OWA GLOBE PROJECT WEBINAR 2

Modelling and Accounting for Wake and Blockage Effects

Carbon Trust and RWE

8th August 2024

OWA GloBE Project Webinars

Welcome, and thanks for joining!

Webinar 1: Measuring the Global Blockage Effect (Tuesday)

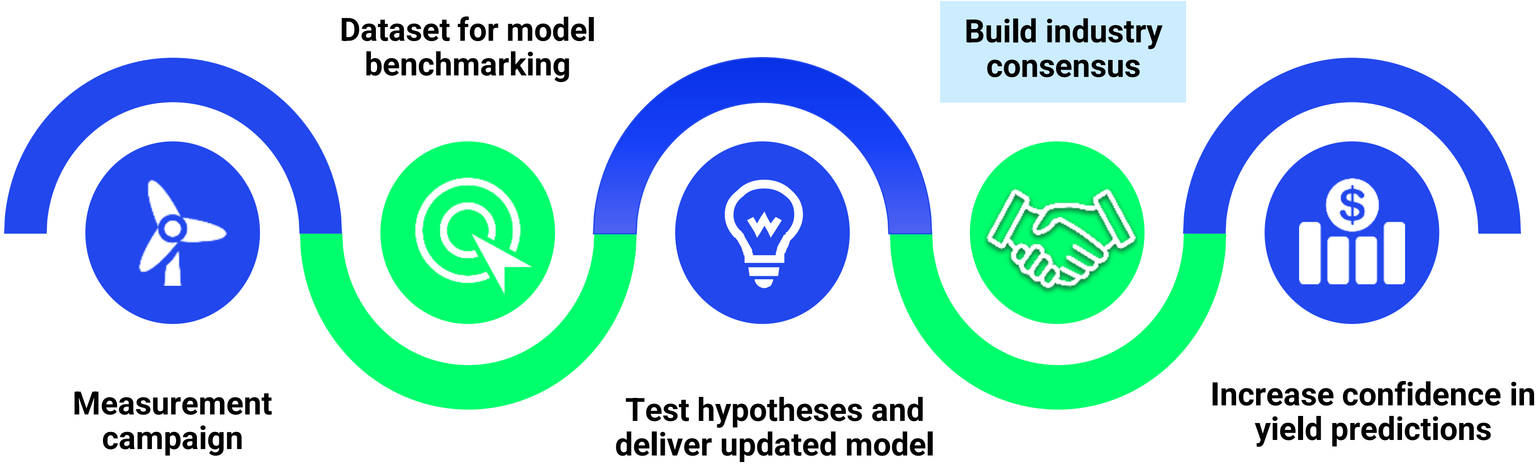
- Background & motivation for the project
- Objectives
- Project participants and structure
- Measurement campaign design
- Validation & verification
- Blockage measurements
- Q&A

Webinar 2: Modelling and Accounting for Wake and Blockage Effects (Today)

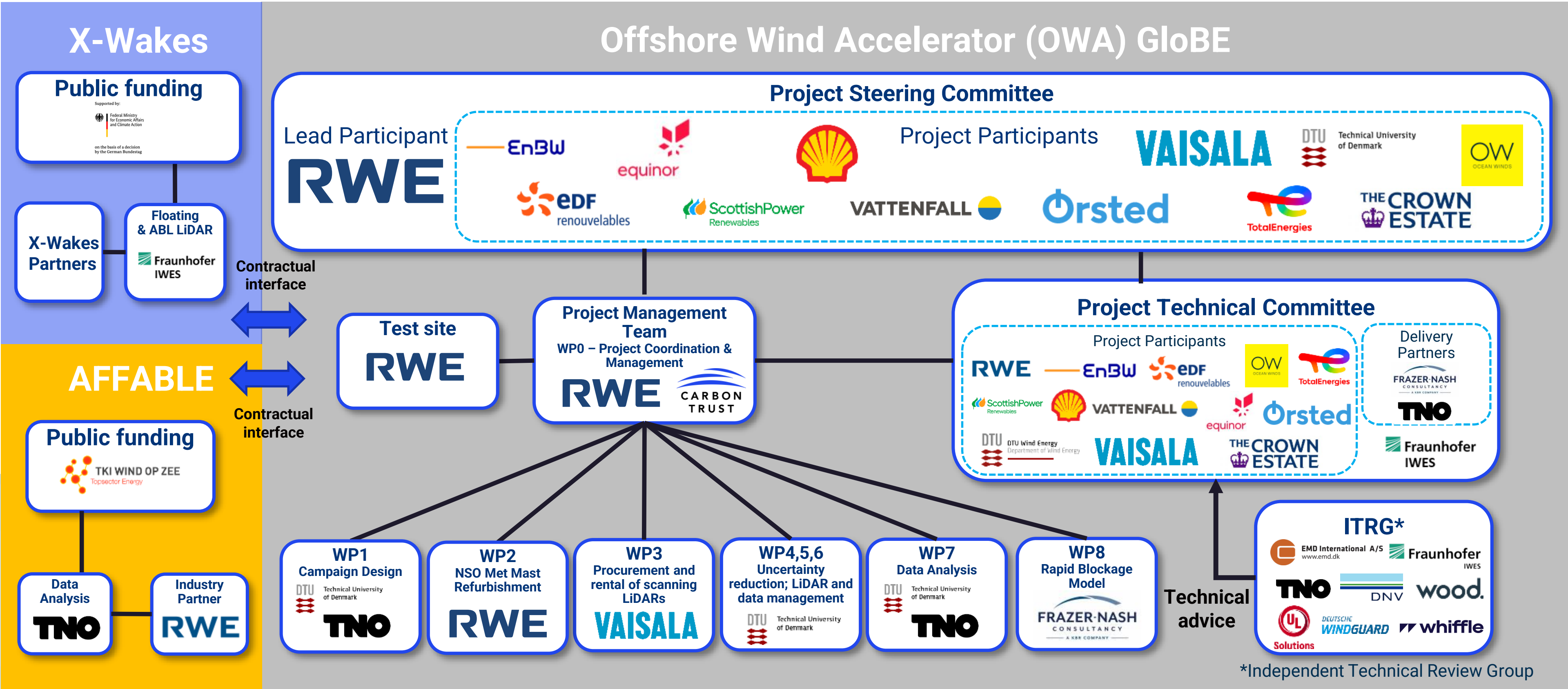
- Recap of objectives
- Modelling approaches
- Validation against measurements
- Conclusions
- Joint Statement
- Q&A

Recap: Objectives of GloBE

Recap: Objectives of GloBE



GloBE Project Structure



Forum for Consensus-Building: ITRG

RWE CARBON TRUST

Independent Technical Review Group

EMD International A/S www.emd.dk · DNV · wood. · natural power · Fraunhofer IWES · whiffle · DEUTSCHE WINDGUARD · UL Solutions · TNO

GloBE project

Provide a limited dataset from the measurement campaign

ITRG

Provide technical input and advancement of science:

- Review campaign design
- Run in-house blockage models and provide validation reports
- Help build industry consensus

RWE | GLOBE Global Blockage Effect

Modelling & Accounting for Blockage & Wake Effects

Carbon Trust Webinar Session 2

8th August 2024

CARBON TRUST

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[1]RWE Renewables, [2]DTU Wind Energy, [3]TNO, [4]Fraunhofer-IWES, [5]Carbon Trust

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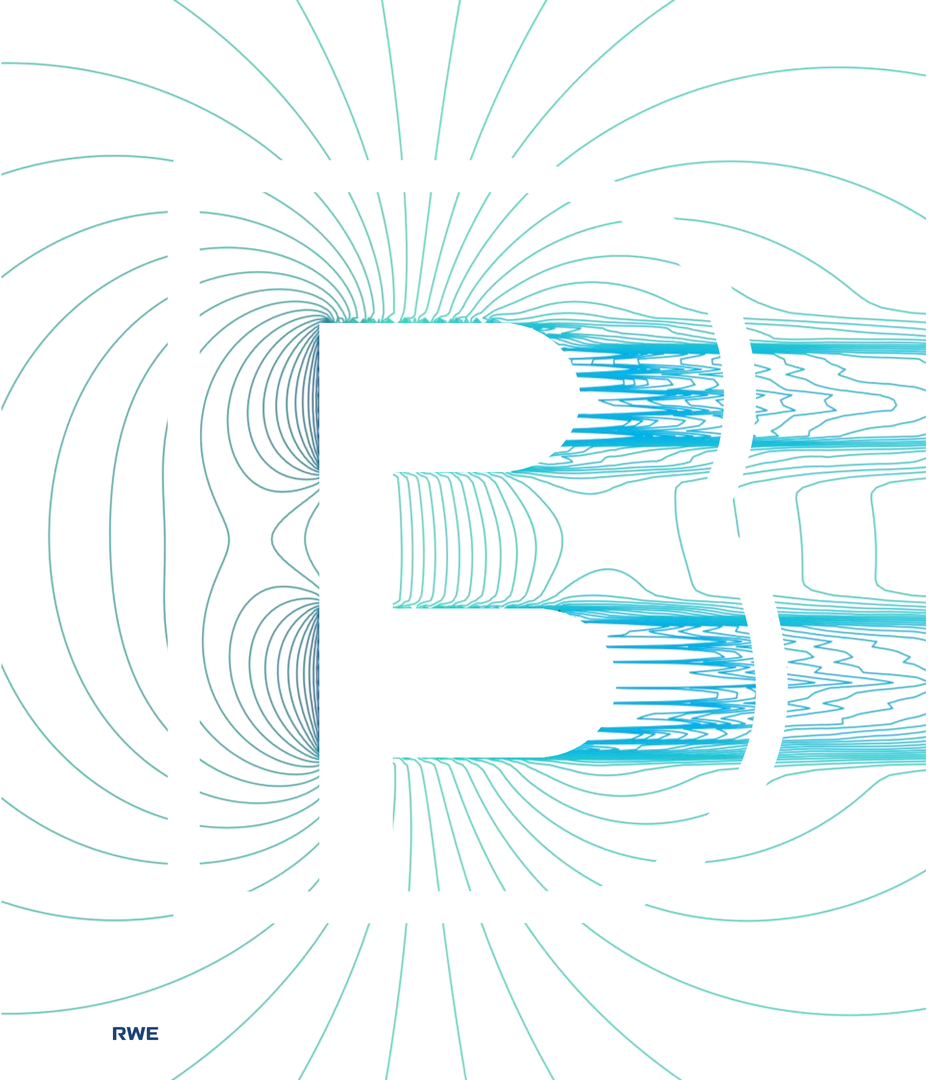
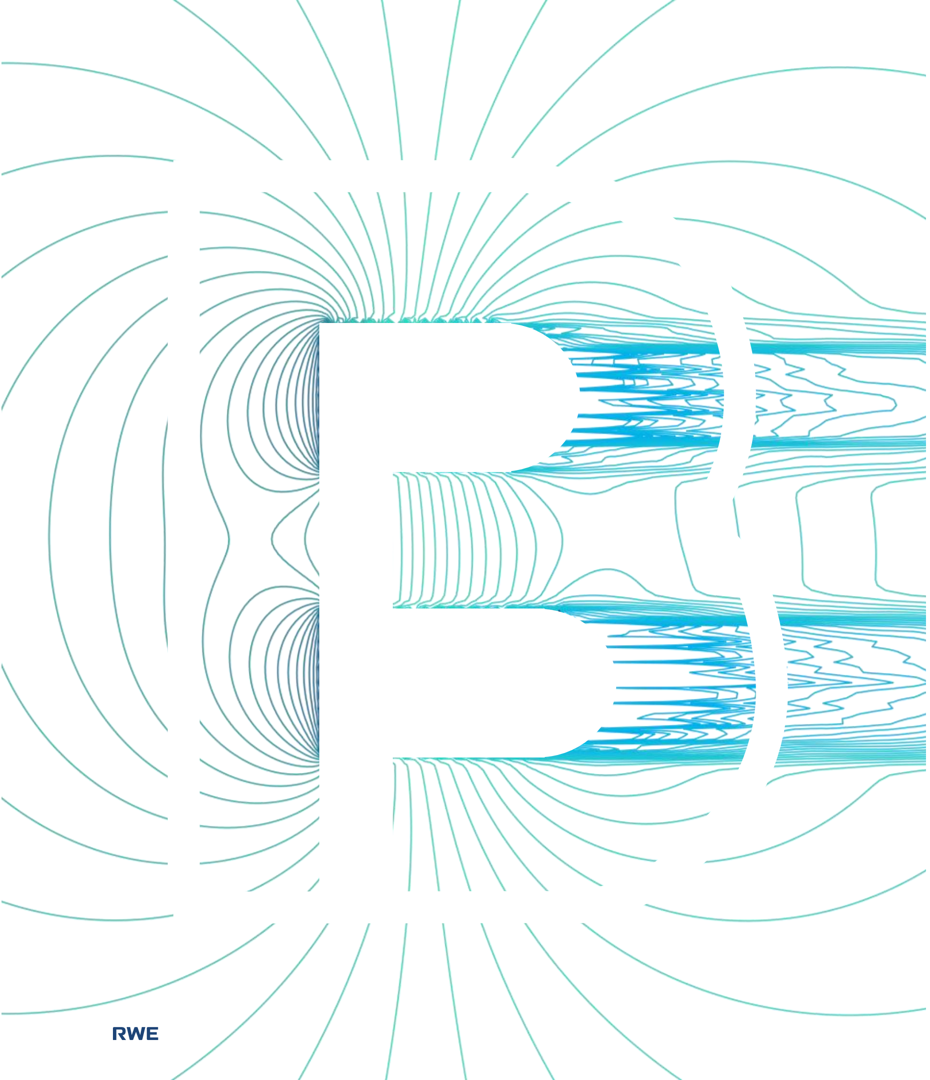
Computing resources were partly provided by the North-German Supercomputing Alliance (HLRN).
HLRN

Ministerie van Economische Zaken en Klimaat



RWE | GLOBE
Global Blockage Effect

- Introduction & Recap
- Model Comparisons
- Hypothesis Testing
- Accountancy & Conclusions
- Questions



RWE | GLoBE
Global Blockage Effect

- Introduction & Recap
- Model Comparisons
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- Questions

Introduction & recap

Objectives of this session

Delineate Blockage Physics and Accountancy

A set of proven / dis-proved hypotheses

A physics recipe

An accountancy recipe

↓

Joint Statement on the Global Blockage Effect

Introduction & recap

Recap of previous session

Focus on Measurements and Observations

End-to-end measurement and processing of scanning LiDAR data to get wind speed gradients for pattern of wind speed analysis

Processing and initial analysis of ABL height measurements

Processing and use case of the NSO met mast and FLS data as trusted references for confidence-building

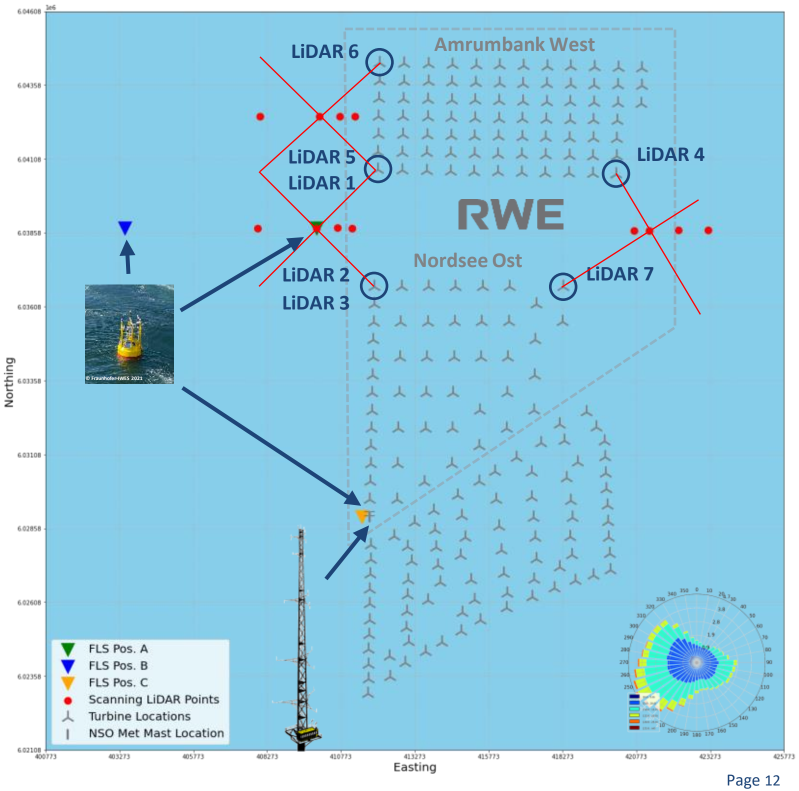
Processing of short-term wind farm SCADA data for pattern of production analysis

Experiment design

Summary of GloBE measurement campaign

GLoBE
Global Blockage Effect

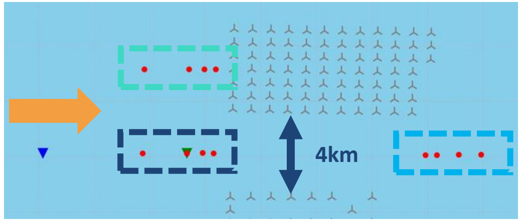
1. **6x WindCube 400s scanning in 3x dual Doppler pairs to conduct dual Doppler reconstruction (DDR) of wind speed from LoS:**
   - Operating in step-stare scanning patterns
   - Motion corrected, de-biased, levelled, time synchronised
2. **Dedicated WindCube 200s for ABL:**
   - Boundary layer height
   - VAD tall profiles
3. **Floating LiDAR System (FLS)**
   - Measuring in 3 locations, 2x co-located with scanning LiDAR and mast as trusted reference
4. **Met mast**
   - Refurbished with high-frequency sampling inc. ultrasonics for atmospheric stability and SST

