INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems
Task 11

62nd IEA Topical Expert Meeting

MICRO METEOROLOGY INSIDE WIND FARMS AND WAKES BETWEEN WIND FARMS

May 5-6, 2010
National Renewable Energy Center (CENER)
Sarriguren – Navarra (Spain)

Organized by: CENER

Scientific Co-ordination:

Félix Avia Aranda

CENER (Centro Nacional de Energías Renovables)

Urb. La Florida C/ Somera 7-9, 1ª

28023 - Madrid – Spain

Disclaimer:

Please note that these proceedings may only be redistributed to persons in countries participating in the IEA RD&D Task 11.

The reason is that the participating countries are paying for this work and are expecting that the results of their efforts stay within this group of countries.

The documentation can be distributed to the following countries: Canada, Denmark, European Commission, Finland, Germany, Ireland, Italy, Japan, Korea, Mexico, the Netherlands, Norway, Spain, Sweden, Switzerland, United Kingdom, United States.

After one year the proceedings can be distributed to all countries, that is June 2011

Copies of this document can be obtained from:

CENER
Félix Avia Aranda
Urb. La Florida. C/ Somera 7-9, 1ª
C.P.: 28023 - Madrid – Spain
Phone: +34 91417 5042
E-mail: favia@cener.com

For more information about IEA Wind see www.ieawind.org

International Energy Agency

Implement Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems: IEA Wind

The IEA international collaboration on energy technology and RD&D is organized under the legal structure of Implementing Agreements, in which Governments, or their delegated agents, participate as Contracting Parties and undertake Tasks identified in specific Annexes.

The IEA's Wind Implementing Agreement began in 1977, and is now called the Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems (IEA Wind). At present, 24 contracting parties from 20 countries, the European Commission, and the European Wind Energy Association (EWEA) participate in IEA Wind. Australia, Austria, Canada, Denmark, the European Commission, EWEA, Finland, Germany, Greece, Ireland, Italy (two contracting parties), Japan, the Republic of Korea, Mexico, the Netherlands, Norway (two contracting parties), Portugal, Spain, Sweden, Switzerland, the United Kingdom, and the United States are now members.

The development and maturing of wind energy technology over the past 30 years has been facilitated through vigorous national programs of research, development, demonstration, and financial incentives. In this process, IEA Wind has played a role by providing a flexible framework for cost-effective joint research projects and information exchange.

The mission of the IEA Wind Agreement continues to be to encourage and support the technological development and global deployment of wind energy technology. To do this, the contracting parties exchange information on their continuing and planned activities and participate in IEA Wind Tasks regarding cooperative research, development, and demonstration of wind systems.

Task 11 of the IEA Wind Agreement, Base Technology Information Exchange, has the objective to promote and disseminate knowledge through cooperative activities and information exchange on R&D topics of common interest to the Task members. These cooperative activities have been part of the Wind Implementing Agreement since 1978.

Task 11 is an important instrument of IEA Wind. It can react flexibly on new technical and scientific developments and information needs. It brings the latest knowledge to wind energy players in the member countries and collects information and recommendations for the work of the IEA Wind Agreement. Task 11 is also an important catalyst for starting new tasks within IEA Wind.

IEA Wind TASK 11: BASE TECHNOLOGY INFORMATION EXCHANGE

The objective of this Task is to promote disseminating knowledge through cooperative activities and information exchange on R&D topics of common interest. Four meetings on different topics are arranged every year, gathering active researchers and experts. These cooperative activities have been part of the Agreement since 1978.

Two Subtasks

The task includes two subtasks. The objective of the first subtask is to develop recommended practices for wind turbine testing and evaluation by assembling an Experts Group for each topic needing recommended practices. For example, the Experts Group on wind speed measurements published the document titled "Wind Speed Measurement and Use of Cup Anemometry". A document dealing with Sodar measurements are presently under development.

The objective of the second subtask is to conduct topical expert meetings in research areas identified by the IEA R&D Wind Executive Committee. The Executive Committee designates topics in research areas of current interest, which requires an exchange of information. So far, Topical Expert Meetings are arranged four times a year.

Documentation

Since these activities were initiated in 1978, more than 60 volumes of proceedings have been published. In the series of Recommended Practices 11 documents were published and five of these have revised editions.

All documents produced under Task 11 and published by the Operating Agent are available to citizens of member countries participating in this Task.

Operating Agent

CENER
Félix Avia Aranda
Urb. La Florida. C/ Somera 7-9, 1ª
C.P.: 28023 - Madrid – Spain
Phone: +34 91417 5042
E-mail:favia@cener.com

COUNTRIES PRESENTLY PARTICIPATING IN THE TASK 11	
COUNTRY	**INSTITUTION**
Canada	National Resources Canada
Denmark	Risø National Laboratory - DTU
European Commission	European Commission
Finland	Technical Research Centre of Finland - VTT Energy
Germany	Bundesministerium für Unwelt , Naturschutz und Reaktorsicherheit -BMU
Ireland	Sustainable Energy Ireland - SEI
Italy	Ricerca sul Sistema Energetico - RSE S.p.A.
Japan	National Institute of Advanced Industrial Science and Technology AIST
Republic of Korea	POHANG University of Science and Technology - POSTECH
Mexico	Instituto de Investigaciones Electricas - IEE
Netherlands	SenterNovem
Norway	The Norwegian Water Resources and Energy Directorate - NVE
Spain	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas CIEMAT
Sweden	Energimyndigheten
Switzerland	Swiss Federal Office of Energy - SFOE
United Kingdom	Uk Dept for Bussines, Enterprises & Regulatory Reform - BERR
United States	The U.S Department of Energy -DOE

Blank page

CONTENTS

Page

<u>SUMMARY</u>

INTRODUCTORY NOTE

Prepared by Daniel Cabezon and Ignacio Martí, CENER

a) Background

Power output and feasibility of big wind farms deployed in large arrays may be dramatically decreased by wake effects, largely influenced by local atmospheric boundary layer. On average these power losses can reach 10-20% of the wind farm power output. In addition to the power losses an increase on fatigue loading is generated at those turbines operating under wake conditions.

Average evolution of power losses in wind farms may be affected by several effects mainly related to the wind farm topology and local wind climate, characterized by wind speed, wind direction, atmospheric turbulence and stability.

From this point of view, wind turbine wakes represents an interesting topic of study due to the momentum deficit and the increased level of turbulence created by turbines inside a wind farm may cause an important reduction in power output and an increase on unsteady and fatigue loads on downstream wind turbines. Besides, a good knowledge of the aerodynamics in the near wake region is essential to understand the physics of power extraction by wind turbines.

Recently a Euromech Coloquium on Wind Turbines Wakes was organized to discuss about this specific topic (Madrid, October 2009), and was clearly demonstrated the large number of on going research activities, with the target to go deeper in the knowledge of the physical phenomena of the wake effects inside Wind Farms, as well as the wake effects between neighbor Wind Farms.

b) Techniques

The state of the art to estimate wake effects of wind turbines in wind farms, is to solve the incompressible Navier-Stokes equations closed using CFD turbulent models coupled to actuator disk-type approximations of wind turbine rotors.

Due to the fact that the cost of computers is decreasing, modelling wind turbines and wind farms wakes using CFD methods is an alternative to the faster engineering models.

Wind turbines are modelled as actuator discs in atmospheric flows using RANS methods. Turbulent length scales inside wind farms are modelled at the same time. The RANS methods are modelling all the scales of turbulence together, estimating an equivalent length scale and velocity scale. These two scales are combined to form the eddy viscosity concept. The Reynolds stresses are then estimated using this eddy viscosity and the local wind speed gradient using the so-called Boussinesq approximation.

The different size in turbulent length scales between the freestream flow typical of the atmospheric boundary layer and the wake flow inside wind farms introduces an imbalance problem and supposes a real challenge to the turbulence models used in RANS methods, unsolved up to now.

c) Topics to be addressed

The main objective is to hold a meeting to discuss and gather information on:

- Numerical and analytical models of wind turbine wakes in wind farms
- Turbulence closure models
- Experimental work based on wind tunnel and full scale field experiments.
- Influence of atmospheric stability
- Influence of topography
- Fatigue and loads
- Offshore wind farms

The participants are encouraged to prepare presentations relevant to these objectives.

d) Expected outcomes

One of the goals of the meeting will be to gather the existing knowledge on the subject and come up with suggestions / recommendations on how to proceed for future developments. Based on the above a document will be compiled containing:

- Presentations by participants
- Compilation of the most recent information on the topic
- Main conclusions of the discussion session.
- To define IEA Wind RD&D’s future role in this topic

e) Agenda

Wednesday, May 5th

9:00 **Registration**. Collection of presentations and final Agenda
9:30 **Introduction by Host**
Mr. Ignacio Marti, CENER
10:00 **Introduction by AIE Task 11 Operating Agent. Recognition of Participants**
Mr. Felix Avia, Operating Agent Task 11 IEAWind R&D
10:30 **Presentation of Introductory Note**
Mr. Daniel Cabezon, CENER

●11:00 Coffee Break

1st Session Individual Presentations:

11:30 **Overview of Modeling and Measurements on Flow in and around Wind Farms**
Arno J. Brande, ECN Wind Energy, The Netherland
12:00 **Multi-Array Windfarm Modeling Program Initiative**
Michael Robinson, National Renewable Energy Laboratoy (NREL), USA
12:30 **CFD Modeling of Wind Farms in Complex Terrain**
Daniel Cabezón, CENER, Spain

●13:15 Lunch

2nd Session Individual Presentations

15:00 **Wind turbine wakes at Horns Rev wind farm**
Anders Sommers, Vatenfall Vindkraft AB, Denmark
15:30 **Coupled Turbine/Atmosphere Modeling at Los Alamos National Laboratory**
Rodman Linn, Alamos National Laboratory, USA
16:00 **Some Selected Results from Early WT-studies and Wake Effects in the Closely Spaced Lillgrund Offshore Wind Farm**
Jan-Ake Dahlberg, Vatenfall Vindkraft A, Sweden

●16:30 Coffee Break

17:00 **Wake Combination Models**
Peter Stuart, RES, UK
17:30 **Presentation 8 Title**
Juan Jose Trujillo, Carl Von Ossieztky University of Oldenburg, Germany

18:00 **Adjourn**

21:30 Dinner

Thursday, May 6th

3rd Session Individual Presentations

09:00 Numerical Site Calibration for estimating a performance of wind turbine at complex terrain
Iida Makoto, The Univ. of Tokyo, Japan

09:30 Presentation 10
Alla Sapronova, Uni Research, BCCS, Norway

10:00 Wake effects within and between large wind projects
Nick Baldock, Garrad Hassan, UK

10:30 Presentation 12
Peter Clive, SgurrEnergy Ltd, UK

11:00 Coffee Break

11:30 Presentation 13
Cesar Castillo, *Garrad Hassan Ibérica L.S.U., Spain*

12:00 Discussion

13:00 Summary of Meeting

13:30 Technical Tour: Visit to the Experimental Wind Farms

16:00 End of the meeting

PRESENTATIONS

ECN

Energy research Centre of the Netherlands

Overview of Models and Measurements of Flow in and around Wind Farms

Arno Brand
Benjamin Sanderse
Edwin Bot
Tamar Nieuwenhuizen
Erman Erek
Jan Willem Wagenaar
Hans Verhoef

ECN Wind Energy

www.ecn.nl

ECN

Outline

- Numerical and analytical models
- Turbulence closure
- Measurements and databases

2 Outline - Numerical and analytical models - Turbulence closure - Measurements and databases - Summary

ECN

- Numerical and analytical models
  - Flow in a wind farm
  - Wakes in offshore wind farms
  - Wake of an offshore wind farm
  - Coupling of turbines via wakes
  - Flow near a wind farm

ECN

Numerical & Analytical

Flow in a wind farm

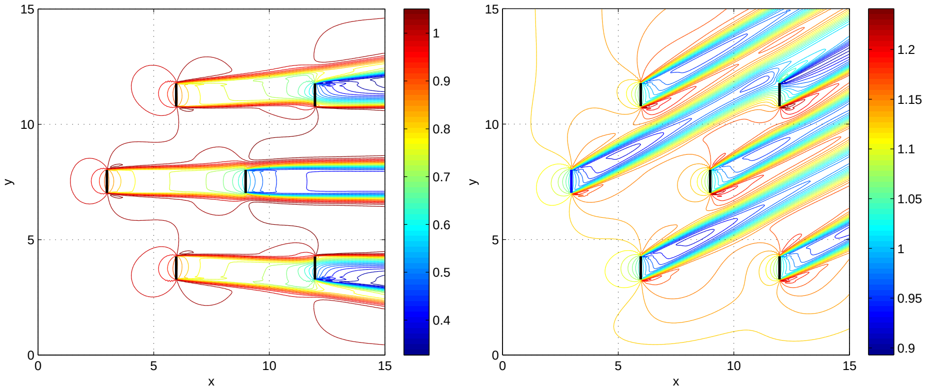
Benjamin Sanderse

- Incompressible flow with body forces
  - Steady or unsteady
  - Two-dimensional
  - Wind turbine modelled by actuator disk or actuator line
- Numerical representation
  - Finite volume on staggered Cartesian grid
  - Mimetic discretisation:
    1) Low numerical diffusion
    2) Local energy conservation
  - Discretisations:
    1) Space: Second order and Fourth order
    2) Time: Implicit (steady) or Explicit (unsteady)
  - Pressure correction

CWI

ECN **Numerical & Analytical**

Flow in a wind farm



CWI

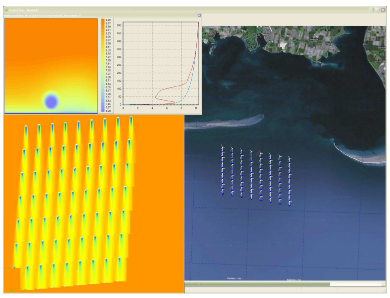
ECN **Numerical & Analytical**

Wakes in a wind farm

Edwin Bot

WakeFarm wind farm flow model

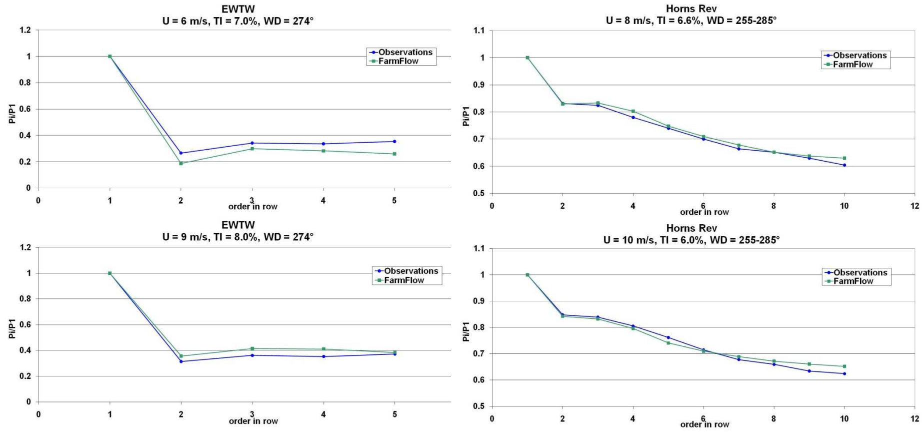
- Mean velocity components: parabolized Navier Stokes equation
- Turbulence closure: k-ε, with reduced turbulent mixing in near wake
- Velocity gradient in near wake: free-vortex wake model
- Intermediate wake: turbulent mixing concentrated in annular shear layer



Nysted wind farm

ECN **Numerical & Analytical**

Wakes in a wind farm



7 Outline - Numerical and analytical models - Turbulence closure - Measurements and databases - Summary

ECN **Numerical & Analytical**

Wake of a wind farm

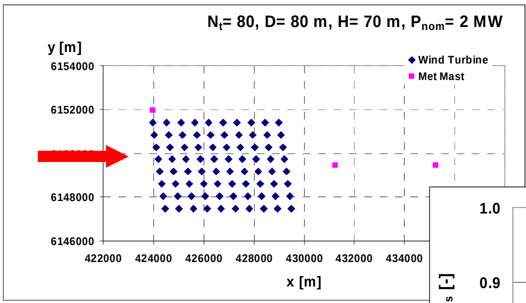
Arno Brand

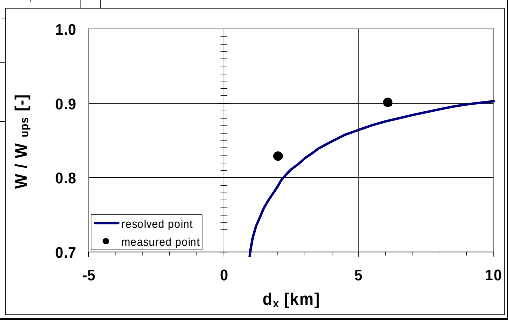
- Neutral planetary boundary layer flow with wind farms
  - Steady and two-dimensional
  - Equilibrium between
    1) Convective forces
    2) Coriolis forces
    3) Vertical and spanwise turbulent momentum flux gradients
    4) Forces due to wind turbines
- Numerical representation
  - Implicit solution in vertical direction
  - Marching solution in horizontal directions
  - Implicit Lagrange multiplier velocity correction
- Translation of grid cell velocities into point velocities

8 Outline - Numerical and analytical models - Turbulence closure - Measurements and databases - Summary

ECN **Numerical & Analytical**

Wake of a wind farm





Horns Rev wind farm

ECN **Numerical & Analytical**

Coupling of turbines via wakes

Arno Brand

Quasi-steady wind farm flow model

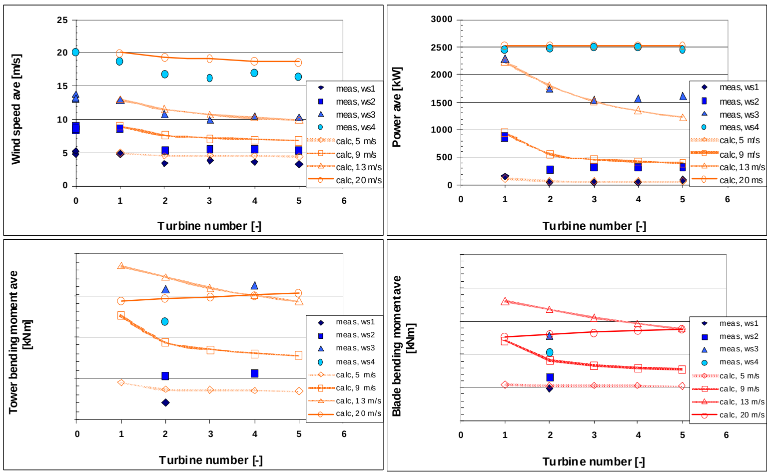
- Gridless
- Momentum theory for turbine wakes and states
- Normally distributed wind speed and derived quantities
- Model output:
  - External conditions: Wind speed, Wind direction, Turbulence intensity
  - State of turbines: Hub wind speed, Blade pitch angle, Rotor speed
  - Output of turbines: Power, Loads

Validation

- Observations from five 2.5 MW turbines in EWTW
- Four wind speed cases in combination with Two wind direction cases

ECN — Numerical & Analytical

Coupling of turbines via wakes



11 Outline - Numerical and analytical - Turbulence closure - Measurements and databases - Summary

ECN — Numerical & Analytical

Flow near a wind farm

Tamar Nieuwenhuizen

Advanced Research WRF

- Grid cells: 61x61x30
- Horizontal grid sizes: 25 km, 5 km, 1 km
- Mellor-Yamada Level 2½ turbulence closure; prognostic TKE

Case

- Winter storm Kyrill (18 January 2007)
- Initial condition from NCEP reanalysis

Validation

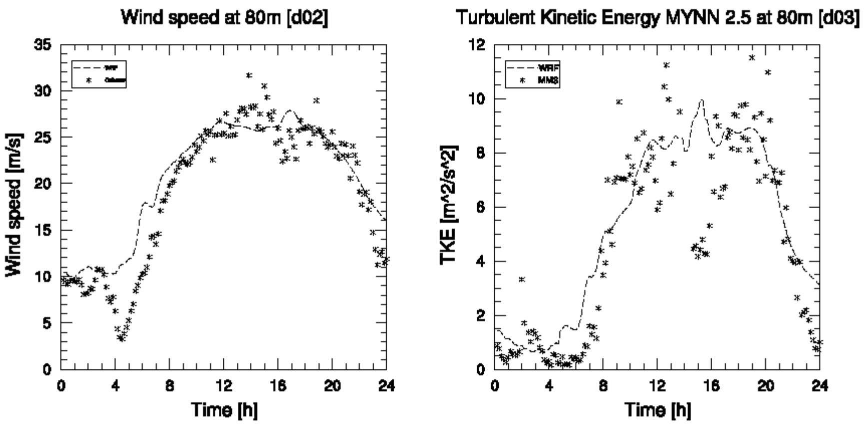
- Observations from EWTW-MM3, Cabauw, AWS Berkhout
- Wind speed and direction, temperature, pressure

12 Outline - Numerical and analytical models - Turbulence closure - Measurements and databases - Summary

ECN

Numerical & Analytical

Flow near a wind farm



13 Outline - Numerical and analytical models - Turbulence closure - Measurements and databases - Summary

WAGENINGEN UR for quality of life

ECN

- Turbulence closure
  - Improved k-ε model
  - Mellor-Yamada model

14 Outline - Numerical and analytical models - Turbulence closure - Measurements and databases - Summary

ECN **Turbulence closure**

Improved k-ε model

Edwin Bot

In the near wake region:

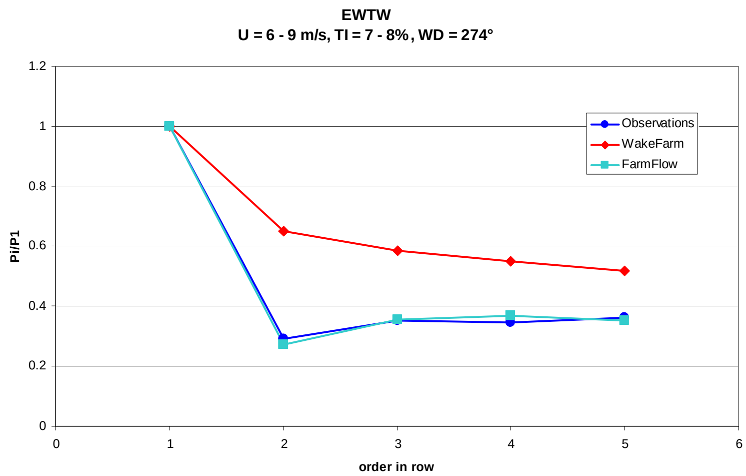
- Dissipation rate of turbulent kinetic energy is reduced by increasing the value of the model constant $C_{\varepsilon 1}$
- Turbulent viscosity is reduced by decreasing the value of the model constant C_{μ}

matching the experimental results of the 2.5 MW wind turbines in the EWTW

15 Outline - Numerical and analytical models - Turbulence closure - Measurements and databases - Summary

ECN **Turbulence closure**

Improved k-ε model



16 Outline - Numerical and analytical models - Turbulence closure - Measurements and databases - Summary

ECN **Turbulence closure**

Mellor-Yamada model

Erman Erek

Turbulence model for flow with buoyancy and shear

Equations for

❑ Turbulent momentum flux	$D\,\overline{u_i'u_j'}/Dt = f\left(\overline{u_i'u_j'},\ \overline{u_j'\theta'},\ \ell,\ \ell_1,\ \Lambda_1\right)$
❑ Turbulent heat flux	$D\,\overline{u_j'\theta'}/Dt = g\left(\overline{u_i'u_j'},\ \overline{u_j'\theta'},\ \ell,\ \ell_2\right)$
❑ Temperature variance	$D\,\overline{\theta'\theta'}/Dt = h\left(\overline{u_j'\theta'},\ \overline{\theta'\theta'},\ \ell,\ \Lambda_2\right)$

Hierarchy of models

- ❑ Level 4: Full system for second-order variables
- ❑ Level 3: High-order anisotropy in turbulent momentum flux neglected
- ❑ Level 2½: Temporal changes and diffusion of temp. variance neglected
- ❑ Level 2: Temporal changes and diffusion of turb. mom. flux neglected
- ❑ Level 1: Temperature variance neglected

ECN **Turbulence closure**

Mellor-Yamada model

Various versions:

- ❑ Eddy viscosity/diffusity via Boussinesq hypothesis
- ❑ Boundary layer approximations

Planetary boundary layer Level 2½ model and Level 2 model

- ❑ Essential role of length scales, empirical constants and “stability functions”
- ❑ Performance comparable to k-ε in shear dominated flow

Advantages	Disadvantages
Takes buoyancy into account	Unrealistic behaviour has been reported
Low cost Level 2½ and lower	High cost Level 4 and Level 3
L 4 and L 3 solve 2nd-order var.	Boussinesq hypo. in Level 2½ and lower

ECN

- Measurements and databases
  - ECN Wind Turbine test site Wieringermeer
  - ECN Scale Wind Farm
  - Offshore Wind farm Egmond aan Zee

19 Outline - Numerical and analytical models - Turbulence closure - Measurements and databases - Summary

ECN

Measurements & Databases

EWTW

Jan Willem Wagenaar

Five research wind turbines

- Nominal power: 2.5 MW
- Hub height: 80 m
- Rotor diameter: 80 m
- Turbine separation: 3.8D

Three meteo masts

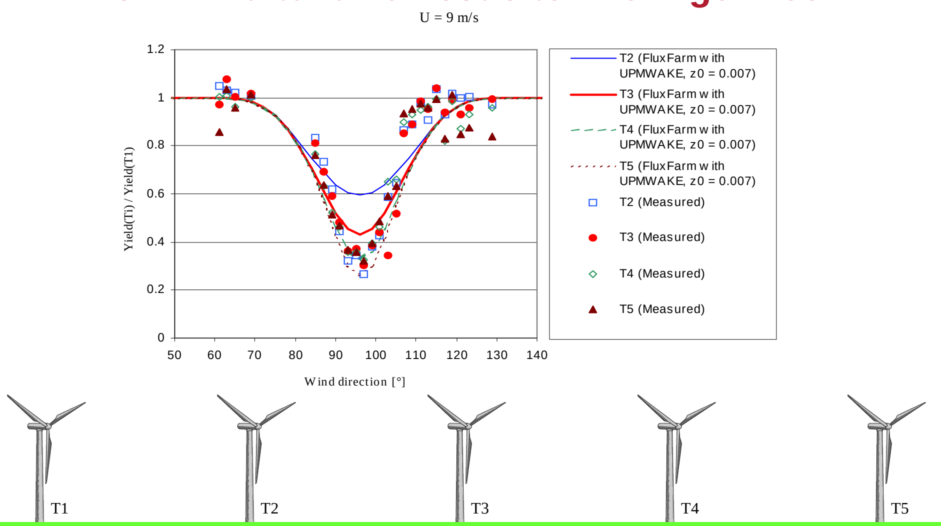
- Top heights: 100 and 108 m
- Number of measuring heights: 4 + 1
- Wind: Cup and vane, and sonic
- Temperature and pressure

20 Outline - Numerical and analytical models - Turbulence closure - Measurements and databases - Summary

ECN

Measurements & Databases

ECN Wind turbine Test site Wieringermeer



21 Outline - Numerical and analytical models - Turbulence closure - Measurements and databases - Summary

ECN

Measurements & Databases

ECN Scale Wind Farm

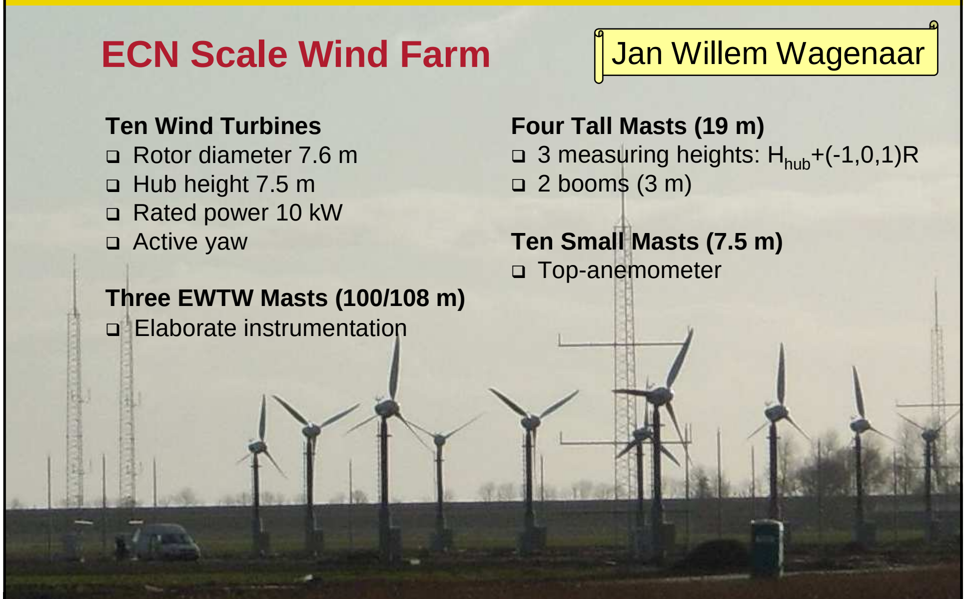
Jan Willem Wagenaar

Ten Wind Turbines
- Rotor diameter 7.6 m
- Hub height 7.5 m
- Rated power 10 kW
- Active yaw

Three EWTW Masts (100/108 m)
- Elaborate instrumentation

Four Tall Masts (19 m)
- 3 measuring heights: H_{hub}+(-1,0,1)R
- 2 booms (3 m)

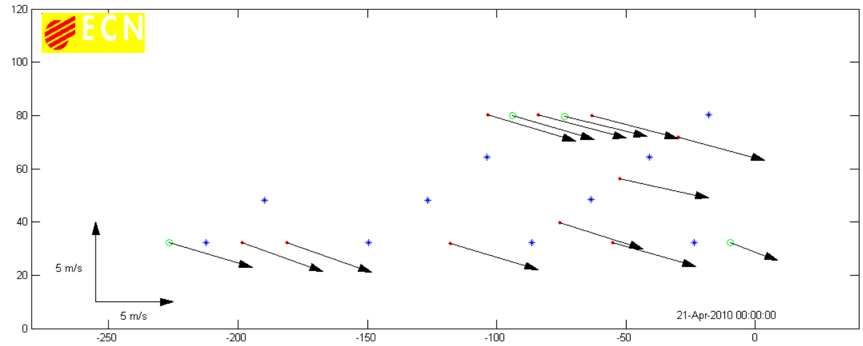
Ten Small Masts (7.5 m)
- Top-anemometer



