Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

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

Ministerie van Economische Zaken en Klimaat

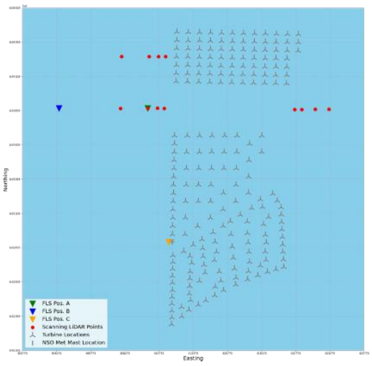
CARBON TRUST

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.

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	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. **Ground:** Implicit 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. **Ground:** Wind farm mirroring for GBE.	**Wake:** RANS[4] / LES[5] CFD (steady state or unsteady or timeseries) + turbine AD[6] + buoyancy (inc. Coriolis forcing). **GBE:** Inherent. **Wake/GBE model coupling:** Inherent. **Thermal stratification / simplified BLH:** Inherent (inc. gravity waves). **Ground:** Inherent.
GBE Accountancy	- Computed GBE losses should be factored on "wake only" to arrive at a total turbine interaction loss inclusive of wake and GBE. - **AEP losses due to GBE will nearly always be negative** as a lead row correction based on erroneous wake model assumption lead row assumption.	- Computed upfront as a total turbine interaction loss inclusive of wake and GBE. Can also be separated if required by running in "tightly coupled" and "wake-only" modes and taking the factor between them. - **AEP losses due to GBE can be positive or negative**.	- Computed upfront as a total turbine interaction loss inclusive of wake and GBE. - **AEP losses due to GBE will not be possible to calculate** due to wake and GBE being inherent within model.
Model Validation Prerequisite	- Testing / calibration against normalised wind farm operation data should be done when the turbine interaction model is in "wake only" mode else GBE losses will be double-counted.	- Testing / calibration against normalised wind farm operation data should be done when the turbine interaction model is in "coupled wake GBE" mode else GBE will be underestimated.	- Testing / calibration against normalised wind farm operation data should be done using boundary conditions that match real world conditions as closely as possible in order to capture GBE induced gradients accurately.
Important Considerations	- Any lead row GBE correction factor computed using another model e.g. RANS CFD or analytical, should have the correct physics attributes / setup in order to capture the effect magnitude correctly (see "tightly coupled" and "fully coupled"). - Any analytical potential flow (e.g. vortex ring, RHB) GBE model should model both decelerations and acceleration (mass conservative at a wind farm level).	- Care must be taken to prescribe model parameters such as turbulence intensity, roughness, BLH and stability which are consistent with each other. This can be challenging when concurrent site measurements do not exist for all parameters. - Any analytical potential flow (e.g. vortex ring, RHB) GBE model should model both decelerations and acceleration (mass conservative at a wind farm level). - If using the same engineering wake model as used in a "decoupled" approach, wake model constants / tuning parameters must be modified and appropriate when coupled to the GBE model else GBE errors will be introduced. The "wake only" result will therefore be different between "decoupled" and "tightly-coupled" approaches.	- Boundary conditions (roughness, turbulence intensity, BLH and stability) and proximity to the wind farm must be extremely carefully prescribed in order to minimise undesirable flow development / oscillations else GBE can be masked. - Mesh resolution must be high enough to capture turbine level effects and ensure accurate modelling or internal power redistributive effects. - Determination of representative atmospheric conditions for pseudo-steady-state CFD is challenging. Time series modelling using downscaled boundary conditions can more acc-urately capture the range of atmospheric conditions that drive GBE. - Buoyancy must be included in the momentum equations else GBE effects will be significantly under-estimated due to an absent inversion layer. Domain limits should not be used to simulate the inversion layer. - CFD models must be elliptic / hyperbolic in order to capture the upstream flow impact else GBE cannot be modelled.
Limitations	- Lead row GBE correction factor is inherently tied to any validation and wake model constant tuning. Significantly changing the wind farm characteristics away from those tested will introduce GBE loss biases / uncertainty.	- GBE models using simplified boundary layer representations will likely exclude dynamic atmospheric responses e.g. gravity waves which could introduce AEP biases / uncertainty.	- Steady state CFD will likely only consider a limited set of atmospheric conditions e.g. BLH only thereby limiting the spectrum of modelled GBE-related losses that could be non-linear.

[1]Computational Fluid Dynamics; [2]Rankine Half Body; [3]Boundary Layer Height; [4]Reynolds Averaged Navier Stokes; [5]Large Eddy Simulation; [6]Actuator Disk