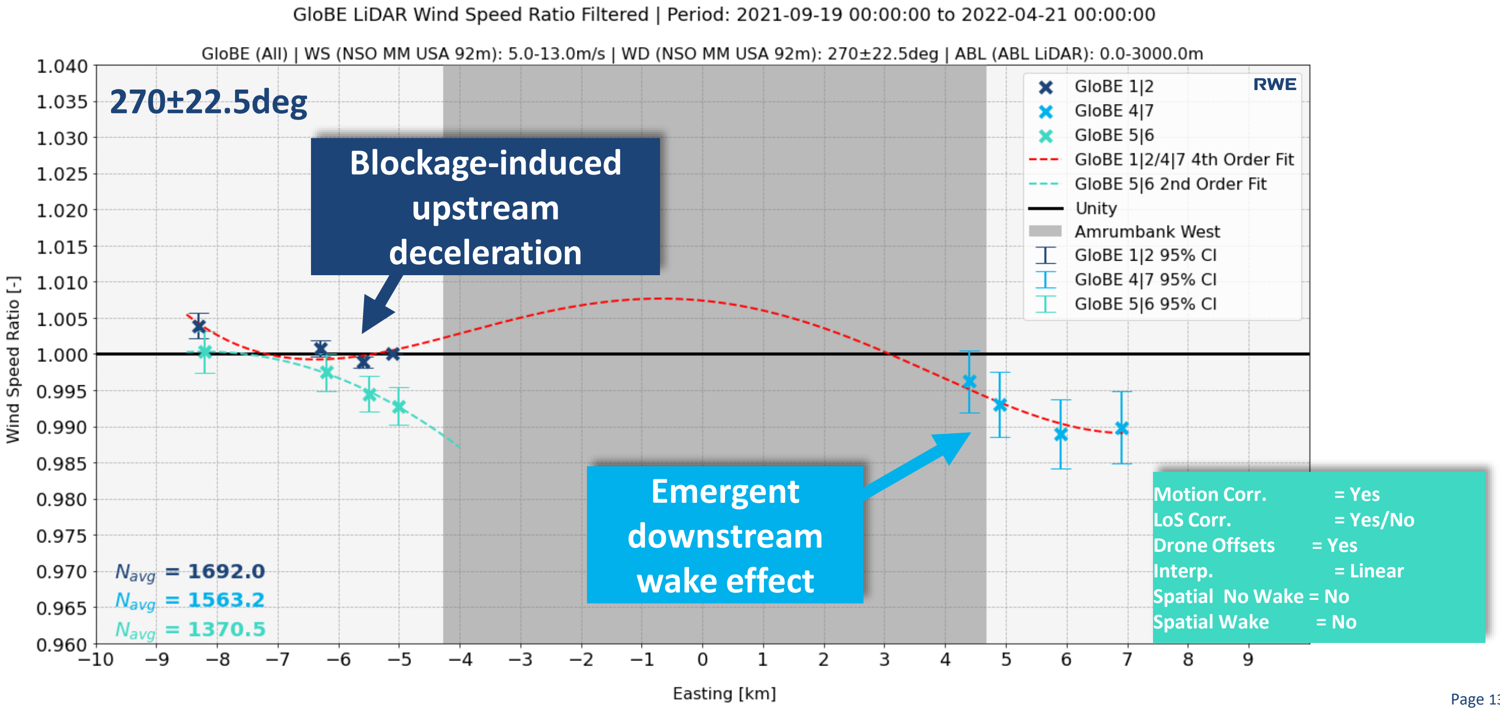


Results & observations

Blockage-induced speedups

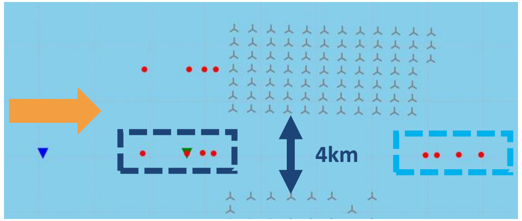
Transects upstream of AMK and "Kaskasi gap"



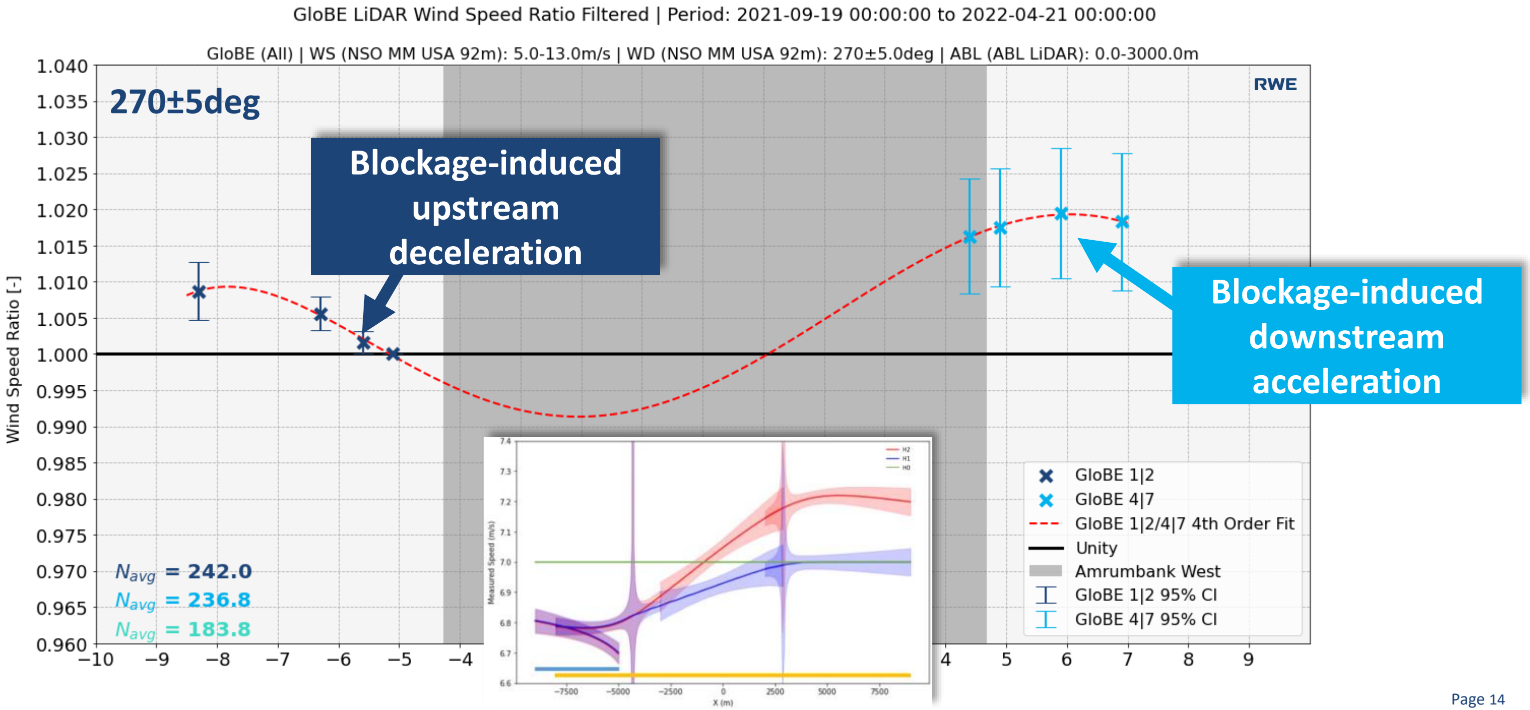


Results & observations

Blockage-induced speedups

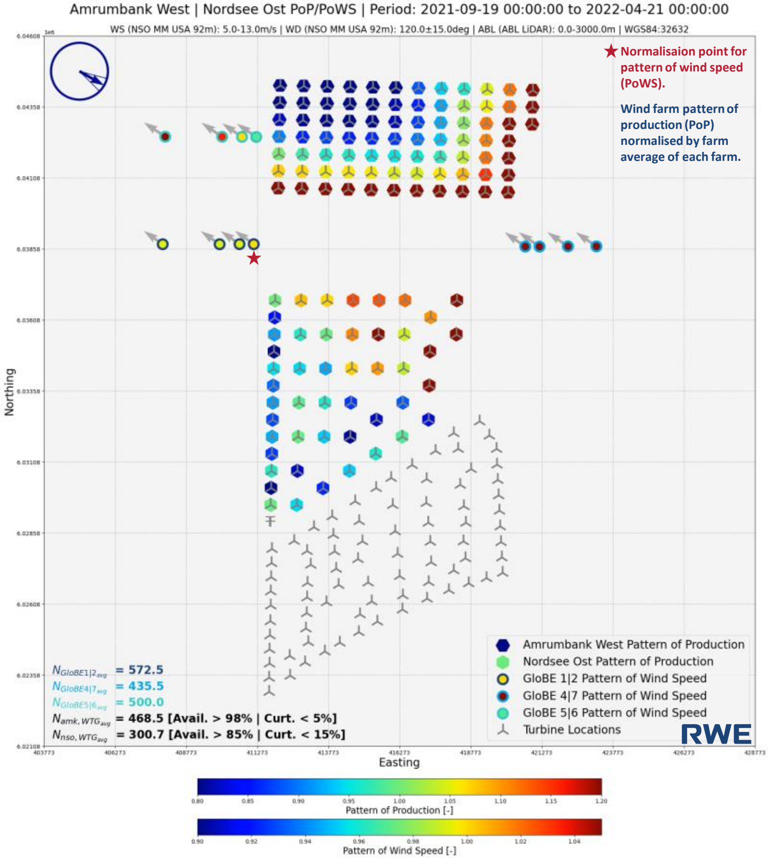


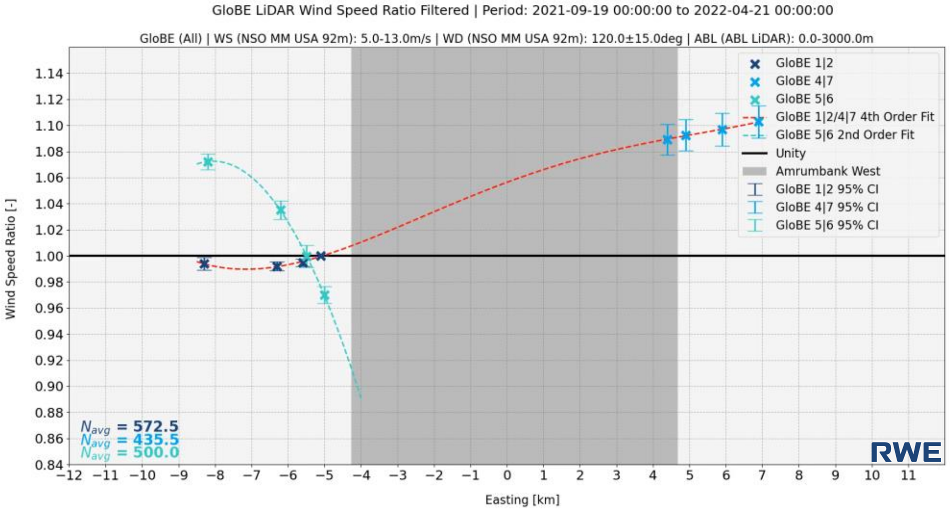
"Kaskasi gap" Transect Only



Results & observations

Pattern of wind speed & power





Assuming

Final dataset inc. all corrections

WS bin: 5-13m/s

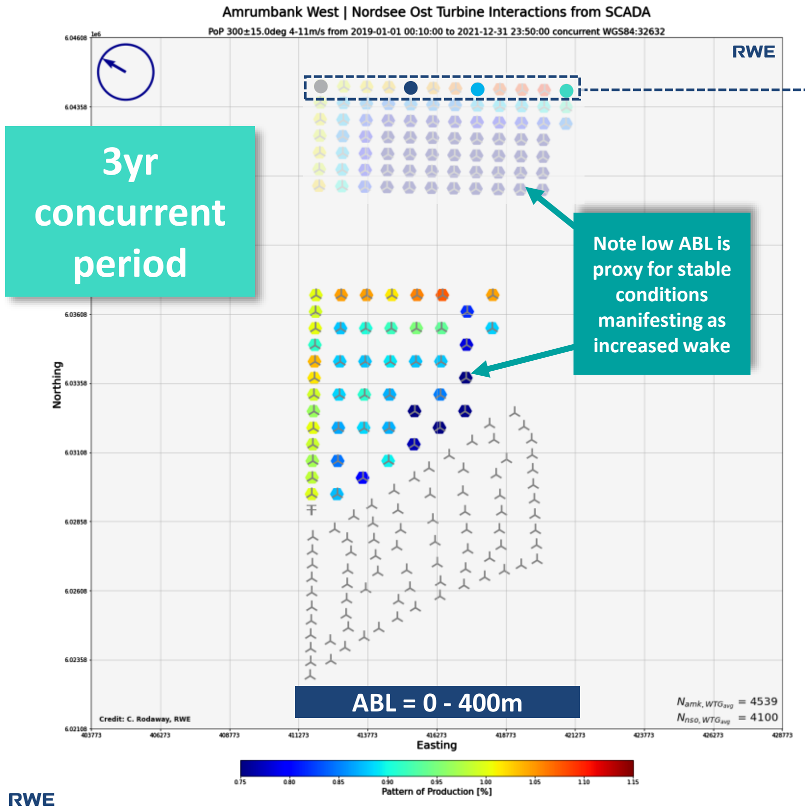
WD range: 120-360deg in 0.5deg increments

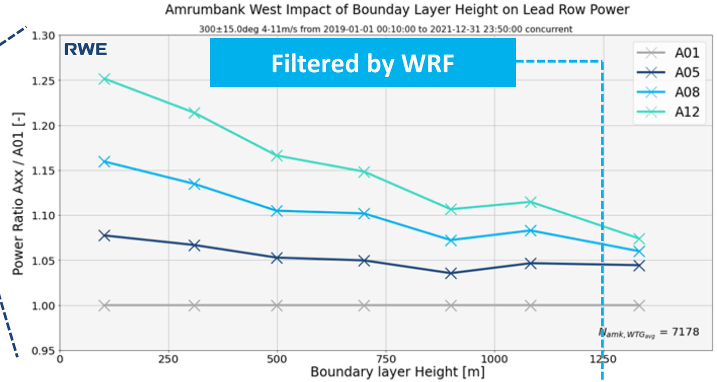
WD bin: x±15deg

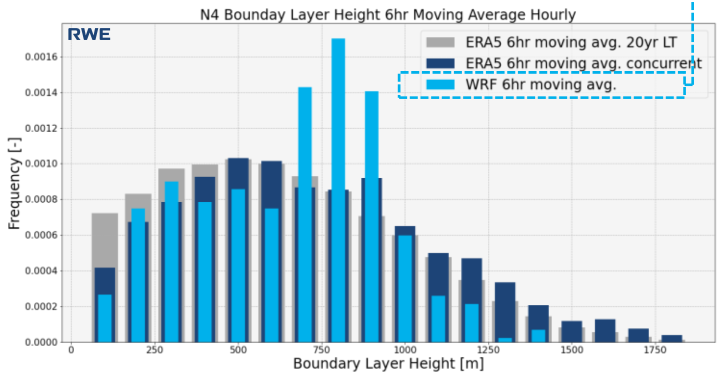
ABL: 0-3000m

Results & observations

Impact of boundary layer height on pattern of production



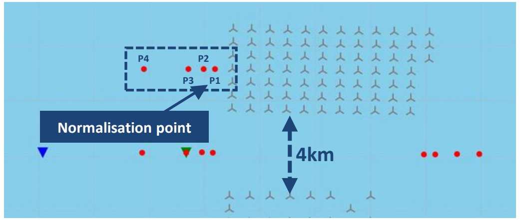


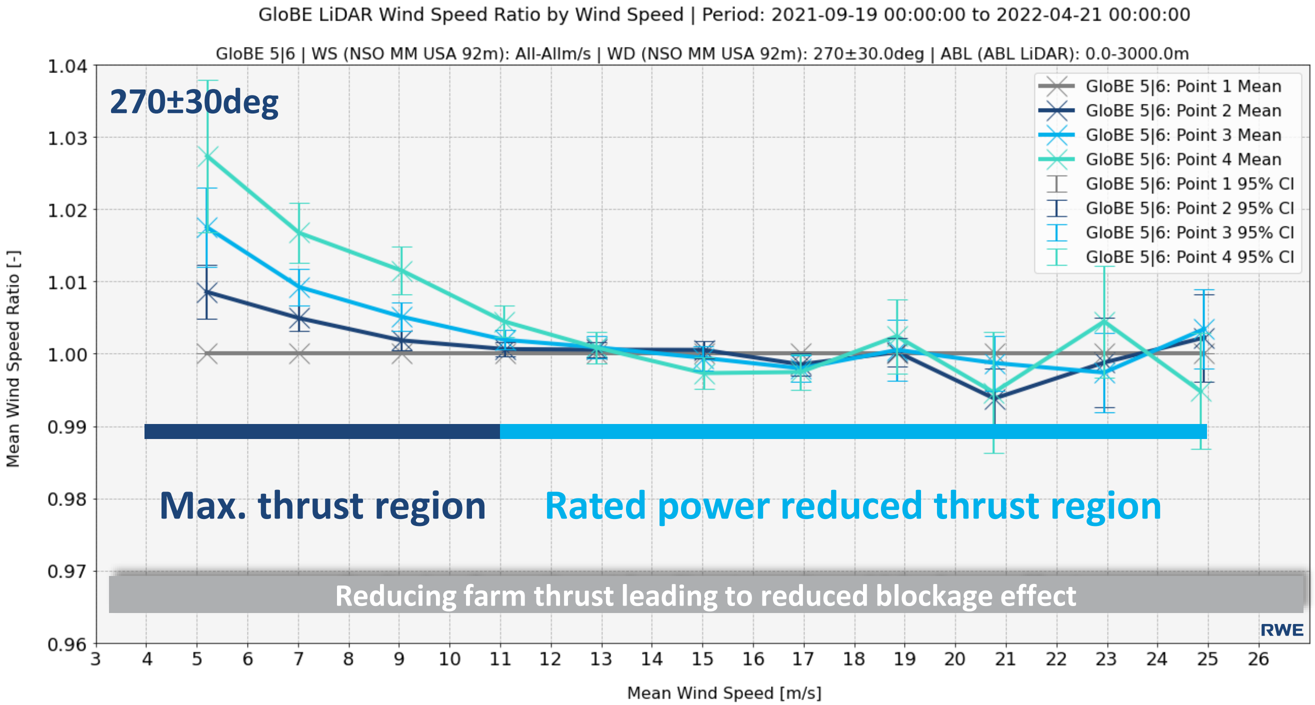


Results & observations

Wind gradients by wind speed

Trends by Wind Speed – Pair 5|6





Hypothesis testing of physics

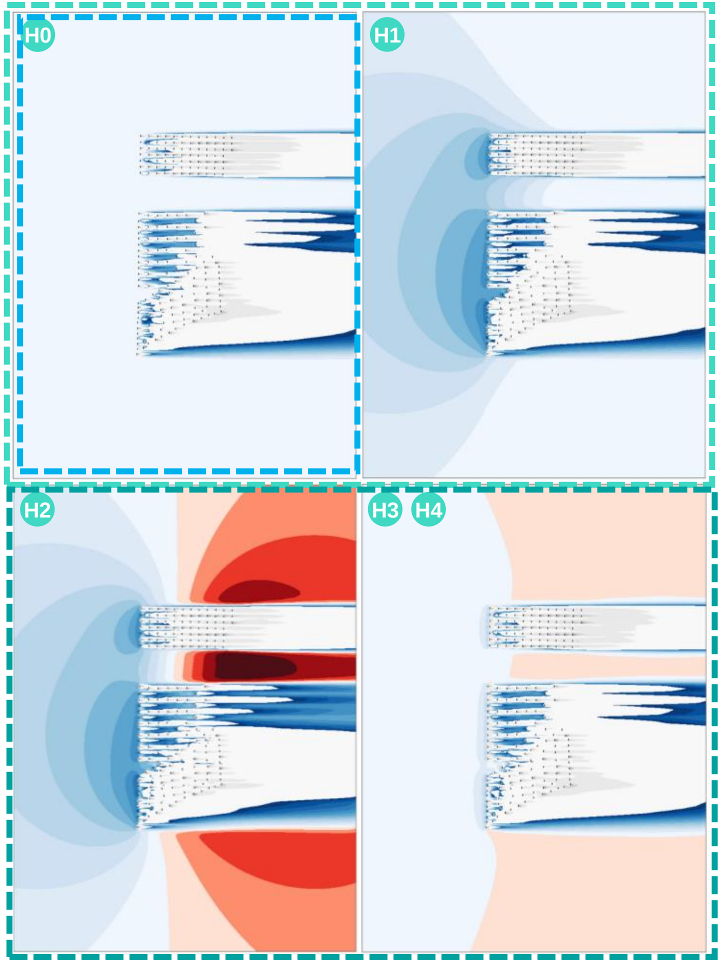
Proving / disproving hypotheses

- H0 There is no GBE
- H1 GBE results only in a downwards bias in AEP
- H2 GBE results in a downwards or upwards bias in AEP
- H3 Geostrophic height (ABL) has little impact on GBE
- H4 Geostrophic height (ABL) has large impact on GBE