22 Outline - Numerical and analytical models - Turbulence closure - Measurements and databases - Summary

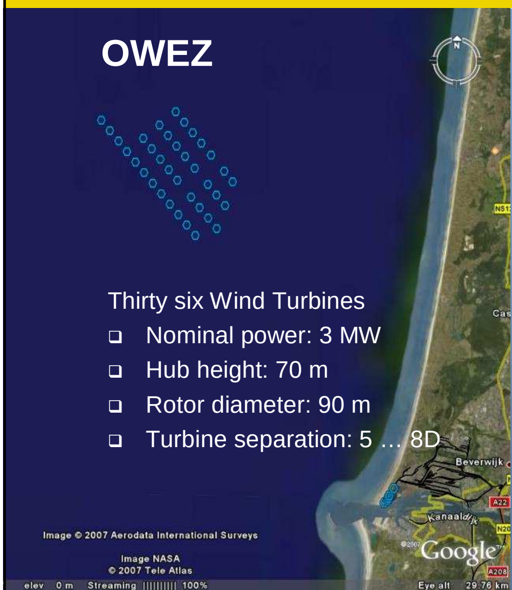
ECN **Measurements & Databases**

ECN Scale Wind Farm



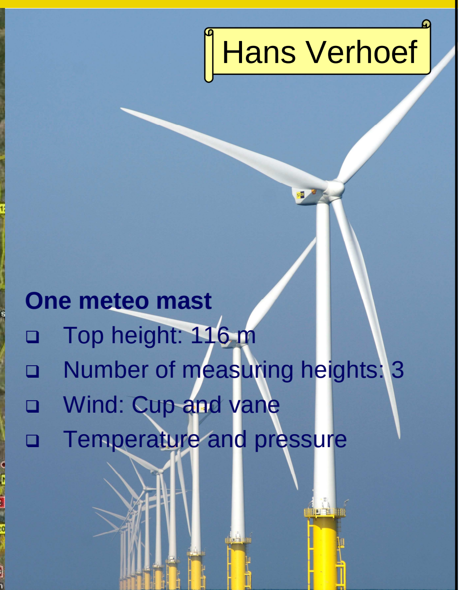
ECN **Measurements & Databases**

OWEZ



Thirty six Wind Turbines

- Nominal power: 3 MW
- Hub height: 70 m
- Rotor diameter: 90 m
- Turbine separation: 5 … 8D



Hans Verhoef

One meteo mast

- Top height: 116 m
- Number of measuring heights: 3
- Wind: Cup and vane
- Temperature and pressure

ECN **Measurements & Databases**

Offshore Wind farm Egmond aan Zee

Information in public domain

- Reports and data on
  - Technology, e.g. wake measurements and site conditions wind
  - Ecology
- Readily available at
  - www.offshorewind.nl
  - www.noordzeewind.nl

Commercially sensitive and (temporarily) confidential information

- Enter procedure
  - Apply for permission to use information at Project Organisation
  - If permission is granted, information is delivered by ECN

25 Outline - Numerical and analytical models - Turbulence closure - Measurements and databases - Summary

ECN

Arno J. Brand

ECN Wind Energy
Wind turbine rotor and Wind farm Aerodynamics

M: P.O. Box 1, NL 1755 ZG Petten, Netherlands
E: brand@ecn.nl
T: +31 224 56 4775
F: +31 224 56 8214
I: linkedin.com/in/arnobrand

26 Outline - Numerical and analytical models - Turbulence closure - Measurements and databases - Summary

National Renewable Energy Laboratory
Innovation for Our Energy Future

Multi-Array Windfarm Modeling Program Initiative

IEA Wind Task 11:

Micro Meteorology & Wind Farm Wakes

May 5-6, 2010

Michael Robinson, PhD
Pat Moriarty, PhD
Matt Churchfield, PhD

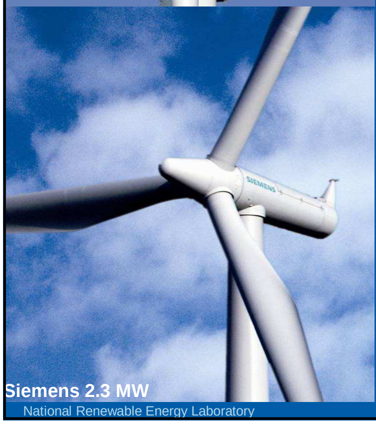
NREL's National Wind Technology Center

National Wind Technology Center Overview

- Turbine testing since 1977
- Development of design and analysis codes
- Pioneers in component testing
- Unique test facilities
  - Blade Testing
  - Dynamometer
  - CART turbines
- Modern utility-scale turbines
- Approx. 160 staff on-site
- Budget approx. $35M
- Many CRADAs with industry
- Leadership roles for international standards

National Renewable Energy Laboratory   Innovation for Our Energy Future

Multi-MW Turbines at the NWTC



DOE 1.5 MW GE Turbine:

- Model: GE 1.5SLE
- Tower Height: 80 m
- Rotor Diameter: 77 m
- Custom elevator and observation platform
- DOE owned; used for research and education

Siemens 2.3 MW Turbine:

- Model: SWT-2.3-101
- Tower Height: 80 m
- Rotor Diameter: 101 m
- Custom service lift
- Siemens owned and operated
- Multi-year R&D CRADA; aerodynamics and rotor performance

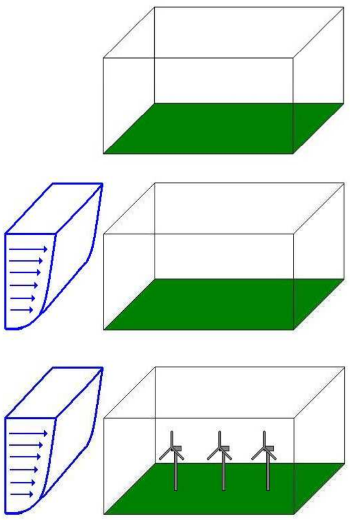
National Renewable Energy Laboratory Innovation for Our Energy Future

NWTC Field Testing Capability

Technical Approach

High Resolution CFD methodology:

- OpenFOAM finite volume solver:
  - Large Eddy Simulation (LES) – computationally expensive.
  - Reynolds Averaged Navier Stokes (RANS) – less expensive.
- Precursor simulation - Create realistic atmospheric boundary layer (ABL):
  - Neutral boundary layer only to date.
  - Quality checks vs. known ABL behavior.
- Turbine wake simulation:
  - Two turbines interact in ABL.
  - Modeled as actuator disks.
  - Spacing effect.
  - Aligned and skewed flow.
- Data validation & model comparison:
  - Power production loss in wake.
  - Mean velocity profiles.
  - LES, RANS, & PARK models.



Why Use OpenFOAM?

- Free and open source code http://www.openfoam.com/
- Large user base
  - Big growth in wind
  - Governmental agencies, universities and industry
- Annual users' meeting
- Active online help forum
- Developing Special Interest Group for wind energy
  - Currently resides in Turbomachinery SIG http://openfoamwiki.net/index.php/Sig_Turbomachinery
  - Wide interest in both siting and turbine specific domains
- Interfaces for many pre- and post-processing tools

OpenFOAM Technology

- Technically not a CFD solver, but a collection of C++ classes that perform various operations for numerically solving equations
- Comes with various solvers
  - Ranging from Navier-Stokes to solid mechanics to financial
  - Extremely flexible & easily modified
- CFD Toolbox
  - Unstructured finite-volume
  - OpenMPI for parallel processing
  - Many turbulence closure schemes already coded
    - 17 RANS & 16 LES
  - Limited to 2nd order accuracy at present
  - Includes 30+ convection schemes

Code Example

- OpenFOAM implicit solver:

$$\frac{\partial \bar{T}}{\partial t} + \frac{\partial}{\partial x_j}\left(\bar{T}\bar{u}_j\right) - \kappa_{eff}\frac{\partial}{\partial x_k}\left(\frac{\partial \bar{T}}{\partial x_k}\right) = 0$$

Thermal diffusivity defined

```
volScalarField kappaEff
    (
        "kappaEff",
        turbulence->nu()/Pr + turbulence->nut()/Prt
    );
```

Linear system matrix assembled

```
    fvScalarMatrix TEqn
    (
        fvm::ddt(T)
      + fvm::div(phi, T)
      - fvm::laplacian(kappaEff, T)
    );
```

Linear system of equations solved using a choice of iterative solvers (preconditioned CG, AMG, etc.)

```
    TEqn.solve();
```

Extremely Flexible & Easily Modified

- Changing to an explicit solver is easy:

$$\frac{\partial \bar{T}}{\partial t} + \frac{\partial}{\partial x_j}\left(\bar{T}\bar{u}_j\right) - \kappa_{eff}\frac{\partial}{\partial x_k}\left(\frac{\partial \bar{T}}{\partial x_k}\right) = 0$$

fvm: implicit operation
fvc: explicit operation

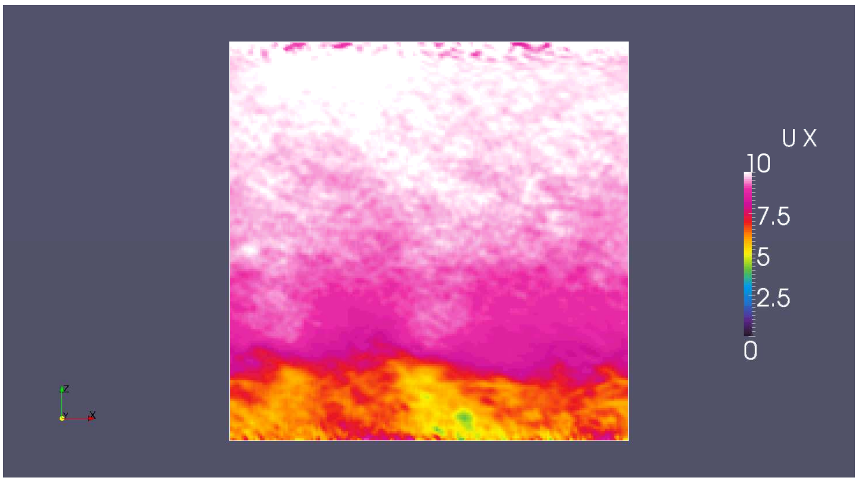
```
volScalarField kappaEff
    (
        "kappaEff",
        turbulence->nu()/Pr + turbulence->nut()/Prt
    );

    fvScalarMatrix TEqn
    (
        fvm::ddt(T)
      + fvc::div(phi, T)
      - fvc::laplacian(kappaEff, T)
    );

    TEqn.solve();
```

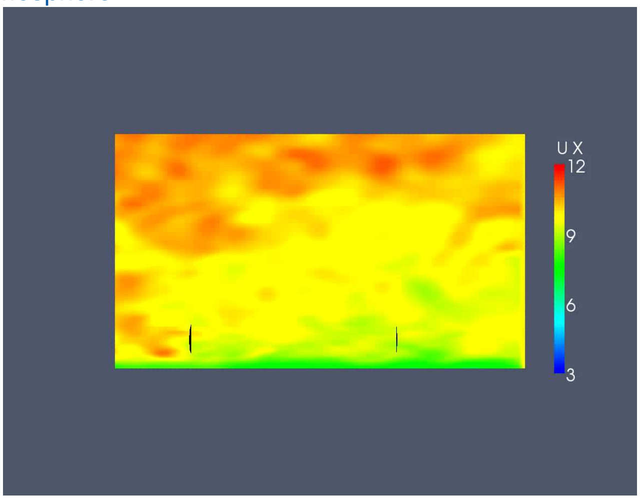
Accomplishments / Progress / Results

- **Atmospheric flow successfully modeled:**
  - Neutral ABL only.



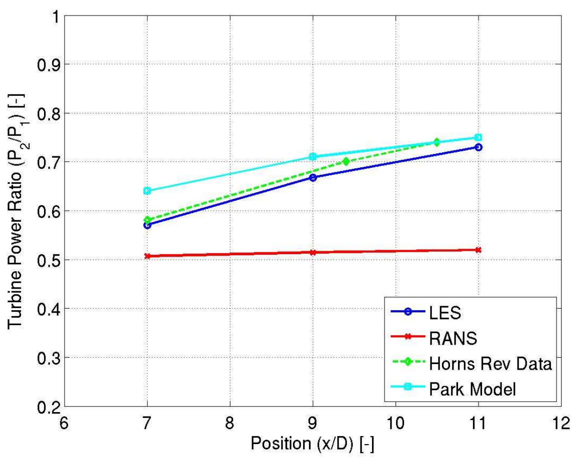
Accomplishments / Progress / Results

- **Wind Turbine Wake Modeling**:
  - Successful simulation of two turbines interacting with realistic atmosphere.



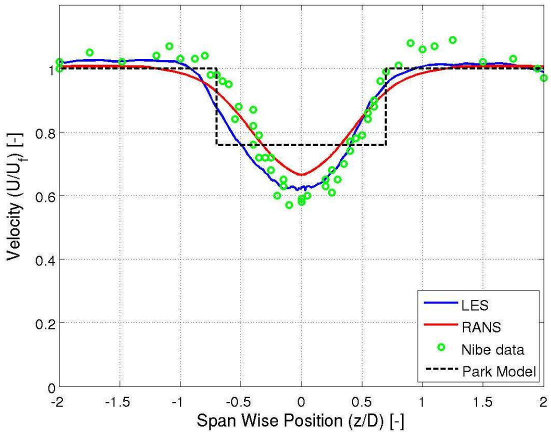
Accomplishments / Progress / Results

- Power loss decreases with increased turbine spacing.
- LES and PARK models close to data – RANS is poor.



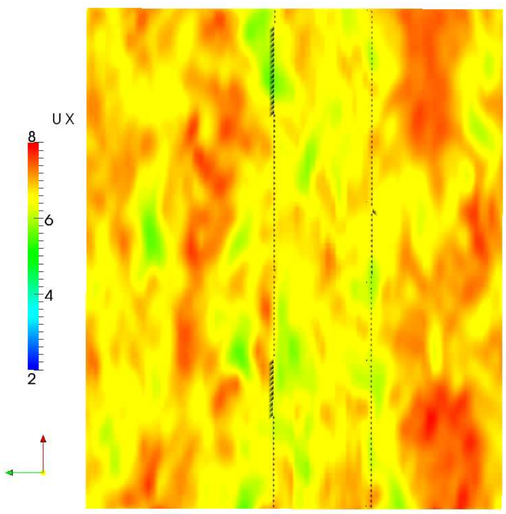
Accomplishments / Progress / Results

- Higher fidelity models better for mean wake profiles.
- Less important for power – may be more important for loads.



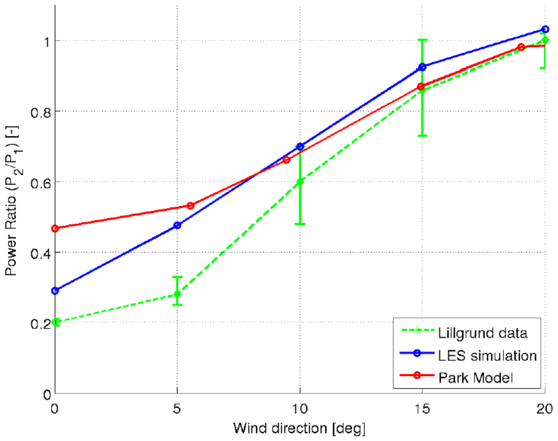
Accomplishments / Progress / Results

- Skewed flow common within wind farms.



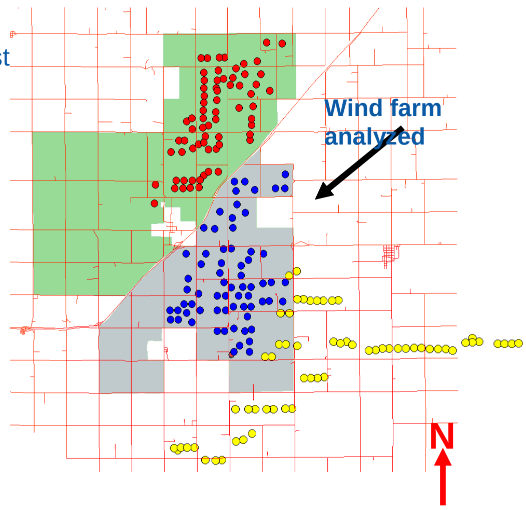
Accomplishments / Progress / Results

- LES and PARK model similar agreement with data in skewed flow.
- Aligned case (0°) LES is better - near wake - 3.3 D spacing



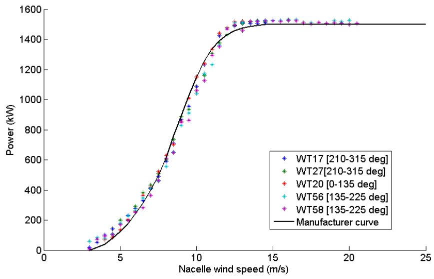
Technical Approach

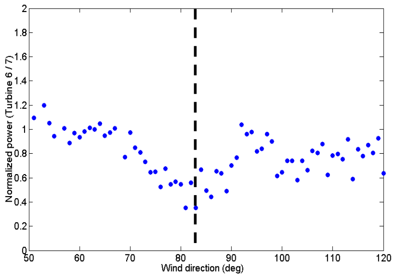
- Wind farm data analysis:
  - Data from May 09 onward.
  - Onshore wind farm in Midwest
  - CRADA partner Xcel energy.
- Quality check of data:
  - Eliminate faults and data anomalies.
  - Eliminate neighboring farm sectors.
- Create power curves for turbines:
  - Use as a check of met mast data.
- Identify wake effects:
  - Different turbine spacing.
  - Different atmospheric conditions.



Accomplishments / Progress / Results

- Power curves well quantified.
- Some wake effects calculated:
  - Impacts not as obvious as for offshore wind farms.
  - Higher turbulence levels diminish wake impacts.
- Further analysis needed.





Proposed Next Steps

Project plans for the rest of FY 2010:

- **Continue improving and validating models:**
  - Non-neutral atmospheric conditions.
  - Higher fidelity turbine model – actuator line.
- **Continue wind farm data analysis to examine onshore wind farm behavior.**
  - SNL Red Mesa
- **Couple with mesoscale models:**
  - Large wind farms
  - Interactions between wind farms
- **Develop IEA Annex for turbine wake model validation.**

Future critical needs:

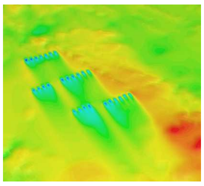
- **Include effects of terrain and vegetation**
- **Couple aeroelastic code to wind farm simulations:**
  - Loads prediction
  - Estimate maintenance impacts
- **Detailed Field Measurement Campaigns**
- **Better lower fidelity models:**
  - LES may be too computationally intensive for industry
- **National integrated working group:**
  - Coordinate similar efforts around country at universities and other labs

CFD MODELING OF WIND FARMS IN COMPLEX TERRAIN

D. Cabezon
Wind Energy Department
National Renewable Energy Centre of Spain (CENER)
dcabezon@cener.com

K. S. Hansen
Department of Mechanical Engineering,
Technical University of Denmark (RISO-DTU)

R. J. Barthelmie
Atmospheric Science and Sustainability
Indiana University (USA)



IEA Topical Expert Meeting on "Micrometeorology inside wind farms and wakes between wind farms"

Pamplona (Spain)

5-6 May 2010

INDEX

1. Introduction
2. Test case
3. Wind farm model
   A. Freestream flow
   B. Rotor modelling
   C. Numerical method
4. Results
5. Conclusions

Wind power

1. INTRODUCTION

- Output power and fatigue loads inside big wind farms dependent on:
  - Wind farm design
  - Wake flow recovery
- Wakes inside wind farms mainly influenced by:
  - Turbine characteristics and spacing
  - Wind speed and direction
  - Turbulence intensity / atmospheric stability
- 'Wind Turbine - Wind Turbine' Wakes
  - Analyzed in depth during the last decades
  - Superposition of wind speed deficit between wind turbines
  - Firstly studied by Lissaman (linear) -> overestimation of power deficit
  - Corrected by Katic (quadratic linear) -> depending on a decay constant
- New factor: Topography
  - Complex terrain ⟺ wakes interaction in big wind farms
  - Important impact on wakes evolution and recovery

Wind power

cener
centro nacional de energías renovables
national renewable energy centre

1. INTRODUCTION

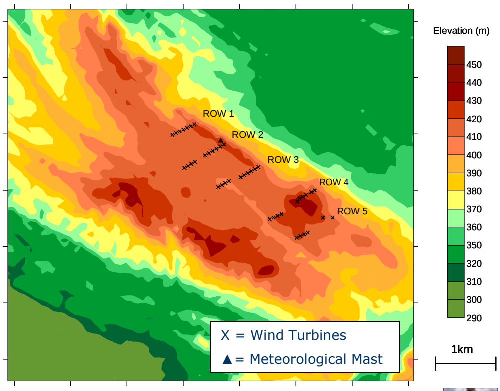
- 'Wind Turbine - Wind Turbine - Complex terrain' Wakes
  - A priori unknown phenomenon
  - Analysis during early nineties:
    - Taylor and Smith: wind tunnel experiments (1991)
    - Crespo A., Manuel F. et. al: field experiments (1993)
      - 1WT + complex terrain: linear hypothesis roughly valid
      - 2WTs + complex terrain: linear hypothesis less valid
    - Van Oort (1989) / Voutsinas (1990) / Hemon (1991) / Helmis (1995)...
  - Current wake models do not deal wake-terrain interaction directly
  - Critical issue not very deeply analyzed during the last years
- CFDWake: Elliptic CFD wind farm model
  - Based on coupling CFD wind flow model + ACTUATOR DISK technique
  - Combined WT-terrain wake effects: rapidly solved
  - Topographic wind speed-ups + WT wake deficit: non-linear effect
  - Validation in an operating complex terrain wind farm

Wind power

cener
centro nacional de energías renovables
national renewable energy centre

2. TEST CASE

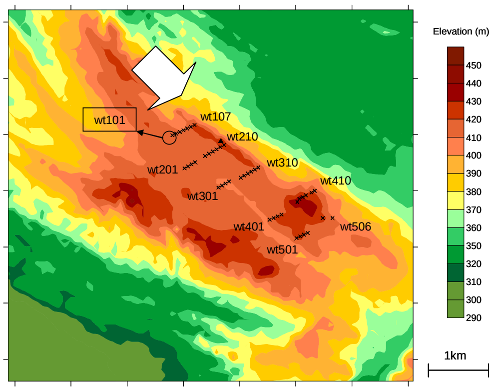
- Moderately complex terrain: plateau with isolated rising grounds
- 43 wind turbines in 5 rows
- Separation along main flow: 13 rotor diameters
- Separation normal to main flow: 1.5 rotor diameters
- Hub height = 45m/55m
- Rotor diameter = 48.4m
- Data from met mast (45m):
  - Wind speed (average and standard deviation)
  - Wind direction
- Data from wind turbines:
  - Nacelle wind speed
  - Nacelle wind direction
  - Nacelle output power
  - Status signal
- Period: 7 months (Apr06-Nov06)



Wind power

2. TEST CASE

- Data collected, filtered and validated
- Wind turbines numbered from W to E
- 1 representative flow case:
  - Wind direction: **325±5º**
  - Wind speed: **8±0.5m/s**
  - Turbulence intensity: 12%
- Reference wind turbine: wt101
- Freestream conditions:
  - Turbulence intensity (met mast)
  - Nacelle wind direction
  - Wind speed from wt101 (inverse power curve)



Wind power

3. WIND FARM MODEL

FREESTREAM FLOW

- Fully developped profiles for the Surface Boundary Layer (SBL)
- Non-uniform shear boundary layer flow based on Monin-Obukhov theory
- Inflow wind velocity profile for neutral stratification:

$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right)$$

κ=von karman cosntant
u_*=friction velocity
z_0=roughness length

- Inflow turbulent kinetic energy TKE and its dissipation rate ε profiles, (assuming equilibrium of production and dissipation in the SBL)

$$k(z) = \frac{u_*^2}{\sqrt{C_\mu}} \qquad \varepsilon(z) = \frac{u_*^3}{\kappa z}$$

- Constant roughness on ground z_0=0.03m

Wind power

cener

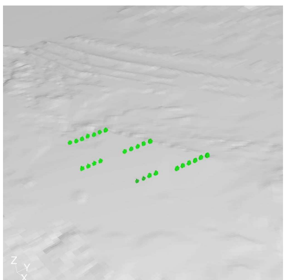
3. WIND FARM MODEL

ROTOR MODELLING

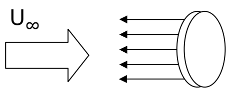
- Based on the 1D axial momentum theory
- Rotors approximated by actuator disks acting over the incoming flow
- Momentum sink term

$$F[N/m^2] = -0.5 \cdot \rho \cdot C_t \cdot U^2_\infty$$

ρ=air density
C_t=thrust coefficient
U_∞=upstream velocity



- Uniformly loaded rotor
- Azimuthal induction neglected -> non-rotating flow
- Change of momentum entirely from pressure difference on the actuator disk
- Input data:
  - UTM coordinates
  - Hub height
  - WT specification: Power curve / C_t curve



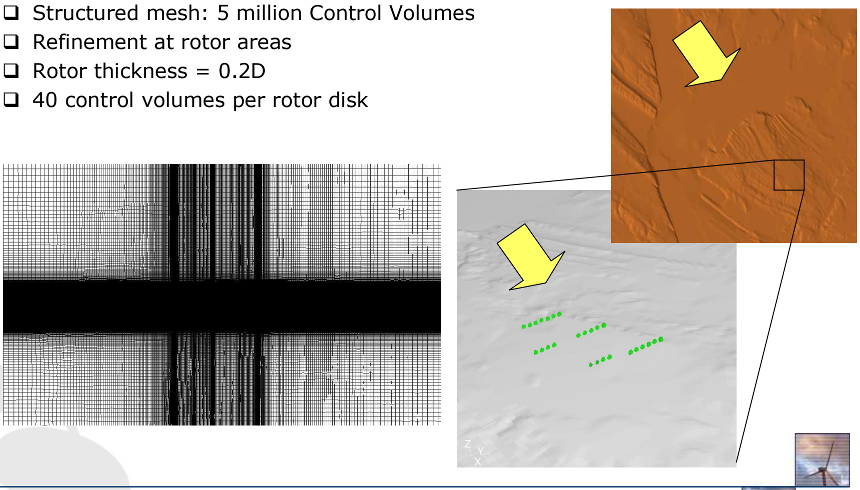
Wind power

cener

3. WIND FARM MODEL

NUMERICAL MODEL:

- Domain size (km): 15 x 15 x 2
- Structured mesh: 5 million Control Volumes
- Refinement at rotor areas
- Rotor thickness = 0.2D
- 40 control volumes per rotor disk



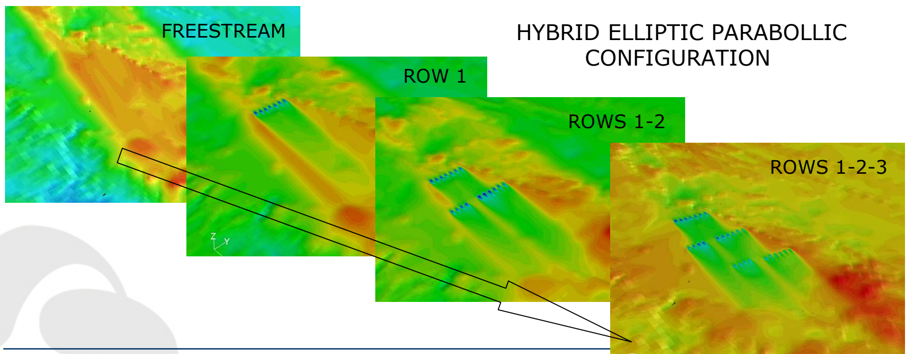
Wind power

cener
centro nacional de energías renovables
national renewable energy centre

3. WIND FARM MODEL

NUMERICAL MODEL:

- Solver based on FLUENT 12.0 platform
- Steady state / Second-order upwind scheme
- Boundary conditions for SBL / Standard kε turbulence model
- Wind farm sequentially solved from row 1 up to row 4
- Reference wind speed obtained from previous simulation
- Computational time for wind farm solution: 12h



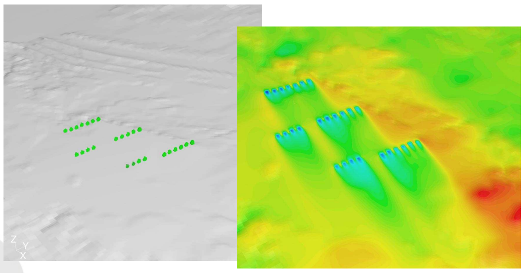
HYBRID ELLIPTIC PARABOLLIC
CONFIGURATION

Wind power

cener
centro nacional de energías renovables
national renewable energy centre

4. RESULTS

- Validation of wake deficits modelled by CFDWake 1.0
- Normalised to power at reference wind turbine wt101
- Comparison to WAsP model as reference for analytical model
  - Standard configuration: wake decay coefficient k=0.075
  - Constant roughness, no RIX correction for complex terrain
  - Linear superposition: Terrain + Wakes
- Non-linear hypothesis
  - 'WT-WT-Complex Terrain' wake interaction
  - Combined effect in one single simulation



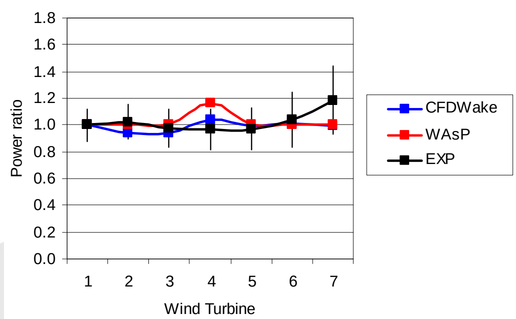
Wind power

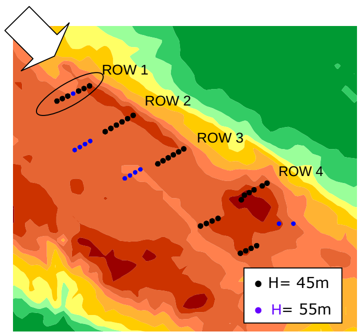
cener

4. RESULTS

ROW 1

- Freestream conditions
- Power ratio due to terrain irregularities
- Close to unity
- wt104: higher hub height with lower elevation





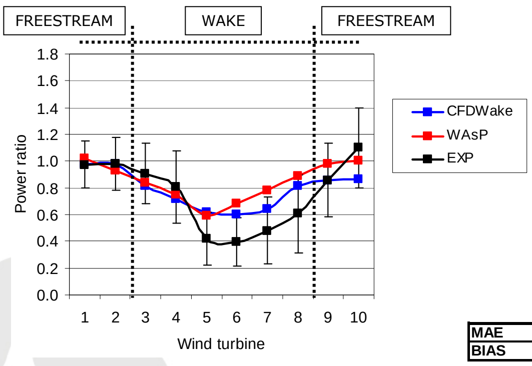
Wind power

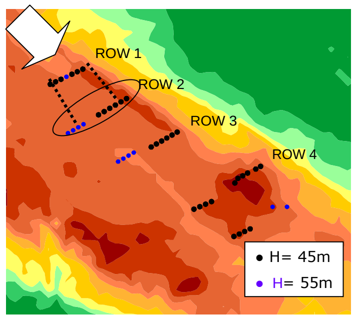
cener

4. RESULTS

ROW 2

- Wake effect of 60% at central positions
- Similar results at freestream area, some discrepancies at wake area
- Coherent evolution of local terrain acceleration for CFDWake and WAsP





