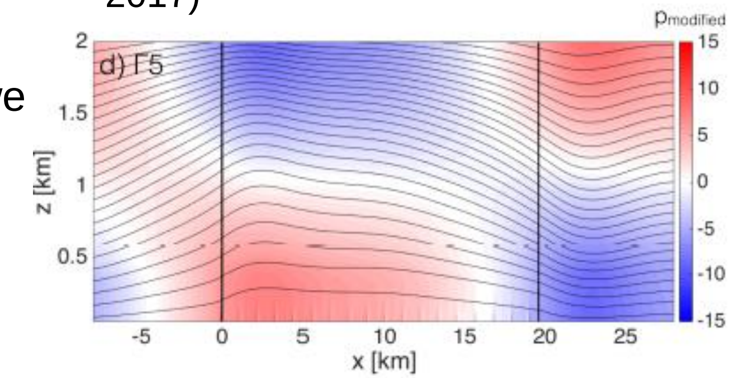
Nygaard and Brink (2017)

Gravity Waves Are Important

- Evidence from Modelling: Wu et al (2017)
  - CFD for large arrays under different thermal regimes
  - Under strong thermal stratification lead row can be affected by ~35% in power
  - Under weak stratification ~ 1-3% in power
  - Attributed to flow criticality state for upstream gravity wave propagation (Fr < 1 possible)
- Thoughts:
  - What would extent of effect be for a finite wind farm?
  - What is the probability of Fr<1 conditions for a site?
  - How might this influence the models and workflows we use to predict GBE?
  - How would we validate this behaviour?
- **Conclusion:**
  - Gravity wave effects can compound basic inviscid contributions
  - Contribution is potentially significant for Fr<1
  - The potential impact on AEP for a finite farm is unclear



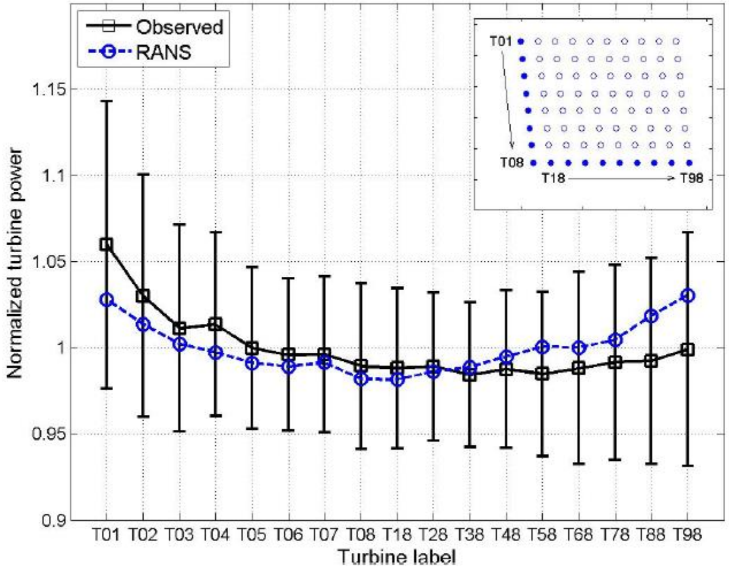
Modification of induction and development regions (Wu et al , 2017)



Vertical potential temperature gradient free stratification strength 5K/km (Wu et al , 2017)

Can Global Blockage Effects be Modelled?