Legacy approach

Lead row correction approach

Tightly / Fully-coupled approach



Hypothesis testing

Evidence-based method

Combining wind speed and power gradients

In order to prove / disprove hypotheses we will use a **body of evidence** comprising of:

- Measured wind speed gradients & what impacts them
- Observed power gradients & what impacts them
- Modelled results to separate physics & what impacts them (use of VV to assist)

Question: What best explains what we are seeing in the observations?

Result: A model physics recipe.

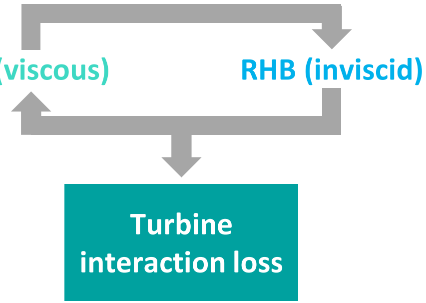
RWE | GLoBE
Global Blockage Effect

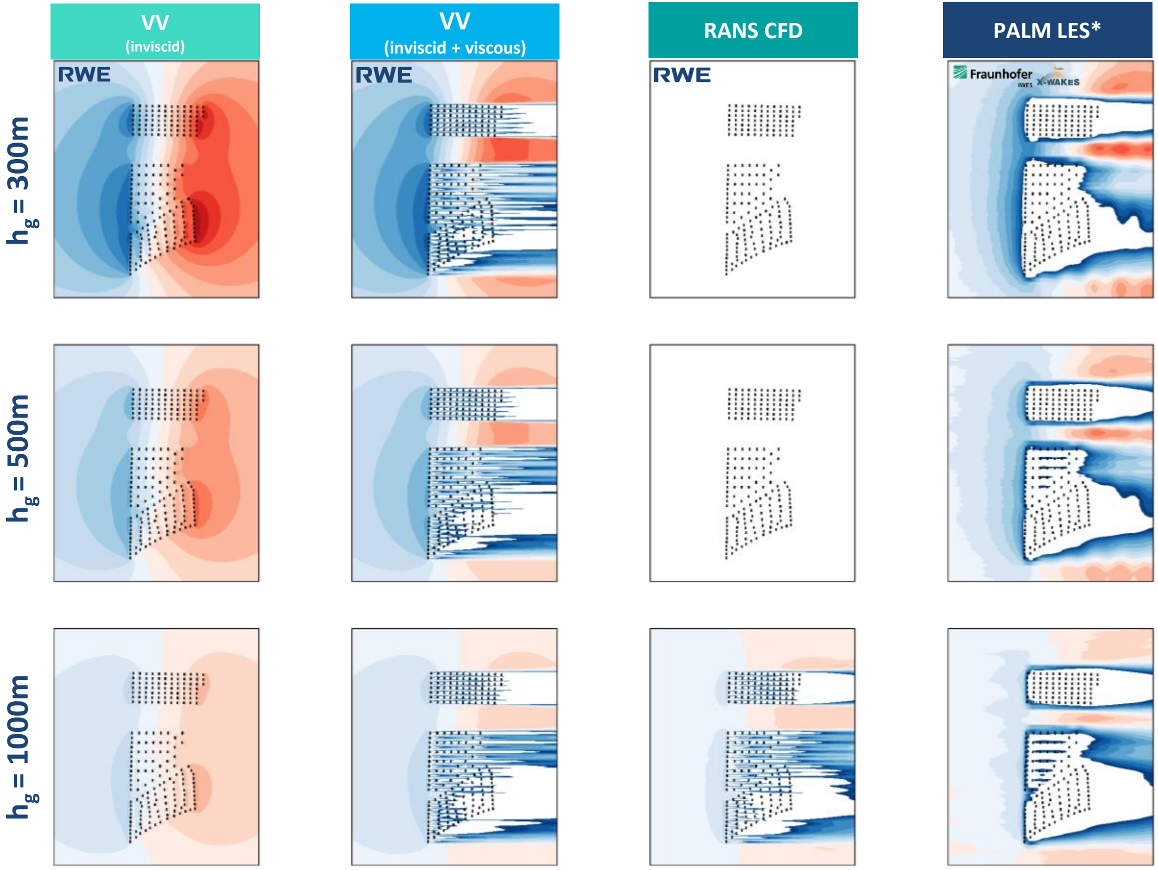
- Introduction & Recap
- **Model Comparisons**
- Hypothesis Testing
- Accountancy & Conclusions
- Questions

Model comparisons

Introducing RWE's VV and RANS CFD model

1. RWE in-house developed "VV" (Viscous Vortex) tested against higher order models
2. No wake model "tuning" or coefficients required
3. VV is EV (Ainslie) coupled to vortex sheet (RHB)





RWE *Courtesy of Fraunhofer-IWES through X-Wake cooperation

Model comparisons

ITRG model contribution

GloBE data

Blockage physics & model representation

Independent Technical Review Group

Blockage technical loss accountancy

Joint Statement on the Global Blockage Effect

Model comparisons

ITRG model contribution

Summary Table

Model	Type	GBE Physics	ABL directly represented?	ABL Heights (m)	Stability Conditions	Plot Designation
A	Fully Coupled	Full	Yes (soft)	300, 600, 1000	Neutral, Stable	A (FC)
B	Fully Coupled	Full	Yes (soft)	Many	Many	B (FC)
C	Tightly Coupled	Full	Yes (hard)	300, 500, 1000	-	C (TC-ABL)
D	Tightly Coupled	Full	No	-	-	D (TC-no ABL)
E	Tightly Coupled	Deceleration	No	Many	-	E (TC-no ABL)
F	Tightly Coupled	Full	Yes	300, 500, 1000	-	F (TC-ABL)
G	Fully Coupled	Full	Yes (hard)	300, 500, 1000	-	G (FC)
H	Tightly Coupled	Full	No	-	-	Not included yet
RWE VV	Tightly Coupled	Full	Yes (hard/soft)	300, 500, 1000	Neutral, Stable	RWE VV
RWE CFD	Fully Coupled	Full	Yes (soft)	700m	Neutral	RWE CFD

Model comparisons

Processing of SCADA data

Summary of data processing

Wind speed distributions

- Shown in the "Wind & Power Observations" session, won't go over this again.

Power distributions

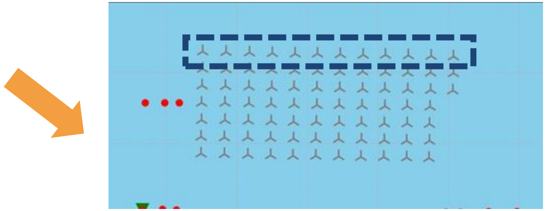
- Uses 4yr long term dataset.
- Filtered for wind speed and direction from lead row turbines, 100% avail. And 0% curt.
- Normalised PoP calculated using lead row average if lead row only.
- Normalised PoP calculated using wind farm average if looking at whole wind farm.

Models

- Model results averaged directionally if available within the same bin widths as measured.
- Model results averaged across multiple ABL heights if available.
- Model results averaged across multiple stability conditions if available.

Model comparisons

Pattern of production

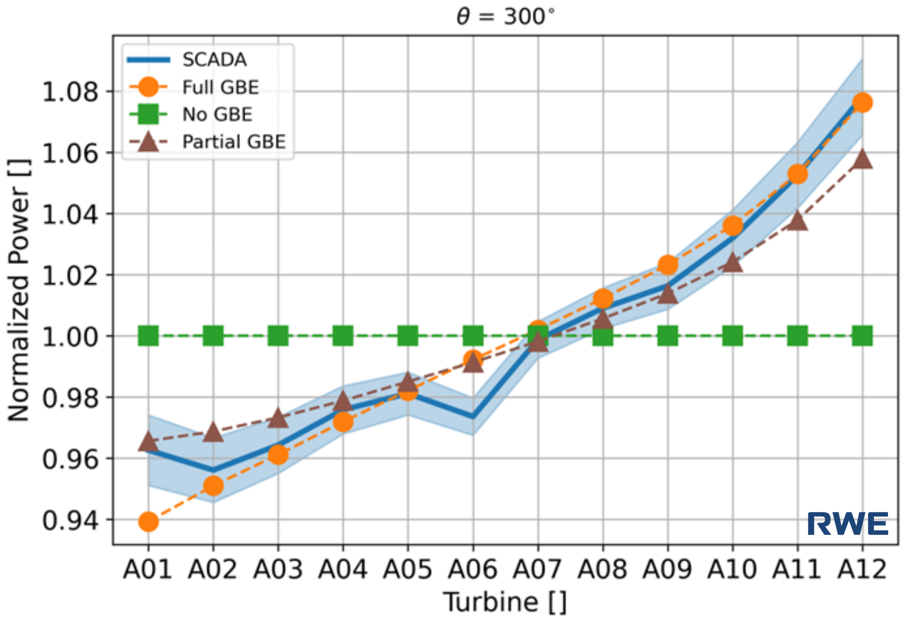


Pattern of Production Along Lead Rows

$$\theta = 300° \pm 5° \qquad U_{ref} = (7.5 \pm 1)\ \mathrm{m/s}$$

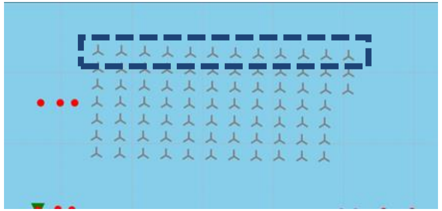
VV only comparing hypotheses (ABL = [300,500,1000m], lid = 0.5):

- **No GBE (H0)** – Shows no variation
- **Partial GBE (H1)** – Shows power gradient
- **Full GBE (H2/3)** – Shows increased power gradient



Model comparisons

Pattern of production



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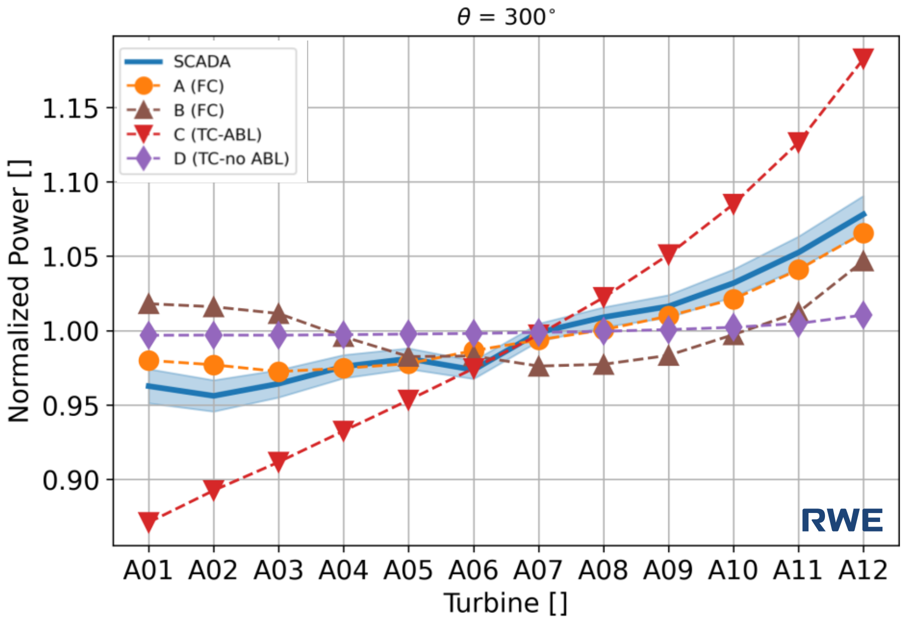
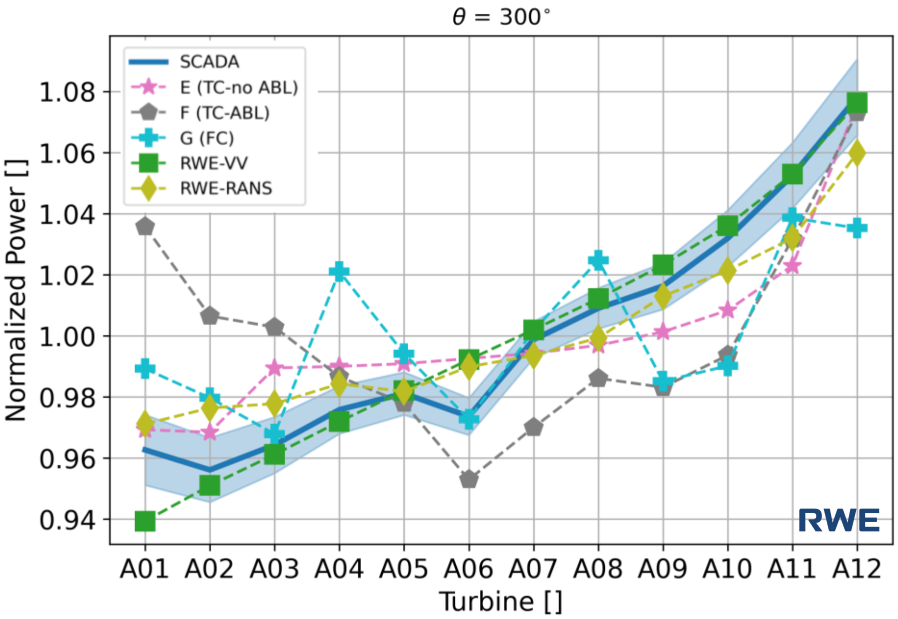
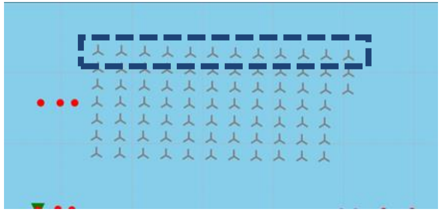