	CFDWake	WAsP
MAE	0.12	0.15
BIAS	0.03	0.09

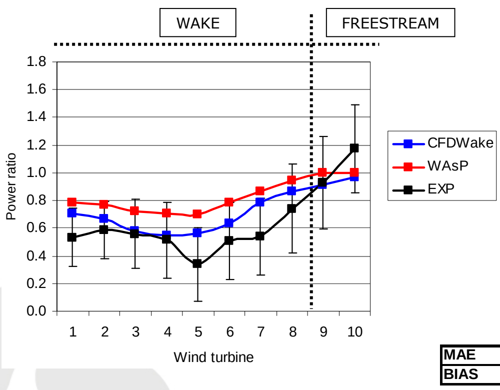
Wind power

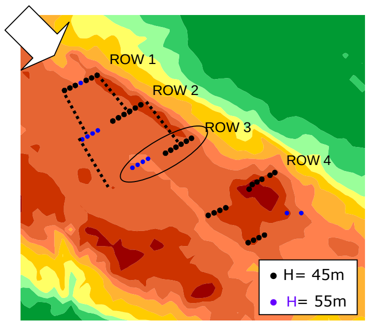
cener

4. RESULTS

ROW 3

- Deep power deficit of 60% remaining at central side of the row
- Constant difference of 10% between estimations by CFD and analytical models
- Coherent evolution with terrain acceleration at final positions





	CFDWake	WAsP
MAE	0.13	0.22
BIAS	0.08	0.19

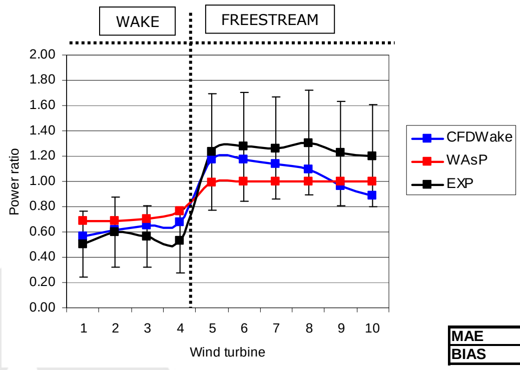
Wind power

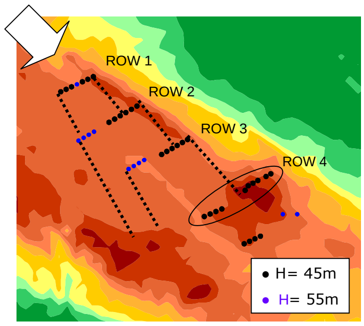
cener

4. RESULTS

ROW 4

- Accurate representation of accumulated power deficit by CFD at wt401 to wt404
- Important increase of power ratio due to local terrain acceleration for wt405 to wt410
- Underestimation of power ratios at the more complex freestream area





	CFDWake	WAsP
MAE	0.14	0.22
BIAS	-0.08	-0.09

Wind power

cener

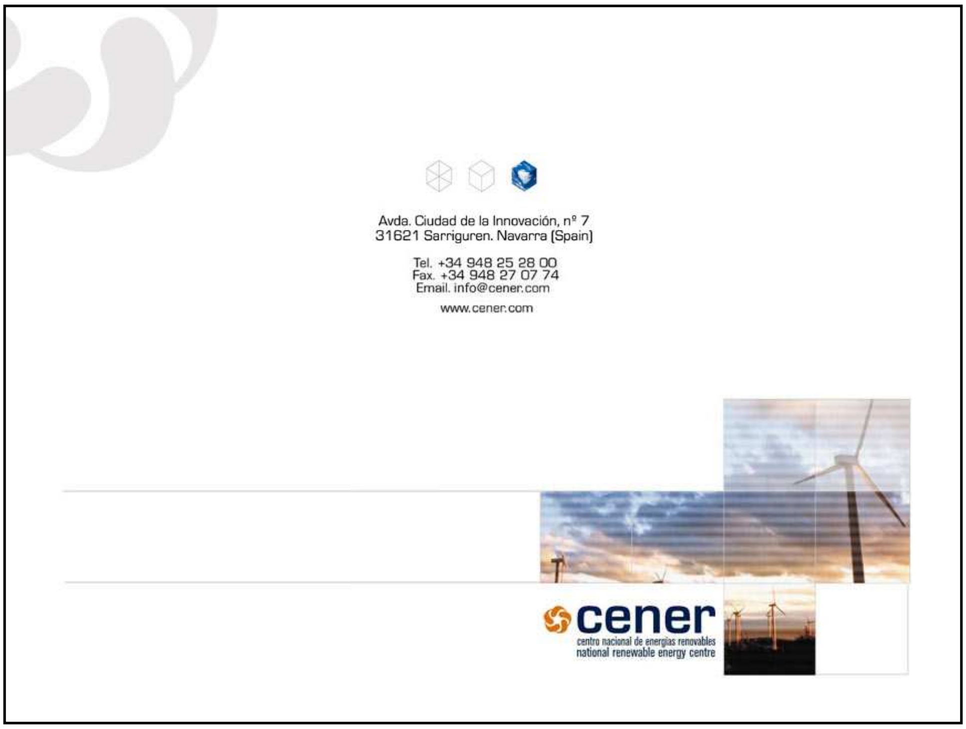
5. CONCLUSIONS

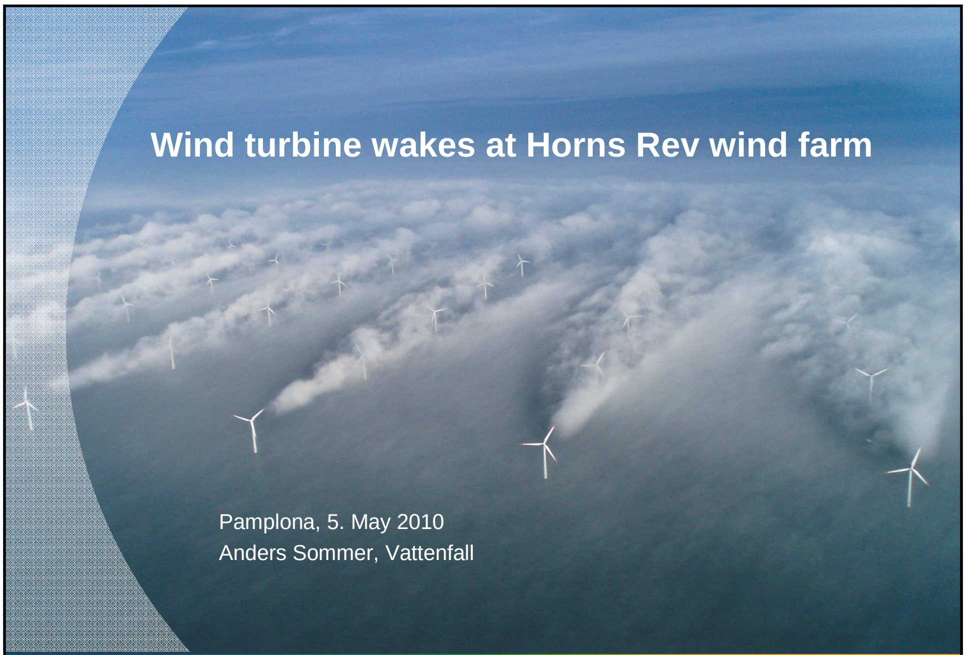
- Elliptic CFD simulations of complex terrain wind farms is feasible and accurate
- Global mae and bias for CFDWake equals 0.13 and 0.01 respectively
- Global mae and bias for WAsP equals 0.20 and 0.06 respectively
- Linear superposition is not so valid for complex terrain and leads to overestimation of power ratio
- CFD wind flow modeling coupled to actuator disk method represents a promising alternative to conventional wake modeling in complex terrain / offshore
- Further work:
  - Migrate CFDWake code to the open source CFD toolbox OpenFoam
  - Automatic grid generation for wake modeling and grid sensitivity analysis
  - Fully elliptic simulations: check procedures for coherent reference wind speeds
  - Modifications to standard kε turbulence model or higher order closures
  - Extend measurement period in order to reduce uncertainty on wind data base
  - Get new data in order to run intensive validations at more wind farms

- Research funded in part by EU project **UPWIND** # SES6 079945
- Special acknowledgements to anonymous wind farm owners for supplying the project with data for the model evaluation

Wind power

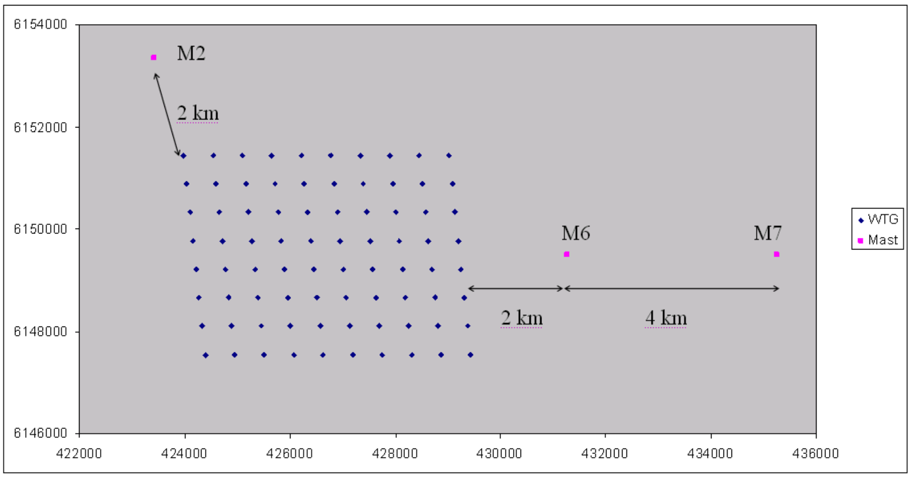
cener


Avda. Ciudad de la Innovación, nº 7
31621 Sarriguren. Navarra (Spain)
Tel. +34 948 25 28 00
Fax. +34 948 27 07 74
Email. info@cener.com
www.cener.com
cener
centro nacional de energías renovables
national renewable energy centre



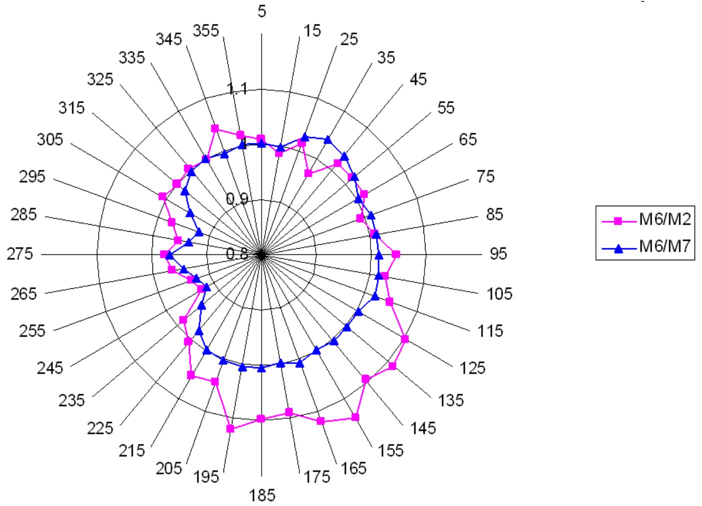
05.05.2010 | Horns Rev Wake | Anders Sommer | Vattenfall R&D 1 VATTENFALL

Horns Rev wind farm and met masts



05.05.2010 | Horns Rev Wake | Anders Sommer | Vattenfall R&D 2 VATTENFALL

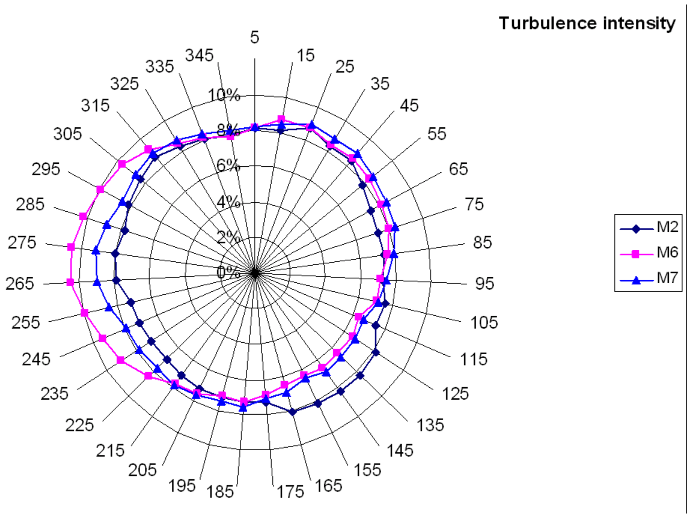
Mean Wind Speed



05.05.2010 | Horns Rev Wake | Anders Sommer | Vattenfall R&D 3

VATTENFALL

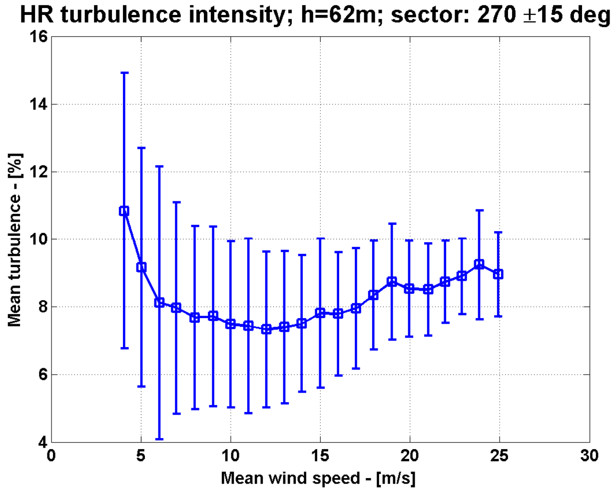
Turbulence Intensity at wake masts



05.05.2010 | Horns Rev Wake | Anders Sommer | Vattenfall R&D 4

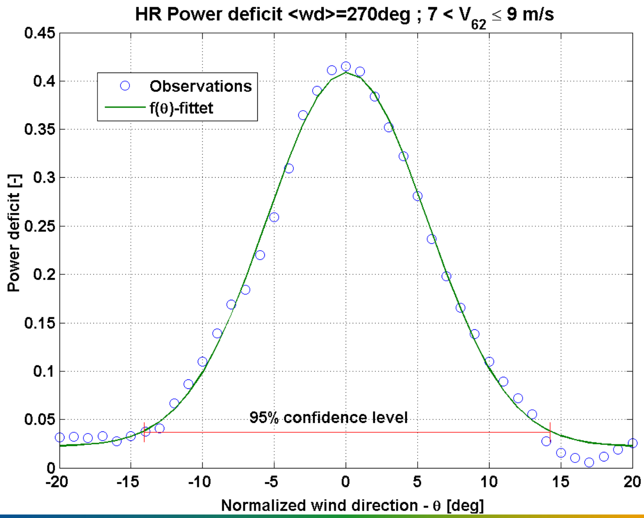
VATTENFALL

Turbulence Intensity as function of wind speed



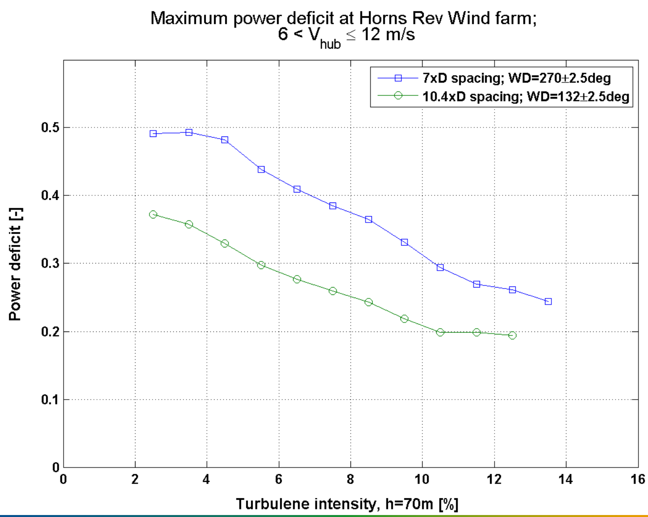
05.05.2010 | Horns Rev Wake | Anders Sommer | Vattenfall R&D 5 VATTENFALL

Power deficit for turbine 17 and 07



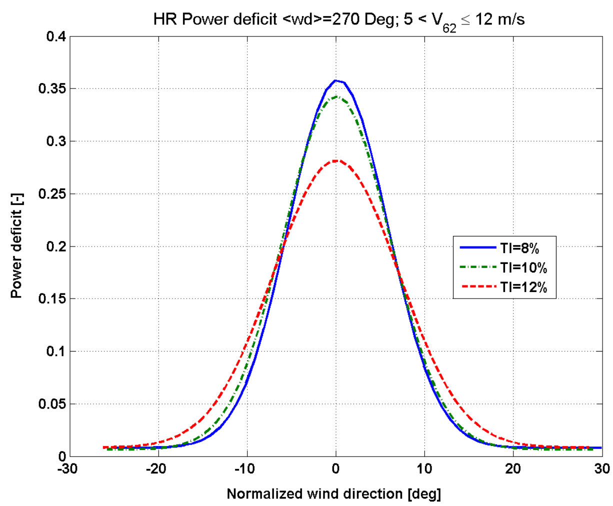
05.05.2010 | Horns Rev Wake | Anders Sommer | Vattenfall R&D 6 VATTENFALL

Maximum power deficit for 7D and 10D



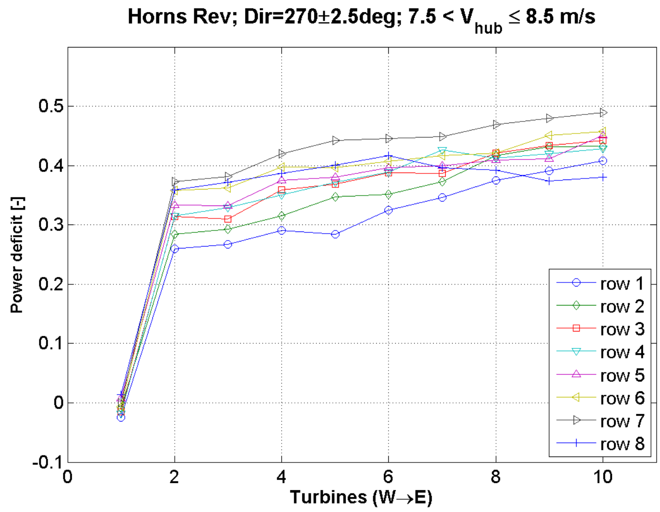
05.05.2010 | Horns Rev Wake | Anders Sommer | Vattenfall R&D 7 VATTENFALL

Power deficit for different turbulence levels



05.05.2010 | Horns Rev Wake | Anders Sommer | Vattenfall R&D 8 VATTENFALL

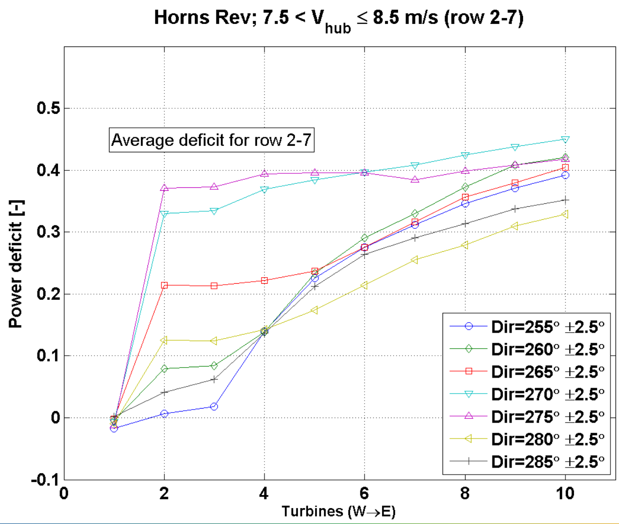
Power deficits along a row of 10 turbines for a small inflow sector of 5 deg.



05.05.2010 | Horns Rev Wake | Anders Sommer | Vattenfall R&D 9

VATTENFALL

Averaged power deficits for 7 inflow sectors, Vhub = 8 m/s

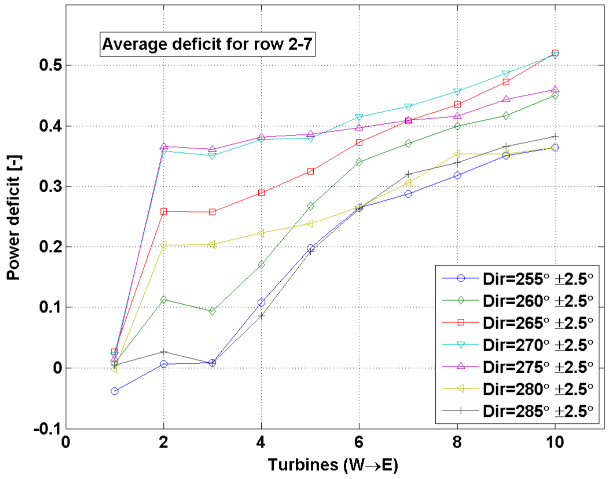


05.05.2010 | Horns Rev Wake | Anders Sommer | Vattenfall R&D 10

VATTENFALL

Averaged power deficits for 7 inflow sectors, Vhub = 6 m/s

Horns Rev; 5.5 < V_{hub} ≤ 6.5 m/s (row 2-7)

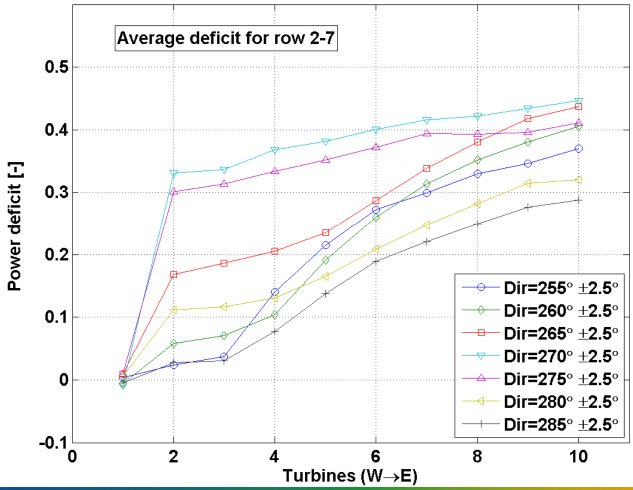


05.05.2010 | Horns Rev Wake | Anders Sommer | Vattenfall R&D 11

VATTENFALL

Averaged power deficits for 7 inflow sectors, Vhub = 10 m/s

Horns Rev; 9.5 < V_{hub} ≤ 10.5 m/s (row 2-7)



05.05.2010 | Horns Rev Wake | Anders Sommer | Vattenfall R&D 12

VATTENFALL

Conclusions

Wind speed reduction of around 5% 2 km downstream of the wind farm

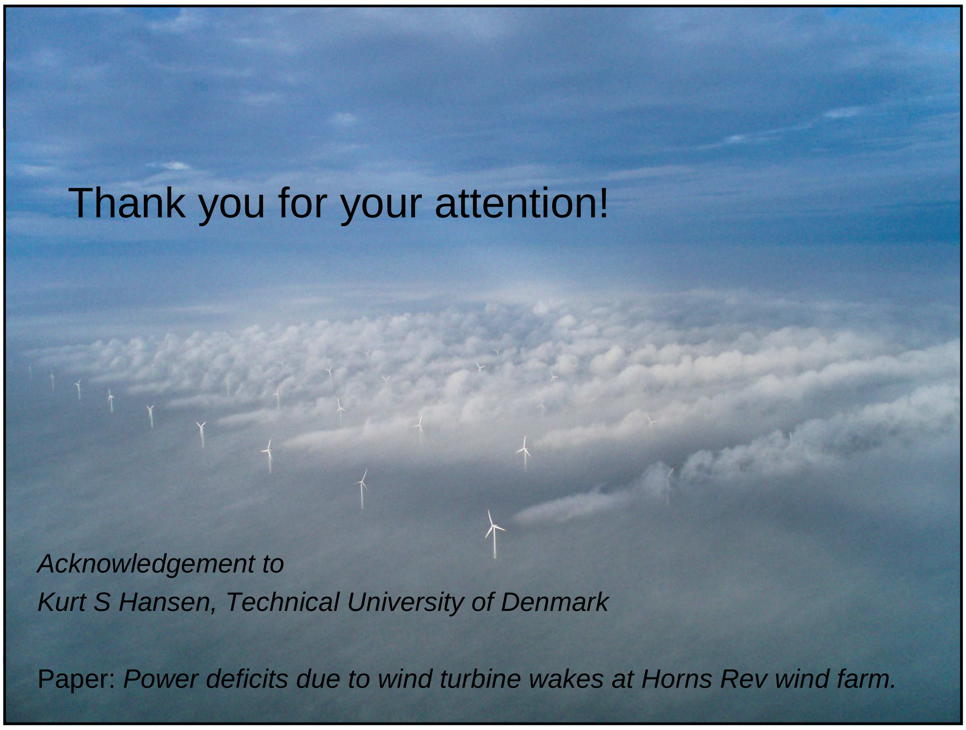
Each turbine generates a flow deficit sector of 25-30 degrees.

The sector size depends both on wind speed and turbulence.

A distinct linear relation between maximum deficit and turbulence, where slope depends on spacing.

Maximum deficit decreases with increasing wind speed.

05.05.2010 | Horns Rev Wake | Anders Sommer | Vattenfall R&D 13 VATTENFALL



Some Selected Results from Early WT-studies and Wake Effects in the Closely Spaced Lillgrund Offshore Wind Farm

By Jan-Åke Dahlberg, Vattenfall Vindkraft AB

IEA-TEM #62, Micro meteorology inside wind farms and wakes between wind farms, Pamplona 5-6 May, 2010

Vattenfall Vindkraft AB

VATTENFALL

1

Scope

- Wind tunnel studies
- Full scale tests
  Alsvik 4x180kW Danwin turbines
  Lillgrund 48x2.3MW Siemens turbines

Vattenfall Vindkraft AB 2 VATTENFALL

2

Scope

- Due to the stream tube expansion, the turbine ”sees” a smaller window upstream
- The development of the wake (distance, velocity deficit) scales on the size of the object
- The wake can be ”pushed” aside