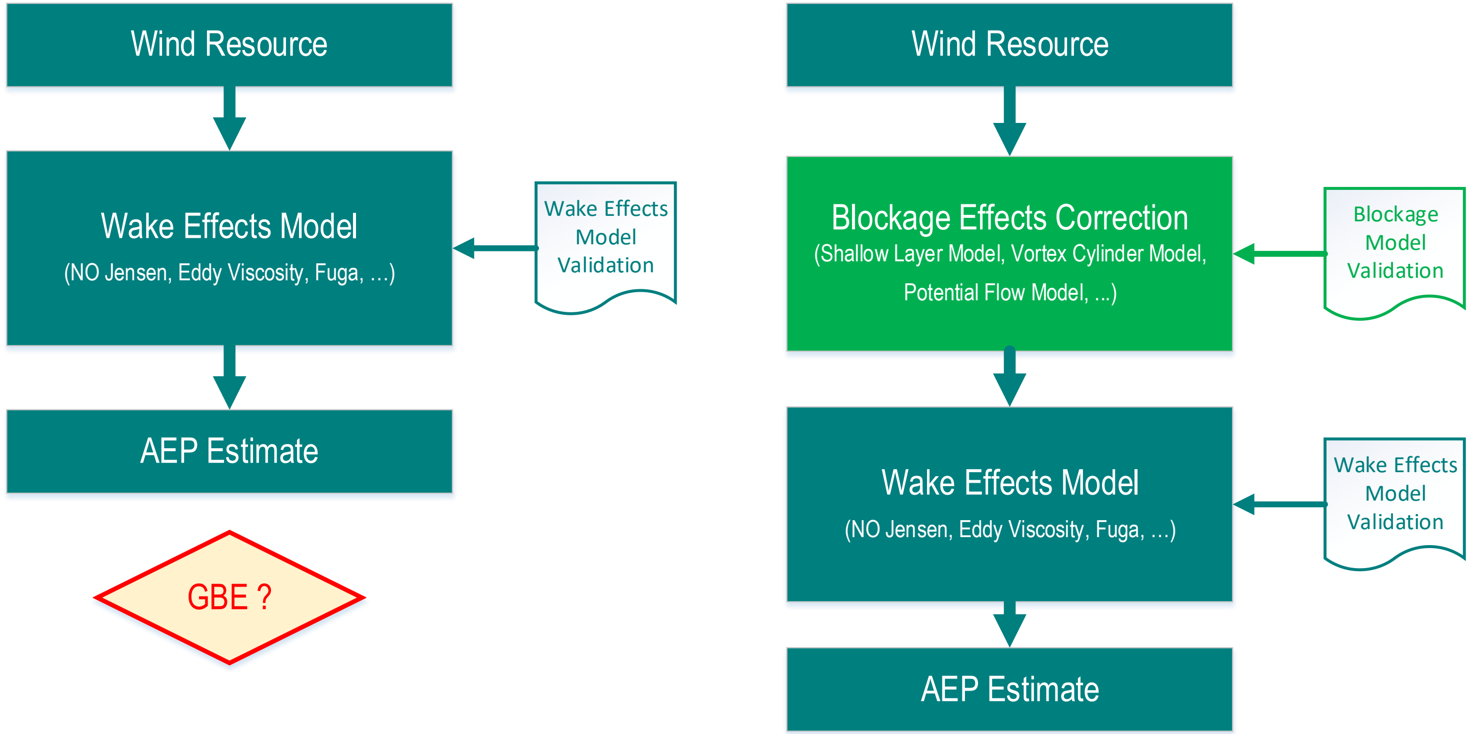
- **CFD tools**
  - Has the potential to capture the salient physics
  - Known to capture gravity waves (damping layer)
  - Wake effects calculations typical assess CNBLs
    - Is this appropriate for blockage effects calculations?
  - Needs further validation for offshore blockage applications
    - Can CFD reliably predict a bias of a few %?
- **Shallow Layer Models**
  - Look effective at incorporating gravity wave effects
  - Comparison to CFD looks promising (Smith 2009 vs Allaerts and Meyers, 2017).
  - Path to relate flow perturbations to AEP is unclear
- **Inviscid Methods**
  - Describes inviscid effect with mirror for ground.
  - Basic cascade neglects modification of thrust on downstream turbines due to wake effects
  - Opportunity to combine with rapid wake effects models?