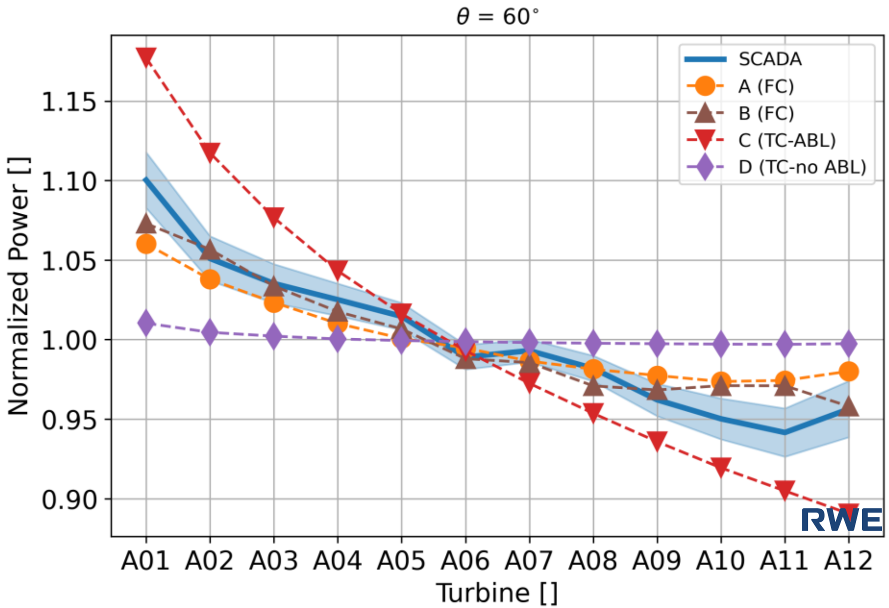
Model comparisons

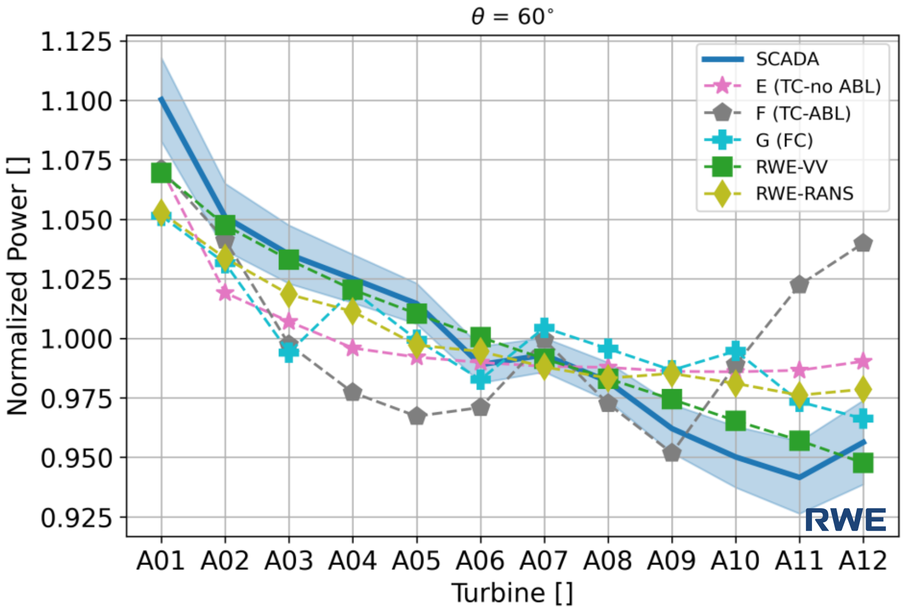
Pattern of production



Pattern of Production Across Wind Farm

$\theta = 60° \pm 5° \qquad U_{ref} = (7.5 \pm 1)$ m/s

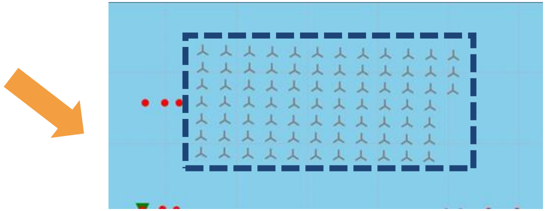




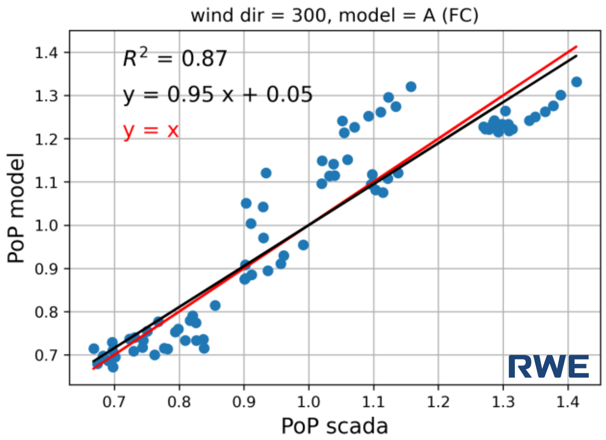
Model comparisons

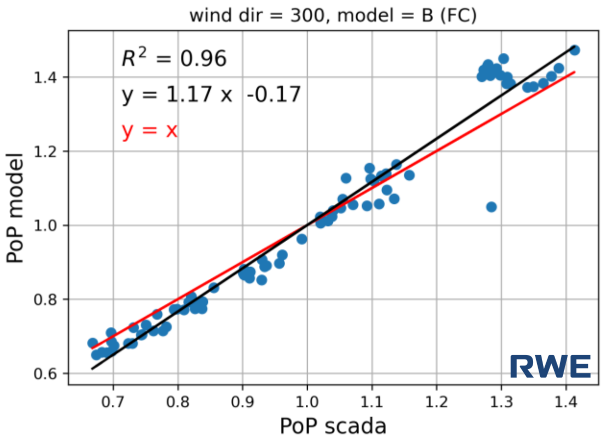
Pattern of production

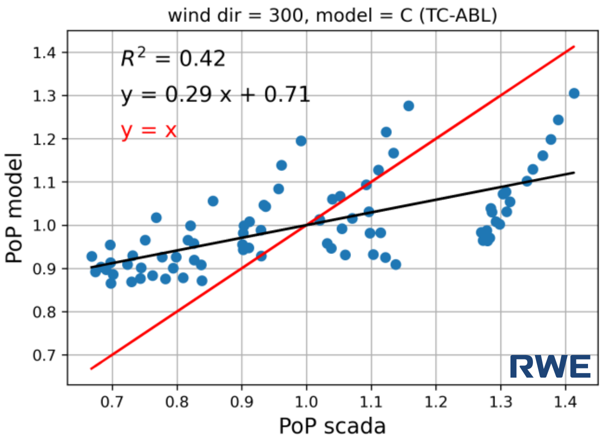
Pattern of Production Across Entire Site



$$\theta = 300° \pm 5° \qquad U_{ref} = (7.5 \pm 1)\ \mathrm{m/s}$$



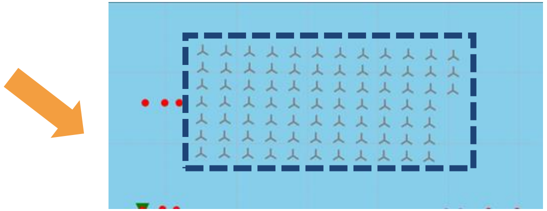




We typically look for "global gradients" and scatter in these plots to assess model performance

Model comparisons

Pattern of production



Pattern of Production Across Entire Site

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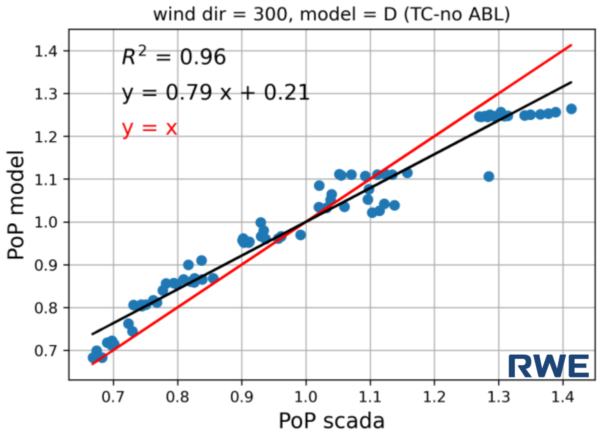

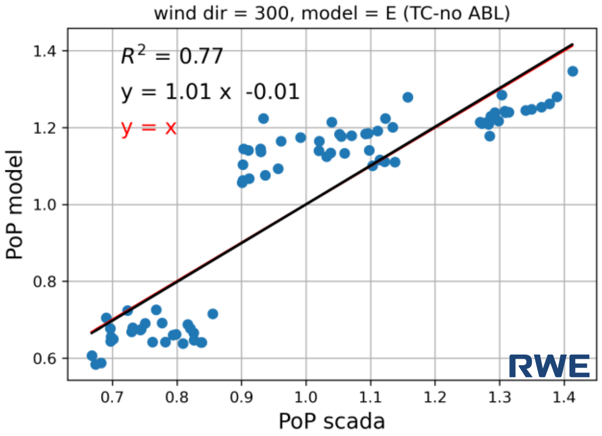

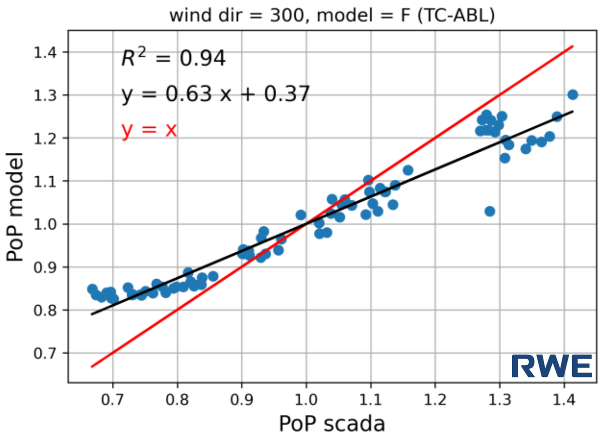

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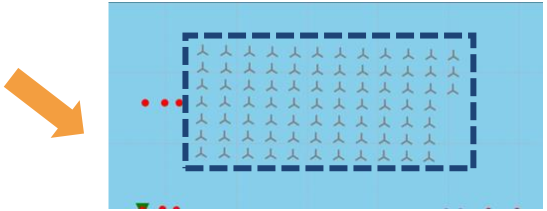
Model comparisons

Pattern of production



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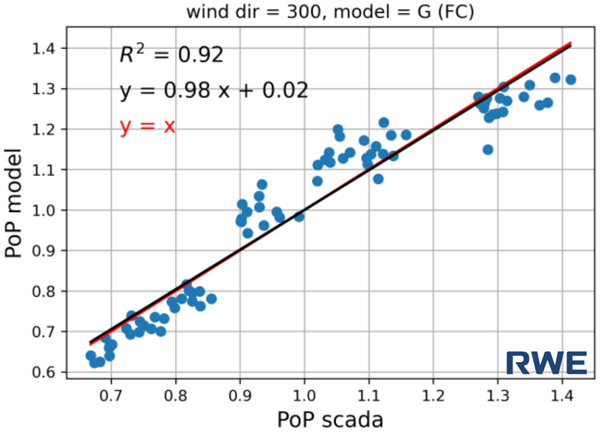

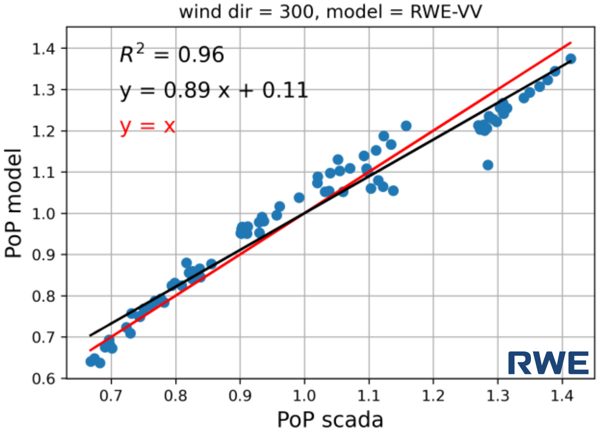

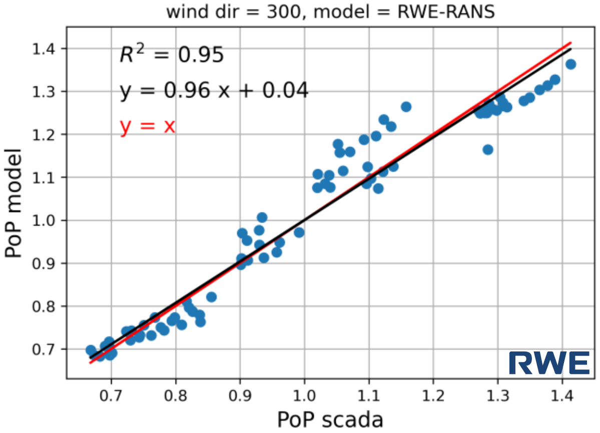

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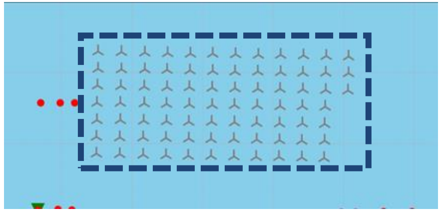
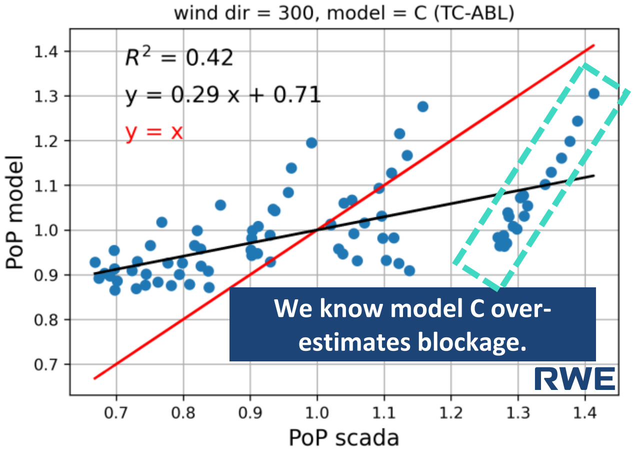
Model comparisons

Pattern of production



Pattern of Production Across Entire Site

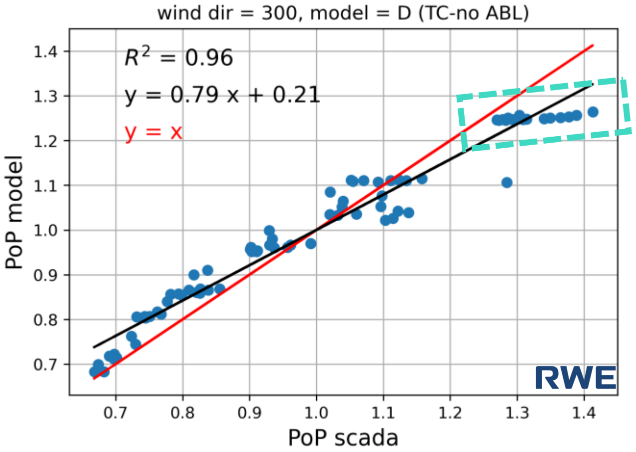
300deg allows us to drill into GBE specifically, let’s see how by looking at models C and D



We know model C over-estimates blockage.

Sub or local power gradients form! What does this mean???

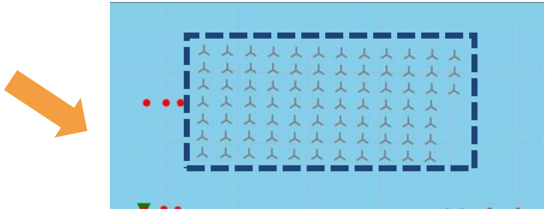
Is global power gradient impacted???



Let’s use VV to answer these questions!

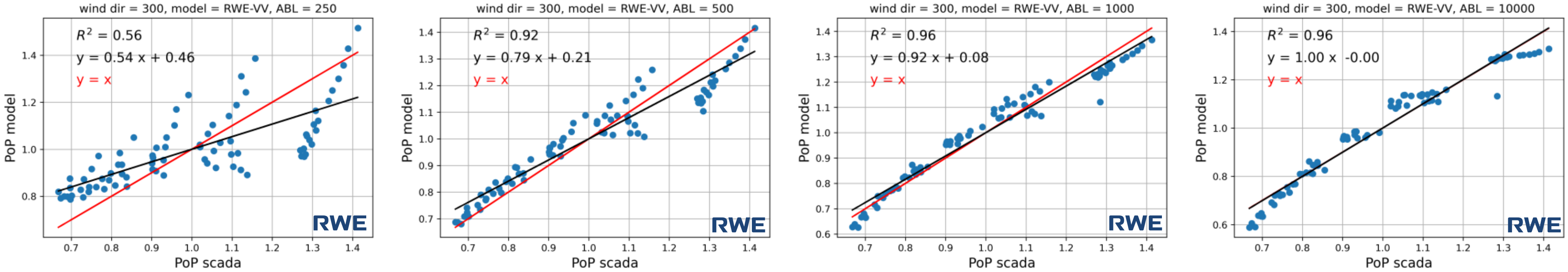
Model comparisons

Pattern of production



Pattern of Production Across Entire Site

VV run for 300deg a range of ABL heights using lid strength = 1 (to exaggerate the effect) → <u>remember this is the same wake model in each case:</u>

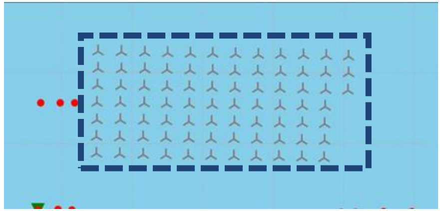


GBE and ABL impacts the local power gradients within the global gradient!

GBE and ABL impacts the global gradient and "appears" as a wake model issue!