Early WT studies

FFA

FLYGTEKNISKA FÖRSÖKSANSTALTEN

THE AERONAUTICAL RESEARCH INSTITUTE OF SWEDEN

TECHNICAL NOTE HU-2189

PART 5

MEASUREMENTS OF WAKE INTERACTION EFFECTS

ON THE POWER OUTPUT FROM SMALL WIND TURBINE MODELS

by

Per-Henrik Alfredsson and Jan-Åke Dahlberg

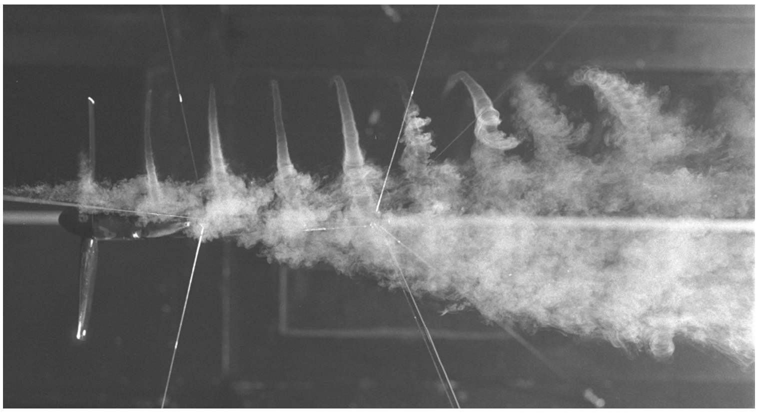
Stockholm 1981

Early WT studies

Vattenfall Vindkraft AB 5 VATTENFALL

5

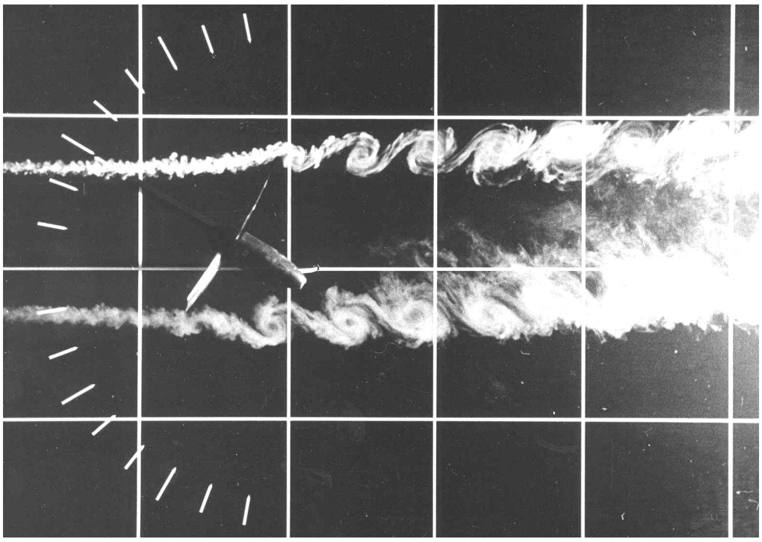
Early WT studies



Vattenfall Vindkraft AB 6 VATTENFALL

6

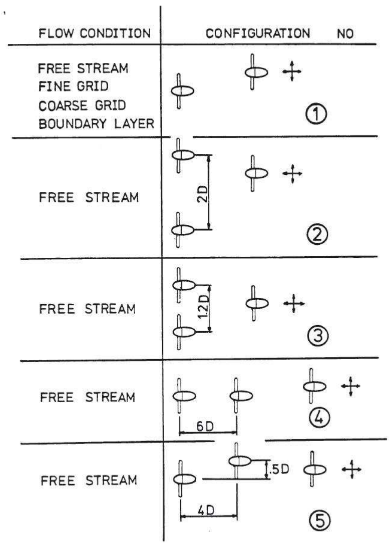
FFA-KTH, 1980:s



Vattenfall Vindkraft AB 7 VATTENFALL

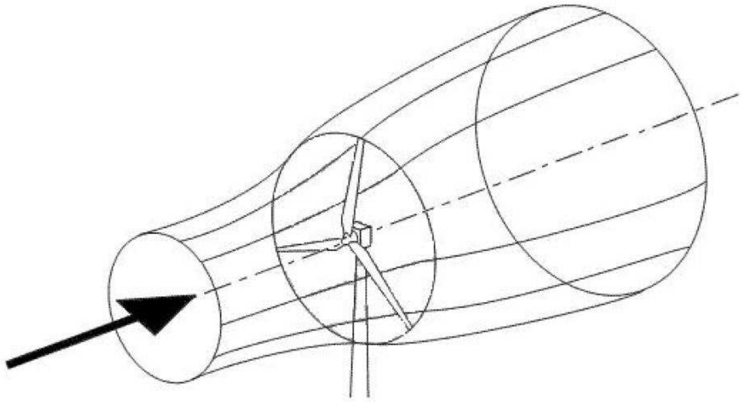
7

Tested configurations



Vattenfall Vindkraft AB 8 VATTENFALL

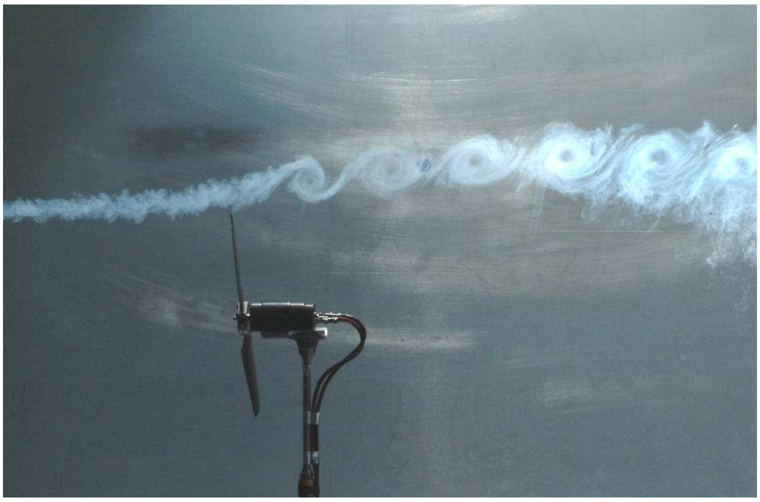
Stream tube



Vattenfall Vindkraft AB 9 VATTENFALL

9

Flow visualisation by smoke



Vattenfall Vindkraft AB 10 VATTENFALL

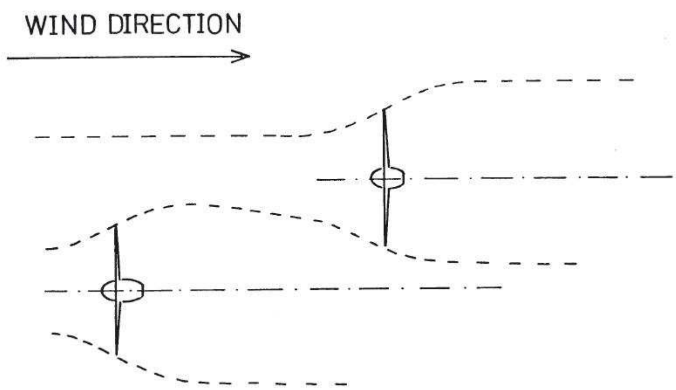
10

Stream tube

Vattenfall Vindkraft AB 11 VATTENFALL

11

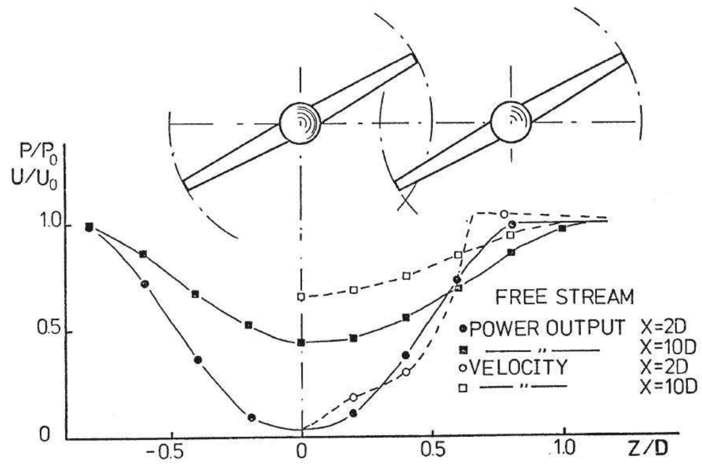
Wake interaction



Vattenfall Vindkraft AB 12 VATTENFALL

12

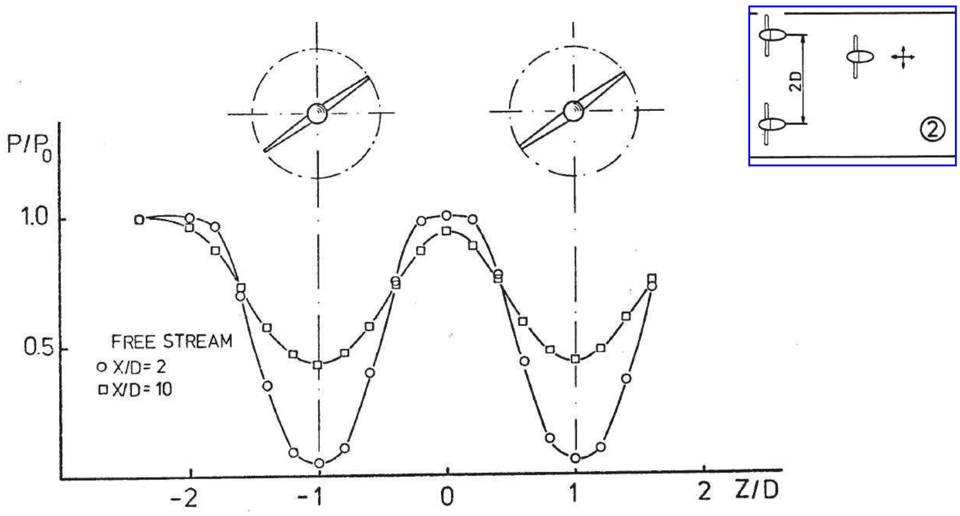
Wake interaction



Vattenfall Vindkraft AB 13 VATTENFALL

13

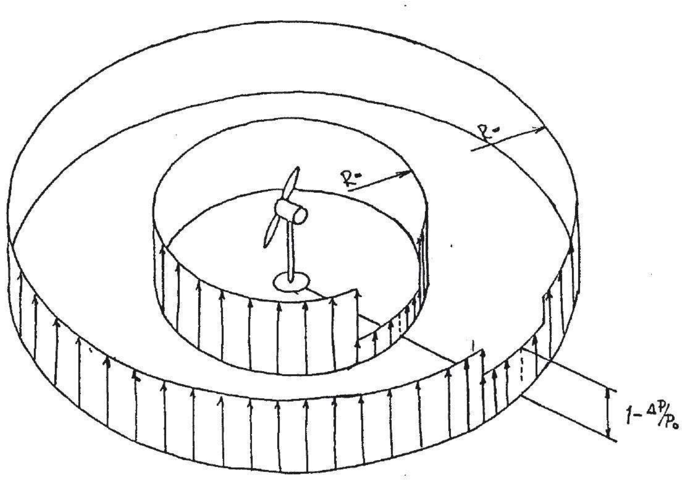
Wake interaction



Vattenfall Vindkraft AB 14 VATTENFALL

14

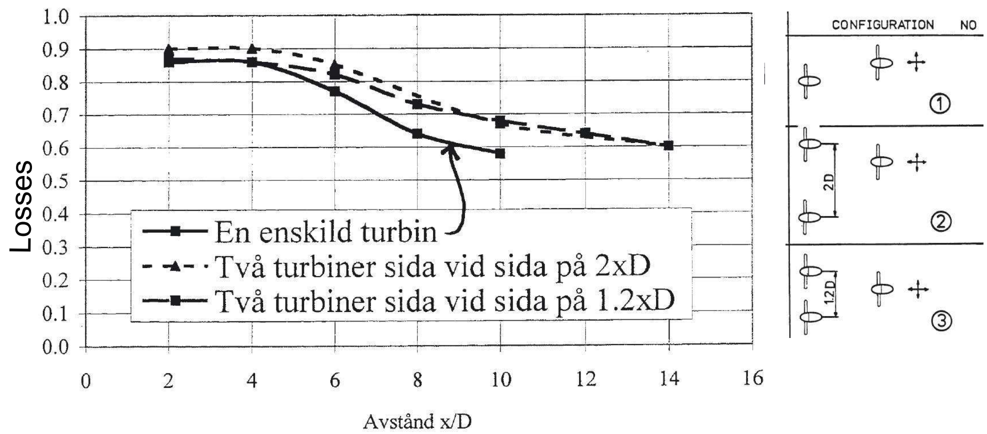
Integrated power loss



Vattenfall Vindkraft AB 15 VATTENFALL

15

Integrated power loss



Wake effects scales on the size of the ”object”

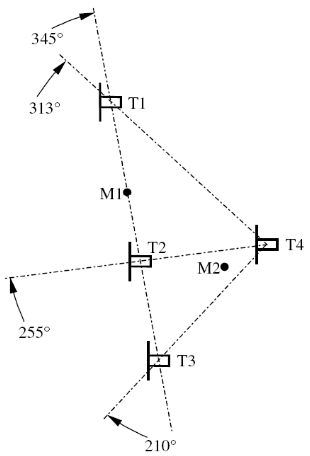
Vattenfall Vindkraft AB 16 VATTENFALL

Alsvik

Vattenfall Vindkraft AB 17 VATTENFALL

17

Layout

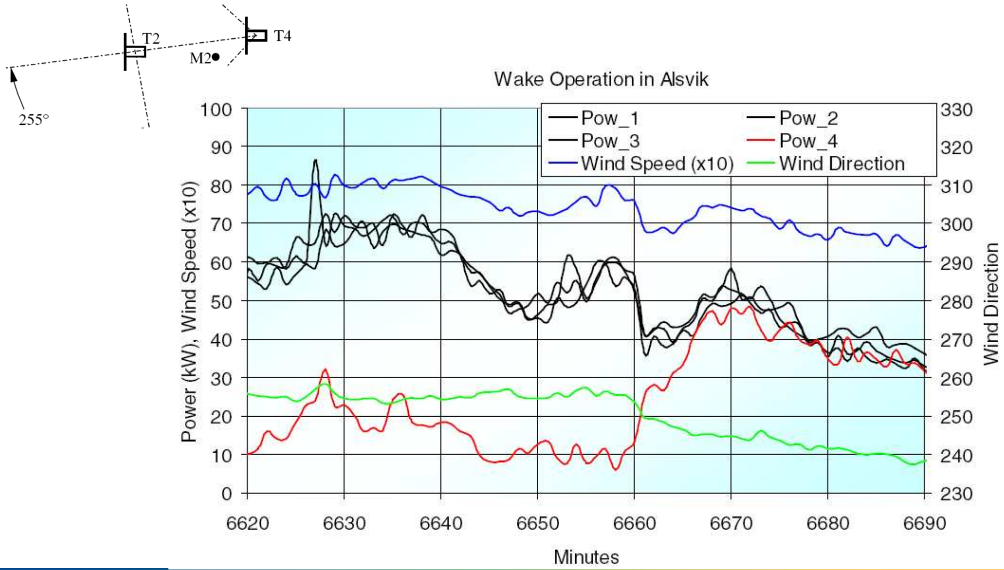


Turbine	Separation
T1-T4	9.4×D
T2-T4	5.0×D
T3-T4	7.1×D
T1-T2	8.0×D
T2-T3	5.0×D

Vattenfall Vindkraft AB 18 VATTENFALL

18

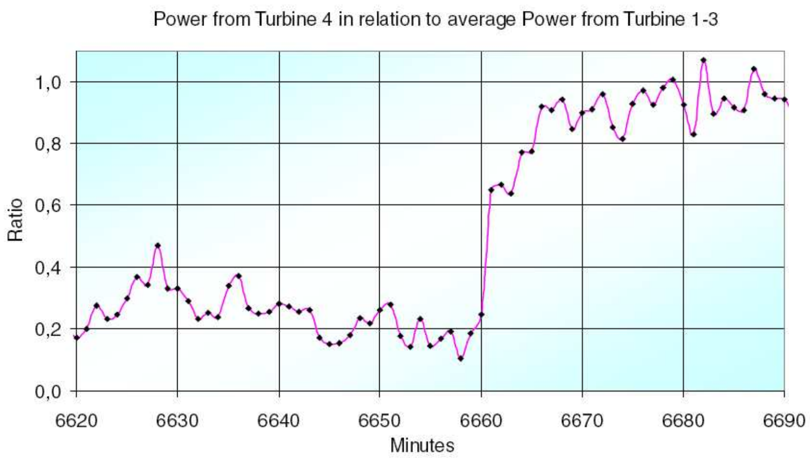
Instantaneous wake effects



Vattenfall Vindkraft AB 19 VATTENFALL

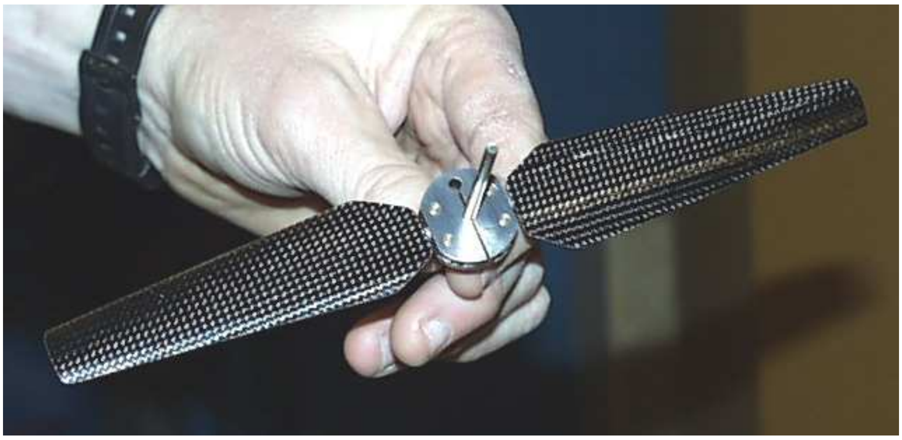
19

Power ratio



Vattenfall Vindkraft AB 20 VATTENFALL

FFA/FOI-LT5, 2000-



Vattenfall Vindkraft AB 21 VATTENFALL

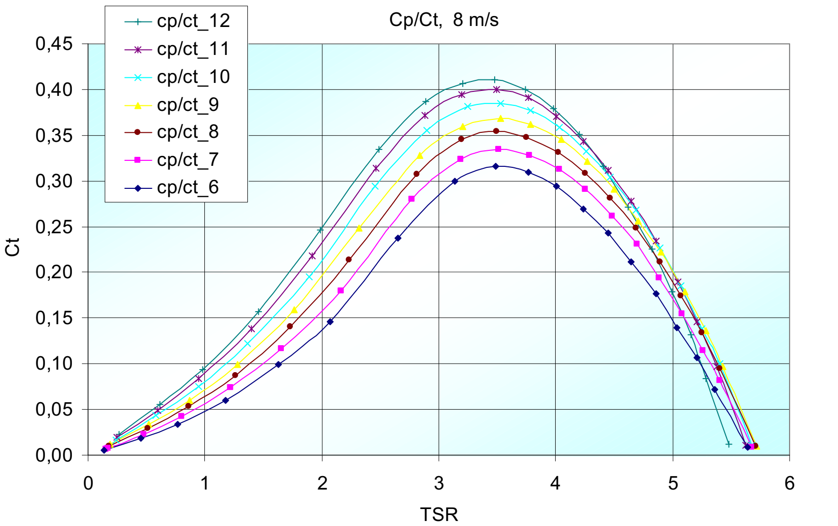
21

FFA/FOI-LT5, 2000-

Vattenfall Vindkraft AB 22 VATTENFALL

22

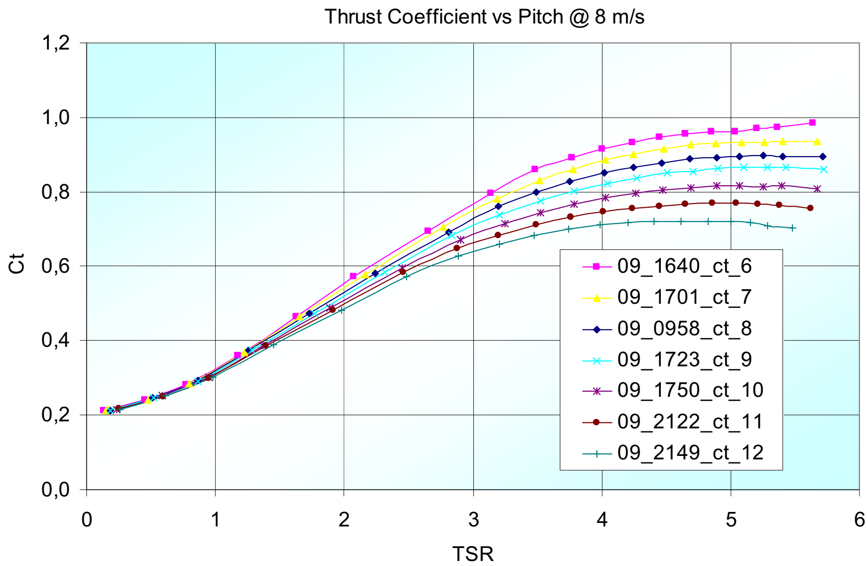
FFA/FOI-LT5, 2000-



Vattenfall Vindkraft AB 23 VATTENFALL

23

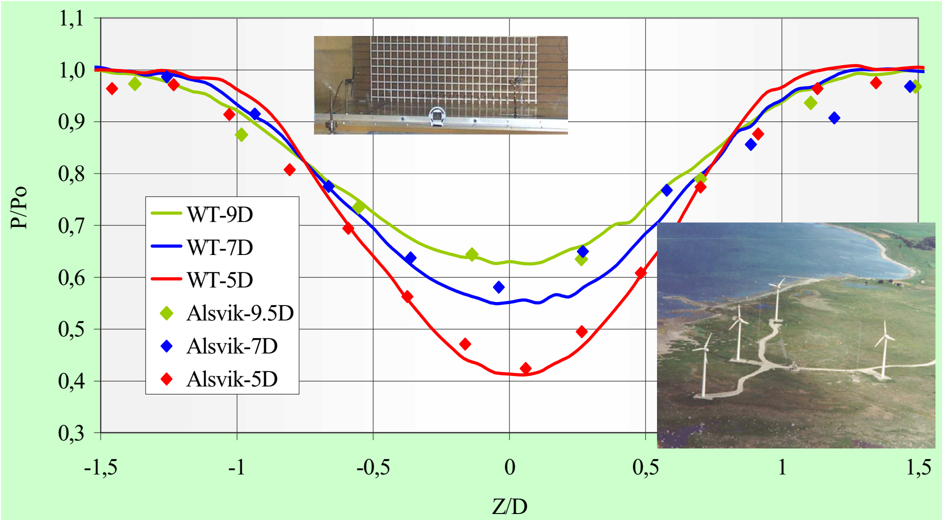
FFA/FOI-LT5, 2000-



Vattenfall Vindkraft AB 24 VATTENFALL

24

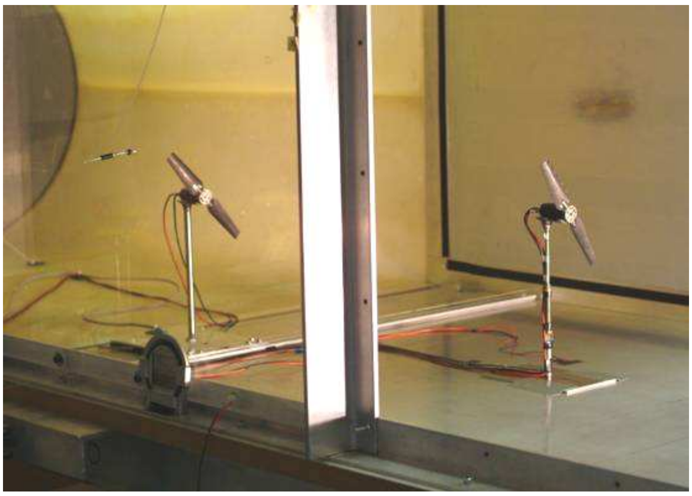
Modelled and real wake effects



Vattenfall Vindkraft AB 25 VATTENFALL

25

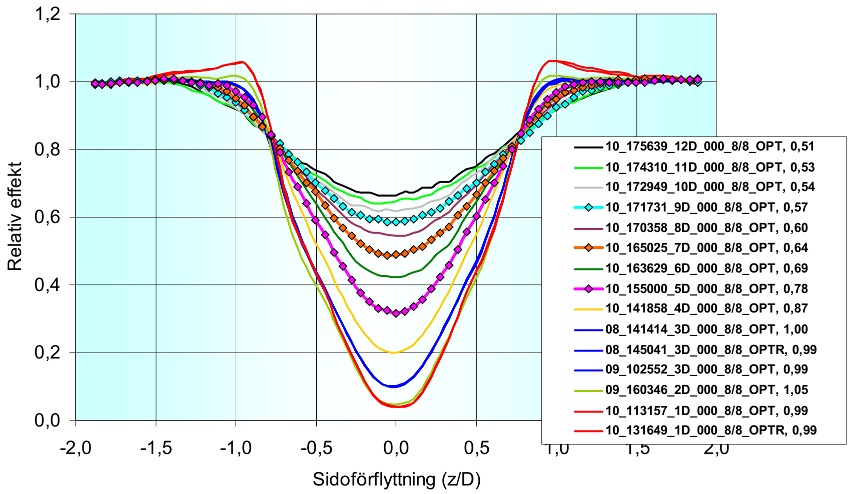
FFA/FOI-LT5, 2000-



Vattenfall Vindkraft AB 26 VATTENFALL

26

Relative Power



Vattenfall Vindkraft AB 27 VATTENFALL

27

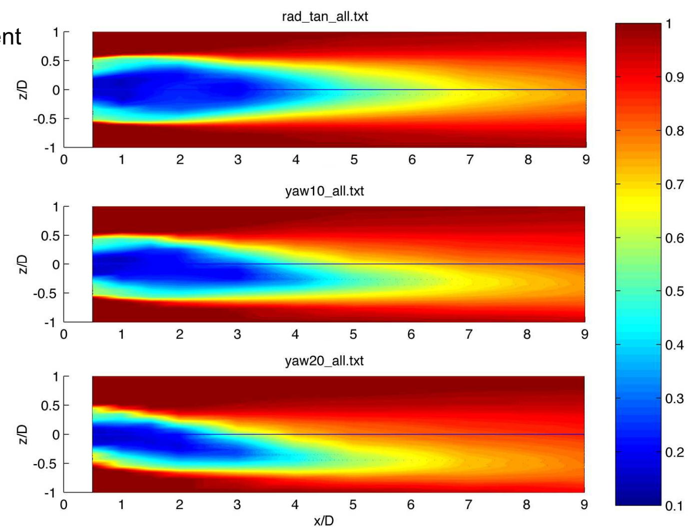
AWC- Active Wake Control

Yaw misalignment

0°

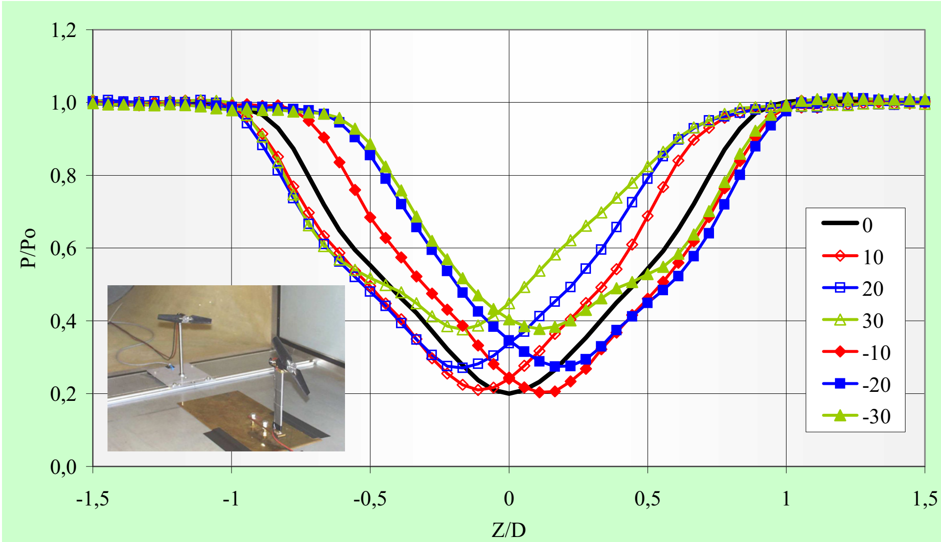
10°

20°



Vattenfall Vindkraft AB 28 VATTENFALL

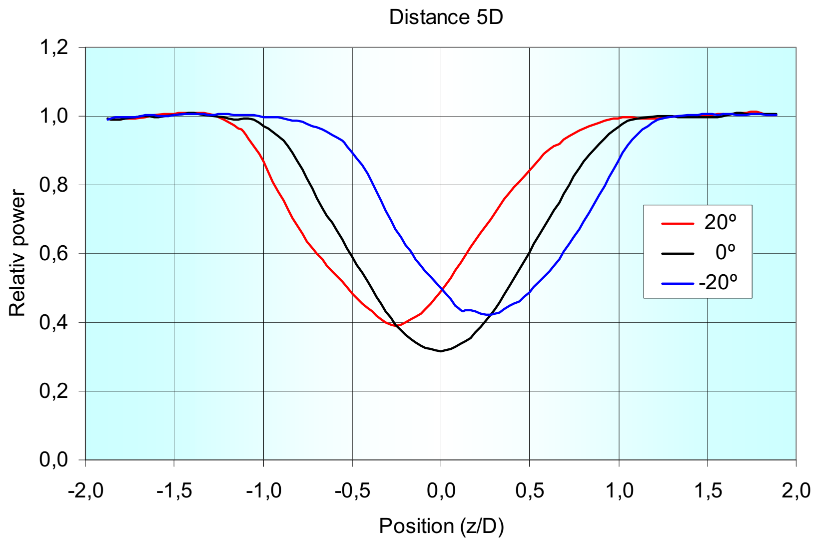
FFA/FOI-LT5, 2000-



Vattenfall Vindkraft AB 29 VATTENFALL

29

FFA/FOI-LT5, 2000-



Vattenfall Vindkraft AB 30 VATTENFALL

30

Conclusions from WT tests

- **The turbine ”sees” the upstream wind through a ”window” that is smaller than the diameter of the turbine**

=> The turbine can see ”free” wind deep inside wind farms
=> The maximum power loss can be significant

- **The development of the wake scales on the size of the object**

=> go further downstream behind a cluster of turbines to reach the same level of recovery as behind individual turbines (simpel scaling)

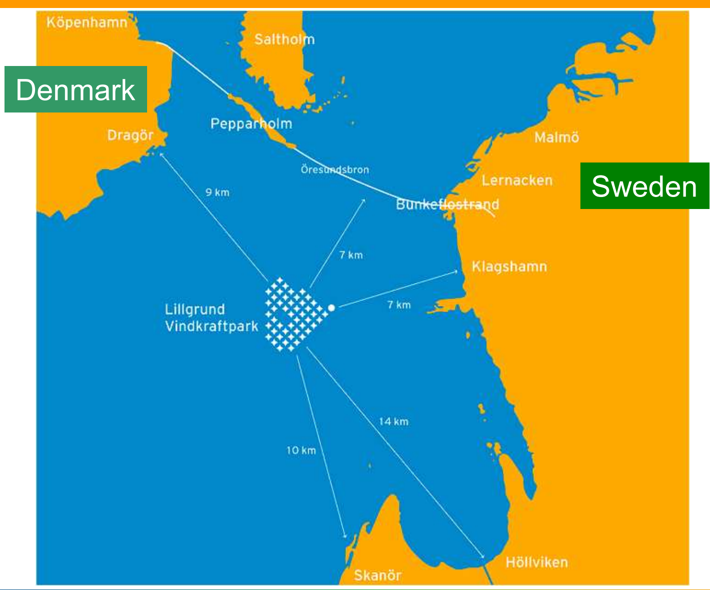
- **The wakes can be ”pushed” aside**

=> Not only wind direction and relative position, but also yaw-misalignment has to be taken into account when predicting the wake development

Vattenfall Vindkraft AB 31 VATTENFALL

31

Lillgrund



Vattenfall Vindkraft AB 32 VATTENFALL

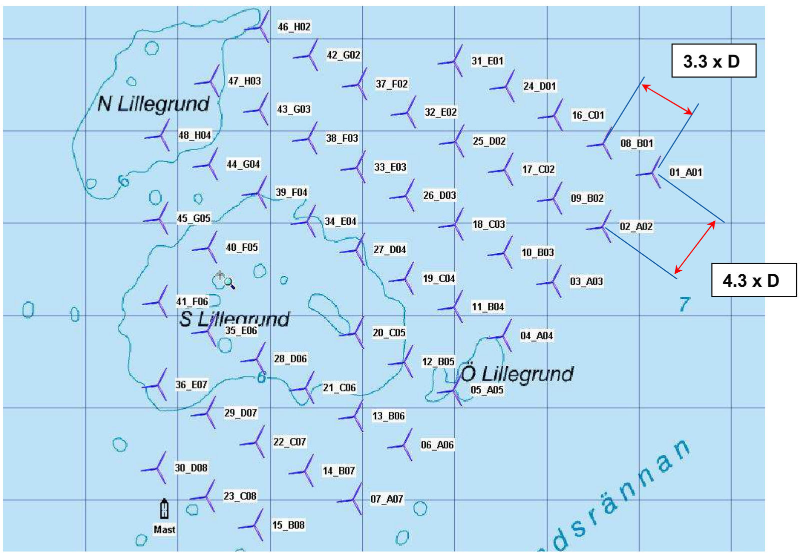
32

Lillgrund

Vattenfall Vindkraft AB 33 VATTENFALL

33

Lillgrund (48 SWT-2.3 MW)