Comparison of CFD and measured data for the perimeter turbines at Horns Rev 1 (Bleeg et al , 2018)

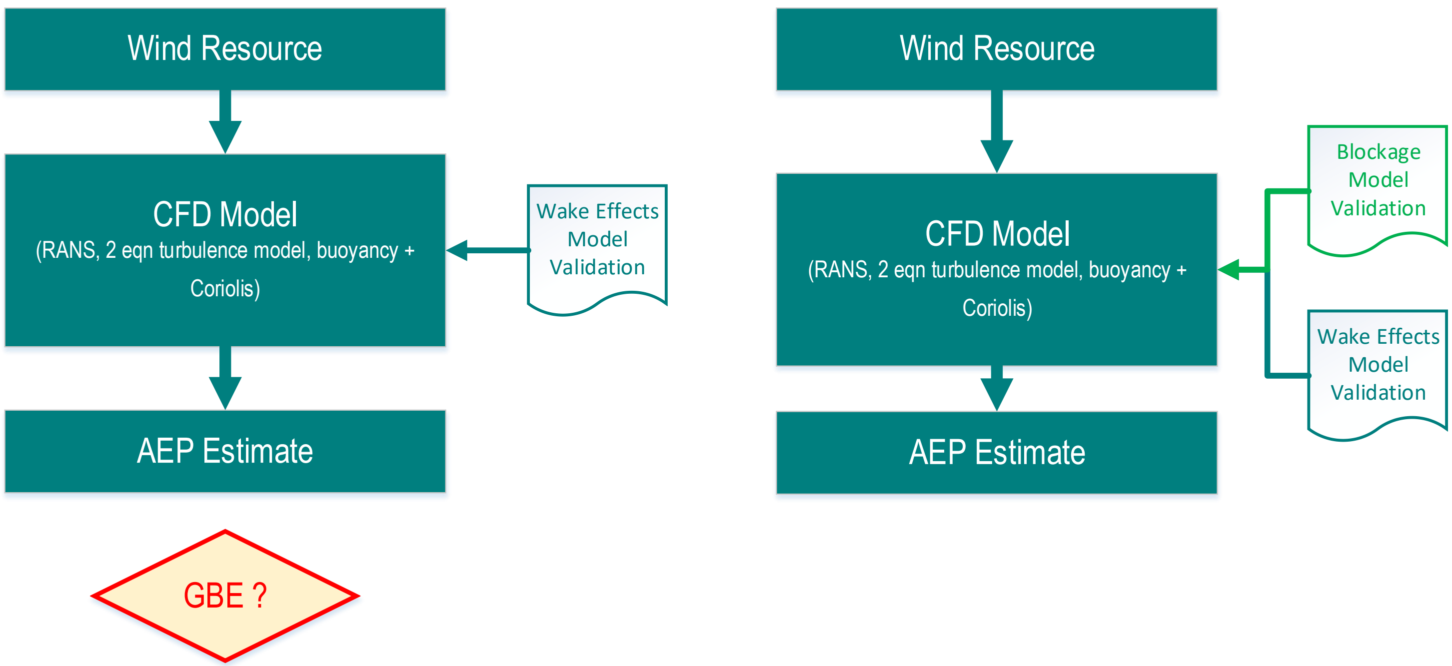
Future Resource Assessment: The End Goal

- Develop a correction to resource estimates for GBE. This could be:
  - Analytical/Empirical: Vortex, potential flow or shallow layer models



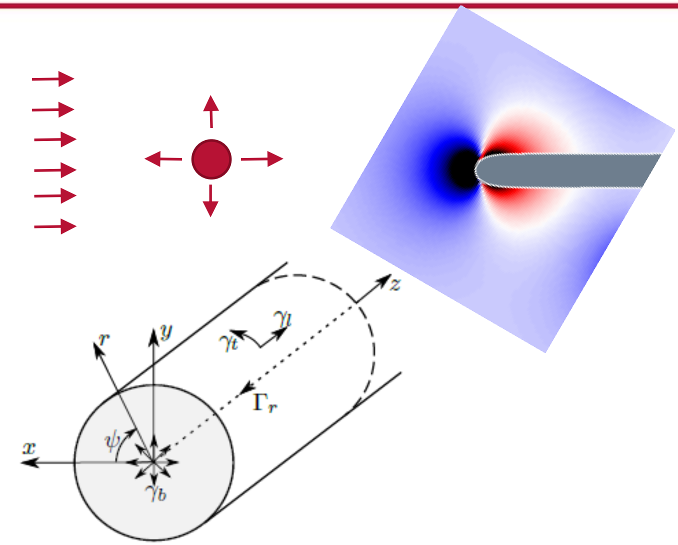
Future Resource Assessment: The End Goal