Model comparisons

Pattern of production



Pattern of Production Across Entire Site

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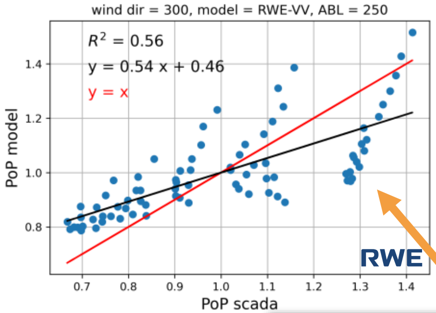
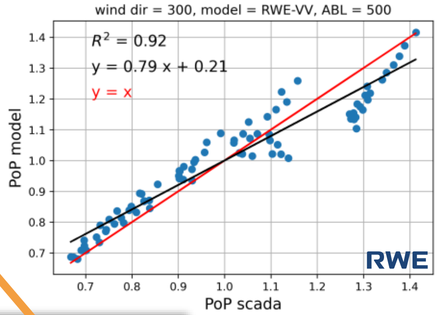
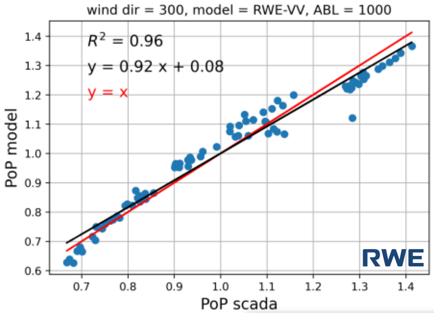
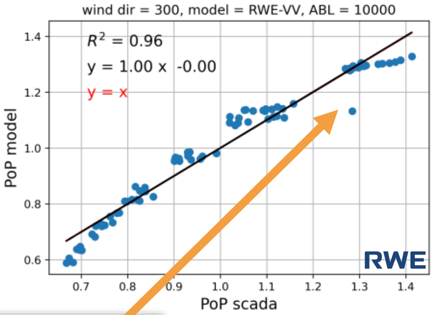
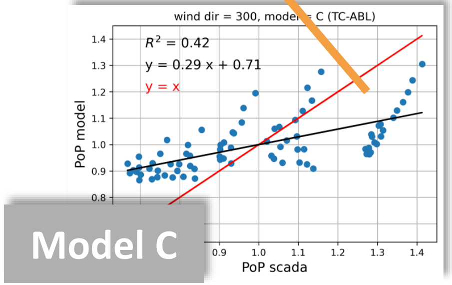


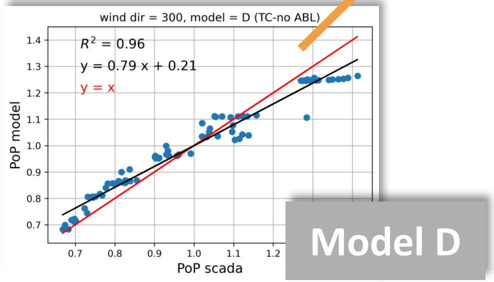








We can explain the behaviour of model C and D



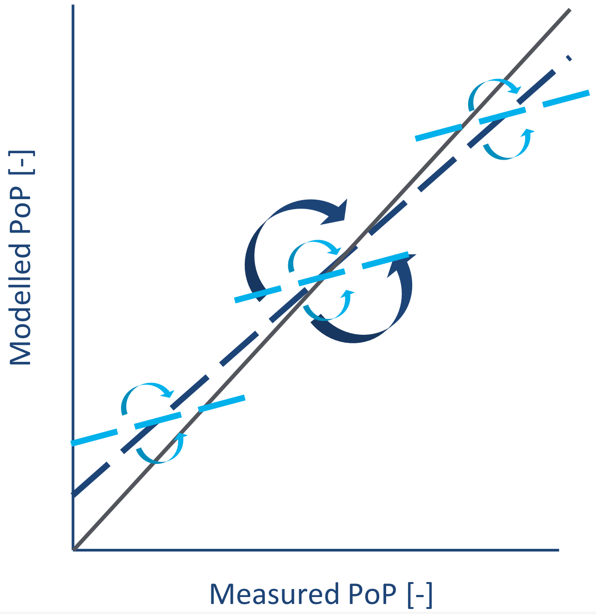
Model comparisons

Impact on pattern of power from wake and GBE

Wake → Change global trend gradient

GBE → Change sub-trend gradient

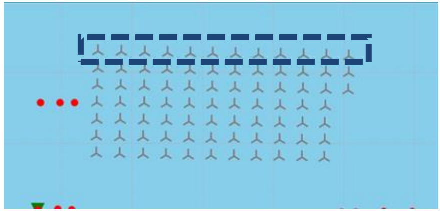
ABL height / inversion Strength → Change sub-trend gradient <u>and</u> Change global gradient at extremes



All contribute to stream-wise power gradients and therefore scatter in PoP comparisons

Model comparisons

Impact of boundary layer height



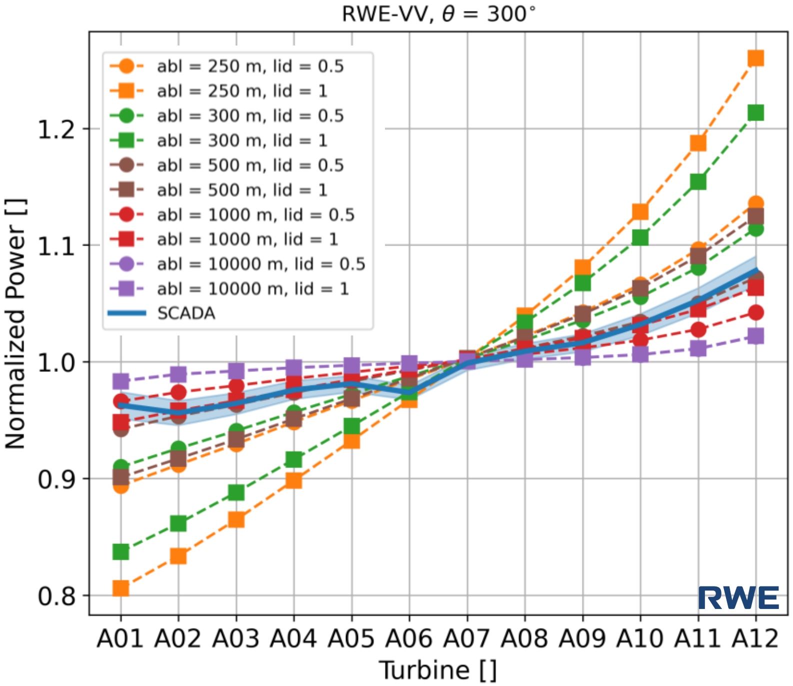
Patter of Production Across Entire Site – ABL Impact

VV run for 300deg a range of ABL heights using lid 9inversion) strength = 0.5 AND = 1

- ABL height has a big impact
- Lid (inversion) strength has an equally big impact
- VV requires a inversion strength of 0.5 to permit a realistic ABL height to be set.

GBE models must have ABL representation and care over inversion strength

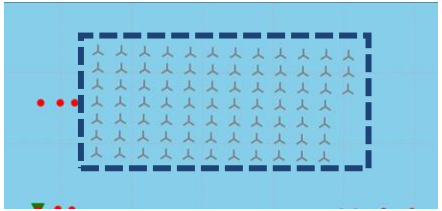
Significant learning for RWE, inversion strength option introduced to VV as a result



Model testing

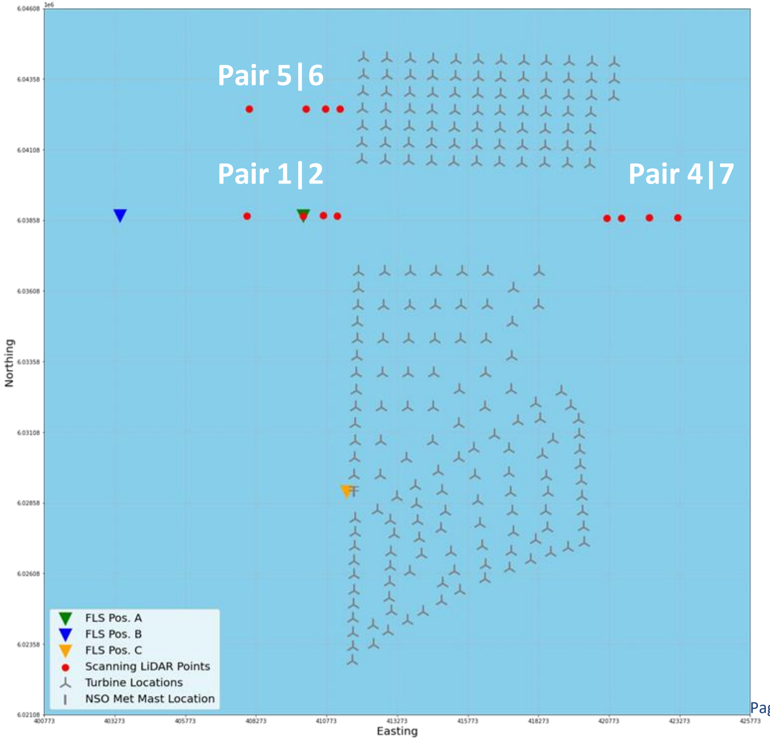
Model comparisons

Pattern of Wind Speed



So far we have looked at long term power only but what has GloBE given us?

- Wind speed gradients along transects for 3 dual Doppler scanning LiDAR pairs.
- Interrogate the model flow fields supplied and compare against the measured data.
- Try and split out the hypotheses, again will use VV for this purpose.

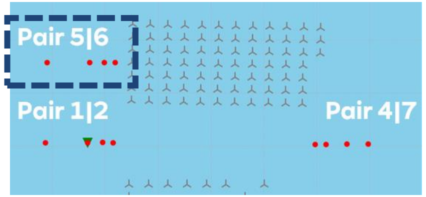


Model testing

Model comparisons

Measurements
WS: 5-13m/s
WD: 270±5deg
ABL: All

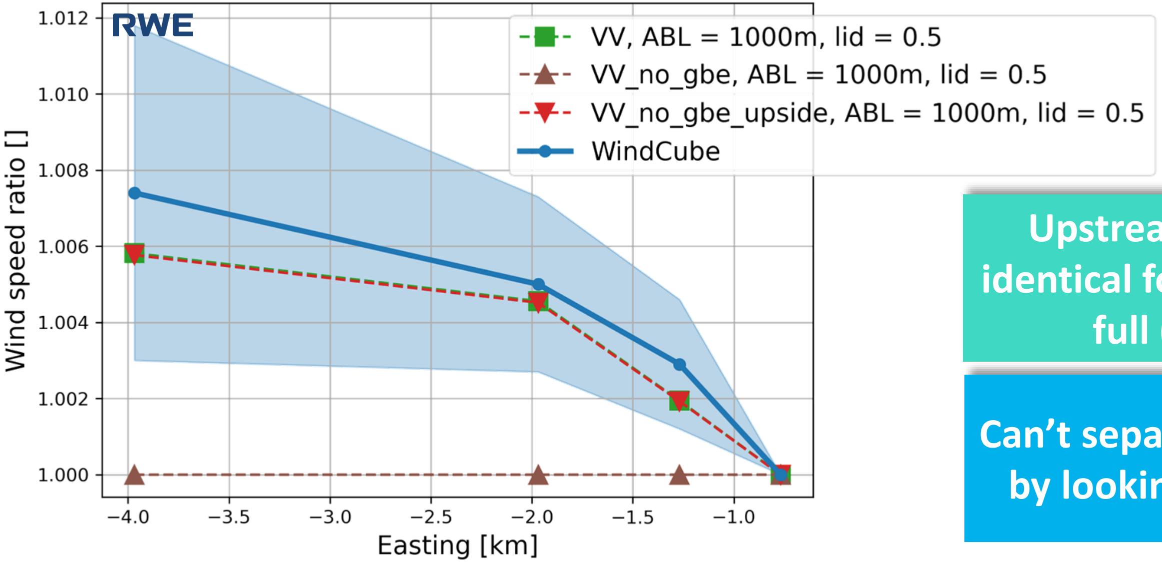
Model
WS: 8m/s
WD: 270±5deg
ABL: 1km (0.5 lid)



Pattern of Wind Speed

Let us use VV to show the impact of the different hypotheses on wind speed gradients:

Pair 5 | 6



Upstream deceleration identical for partial (H1) and full (H2/3) GBE.

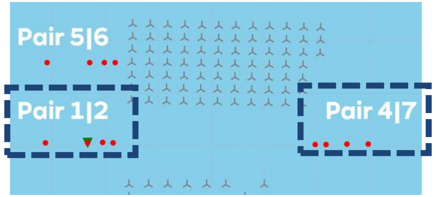
Can't separate H1 from H2/3 by looking upstream only

Model testing

Model comparisons

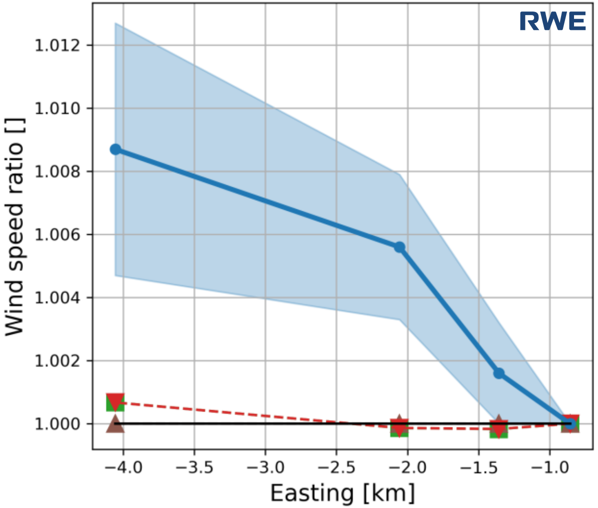
Pattern of Wind Speed

Measurements	Model
WS: 5-13m/s	WS: 8m/s
WD: 270±5deg	WD: 270±5deg
ABL: All	ABL: 1km (0.5 lid)

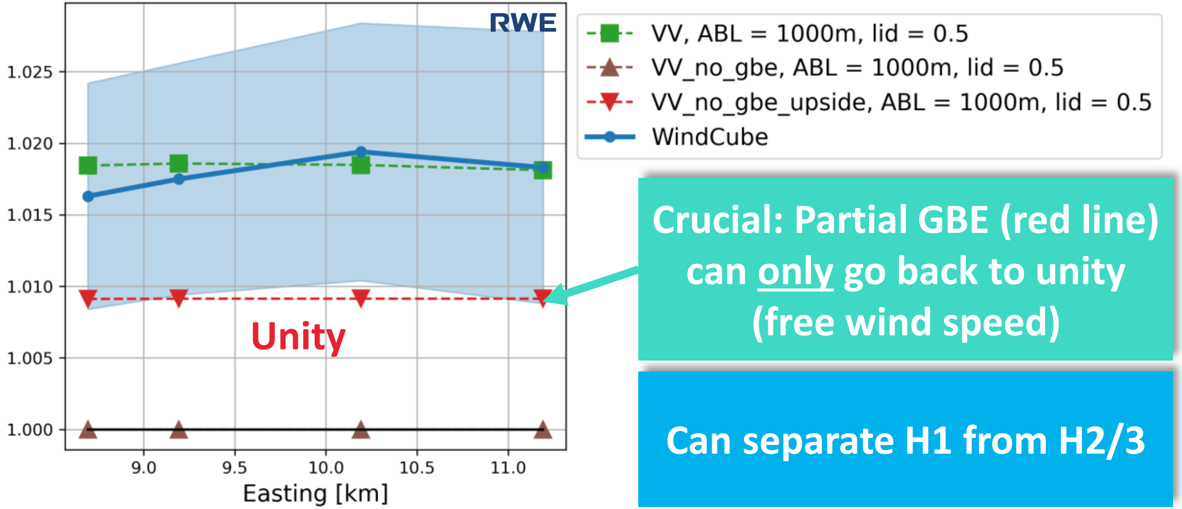


Let us use VV to show the impact of the different hypotheses on wind speed gradients:

Pair 1 | 2



Pair 4 | 7



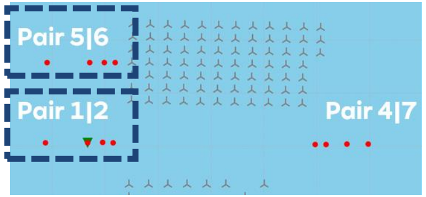
Crucial: Partial GBE (red line) can <u>only</u> go back to unity (free wind speed)

Can separate H1 from H2/3

Model testing

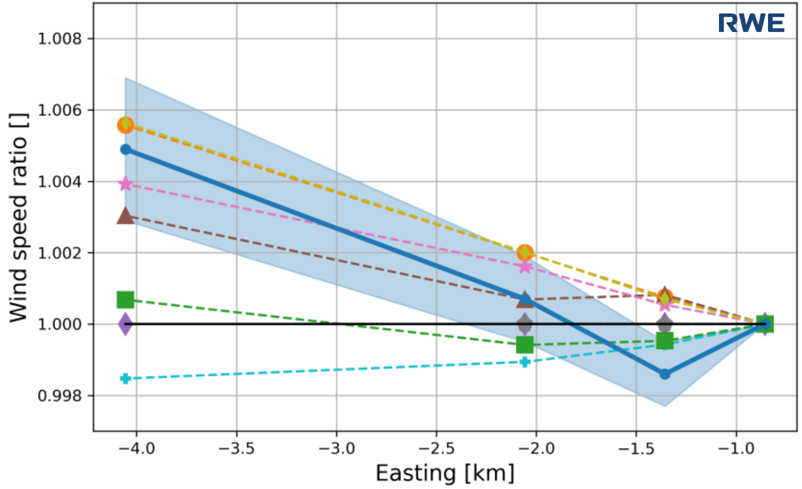
Model comparisons

Measurements	Model
WS: 5-13m/s	WS: 8m/s
WD: 270±22.5deg	WD: 270±22.5deg
ABL: All	ABL: Avg. avail.