Vattenfall Vindkraft AB 34 VATTENFALL

34

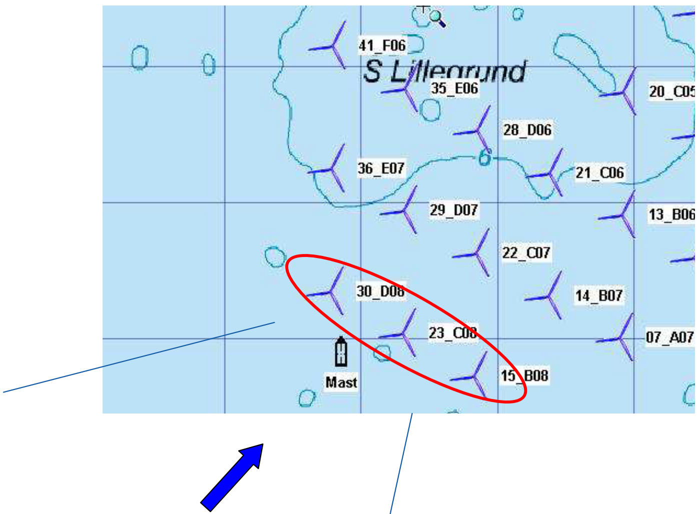
Turbine and Metmast

Turbines:
Power: 2.3 MW
Diameter: 93 m
Hubheight: 65 m

Met Mast:
Height: 65m

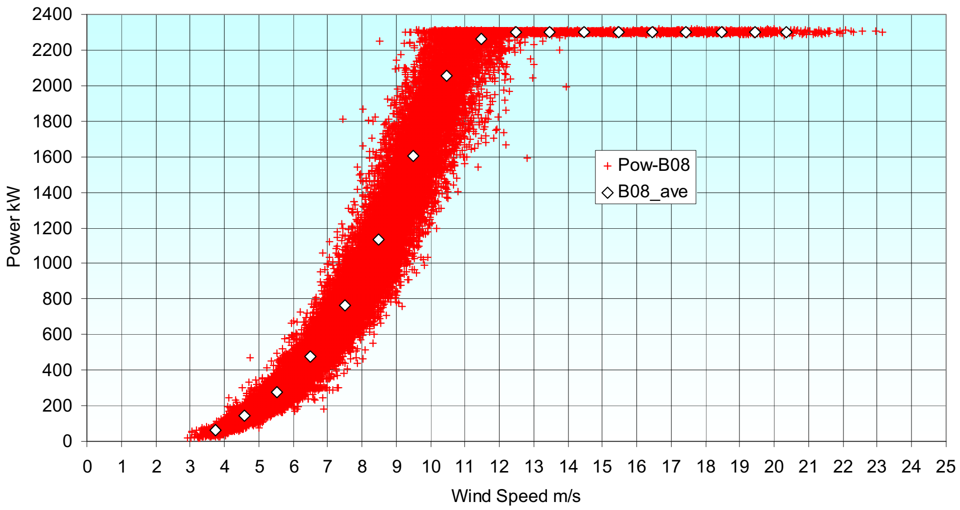
35

Power curve according to IEC 61400-12-1



36

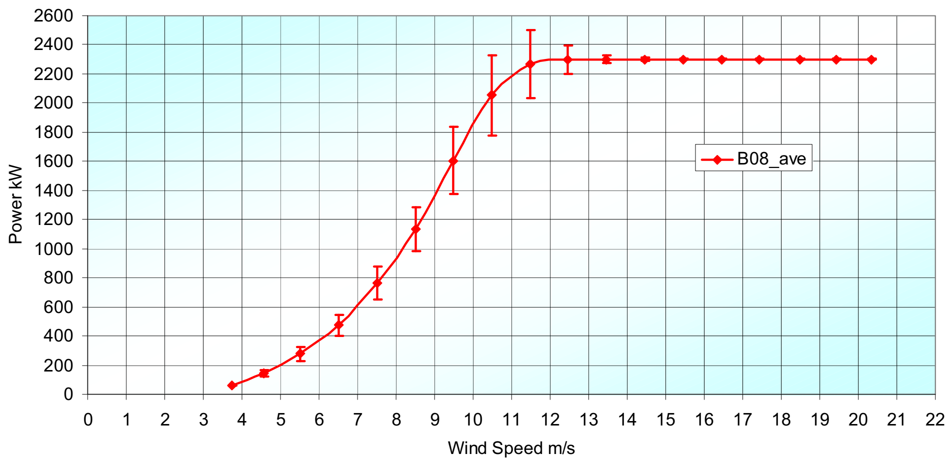
Power curve according to IEC 61400-12-1



Vattenfall Vindkraft AB 37 VATTENFALL

37

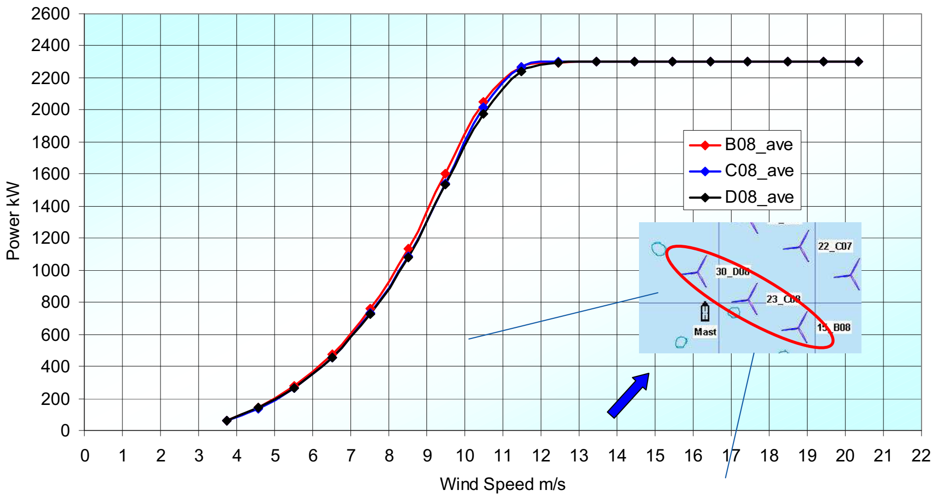
Power curve according to IEC 61400-12-1



Vattenfall Vindkraft AB 38 VATTENFALL

38

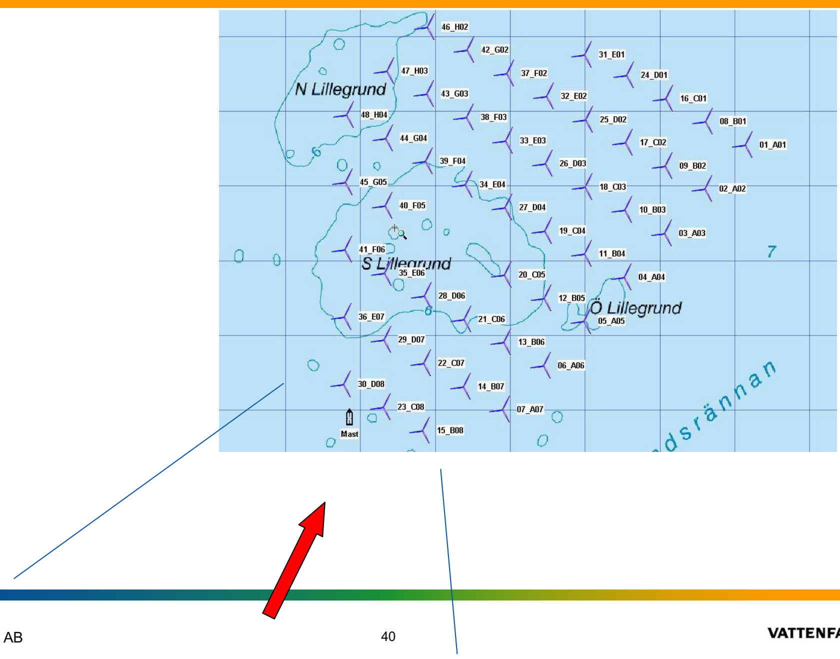
Power curves for the turbines in row 8



Vattenfall Vindkraft AB 39 VATTENFALL

39

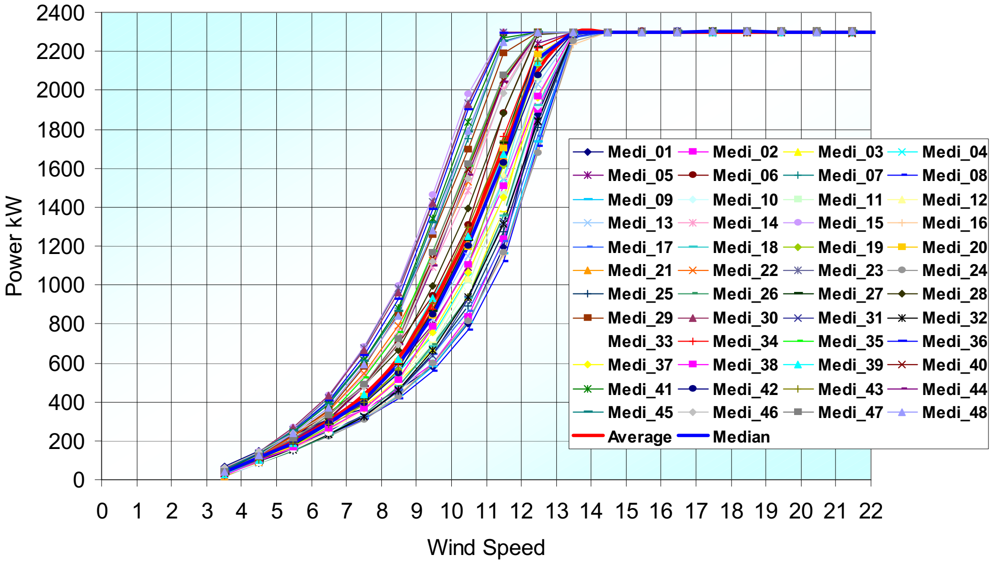
Whole Wind Farm



Vattenfall Vindkraft AB 40 VATTENFALL

40

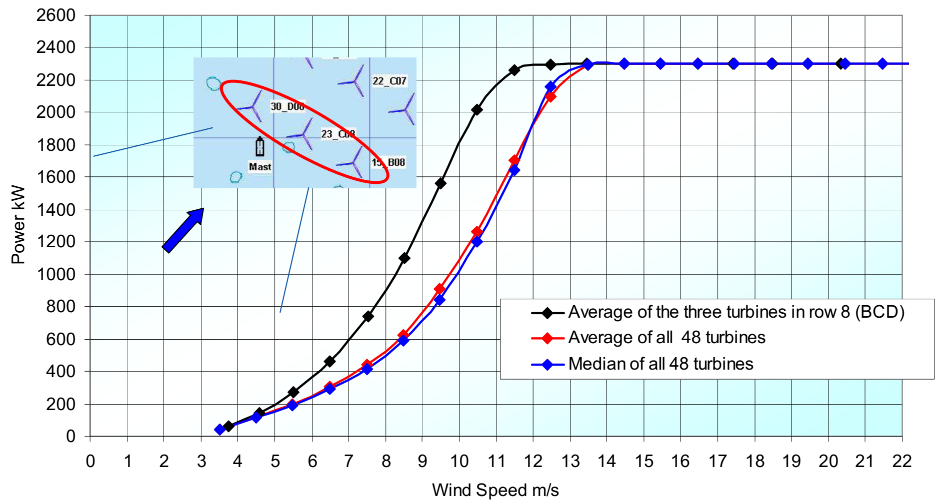
Power curves for all 48 turbines



Vattenfall Vindkraft AB 41 VATTENFALL

41

Front row – Whole Farm



Vattenfall Vindkraft AB 42 VATTENFALL

A “new” method to establish a power matrix for a wind farm

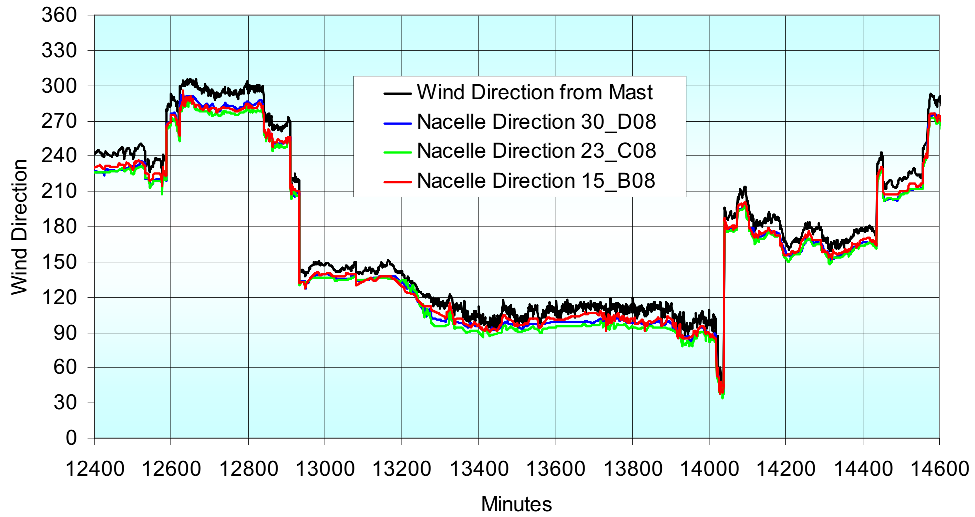
- The relative power is calculated as the ratio between the power output of any turbine in the farm (**object**) and the power level taken from one ore more undisturbed turbine(s) up front (**reference)**

$$P_{REL} = {P_{OBJ}}/{P_{REF}}$$

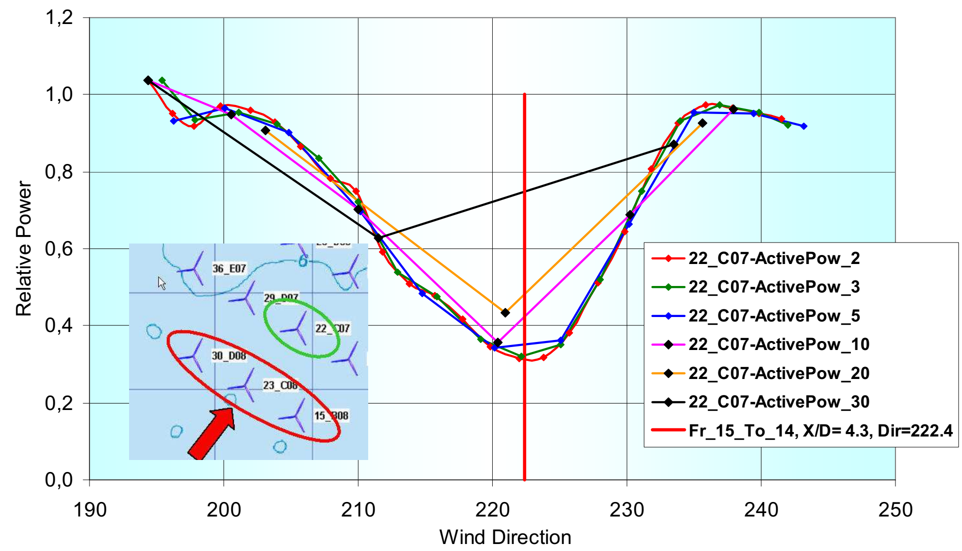
- No met mast is required
- Nacelle direction is used as “indicator” of wind direction
- No wake loses are assumed for wind speeds above rated wind speed

43

Nacelle direction compared to Mast wind direction



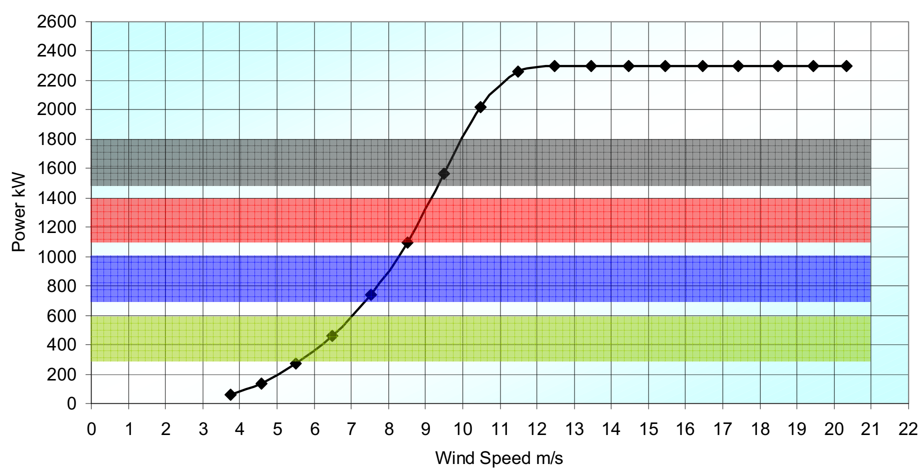
Bin-width from 2° to 30°



Vattenfall Vindkraft AB 45 VATTENFALL

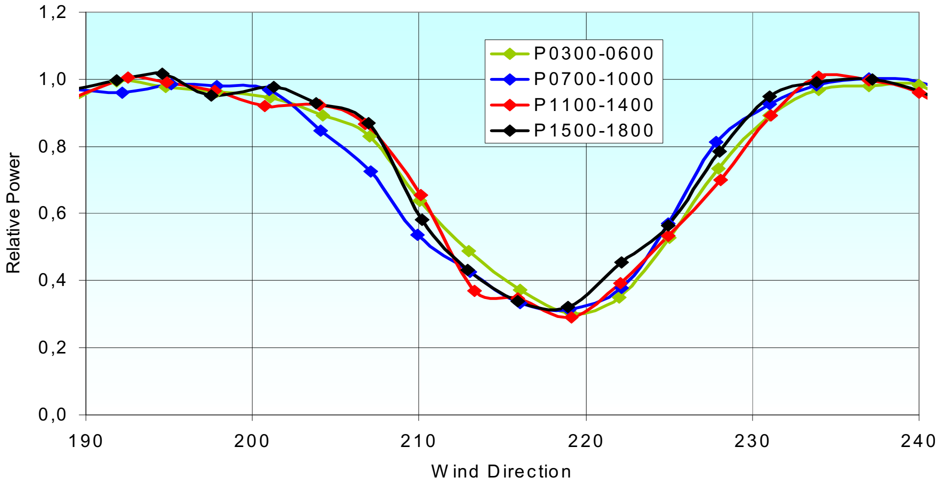
45

Selected Power Ranges



Vattenfall Vindkraft AB 46 VATTENFALL

Relative power for different power ranges

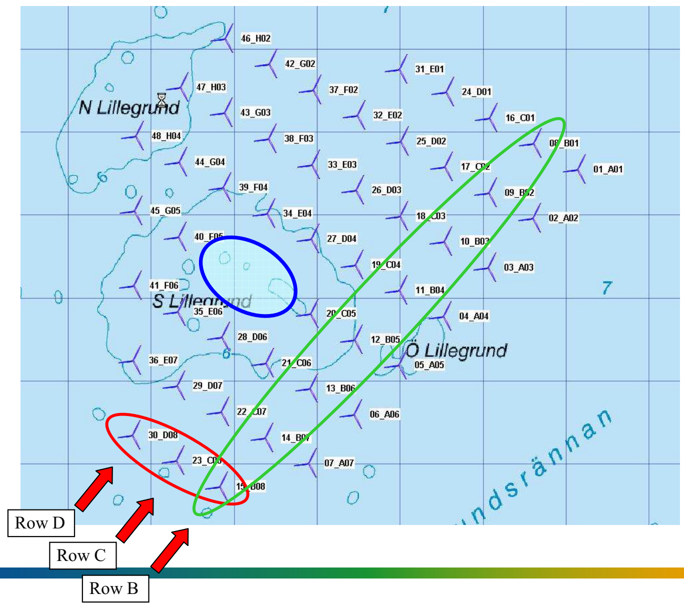


Relative power is ”independent” of power level

Vattenfall Vindkraft AB 47 VATTENFALL

47

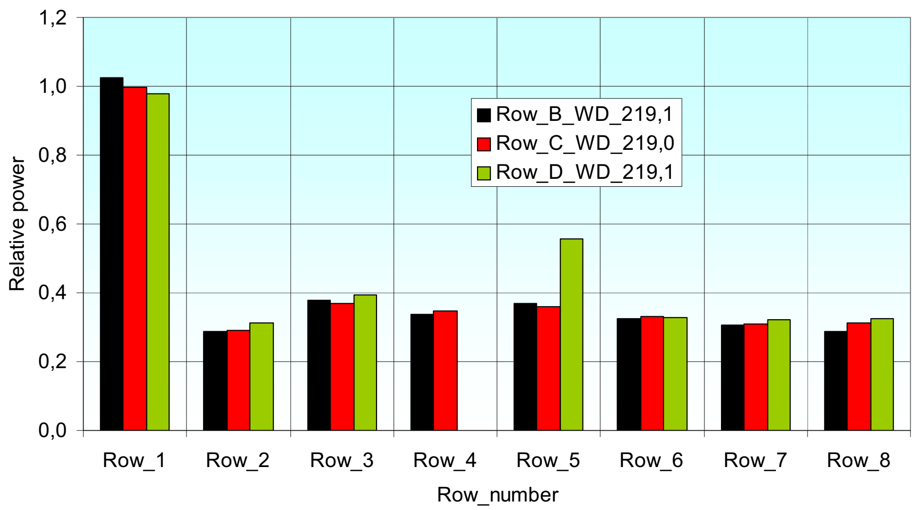
Relative power (4.3xD separation)



Vattenfall Vindkraft AB 48 VATTENFALL

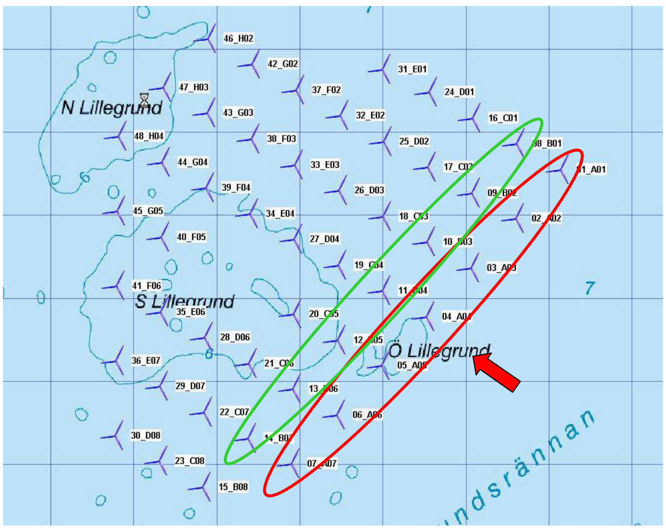
48

Relative power (4.3xD separation)



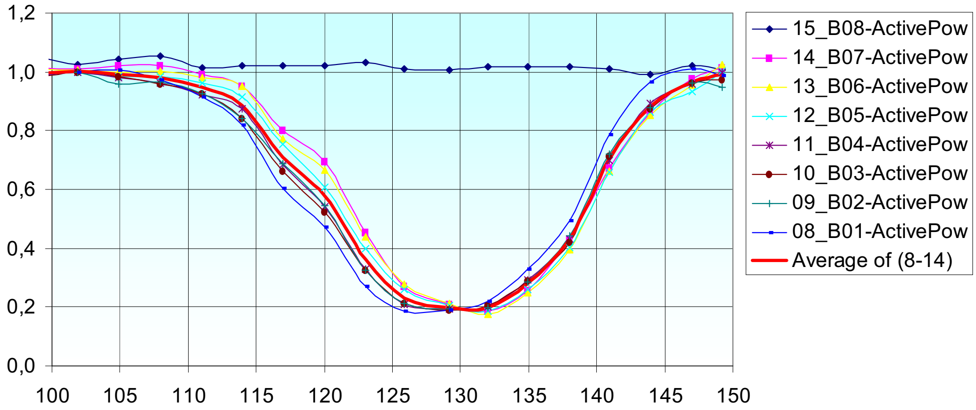
Vattenfall Vindkraft AB 49 VATTENFALL

Relative power (3.3xD separation)



Vattenfall Vindkraft AB 50 VATTENFALL

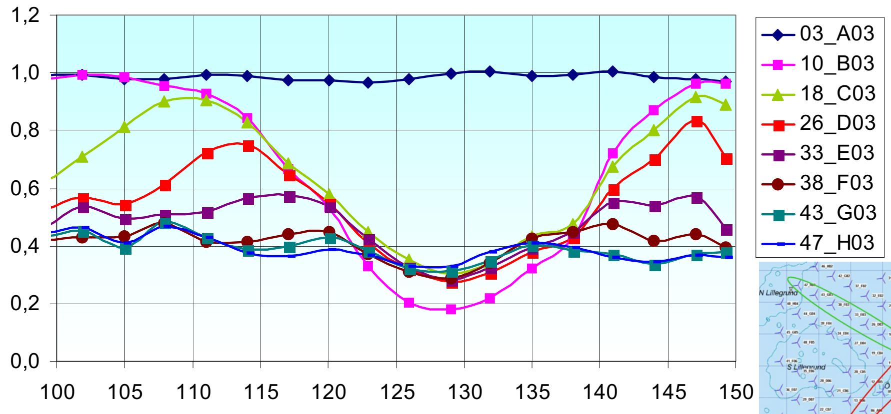
Relative power for 2:nd turbines in the row (3.3xD)

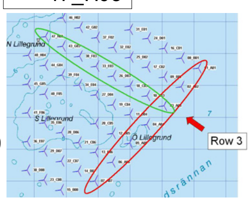


Vattenfall Vindkraft AB 51 VATTENFALL

51

Relative power in row 3 (3.3xD separation)

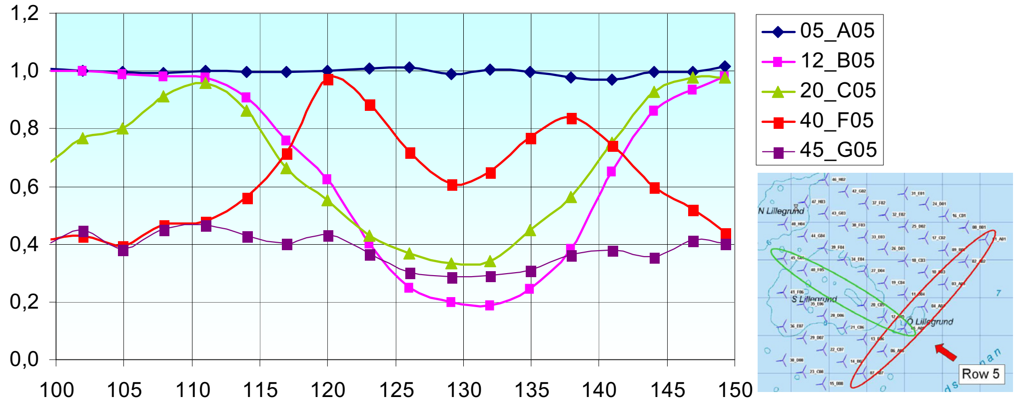




Vattenfall Vindkraft AB 52 VATTENFALL

52

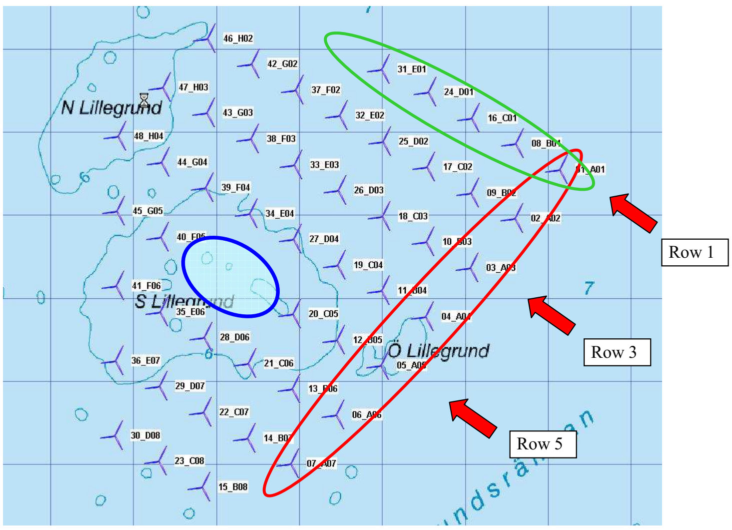
Relative power in row 5 (3.3xD separation)



Vattenfall Vindkraft AB 53 VATTENFALL

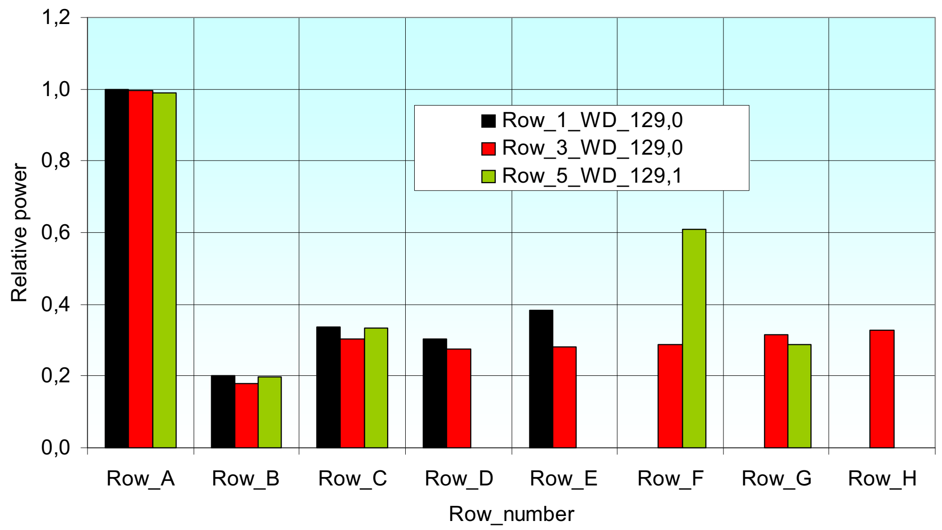
53

Relative power (3.3xD separation)



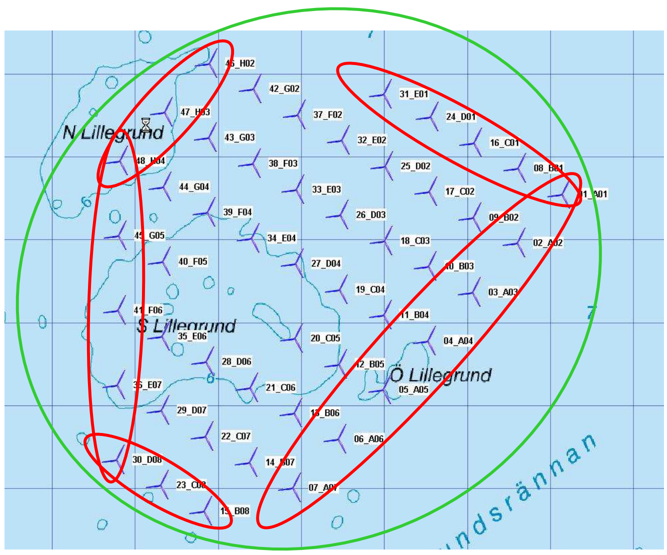
Vattenfall Vindkraft AB 54 VATTENFALL

Relative power (3.3xD separation)



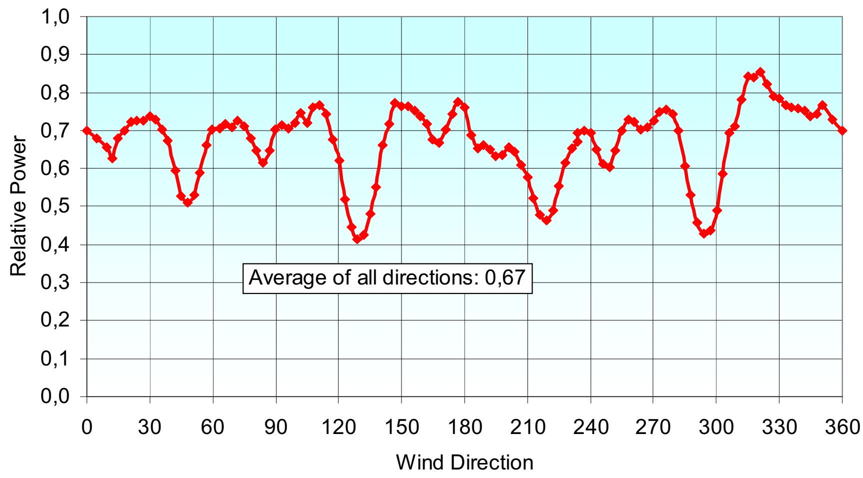
Vattenfall Vindkraft AB 55 VATTENFALL

Whole Windfarm



Vattenfall Vindkraft AB 56 VATTENFALL

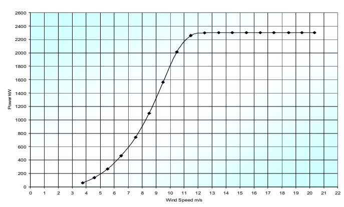
Whole Windfarm



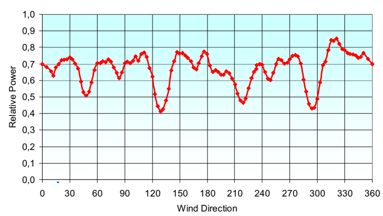
Vattenfall Vindkraft AB 57 VATTENFALL

57

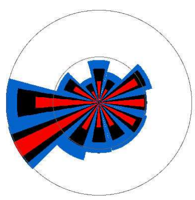
Annual Energy Production for Wind Farms

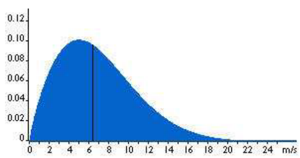


+



+





= AEP (MWh)