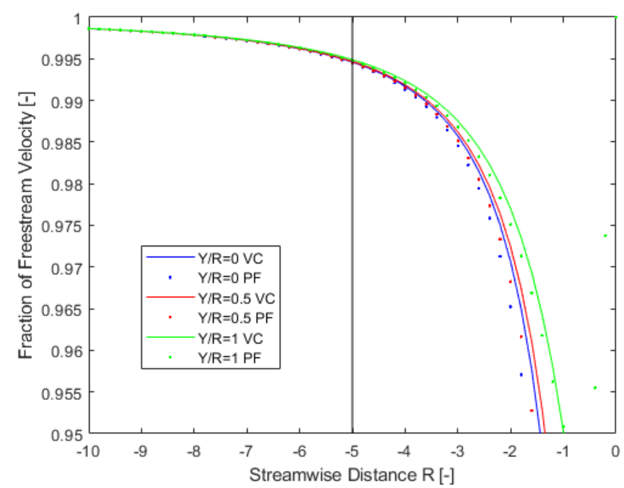
- Develop a correction to resource estimates for GBE. This could be:
  - Analytical/Empirical: Vortex, potential flow or shallow layer models
  - Numerical: Validated CFD approach for GBE quantification



Candidate Model Formulations

- **Potential Flow (PF) model:**
  - 3D source + freestream = Rankine Half Body (RHB)
  - Source strength calculated from Ct and wind speed.
  - RHB representation naturally aligns to the wind.
- **Vortex Cylinder (VC) model:**
  - Root vortex, Semi-∞ vortex cylinder and vortex disk.
  - Basic case – only tangential vorticity is required.
  - More advanced formulation for yawed cases
- **Equivalence:**
  - Compare the axial induction from VC and PF model at different offsets from the hub.
  - X<5R the results diverge due to stagnation in PF
  - X>5R axial induction is practically indistinguishable. It is these distances which are relevant to blockage.
- **Conclusion:**
  - PF model can be used to demonstrate the capabilities of Inviscid-class blockage models





Pseudo Code for Wake Loss / GBE Coupling

Objective:

- The inflow to turbines within array is influenced by those upstream (waking) and those downstream (blocking).
- To conceive a way of coupling a wake-loss models (e.g. Jensen-Park) with simple GBE correction models (of various types)
- Work is ongoing, but preliminary results show some positive and negative contributions

Pseudo Code

For each wind speed & direction combination

loop until convergence

- Order the wind turbines from upwind to downwind.
  - For each wind turbine
    - Estimate the inflow wind speed to this turbine, by subtracting the wake deficit from any upwind turbine which wakes this turbine from the freestream wind speed, and adding or subtracting the blockage effect from all other turbines.
    - Calculate the wake (geometrical extent and wind speed deficit) developed by this turbine.
    - Update C_T values for array based on perturbed inflow
    - Calculate the power generated by each turbine based on the power curve

Aggregate results into annual energy prediction according to frequency distribution of wind speeds and directions.

Conclusions

- There is mounting evidence to show blockage effects are significant offshore at the few % level.
  - The influence on the windward row has been observed for some time but the net effect on the whole array is less clear.

- GBE clearly has a strong inviscid contribution which is dependent on array geometry and thrust coefficient.
  - However, this is modulated by Viscous effects, stability and gravity waves.

- There are a range of candidate modelling options available
  - All require extensive validation and the validation set is limited
  - CFD is potentially capable of capturing the physical process believed to be important. But the industry best practice, workflow and validation is yet to be established.
  - Simple blockage models are an attractive proposition for rapid assessment and might be sufficient as an Engineering Model.
  - The opportunity to couple Potential Flow with simple Wake Loss models has been explained and is being investigated.

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