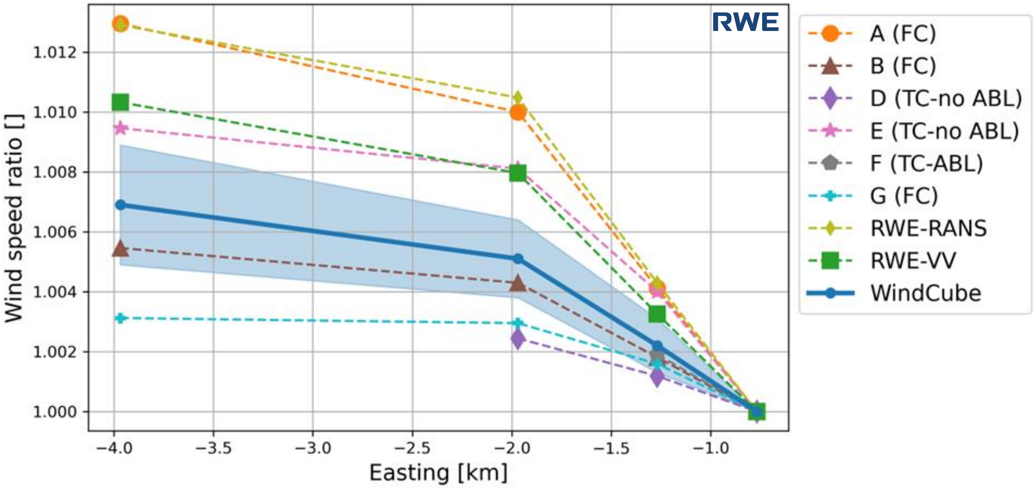


Pattern of Wind Speed

Pair 1 | 2



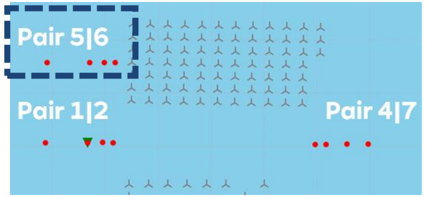
Pair 5 | 6



Model testing
Model comparisons

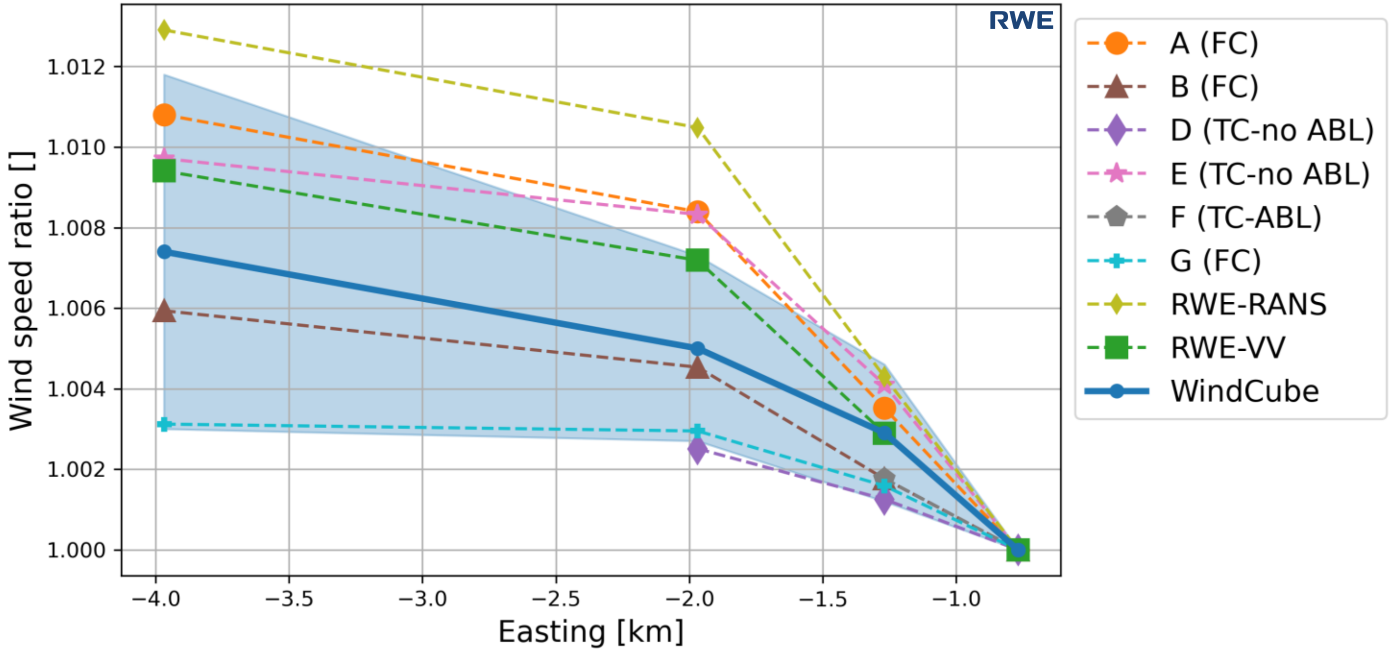
Measurements
WS: 5-13m/s
WD: 270±5deg
ABL: All

Model
WS: 8m/s
WD: 270±5deg
ABL: Avg. avail.



Pattern of Wind Speed

Pair 5 | 6



Model testing

Model comparisons

Measurements
WS: 5-13m/s
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ABL: All

Model
WS: 8m/s
WD: 270±5deg
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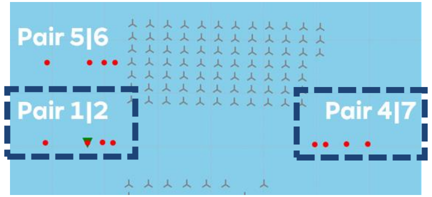
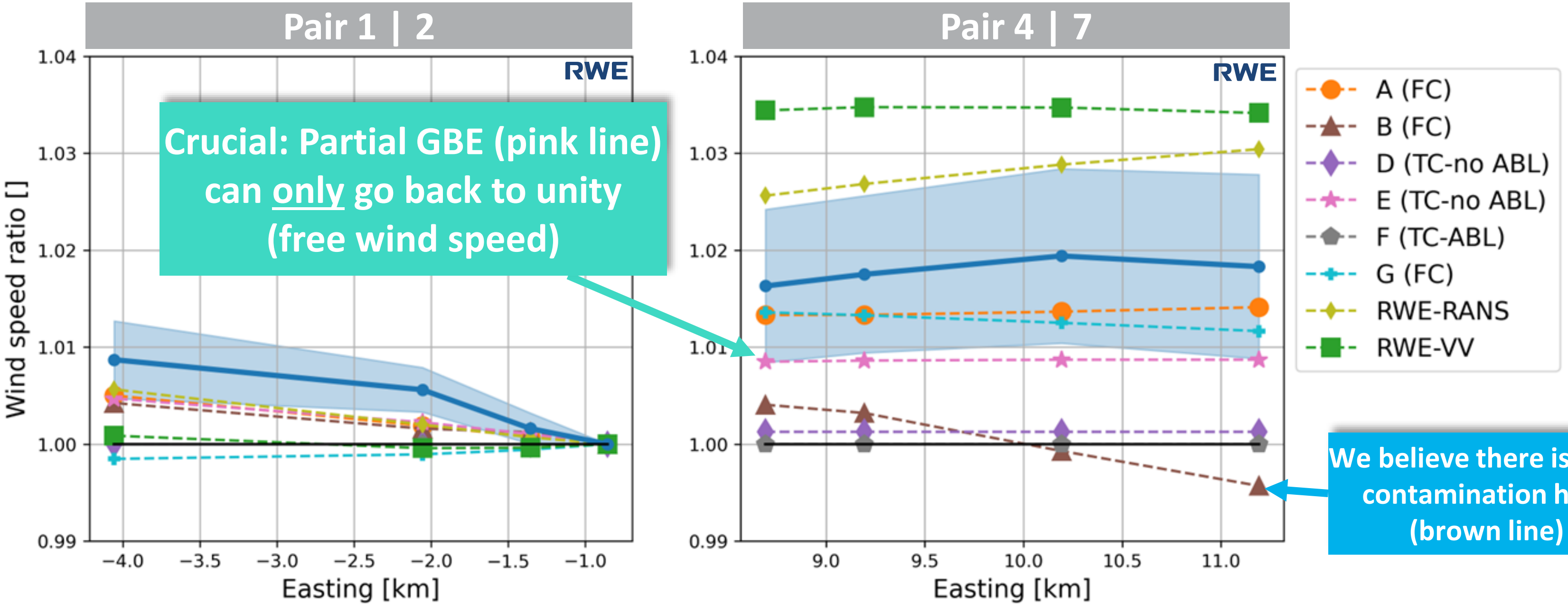


Pattern of Wind Speed



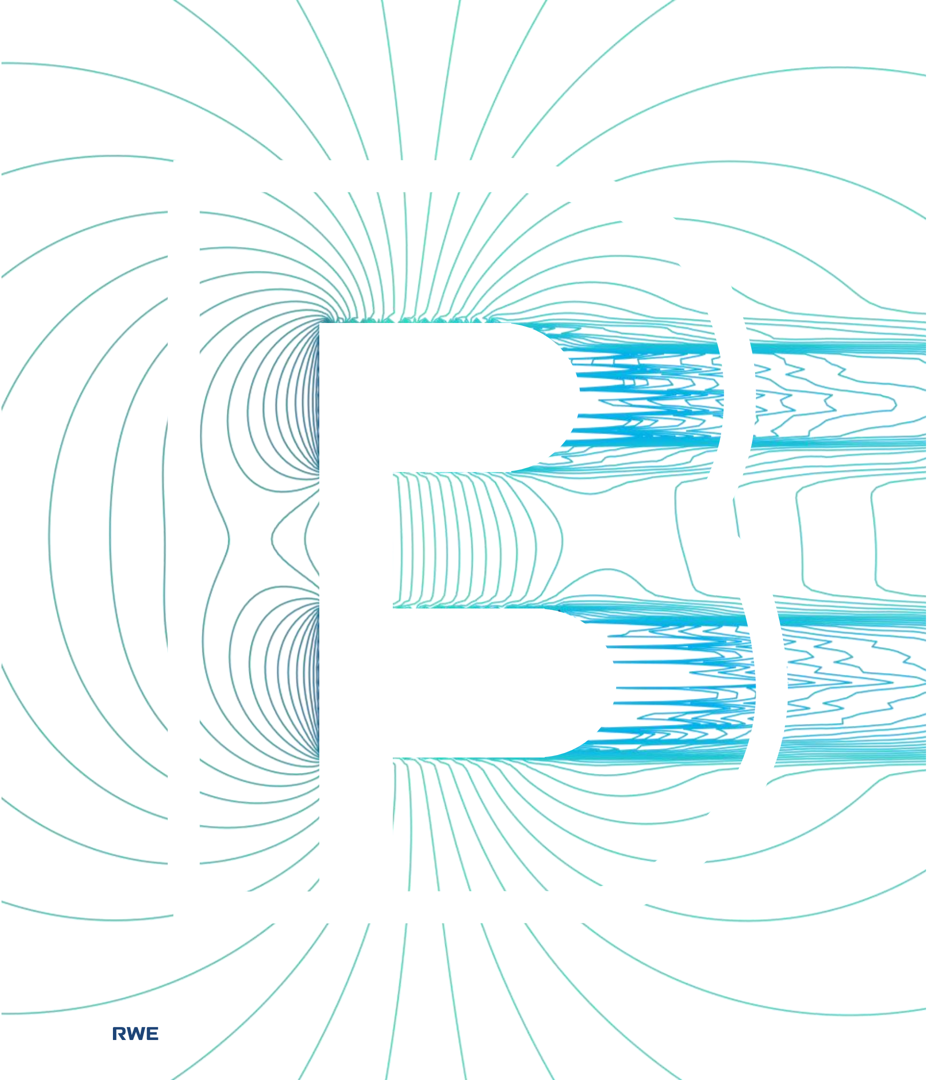
Model comparisons

Findings from comparison exercise

Conclusions

We have seen the following from the model comparison:

1. There is a large spread of methods and therefore a large spread of results, the extent of the spread was a surprise.
2. There are models that clearly perform very well and some pretty poorly specifically for GBE.
3. Tightly coupled models which exclude ABL height representations show negligible GBE impact and therefore are of little value.
4. Tightly coupled models which only contain partial GBE exhibit gradients which do not match observations.
5. Fully coupled higher order models consistently perform the best when including the correct physics.
6. Tightly coupled models with good ABL height representations including soft lid perform very well.



RWE GloBE
Global Blockage Effect

- Introduction & Recap
- Model Comparisons
- **Hypothesis Testing**
- Accountancy & Conclusions
- Questions

Hypothesis testing

Proving / disproving hypotheses

Body of evidence 1

1. Power gradients for un-waked & waked turbines only explainable when including GBE physics

2. Wind speed gradients upstream of wind farm show deceleration only explainable when including GBE physics

3. Wind speed gradients follow expected trends with farm thrust.

Hypothesis testing

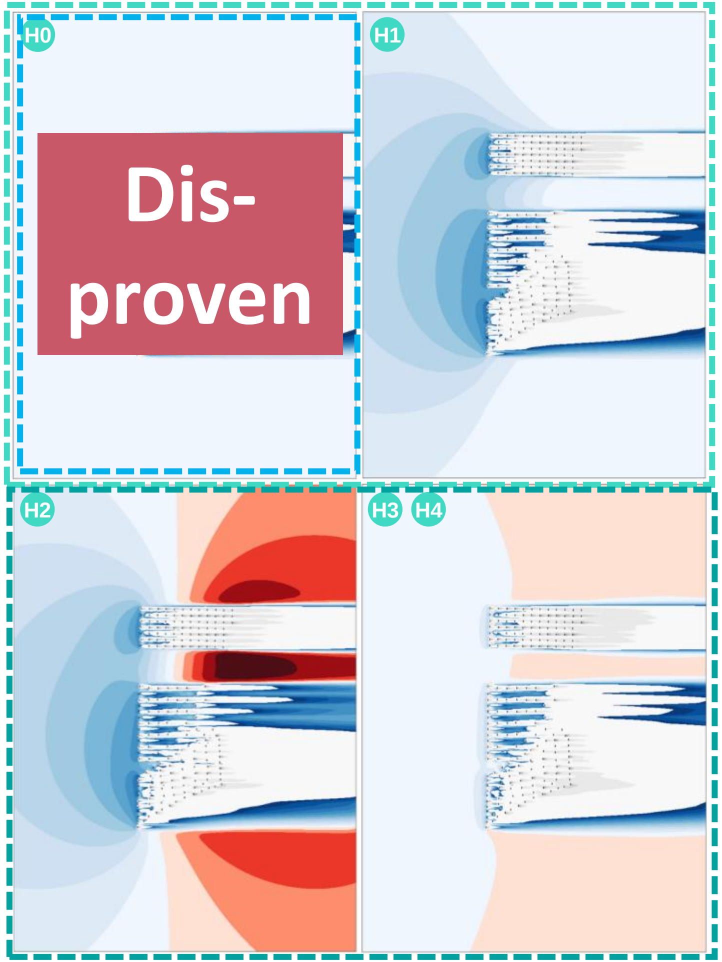
Proving / disproving hypotheses

- H0 There is no GBE
- H1 GBE results only in a downwards bias in AEP
- H2 GBE results in a downwards or upwards bias in AEP
- H3 Geostrophic height (ABL) has little impact on GBE
- H4 Geostrophic height (ABL) has large impact on GBE

Legacy approach

Lead row correction approach

Tightly / Fully-coupled approach



Hypothesis testing

Proving / disproving hypotheses

Body of evidence 2

1. Power gradients for un-waked & waked turbines only explainable when including GBE physics

2. Wind speed gradients upstream of wind farm show deceleration only explainable when including GBE physics

3. Wind speed gradients follow expected trends with farm thrust.

4. Wind speed gradients exhibit acceleration through Kaskasi gap only explainable when GBE models include accelerations.

Hypothesis testing

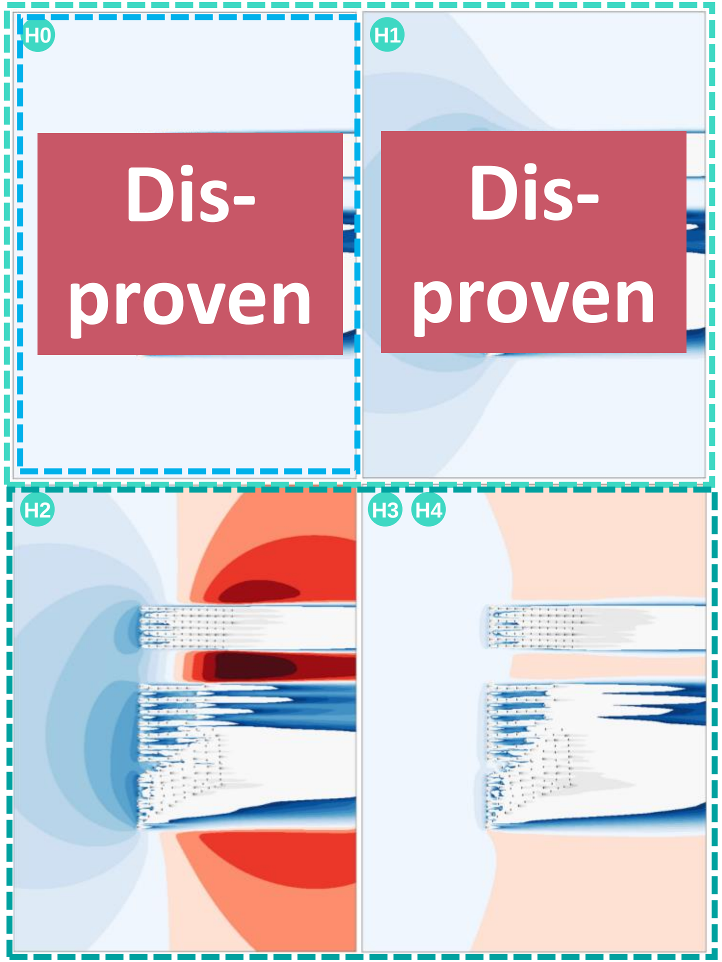
Proving / disproving hypotheses

- H0 There is no GBE
- H1 GBE results only in a downwards bias in AEP
- H2 GBE results in a downwards or upwards bias in AEP
- H3 Geostrophic height (ABL) has little impact on GBE
- H4 Geostrophic height (ABL) has large impact on GBE

Legacy approach

Lead row correction approach

Tightly / Fully-coupled approach



Hypothesis testing

Proving / disproving hypotheses

Body of evidence 3

1. Power gradients for un-waked & waked turbines only explainable when including GBE physics

2. Wind speed gradients upstream of wind farm show deceleration only explainable when including GBE physics

3. Wind speed gradients follow expected trends with farm thrust.

4. Wind speed gradients exhibit acceleration through Kaskasi gap only explainable when GBE models include accelerations.

5. magnitudes of power / wind speed gradients only explainable when including ABL representation.