Vattenfall Vindkraft AB 58 VATTENFALL

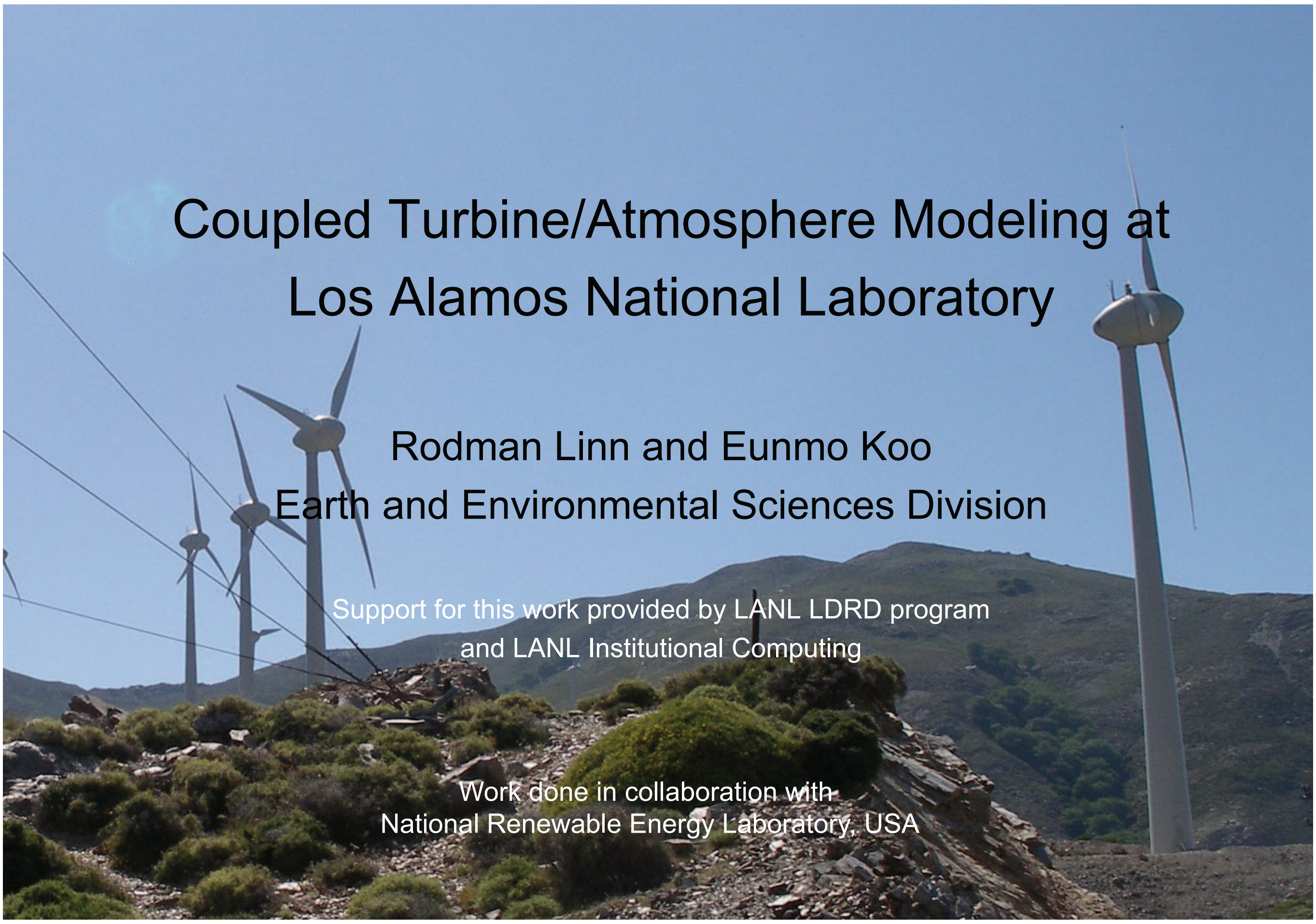
58

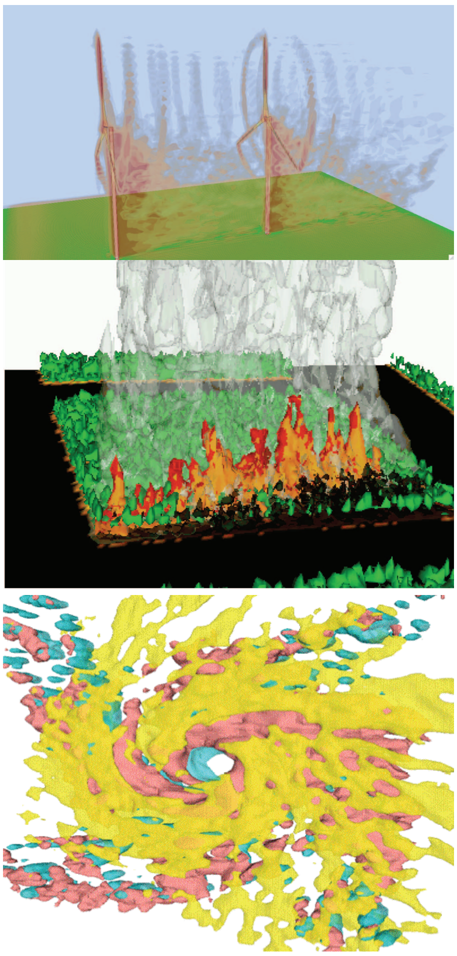
Conclusions

- Wake losses as expected
- Wind farm efficiency of 67% below rated
- Wind farm efficiency of 77-80% for all wind speeds
- Significant wake losses occur when the wind is blowing along the rows
- The second turbine in each row reaches only 20-30%
- The method to establish a matrix of relative power levels appears to work well
- The method is proposed for IEC 61400-12-3 (work now put on hold)

Vattenfall Vindkraft AB 59 VATTENFALL

59

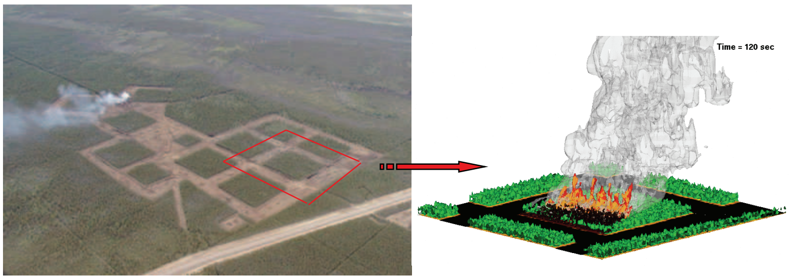




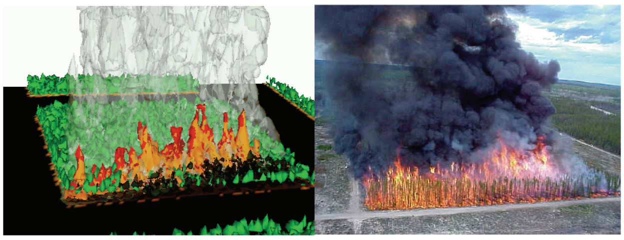
HIGRAD/FIRETEC

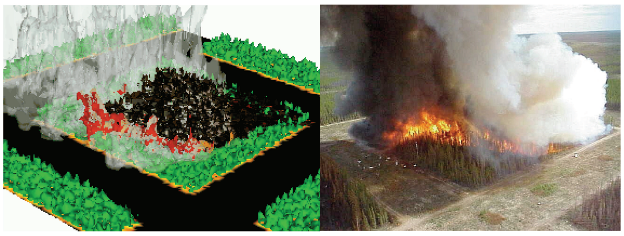
- Atmospheric hydrodynamics model
- Two or three-dimensional calculations
- Fully compressible formulation
- Multi-phase continuum and Lagrangian capabilities
- Test bed for various numerical solution techniques (method of averages, Newton Krylov, etc.)
- Multi-scale TKE LES turbulence closure
- Wide range of applications including
  - Urban dispersion
  - Aerosol transport
  - Explosive dispersion
  - Hurricanes
  - Mars atmospheric processes (dust storms, CO_2 migration)
  - Wildfires
  - Urban firestorms
  - Wind interaction with wind turbines
  - Seed dispersal/Migration of invasive species

Los Alamos NATIONAL LABORATORY



FIRETEC simulations of the International Crown Fire Modeling Experiment (ICFME) plot 1. The following slide contains an illustration of the coupled effects of the fire and vegetation on the flow field in this simulation.


SIMULATION IMAGE AND PHOTOGRAPH FROM THE SOUTH

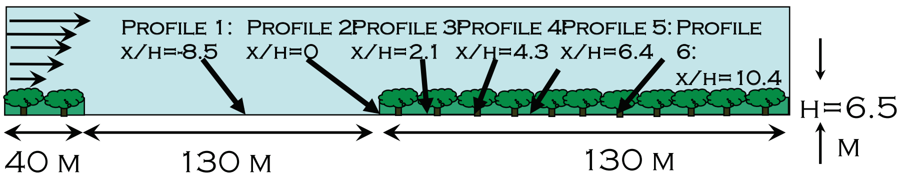

SIMULATION IMAGE AND PHOTOGRAPH FROM THE NORTHWEST


SIMULATION IMAGE AND PHOTOGRAPH FROM THE NORTHWEST

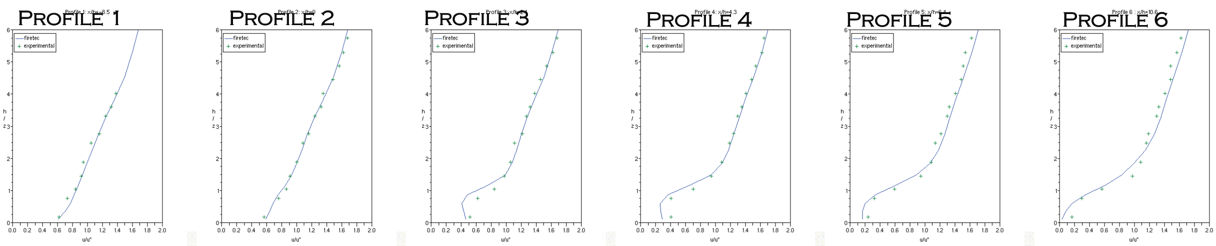

SIMULATION IMAGE AND PHOTOGRAPH OF THE NORTHEAST CORNER

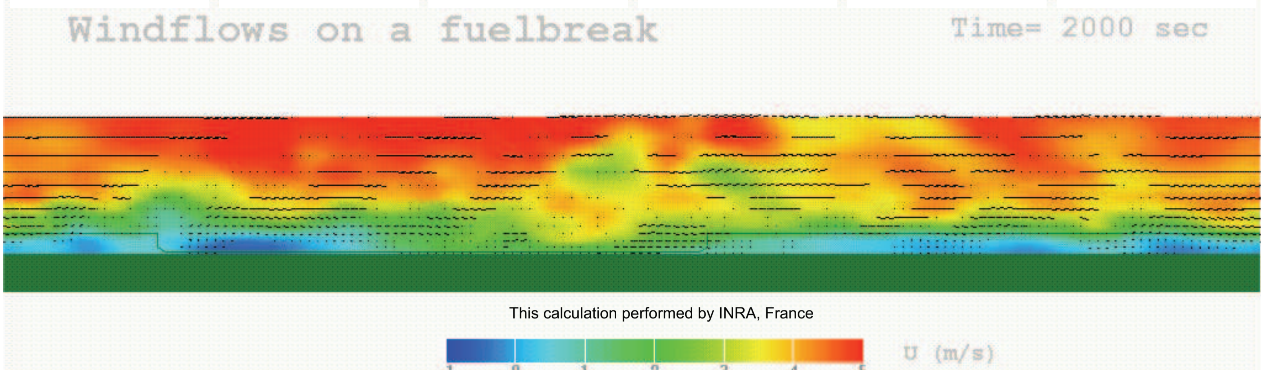
PHOTOGRAPHS COURTESY OF NATURAL RESOURCES CANADA ICFME WEBSITE, HTTP://FIRE.CFS.NRCAN.GC.CA/RESEARCH/ENVIRONMENT/ICFME/PHOTOGRAPHS_E.HTM

Los Alamos NATIONAL LABORATORY



Validated Streamwise Velocities Near a Fuel Break

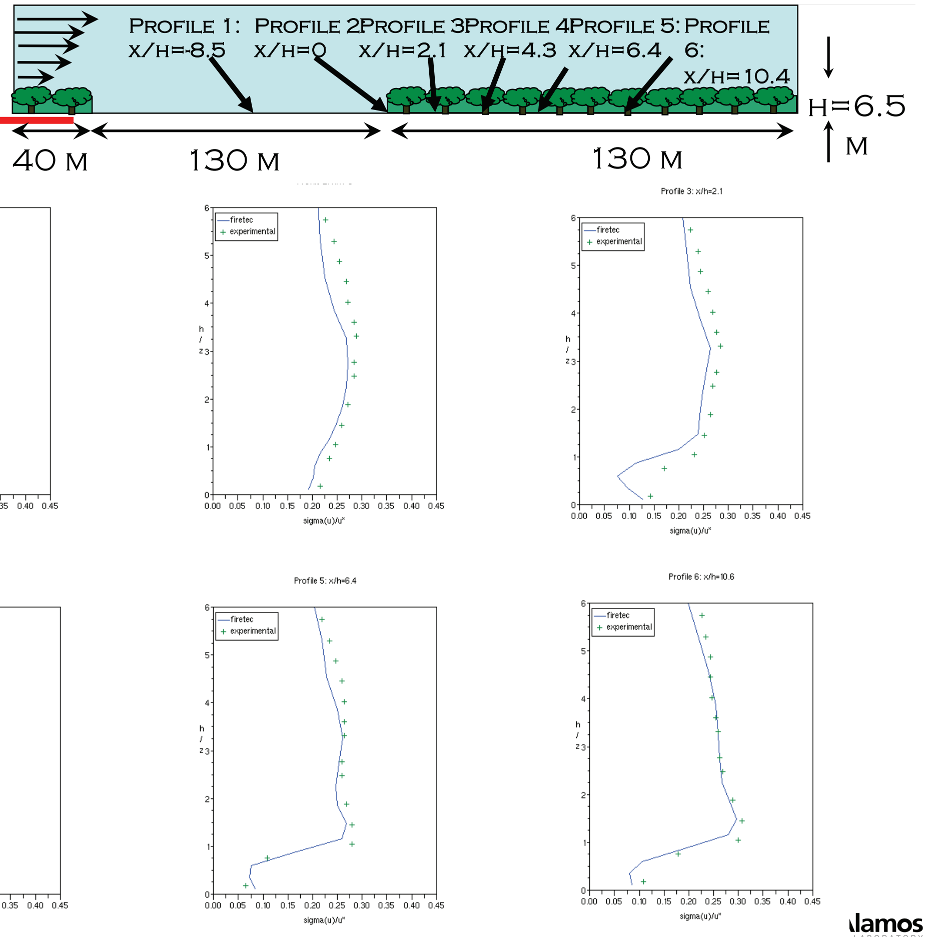




HIGRAD simulates the interaction between winds and canopies including the induced turbulence and mixing. The images on this slide illustrate simulations that have been performed for validation of averaged HIGRAD winds and turbulence against data (shown in the plots in the middle of the slide) for various locations (shown at the top of the slide) in the vicinity of a fuel break. The image at the bottom of the slide illustrates an instantaneous flow field in the presence of the fuel break.

Los Alamos NATIONAL LABORATORY

U deviation

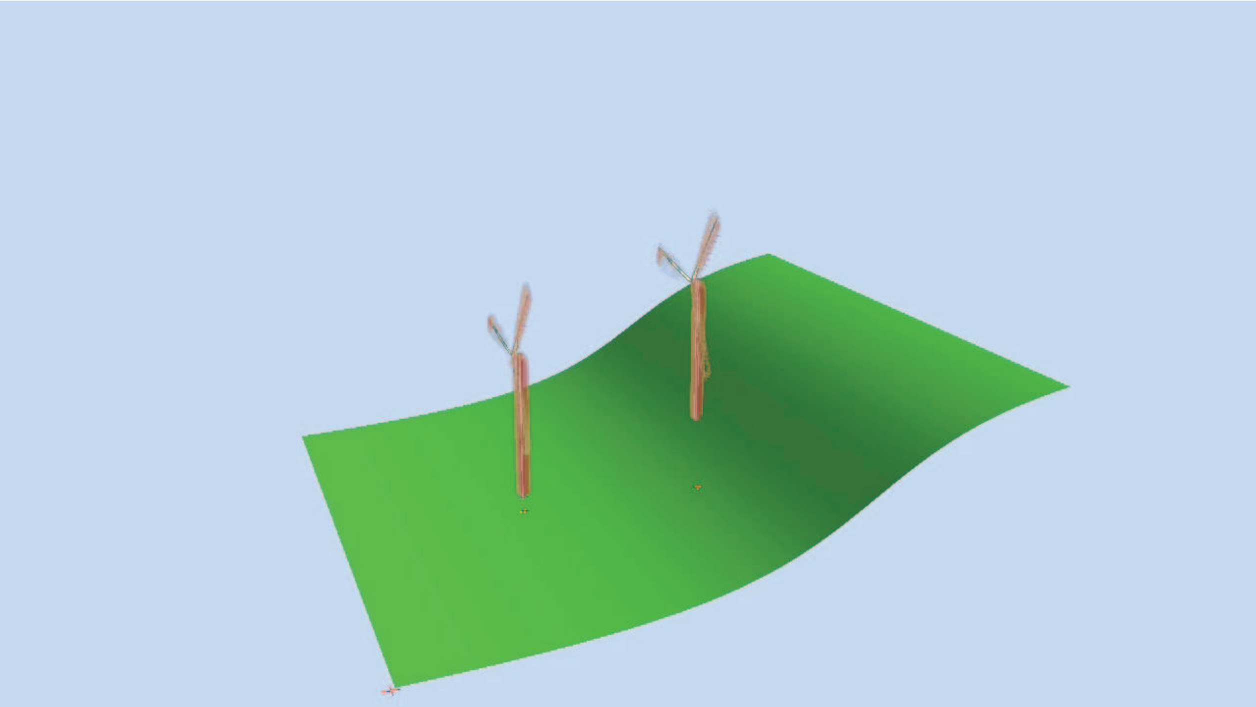


Leveraging HIGRAD development to benefit Wind Energy Research

- HIGRAD provides a capability to study the interactions of winds and turbines in complex situations influenced by:
  - Topography
  - Dynamic/unsteady wind conditions
  - Inhomogeneous vegetation
  - Solar heating/unstable mixing
  - Interaction between multiple turbines

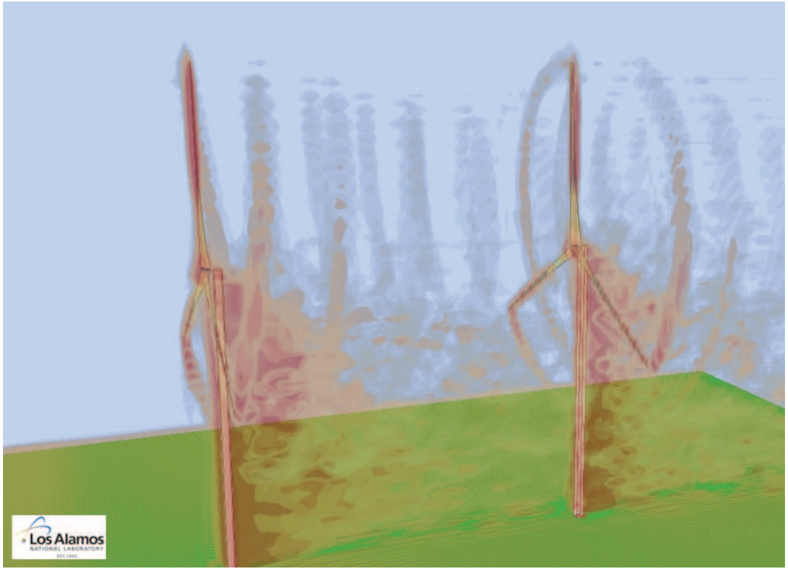
- HIGRAD results can be coupled and will complement existing public and private tools
- HIGRAD can utilize output from larger scale/lower resolution meso-scale/weather modeling tools.

Use of this combination of Eulerian and Lagrangian capabilities to represent wind turbine interaction with the atmosphere



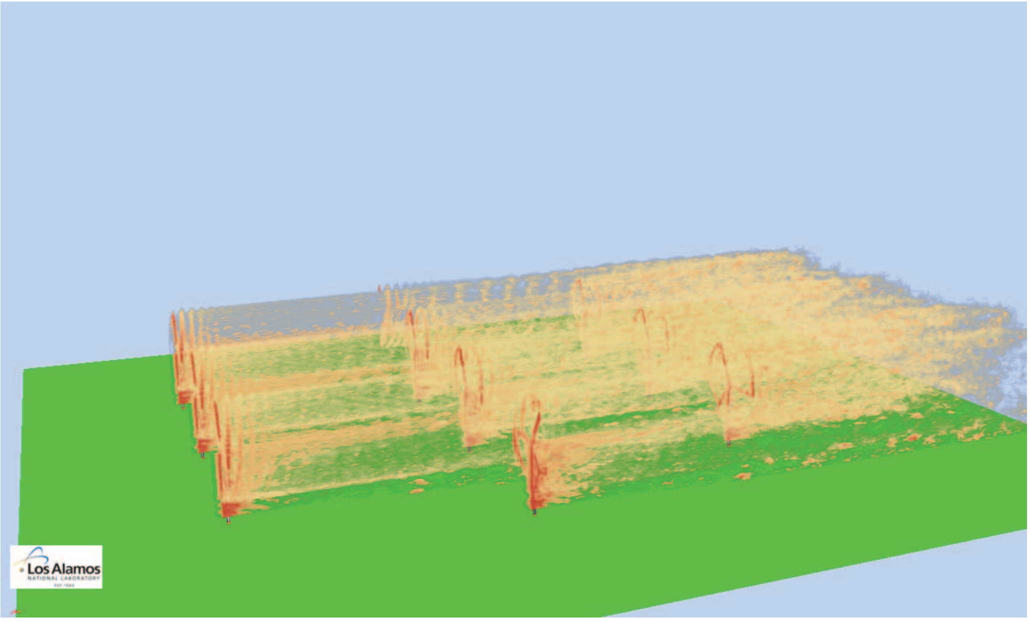
Isosurfaces show wind turbine-induced vorticity

Two-turbine simulations



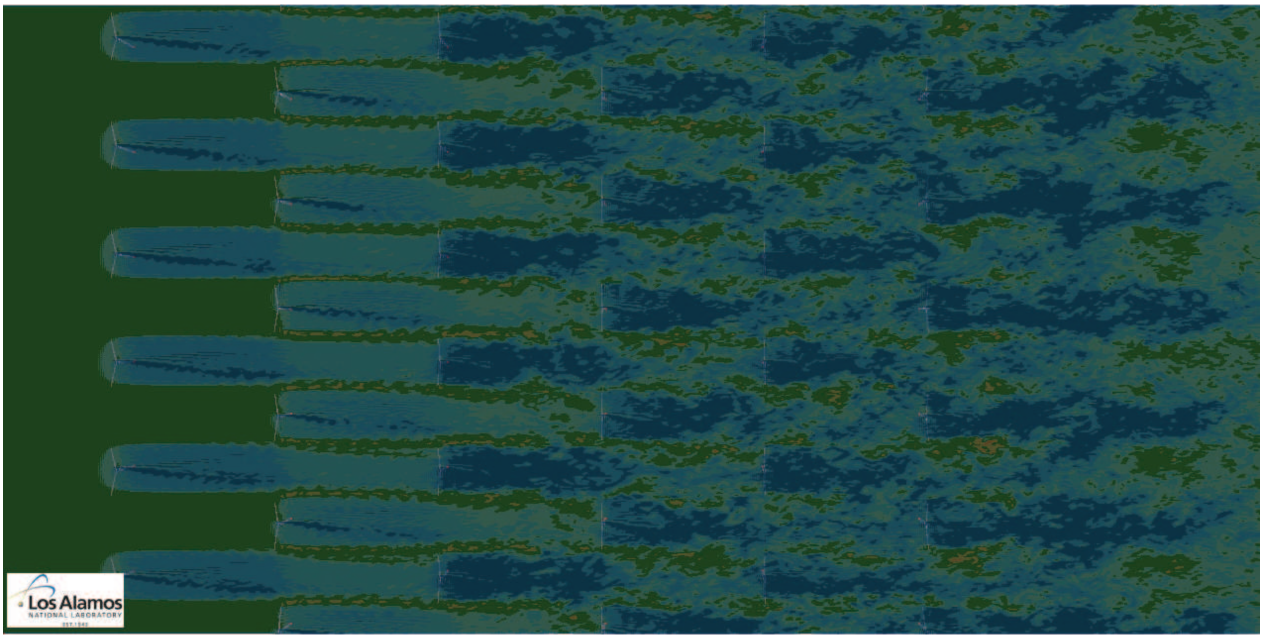
Turbine-induced vorticity

Nine Turbine Simulation in laminar shear (Turbine-induced Vorticity)



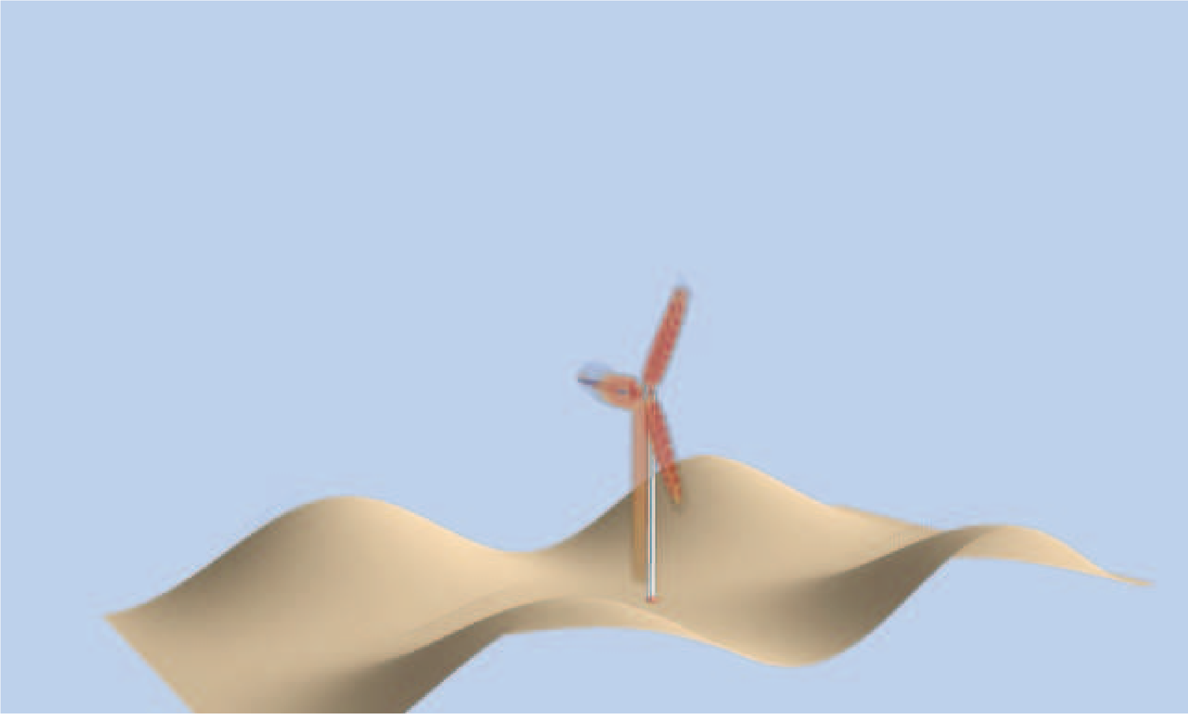
Los Alamos NATIONAL LABORATORY

36 Turbine Simulation in laminar shear (Axial velocity component at hub height)



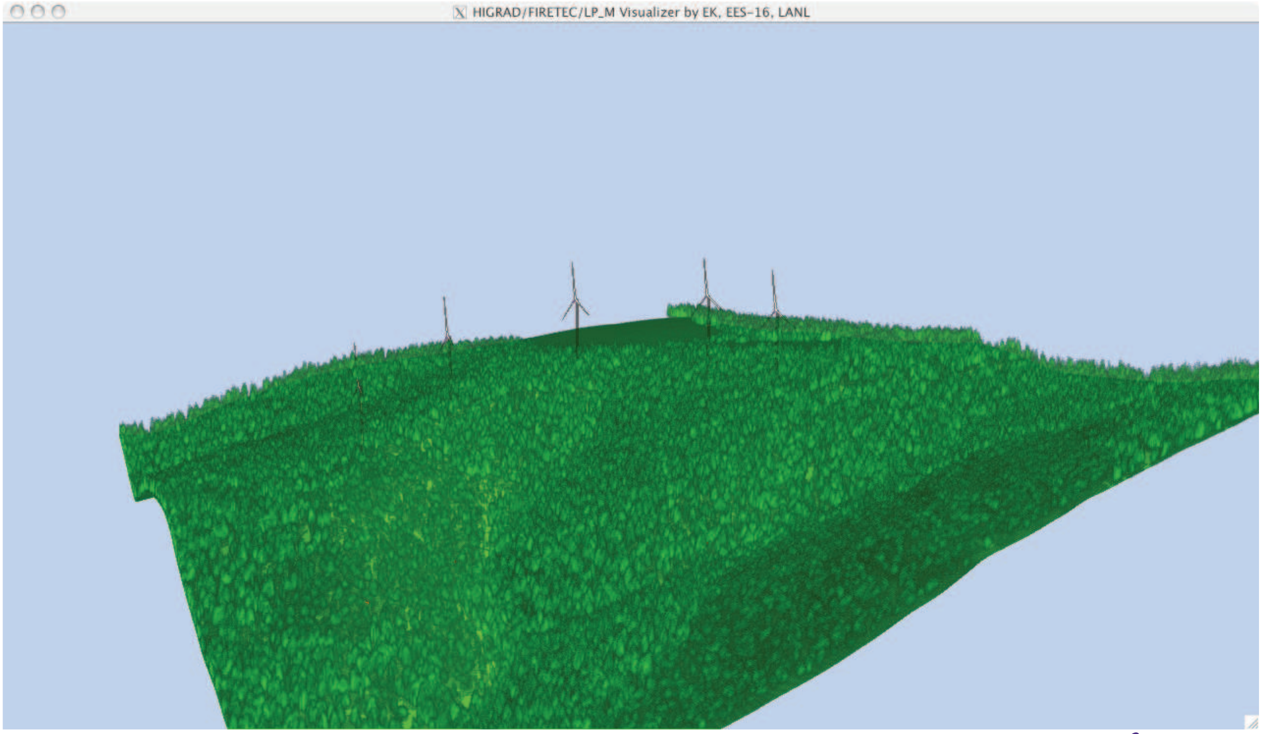
Los Alamos NATIONAL LABORATORY

Turbine/wind/topography



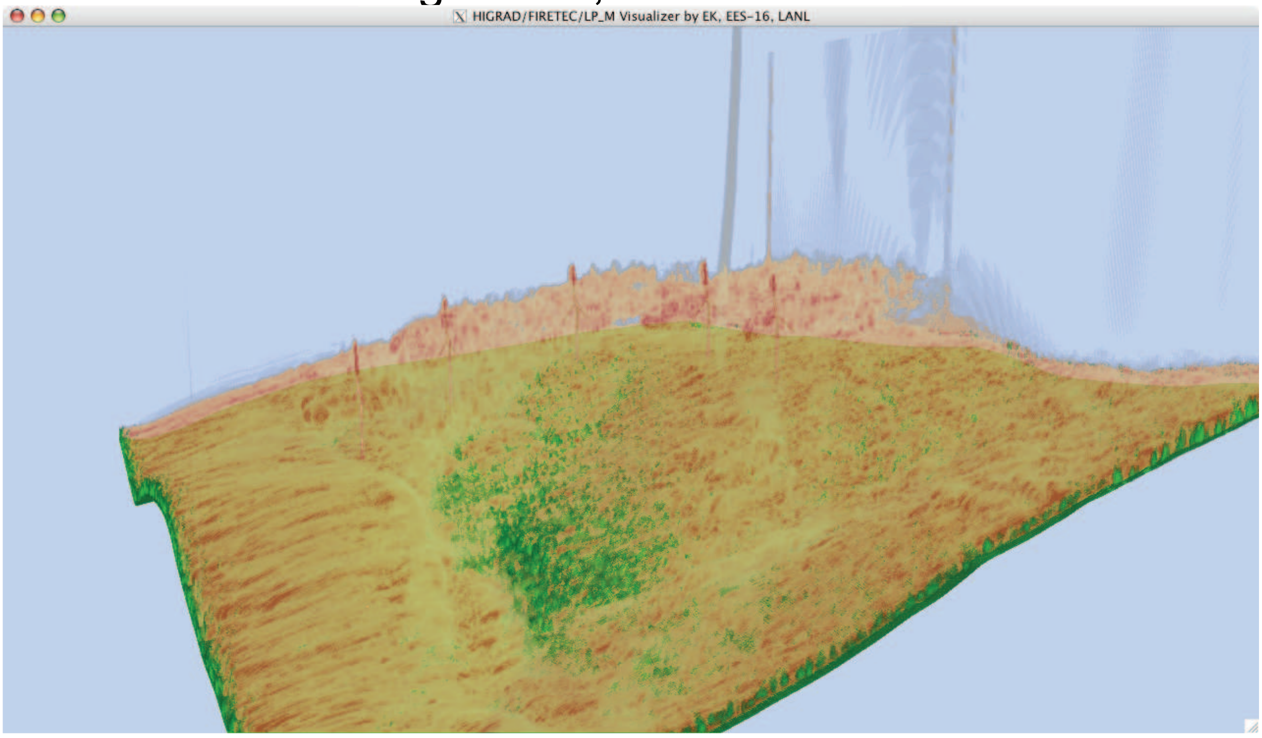
Los Alamos NATIONAL LABORATORY

Wind Turbines on Complex Terrain



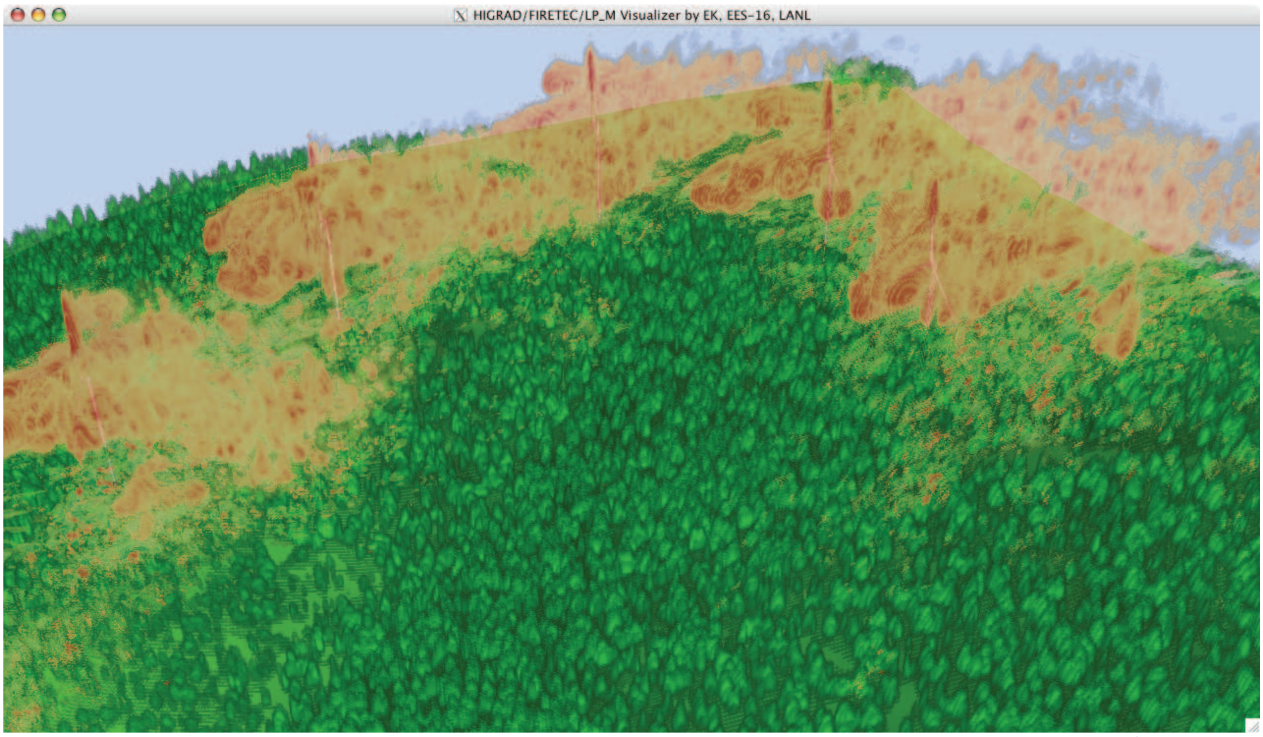
Los Alamos NATIONAL LABORATORY

Total Vorticity Resulting from Topography, Vegetation, and Turbines



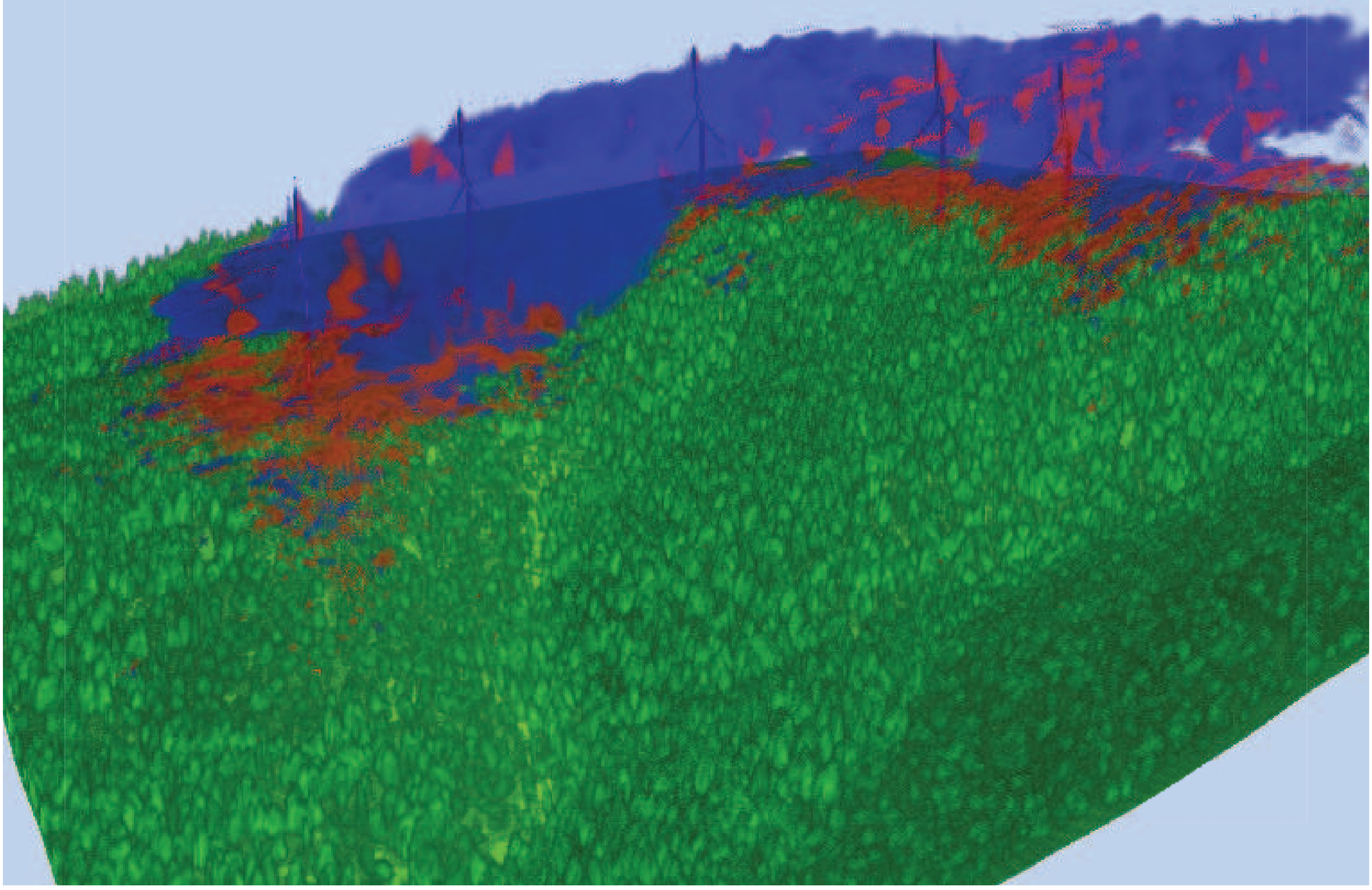
Los Alamos
NATIONAL LABORATORY

Vorticity Difference Resulting from Turbines



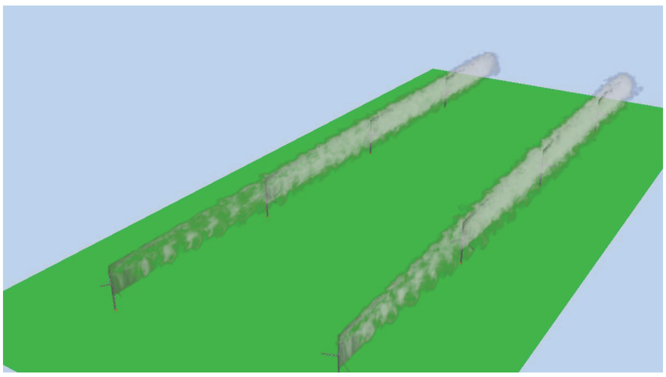
Los Alamos
NATIONAL LABORATORY

X-Velocity Difference Resulting from Turbines



Exploring the complexity of simulating real conditions?

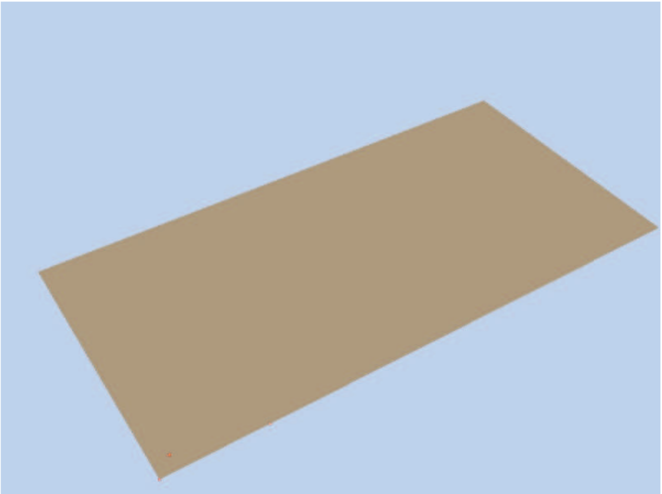
Influence of:
- Turbulence?
- Atmospheric Stability?
- Shear profile?
- Horizontal Gradients?



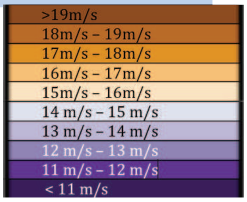
Simulation conditions:
- Laminar wind shear
- UH=10 m/s
- Neutral conditions
- Tracer emitted in single vertical line behind turbines

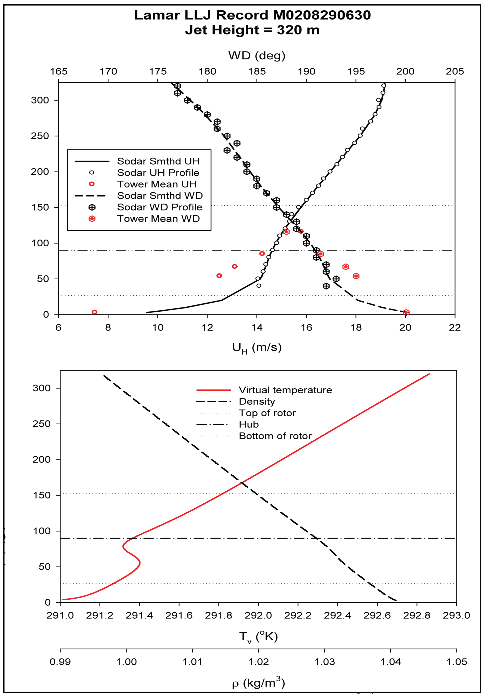
Los Alamos NATIONAL LABORATORY

Integration of TurbSim with HIGRAD (work in progress with NREL)



Streamwise velocity at hub height





Domain size: 1.4 km by .7 km with 2 m horiz. resolution

Current HIGRAD/FIRETEC-WindBlade Activities

- Explore the broad general trends of the model results
- Begin interfacing with mesoscale atmospheric models and TurbSim for definition of dynamic boundary conditions
- Implementing hub/generator resistance characteristics
- Identify partners with whom to work
- Validate the simulations results or identify shortcomings
  - Publicly available data
  - Through partnerships and collaborative agreements

Wake Combination Models

Peter Stuart
Technical Manager

5-6 May 2010

power for good

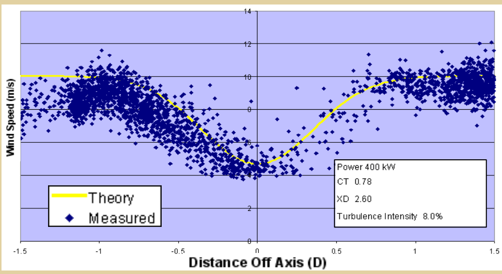
1

Wake Combination Models: Introduction

Common Industry (Velocity Deficit) Wake Models

- Ainslie
- Park

Both are essentially single turbine models and in day to day use must be extended to include the effects of multiple turbines.



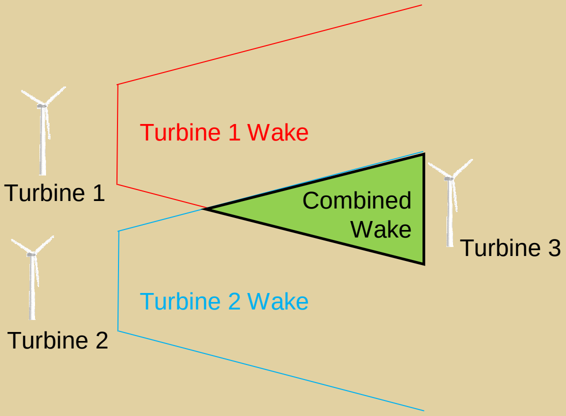
Single Turbine Calculation using Ainslie Model

2

Wake Combination Models: Introduction

Wake Combination Model (Definition)

A method by which many individual calculations using a single turbine wake model may be combined to represent the resultant effect of many wind turbines.



3

Wake Combination Models: Examples

Combination models have limited coverage in the literature, in particular with respect to the important role they play in the most common engineering tools.

Wake combination models are normally a fairly heuristic extension of the underlying velocity deficit model, with some theoretical or empirical basis. Some common examples are:

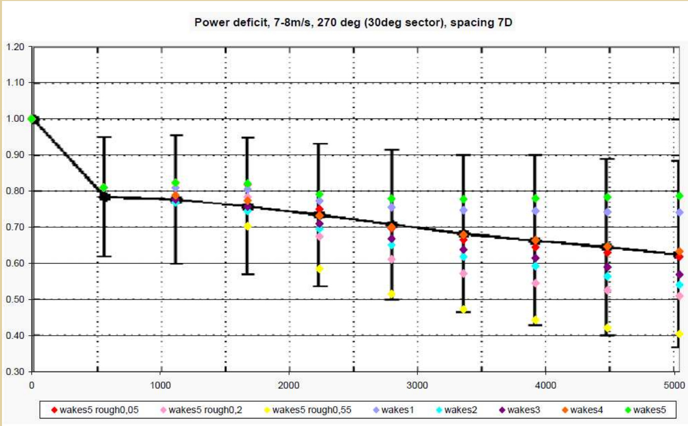
- Linear Combination
- Geometric Superposition
- Root Sum Squared
- Max Deficit (empirical)

Combinations of the above are also used e.g. Average of RSS and Linear. Selection of combination model is normal based on a comparison with data.

4

res

Wake Combination Models: Comparison with Data (Horns Rev)



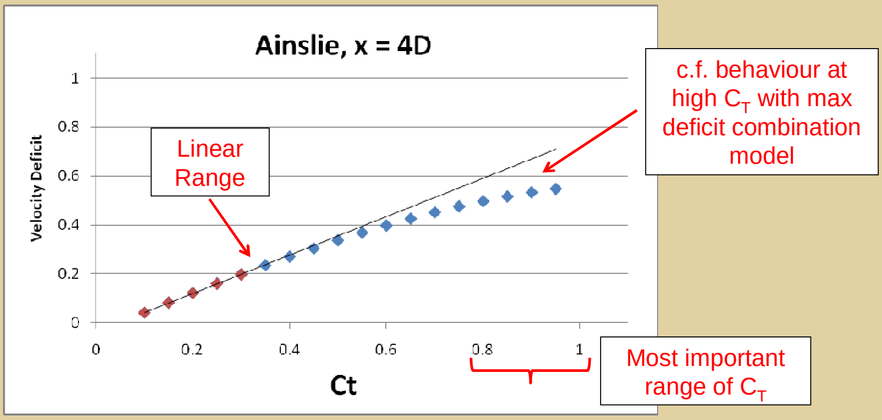
Selection of Wake Combination Model via Comparison with Horns Rev Dataset.
1) RSS, 2) Linear, 3) Geometric, 4) Average RSS & Linear, 5) Max

G. Habenicht, RES, 2008, http://www.dffv.dk/vindkraftnet.htm

5

res

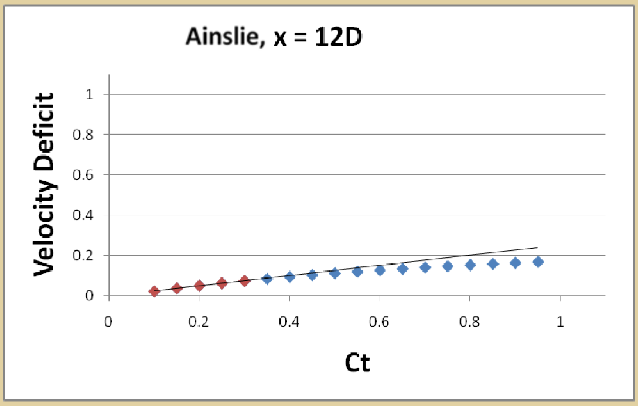
Wake Combination Models: Single wake as a combination of wakes



If effect of increasing C_T on velocity deficit can be thought of as combining wakes originating from the same point in space → different combination methods work for different C_T?

6

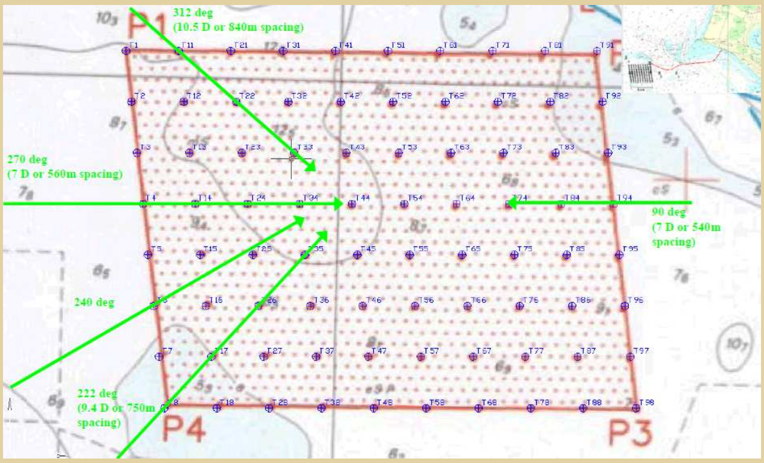
Wake Combination Models: Single wake as a combination of wakes



At large turbine spacing the dependency of velocity deficit on C_T is more linear → different combination methods work for different turbine spacing?

7

Wake Combination Models: Horns Rev, Different Turbine Spacings

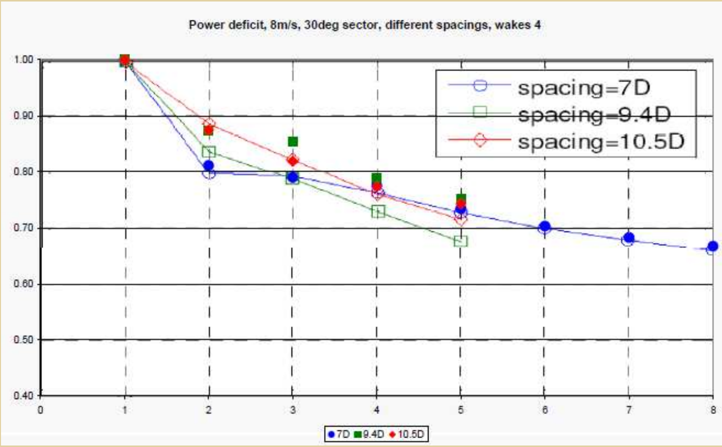


Horns Rev Wind Farm contains turbine spacing ranging from 7D to 10.5D.

8

res

Wake Combination Models: Average of RSS & Linear Validation for Different Spacings

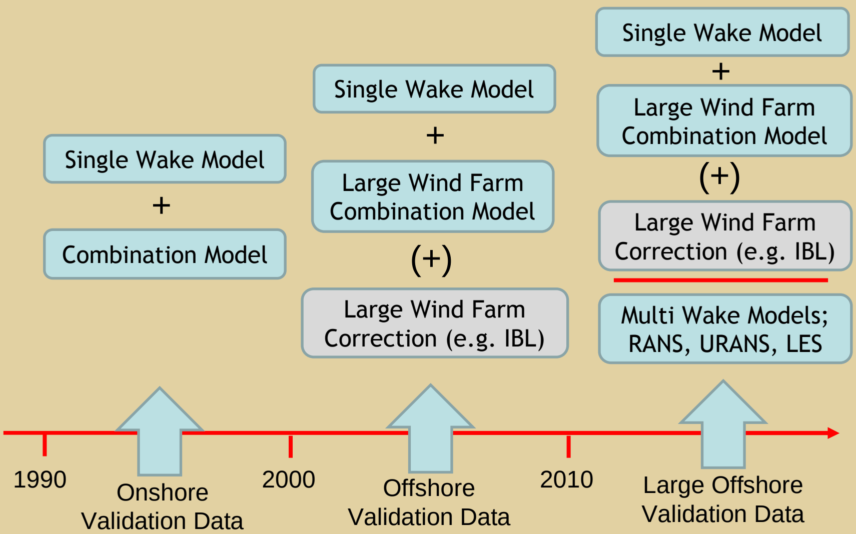


A combination method optimised around one turbine spacing may not work well for a different turbine spacing. Empty symbols = Data, Filled Symbols = Model.

9

res

Wake Combination Models: Industry Time Line



10

Wake Combination Models: Conclusions

- Wake combination models are an essential feature of current engineering models.

- Access to offshore validation dataset has exposed some of the failings of past combination models and helped new models be developed.

- There is still plenty of room for improvement and a risk that models optimised for limited datasets are applied too generally.

- The rise of more advanced true multi-turbine models may make wake combination models redundant...

...however this seems a way off and in the near term more advance models may play an important role in helping improve existing engineering models e.g. by acting as a proxy for more thorough datasets.

11

RAVE

RESEARCH AT ALPHA VENTUS

Eine Forschungsinitiative des Bundesumweltministeriums

Lidar systems for measurement of wake characteristics of multi-MW wind turbines

J. J. Trujillo[1], O. Bischoff[2], M. Hofsäß[2],
A. Rettenmeier[2], D. Schlipf[2], D. Trabucchi[1] and Martin Kühn[1]

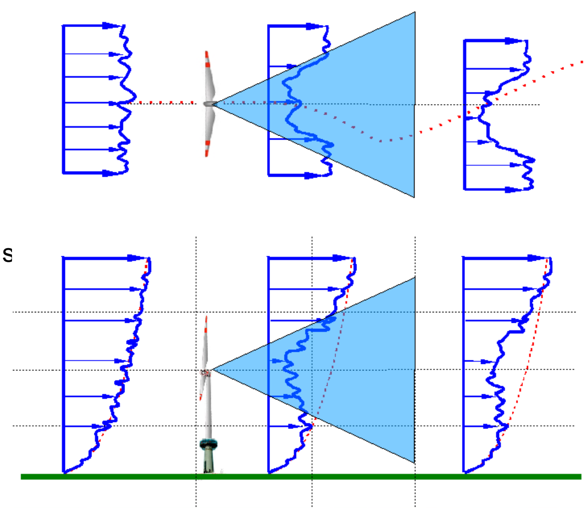
[1] now at ForWind - University of Oldenburg, Germany
[2] Endowed Chair of Wind Energy, Universität Stuttgart, Germany,

SWE Stiftungslehrstuhl Windenergie am Institut für Flugzeugbau
Universität Stuttgart Germany
Carl von Ossietzky Universität Oldenburg Wind energy systems

2

Motivation of full-field wake measurements

- Understanding of wake aerodynamics under real atmospheric conditions
- Full field data for direct validation of wake models



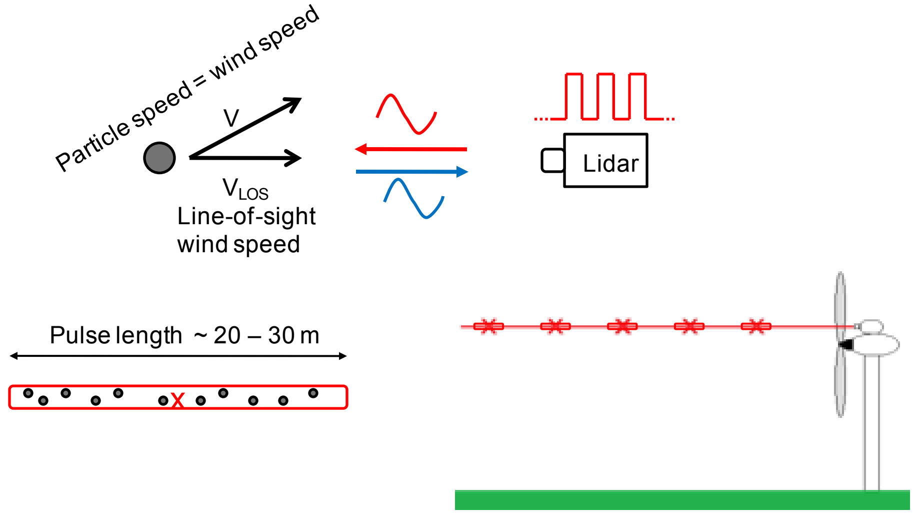
J.J. Trujillo et al.
Lidar systems for wake measurements
IEA Annex XI – Windfarm micro-meteorology
5th May 2010

SWE | Carl von Ossietzky Universität Oldenburg Wind energy systems | RAVE Research at Alpha Ventus

Outline

- Introduction
- Experience
- Remarks
- Outlook

Pulsed lidar (light detection and ranging)



J.J. Trujillo et al.
Lidar systems for wake measurements
IEA Annex XI – Windfarm micro-meteorology
5th May 2010
SWE universität OLDENBURG Wind energy systems RAVE RESEARCH AT ALPHA VENTUS

Lidar systems

- **Pulsed systems**
  - Range
    - Short range: 40 – 200m,
    - Mid range: 100 – 2000m,
    - Long range: 500 – 10000m and more
  - Probe length
  - Slower than CW
  - „Focused“ at several points in the line of sight

- **Continous wave (CW) lidar systems**
  - Range 20m - 150m
  - Probe length dependent on focus distance
  - Very fast measurements
  - Focused at one single point

Short history of lidar wake measurements (scanners)

Far wake

- **2005-2006: Measurements middle-sized WT with CW-Lidar**
  - Short-range nacelle based (Risoe) Bingöl et al.

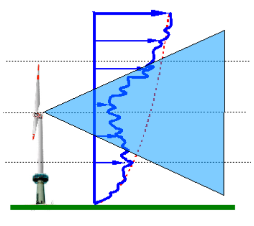
Near wake

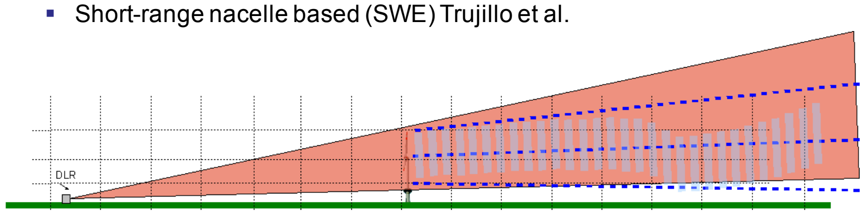
- **2009: Measurements 2-MW WT with CW lidar**
  - Short-range CW (Risoe) Hansen et al.

Far wake

Near wake

- **2009: Measurements 5-MW WT with pulsed lidars**
  - Long-range ground based (DLR) Käsler et al.
  - Short-range nacelle based (SWE) Trujillo et al.