6. The range potential of power / wind speed gradients is large due to the impact of the ABL height.

Hypothesis testing

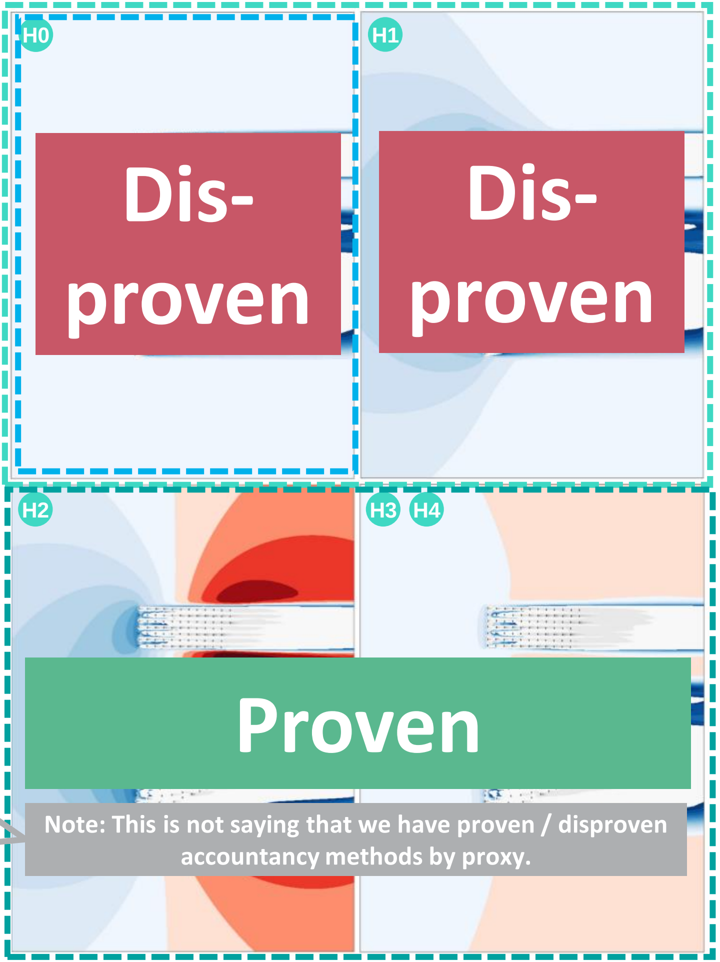
Proving / disproving hypotheses

- ✗ H0 There is no GBE
- ✗ H1 GBE results only in a downwards bias in AEP
- ✓ H2 GBE results in a downwards or upwards bias in AEP
- ✗ H3 Geostrophic height (ABL) has little impact on GBE
- ✓ H4 Geostrophic height (ABL) has large impact on GBE

Legacy approach

Lead row correction approach

Tightly / Fully-coupled approach

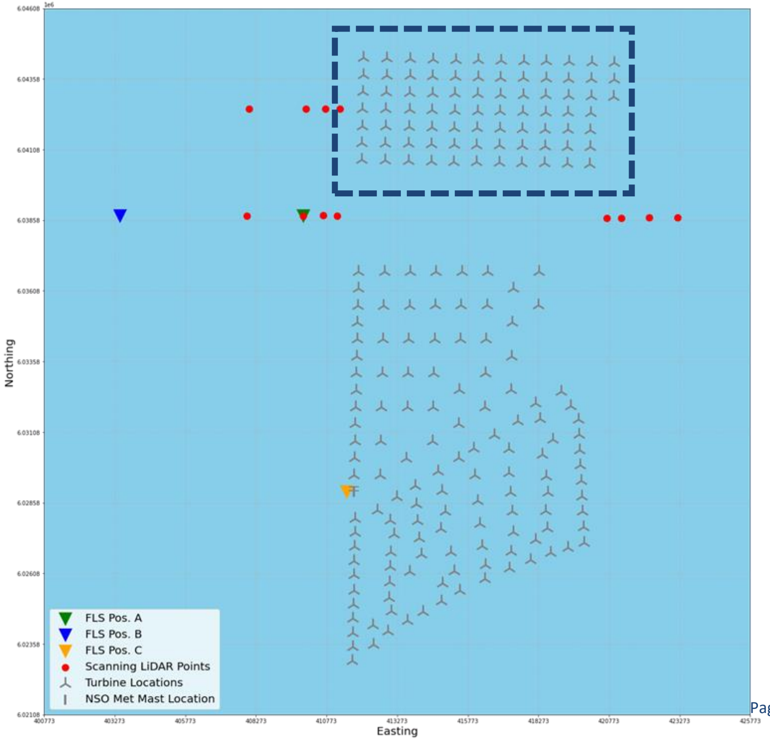


Hypothesis testing

Redistributive effect on power

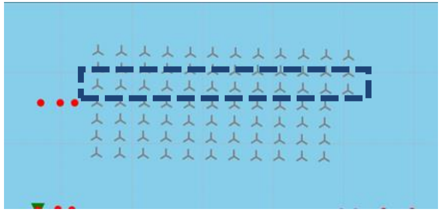
Looking at Different Hypotheses in More Detail

- VV can represent all hypotheses with the **<u>same underlying wake model</u>**!
- Let’s use VV to break this down by looking at Amrumbank West PoP.
- Look at the different hypotheses and why these matter.
- Focus on 270, 000, 180 and 300deg.
- Single ABL height and lid strength @ 9m/s.

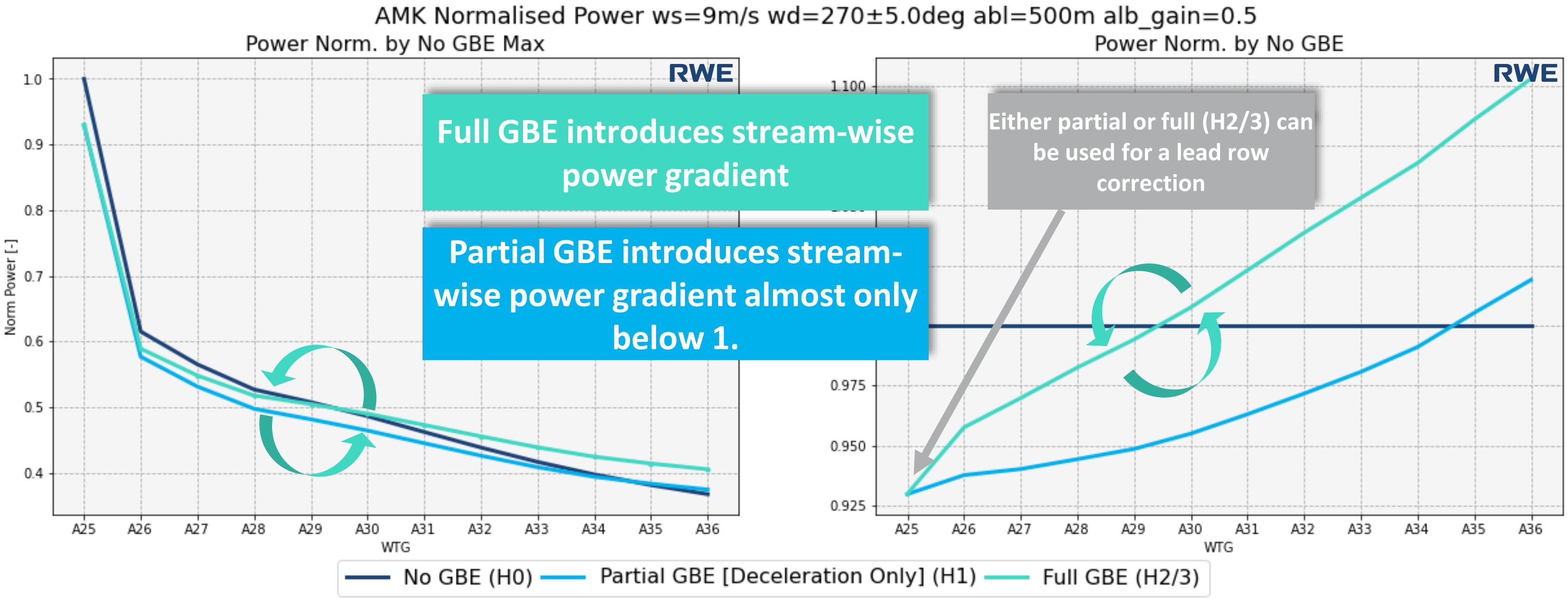


Hypothesis testing

Redistributive effect on power



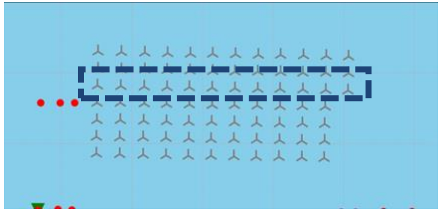
Looking at Different Hypotheses in More Detail



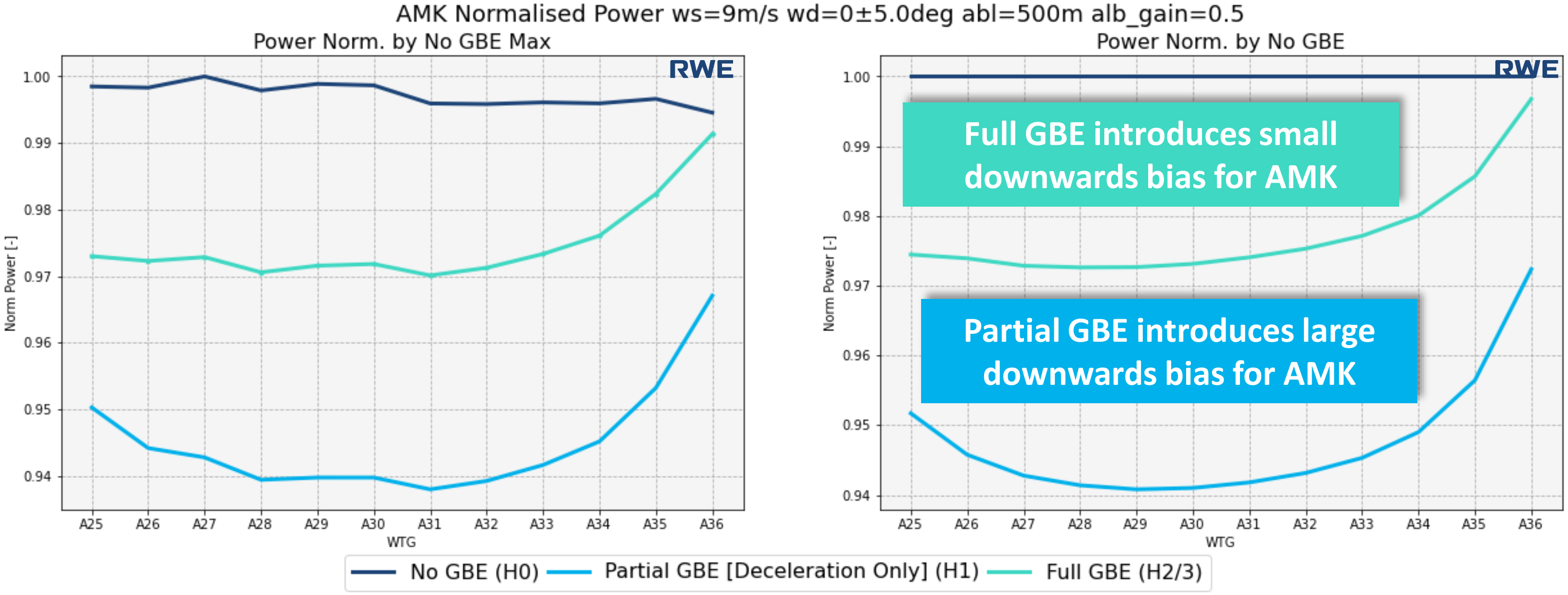
VV shows a power gradient is introduced due to GBE

Hypothesis testing

Redistributive effect on power



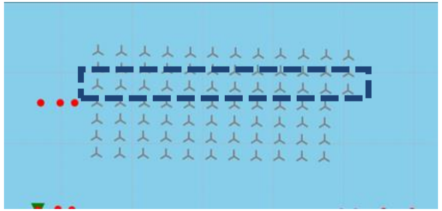
Looking at Different Hypotheses in More Detail



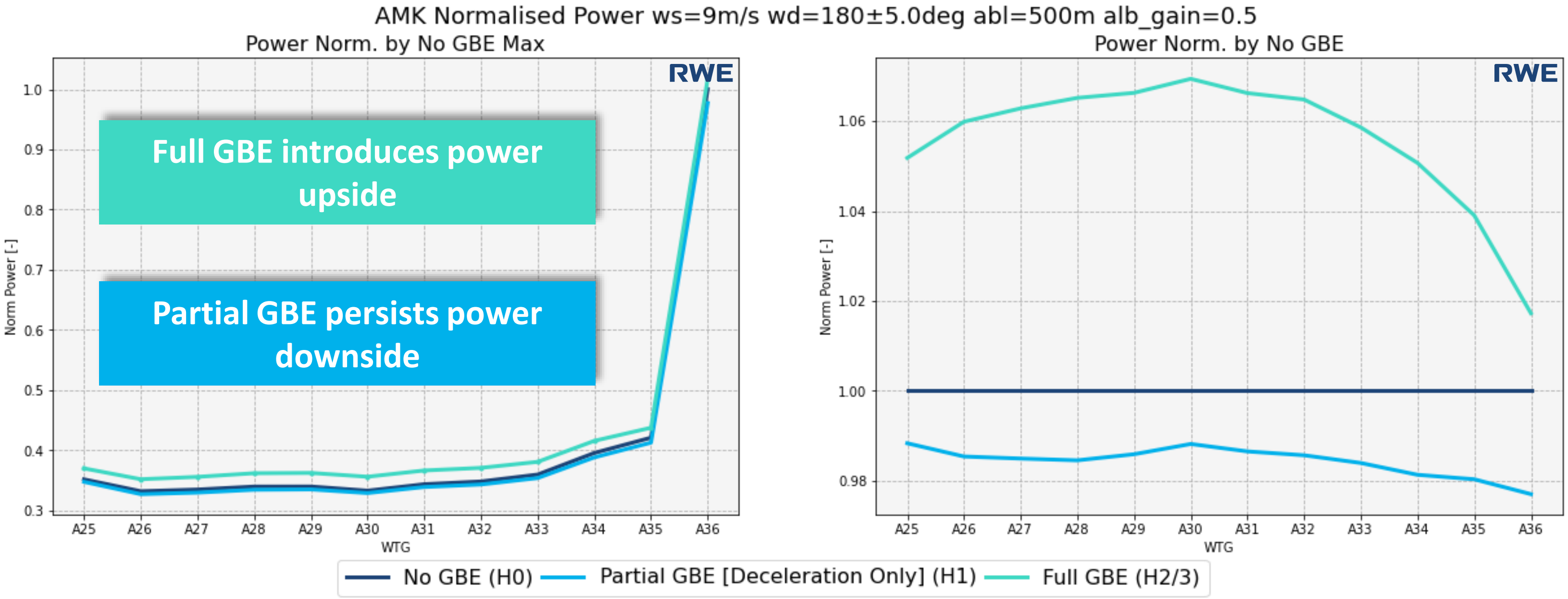
GBE power gradient persists through entire N4 cluster

Hypothesis testing

Redistributive effect on power



Looking at Different Hypotheses in More Detail



GBE power gradient persists through entire N4 cluster

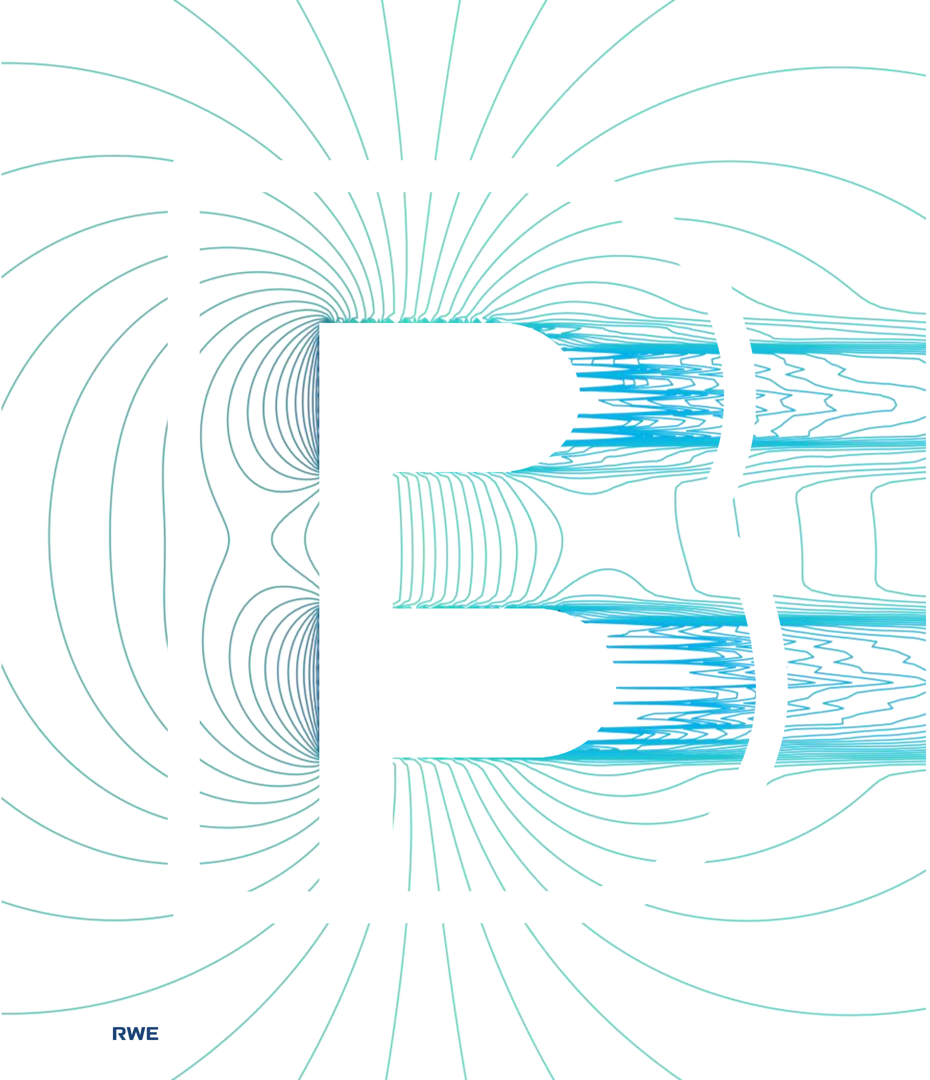
Hypothesis testing

Conclusions

And Some Clarifications

We probably need some clarification here about the hypotheses.

- What we have proven here is the **physics** and what the **physics** of blocakge does to wind turbine/farm power.
- In other words → **The physics of global blockage has a redistributive effect on power within a wind farm / cluster.**
- In other words → We have proven that **there is a power gradient induced by GBE relative to wakes-only (no GBE)**, but how do we deal with that?
- We now need to talk about **accountancy**.



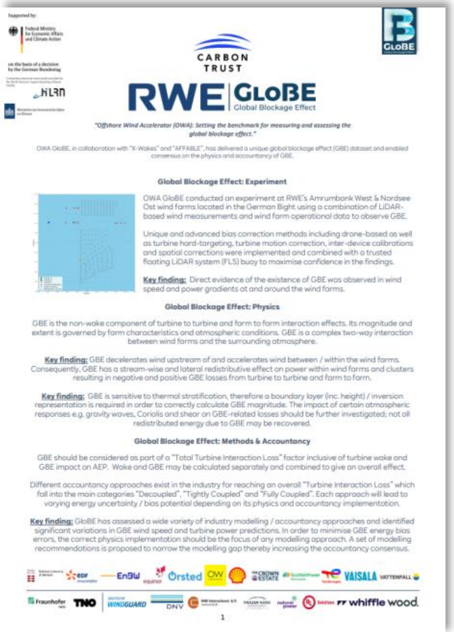
RWE | GLOBE
Global Blockage Effect

Accountancy & conclusions

Jointly agreed public statement

Joint Statement on the Global Blockage Effect

SCAN ME


Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

CARBON TRUST

RWE | GLoBE Global Blockage Effect

"Offshore Wind Accelerator (OWA): Setting the benchmark for measuring and assessing the global blockage effect."

OWA GloBE, in collaboration with "X-Wakes" and "AFFABLE", has delivered a unique global blockage effect (GBE) dataset and enabled consensus on the physics and accountancy of GBE.

Global Blockage Effect: Experiment

OWA GloBE conducted an experiment at RWE's Amrumbank West & Nordsee Ost wind farms located in the German Bight using a combination of LiDAR-based wind measurements and wind farm operational data to observe GBE.

Unique and advanced bias correction methods including drone-based as well as turbine hard-targeting, turbine motion correction, inter-device calibrations and spatial corrections were implemented and combined with a trusted floating LiDAR system (FLS) buoy to maximise confidence in the findings.

Key finding: Direct evidence of the existence of GBE was observed in wind speed and power gradients at and around the wind farms.

Global Blockage Effect: Physics

GBE is the non-wake component of turbine to turbine and farm to farm interaction effects. Its magnitude and extent is governed by farm characteristics and atmospheric conditions. GBE is a complex two-way interaction between wind farms and the surrounding atmosphere.

Key finding: GBE decelerates wind upstream of and accelerates wind between / within the wind farms. Consequently, GBE has a stream-wise and lateral redistributive effect on power within wind farms and clusters resulting in negative and positive GBE losses from turbine to turbine and farm to farm.

Key finding: GBE is sensitive to thermal stratification, therefore a boundary layer (inc. height) / inversion representation is required in order to correctly calculate GBE magnitude. The impact of certain atmospheric responses e.g. gravity waves, Coriolis and shear on GBE-related losses should be further investigated; not all redistributed energy due to GBE may be recovered.

Global Blockage Effect: Methods & Accountancy

GBE should be considered as part of a "Total Turbine Interaction Loss" factor inclusive of turbine wake and GBE impact on AEP. Wake and GBE may be calculated separately and combined to give an overall effect.

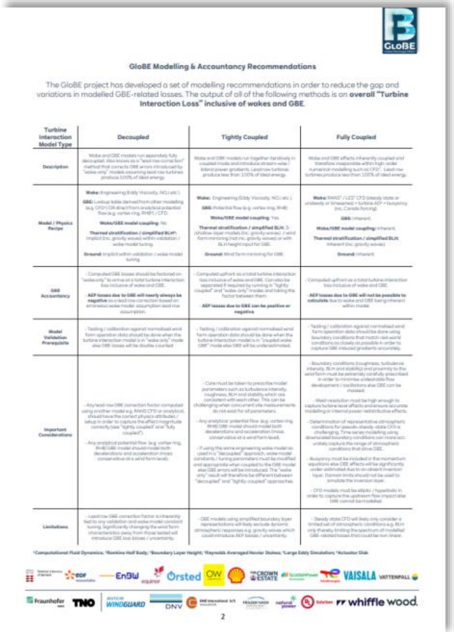
Different accountancy approaches exist in the industry for reaching an overall "Turbine Interaction Loss" which fall into the main categories "Decoupled", "Tightly Coupled" and "Fully Coupled". Each approach will lead to varying energy uncertainty / bias potential depending on its physics and accountancy implementation.

Key finding: GloBE has assessed a wide variety of industry modelling / accountancy approaches and identified significant variations in GBE wind speed and turbine power predictions. In order to minimise GBE energy bias errors, the correct physics implementation should be the focus of any modelling approach. A set of modelling recommendations is proposed to narrow the modelling gap thereby increasing the accountancy consensus.

EDF EnBW equinor Ørsted OW Shell THE CROWN ESTATE ScottishPower TotalEnergies VAISALA VATTENFALL

Fraunhofer TNO WINDGUARD DNV natural power UL whiffle wood.

1


GloBE Modelling & Accountancy Recommendations

The GloBE project has developed a set of modelling recommendations in order to reduce the gap and variations in modelled GBE-related losses. The output of all of the following methods is an **overall "Turbine Interaction Loss" inclusive of wakes and GBE**.

Turbine Interaction Model Type	Decoupled	Tightly Coupled	Fully Coupled
Description	[illegible]	[illegible]	[illegible]
Model / Physics Recipe	[illegible]	[illegible]	[illegible]
GBE Accountancy	[illegible]	[illegible]	[illegible]
Model Validation Prerequisite	[illegible]	[illegible]	[illegible]
Important Considerations	[illegible]	[illegible]	[illegible]
Limitations	[illegible]	[illegible]	[illegible]

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2

Accountancy & Conclusions

GloBE key findings

Key finding 1: Direct evidence of the existence of GBE was observed in wind speed and power gradients at and around the wind farms.

Key finding 2: GBE decelerates wind upstream of and accelerates wind between / within the wind farms. Consequently, GBE has a stream-wise and lateral redistributive effect on power within wind farms and clusters resulting in negative and positive GBE losses from turbine to turbine and farm to farm.

Accountancy & Conclusions

GloBE key findings

Key finding 3: GBE is sensitive to thermal stratification, therefore a boundary layer (inc. height) / inversion representation is required in order to correctly calculate GBE magnitude. The impact of certain atmospheric responses e.g. gravity waves, Coriolis and shear on GBE-related losses should be further investigated; not all redistributed energy due to GBE may be recovered.

Key finding 4: GloBE has assessed a wide variety of industry modelling / accountancy approaches and identified significant variations in GBE wind speed and turbine power predictions. In order to minimise GBE energy bias errors, the correct physics implementation should be the focus of any modelling approach. A set of modelling recommendations is proposed to narrow the modelling gap thereby increasing the accountancy consensus.

Accountancy & Conclusions

GloBE recommendations

The GloBE project has developed a set of modelling recommendations in order to reduce the gap and variations in modelled GBE-related losses. The output of all of the following methods is **an overall "Turbine Interaction Loss" inclusive of wakes and GBE**.

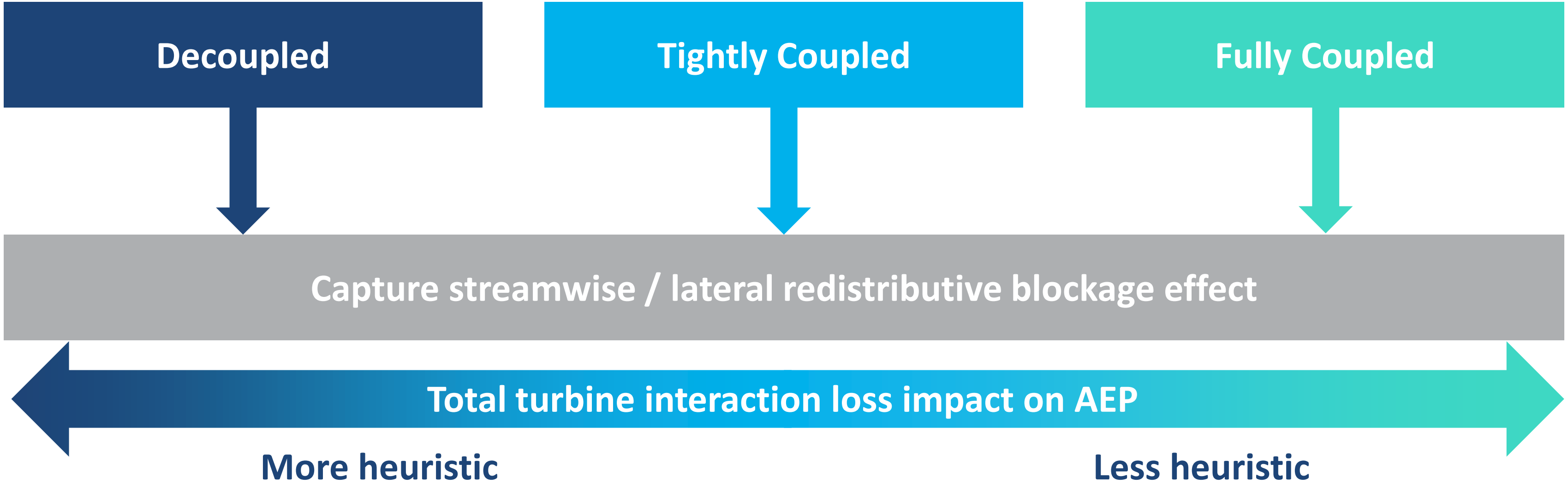
From Joint Statement on GBE

Turbine Interaction Model Type	Decoupled	Tightly Coupled	Fully Coupled
Description	Wake and GBE models run separately fully decoupled. Also knows as a "lead row correction" method that corrects GBE errors introduced by "wake-only" models assuming lead row turbines produce 100% of ideal energy.	Wake and GBE models run together iteratively in coupled mode and introduce stream-wise / lateral power gradients. Lead row turbines produce less than 100% of ideal energy.	Wake and GBE effects inherently coupled and therefore inseparable within high-order numerical modelling such as CFD[1]. Lead row turbines produce less than 100% of ideal energy.
Model / Physics Recipe	**Wake:** Engineering (Eddy Viscosity, NOJ etc). **GBE:** Lookup table derived from other modelling (e.g. CFD[1]) OR direct from analytical potential flow (e.g. vortex ring, RHB[2]) / CFD. **Wake/GBE model coupling**: No **Thermal stratification / simplified BLH[3]:** Implicit (inc. gravity waves) within validation / wake model tuning.	**Wake:** Engineering (Eddy Viscosity, NOJ etc). **GBE:** Potential flow (e.g. vortex ring, RHB) **Wake/GBE model coupling**: Yes **Thermal stratification / simplified BLH:** 3-/shallow-layer models (inc. gravity waves) / wind farm mirroring (not inc. gravity waves) or with BLH height input for GBE.	**Wake:** RANS[4] / LES[5] CFD (steady state or unsteady or timeseries) + turbine AD[4] + buoyancy (inc. Coriolis forcing). **GBE:** Inherent. **Wake/GBE model coupling:** Inherent. **Thermal stratification / simplified BLH:** Inherent (inc. gravity waves).

Accountancy & Conclusions

GloBE recommendations

Categorising Model Types in the Joint Statement



Accountancy & Conclusions

GloBE recommendations

Areas Covered by Joint Statement

- Model Description
- Model / Physics Recipe
- GBE Accountancy
- Model Validation Prerequisite
- Important Considerations
- Limitations

Enables you to map where your modelling and accountancy path sits relative to other methods available in the market and de-risk GBE.

Accountancy & Conclusions
GloBE recommendations

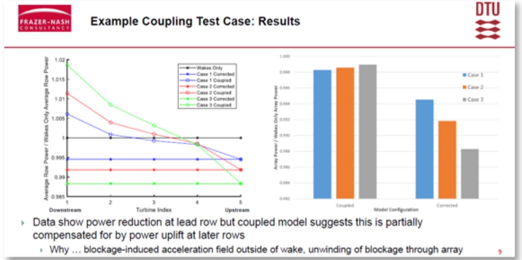
Going Back to Our Original Motivation

[1]

OWA GloBE
Industry split…

Motivation…

1. There are many methods available for assessing blockage impact
2. These are often house-specific and fragmented
3. There is a lack of understanding* due to a lack of data on the mechanics of blockage
4. There is a lack of suitable (rapid) models available* so surrogate methods are sought



Lead row correction OR redistribution OR both? → **It's both!**

Reconciliation of positions on modelling and accountancy required → **Achieved!**

GloBE aims to provide the bespoke dataset and framework to enable consensus → **Mission accomplished!**

RWE *This is changing

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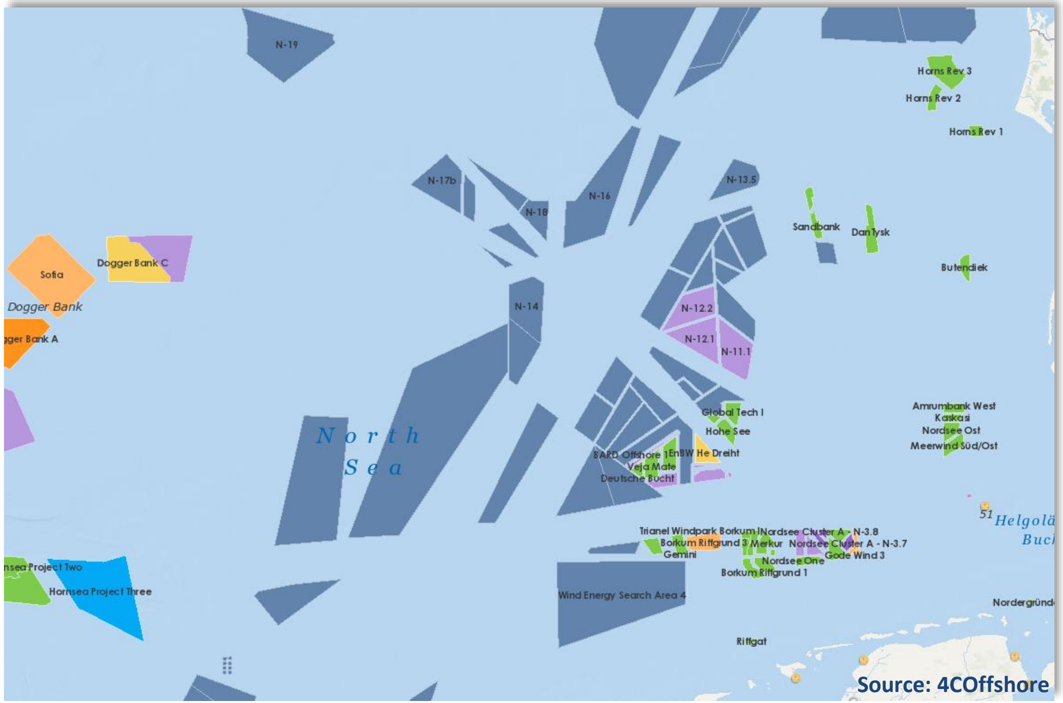
RWE [1]Rodaway, C et al (2022, June). Global Blockage Effect GloBE: Pushing the limits of experimental design. Conference proceedings side event, Brussels.

Accountancy & Conclusions

Increasing risk with larger developments

The Need for Robust Modelling is Increasing!



Source: 4COffshore

How do any of the modelling approaches perform over significant spatial scales and many GW installed capacity???

Accountancy & Conclusions

Considerations & further work

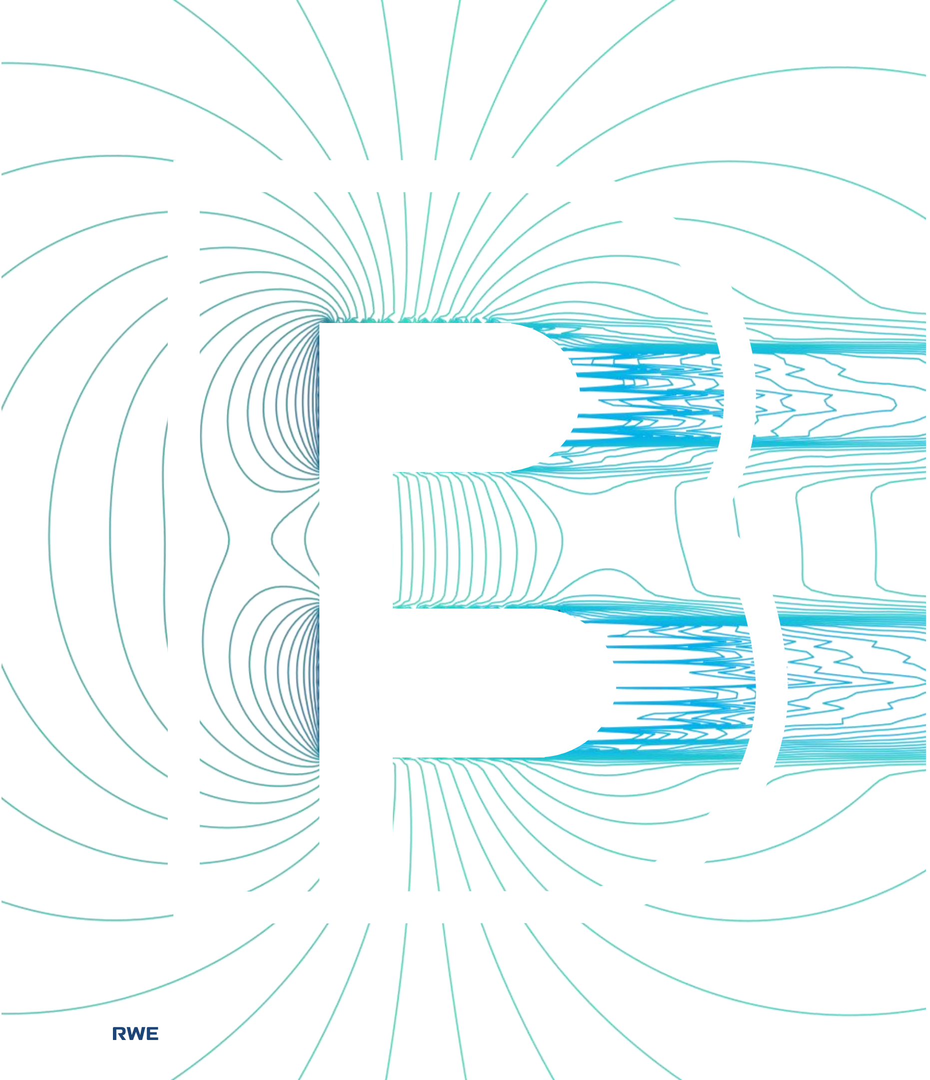
Physics Representation is the Key!!

There are still some remaining research questions:

1. What is the impact of gravity waves on GBE power and/or AEP bias and can they be separated (probably not!)?

2. What is the impact of Coriolis on the global blockage effect?

3. How does blockage effect evolve over “big-huge” clusters?



RWE | GLOBE
Global Blockage Effect

RWE | GLOBE Global Blockage Effect

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RWE | GLOBE Global Blockage Effect

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Any Questions?