Lidar-Scanner at SWE

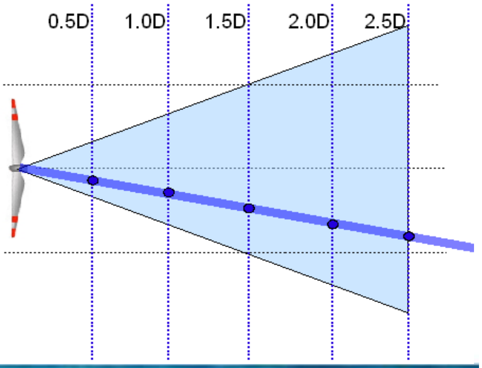
7

Scanning strategies

- Profiling ⇨ Horizontal and vertical profiles
- Slicing ⇨ Using 2D Lissajous-like trajectories for faster and smoother movement

Main characteristics of discrete measurement

- Scanning simultaneously 5 downstream stations
- Coverage of ~0.8D transversal at 1.0D downstream
- Complete trajectory every 5–9s

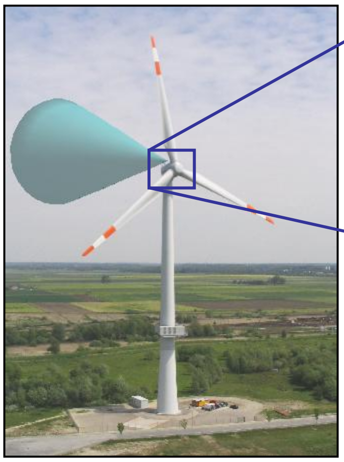


J.J. Trujillo et al.
Lidar systems for wake measurements
IEA Annex XI – Windfarm micro-meteorology
5th May 2010

Measurements of Multibrid Prototype

8

Experiment setup



Multibrid M5000 prototype

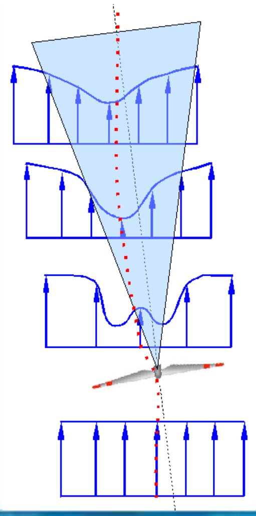
- 5 MW with 116m rotor diameter
- 102m hub height
- Heavily equipped with sensors
- Met mast
- Mounted Lidar-Scanner SWE

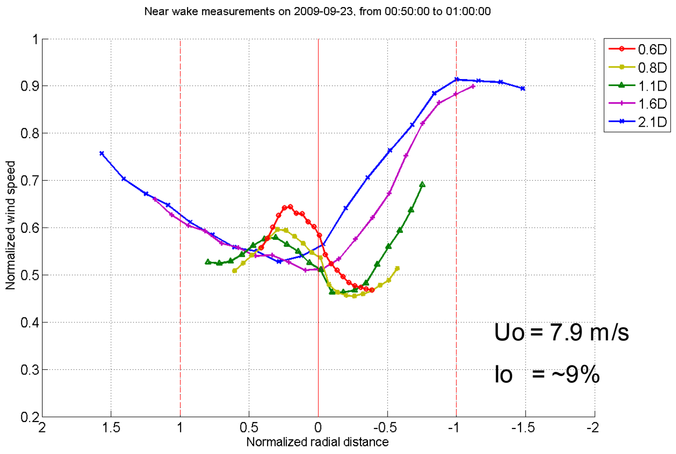
J.J. Trujillo et al.
Lidar systems for wake measurements
IEA Annex XI – Windfarm micro-meteorology
5th May 2010

Measurements of Multibrid Prototype

9

Results: Wind speed 10 min average





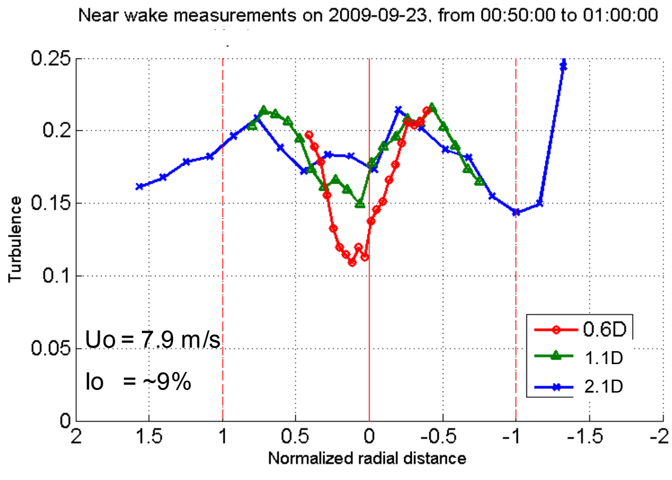
J.J. Trujillo et al.
Lidar systems for wake measurements
IEA Annex XI – Windfarm micro-meteorology
5th May 2010

SWE | Carl von Ossietzky Universität Oldenburg – Wind energy systems | RAVE Research at alpha ventus

Measurements of Multibrid Prototype

10

Results: Local turbulence intensity over 10 min

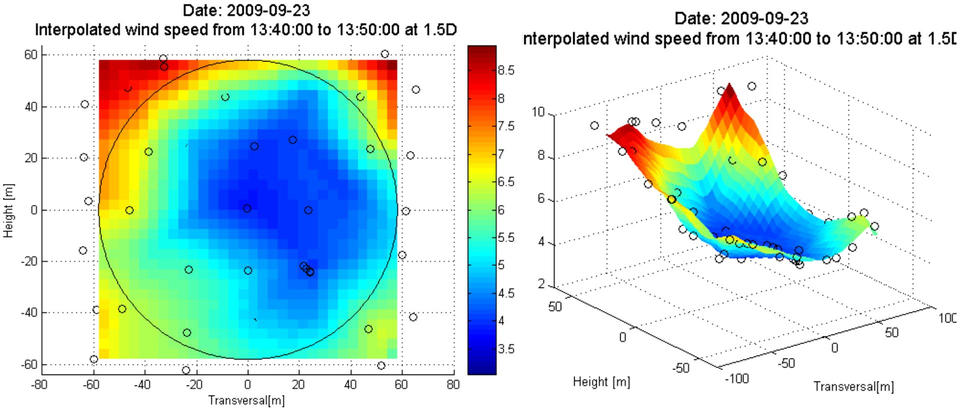


J.J. Trujillo et al.
Lidar systems for wake measurements
IEA Annex XI – Windfarm micro-meteorology
5th May 2010

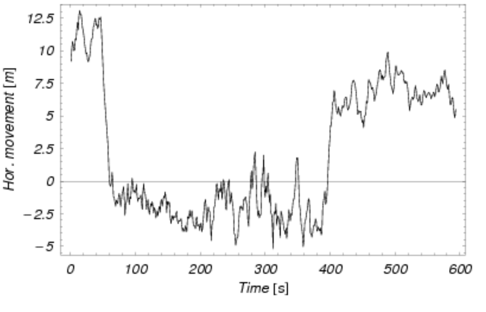
SWE | Carl von Ossietzky Universität Oldenburg – Wind energy systems | RAVE Research at alpha ventus

Measurements of Multibrid Prototype

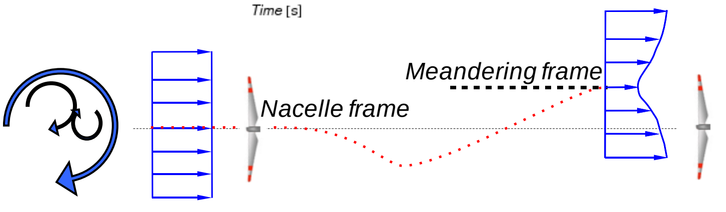
Results: two dimensional fields over 10 min



Large scale wake dynamics



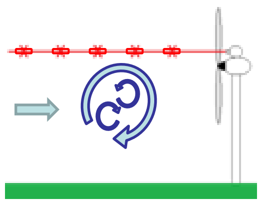
Estimation of wake center horizontal offset obtained by means of bivariate Gaussian fitting procedure

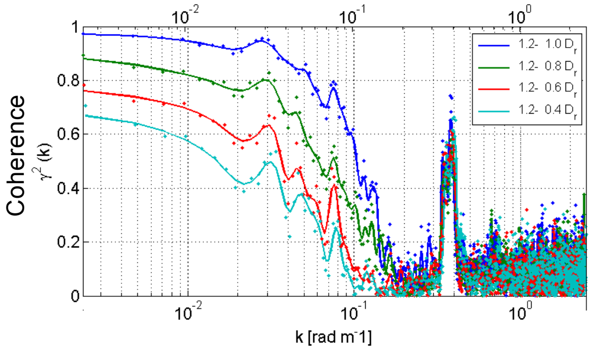


J.J. Trujillo et al., *Light Detection and Ranging Measurements of Wake Dynamics Part II : Two-dimensional Scanning*, Wind Energy 2010 (in publication)

13

Advection of turbulent structures





J.J. Trujillo et al., *Testing of Frozen Turbulence Hypothesis for Wind Turbine Applications with a Staring LiDAR System*, EGU, May 2010

D. Schlipf et al., *Testing of Frozen Turbulence Hypothesis for Wind Turbine Applications with a Scanning LiDAR System*, ISARS, June 2010

J.J. Trujillo et al.
Lidar systems for wake measurements
IEA Annex XI – Windfarm micro-meteorology
5th May 2010

14

Remarks

Lidar techniques offer considerable improvement in the quality of full field measurement data for validation of wake models

Ongoing analysis

- Large scale wake dynamics in the near wake
- Yaw effects on wake skew

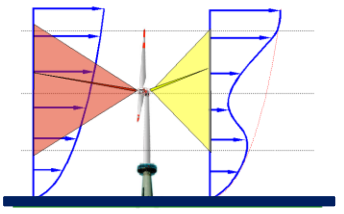
J.J. Trujillo et al., *Near Wake Lidar Measurements for Validation of a Dynamic Meandering Model*, Poster at TWIND, June 2010

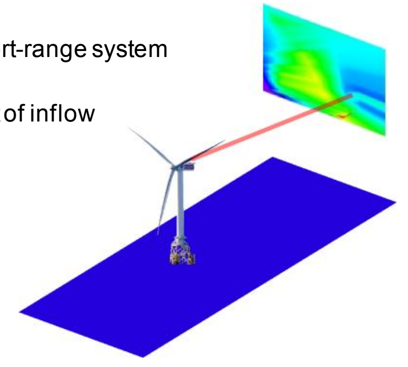
J.J. Trujillo et al.
Lidar systems for wake measurements
IEA Annex XI – Windfarm micro-meteorology
5th May 2010

15

Outlook
Planned measurements at Alpha Ventus

- **Mid-range wake measurements**
  - Range 1D – 7D
  - Same scanning characteristics of short-range system
  - Two different 5MW wind turbines
  - Planned simultaneous measurement of inflow



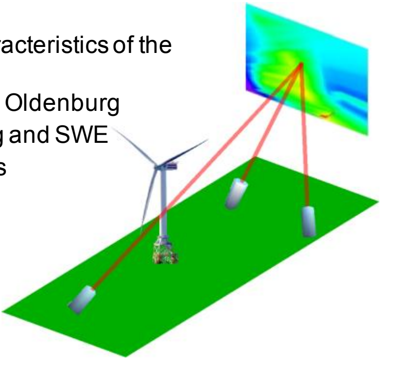


J.J. Trujillo et al.
Lidar systems for wake measurements
IEA Annex XI – Windfarm micro-meteorology
5th May 2010

16

Outlook
Multi dimensional measurement

- **Multi-lidar system**
  - Aim : Resolve three dimensional characteristics of the flow in wakes and in wind farms
  - Systems to be owned by University of Oldenburg
  - Under development by Uni Oldenburg and SWE
  - Based on commercial pulsed systems



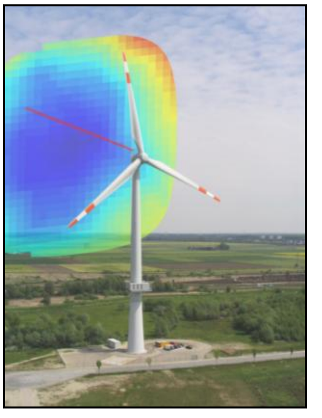
J.J. Trujillo et al.
Lidar systems for wake measurements
IEA Annex XI – Windfarm micro-meteorology
5th May 2010

17

We are available for further information

Universität Stuttgart
Germany
Andreas Rettenmeier
rettenmeier@ifb.uni-stuttgart.de

Carl von Ossietzky Universität Oldenburg
Wind energy systems
Juan José Trujillo
trujillo@forwind.de



J.J. Trujillo et al.
Lidar systems for wake measurements
IEA Annex XI – Windfarm micro-meteorology
5th May 2010

NUMERICAL SITE CALIBRATION FOR ESTIMATING A PERFORMANCE OF WIND TURBINE ON COMPLEX TERRAIN

1

Makoto IIDA
(Associate Prof. in University of Tokyo, JAPAN)
iida@cfdl.t.u-tokyo.ac.jp

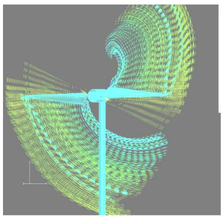
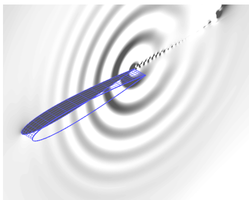
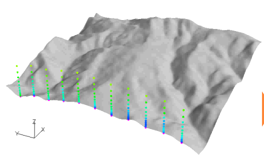
INTRODUCE MYSELF

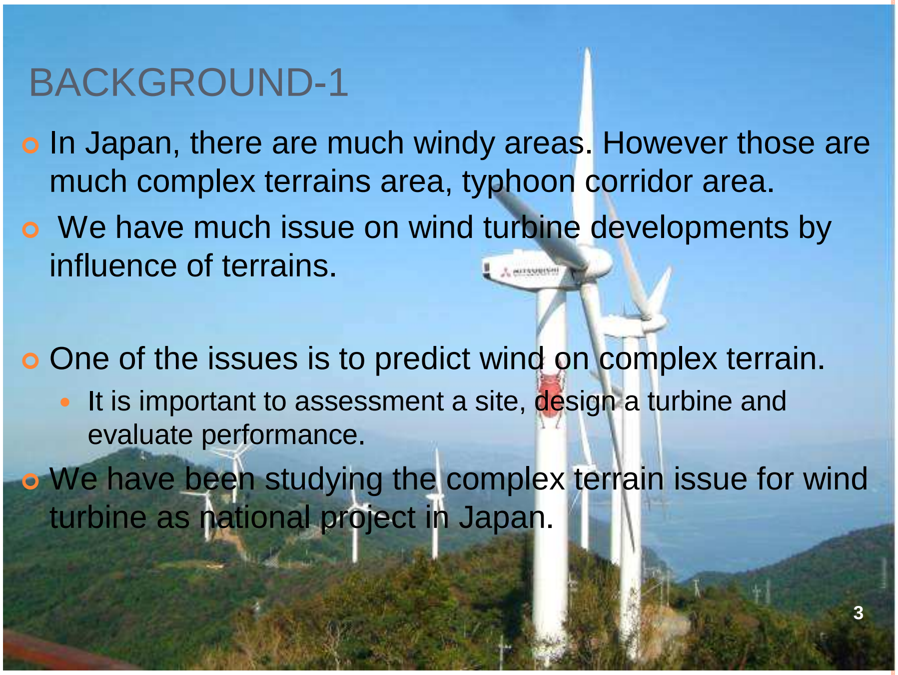
I have been studying CFD applications such as…

- The flow analysis around a wind turbine include a tower.
- The prediction for an acoustics from the blade.
- The site assessment on estimating wind resources.
- The wind power forecasting at the complex terrain.

… and

- Numerical site calibration for estimating the wind turbine performance on complex terrain.



BACKGROUND-1

- In Japan, there are much windy areas. However those are much complex terrains area, typhoon corridor area.
- We have much issue on wind turbine developments by influence of terrains.
- One of the issues is to predict wind on complex terrain.
  - It is important to assessment a site, design a turbine and evaluate performance.
- We have been studying the complex terrain issue for wind turbine as national project in Japan.

3

BACKGROUND-2

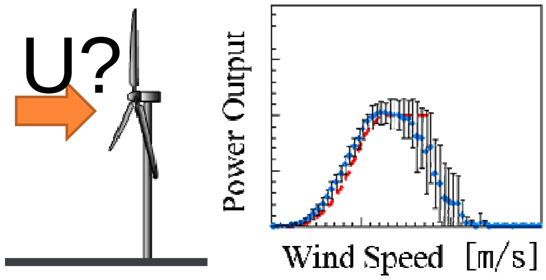
- We have been studying the complex terrain issue for wind turbine as national project in Japan.
- Today I will talk about focused on the numerical site calibration as one of these topics .

4

ESTIMATE PERFORMANCE OF WIND TURBINE

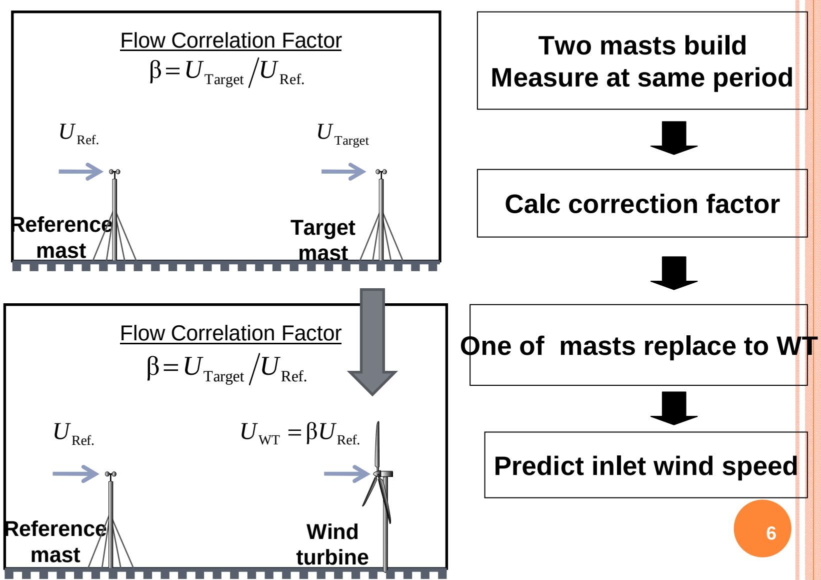
- it is important to evaluate the output of the power and inlet wind speed at wind turbine position

How measure(predict) the wind speed at wind turbine plane?



5

SITE CALIBRATION REF. IEC 61400-12-1

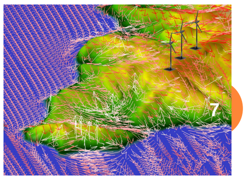


6

However, this method is not applicable on complex terrain!!

THE PROBLEM OF SITE CALIBRATION

- The site calibration technique in IEC 61400-12-1 is NOT always applicable for power curve measurements.
- The site may be in complex terrain without previous site calibration data.
- Hub height wind measurement may be impractical at existing wind turbine site and/or very large wind turbines.
- Numerically predicting the flow field, instead of executing field measurements for site calibration using sophisticated computer model (Computational Fluid Dynamics)



7

TYPICAL OF NUMERICAL SITE CALIBRATION

- NSC use Not only CFD data but also experimental reference mast data.
  (issue: Where is the optimum reference mast position?)
- In complex terrain, there are wind direction variation. NSC could compute the correction factor each direction.
- NSC don't compute a flow field in real time.
- The difference between inlet wind direction on boundary and target wind direction of wind turbine positon, especially complex terrains.

8

ISSUE OF NUMERICAL SITE CALIBRATION

There is concern that:

- Uncertainty of CFD
- Difference of Simulation codes
- Boundary conditions
- Range of applicability how complex terrain is.
- …….etc

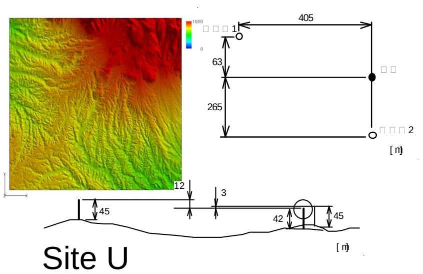
Enforcement of numerical site calibration by some simulation codes in Japan

9

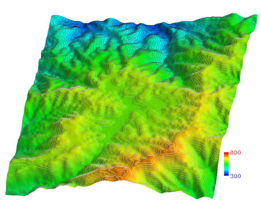
NSC IN JAPAN

- We worked out some terrains
  - Near flat plane Site U
  - Very complex terrain Site Y
  - Now … complex terrain Site I. We measure a filed test data, wind tunnel test data, and CFD.

All CFD results are computed with blinding the experimental data.



Site U



Site Y

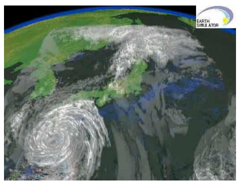
10

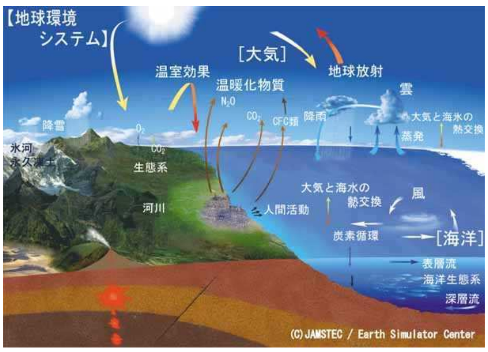
SIMULATION CODES OF PARTICIPANTS

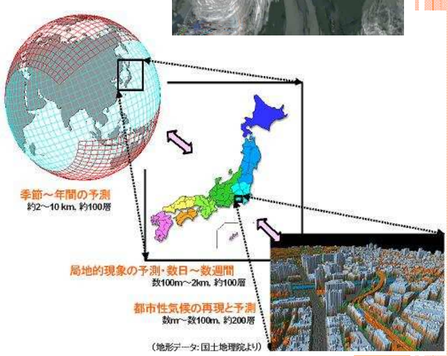
- WAsP x 1 on PC
- Improved RANS with Meso-scale model x 1 on PC
- URANS x 1 on PC
- Standard k-e RANS x 1 on PC
- LES x 1 on WS
- LES x 1 on Super computer

11

ATMOSPHERE SIMULATION CODE MSSG (EARTH SIMULATOR GROUP AND UNIV. OF TOKYO)







12

In NSC, We use only micro scale simulation

MSSG

- MSSG(Multi-Scale Simulator for the Geoenvironment)
  - ✓ Developed by the earth simulator center in JAMSTEC and UT
  - ✓ MSSG-A(Atmospheric part of MSSG)
  - ✓ Compressible-Navier-Stokes eq.
    - ✓ Five-order upwind diff. scheme in space
    - ✓ Third-order Runge - Kutta in time
  - ✓ Smagorinsky LES
  - ✓ Optimized parallelization and vectorization for super computer

$$\frac{\partial \rho'}{\partial t} + \nabla \bullet (\rho \mathbf{v}) = 0$$

$$\frac{\partial \rho v}{\partial t} + \nabla p' + \rho' \mathbf{g} = -\nabla \bullet (\rho \mathbf{v}\mathbf{v}) + 2\rho \mathbf{v} \times \mathbf{f} + \mathbf{F}$$

$$\frac{\partial P'}{\partial t} - \bar{\rho} \mathbf{g} w + \mathbf{v} \nabla P' + P \nabla \mathbf{v} = (\gamma - 1)\kappa \nabla^2 T + (\gamma - 1)\Phi$$

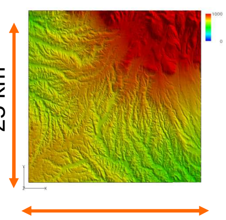
$$P = \rho R T$$

13

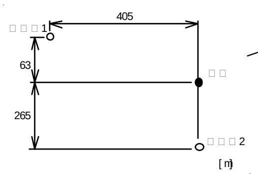
PURPOSE OF BLINDED NSC IS TO

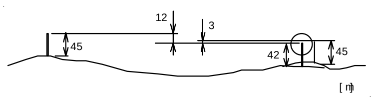
- Concern with possibility of CFD for NSC
- Check an uncertainty of the difference of simulation codes
- Create the guide line of NSC

25 km



25 km

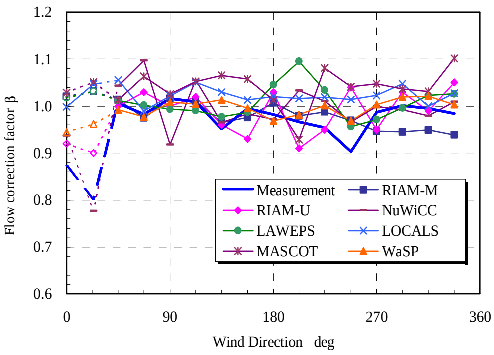




First trial Site U

14

- When we started, there is much deferent of simulation code. Because we didn't control the computational condition, estimating time, map data….
- Experimental data has much uncertainty.



First results of NSC at Site-U

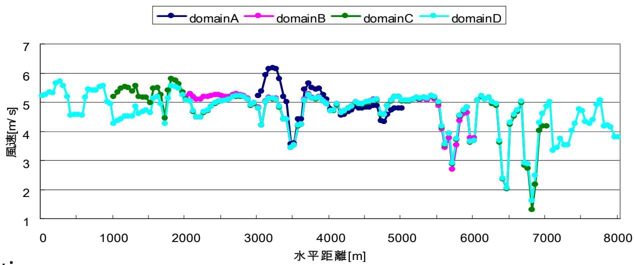
- To solve the problems , we checked some parameters..

15

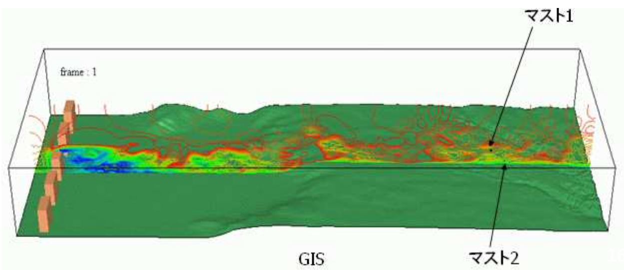
INFLUENCE OF COMPUTATIONAL PARAMETERS

- Region size:

For Site-U, some simulation code is not influence to compute with over 5km square region.



- Inlet wind conditions:

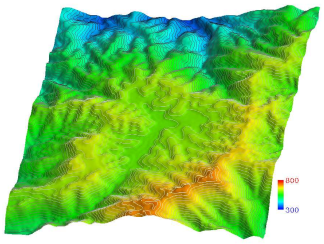


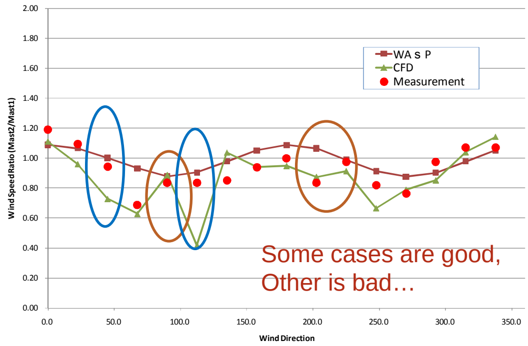
… and so on..

NSC OF SITE Y

- Same basic data (terrain data) used
- We decided NSC procedure, boundary conditions…

ex) wind direction at target position, don't use fixed outlet boundary conditions…



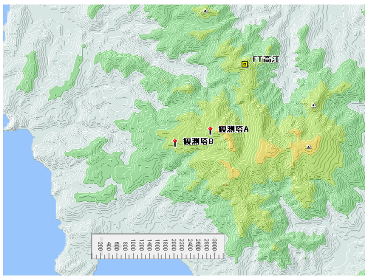


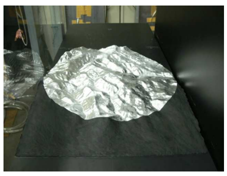
Our simulations can predict less than 7% MAE on correction factors
But, it results depend on terrains…….

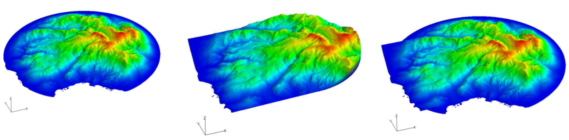
17

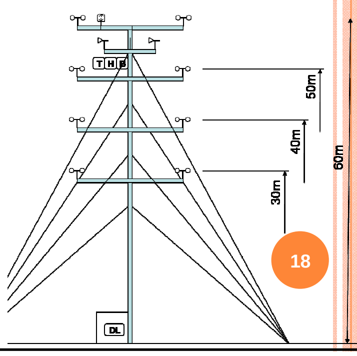
PROGRESSING OUR PROJECT…

- Site I (Complex terrain)
  - Field measurement with 3 mast: 60m Height
  - Wind tunnel test
  - Flow analysis using CFD









18

CONCLUSIONS

- To solve the complex terrain problems, we try to apply CFD In Japan.
- According to some trial simulations, if we simulate the flow field on complex terrain along with some procedure, we can get good wind prediction for estimating wind turbine performance.
- Averaged the prediction error less than 7% compare with experimental correction factors in Site-Y

Future works

- Improve simulation technique and analysis method for complex terrain.
- We should collect much simulation data on same site to check an uncertainty of CFD.

If you want to try simulation, (though we need the nondisclosure agreement,) we could give you the terrain data, and so on.

19

uni Research

Uni Research
Numerical modeling to estimate energy output for offshore wind parks

Alla Sapronova
alla.sapronova@uni.no
Idar Barstad
idar.barstad@uni.no

uni Research

Uni Research: www.uni.no

R&D in the fields of health, language and information technology, marine biology, the environment, climate, petroleum, culture and the social sciences.

Employs 500+ people from 30 countries and turns over NOK 450 million worth of research every year.

Have 9 specialist divisions.

uni Research

* Uni BCCS
* Uni Bjerknes Centre
* Uni CIPR
* Uni Digital
* Uni Environment
* Uni Global
* Uni Health
* Uni Rokkan Centre
* Uni Sars Centre

uni Research

20-20-20:

Europe's new climate and energy targets to be met by 2020

- 20% reduction in greenhouse gas emissions below 2005 levels
- 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency
- 20% of EU energy consumption to come from renewable resources.

⇩

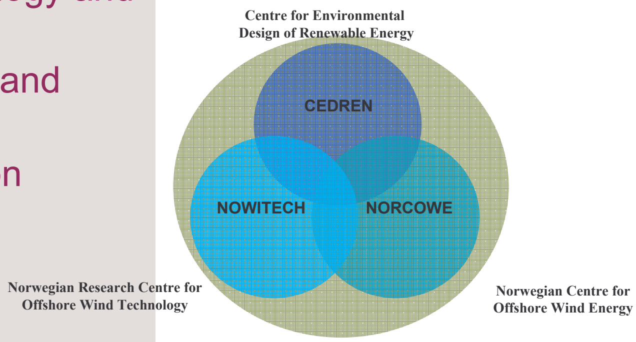
Great effort on offshore wind parks development

Norwegian Centre for Offshore Wind Energy (NORCOWE)

Research and innovations within:

- Wind and ocean conditions
- Offshore wind technology and innovative concepts
- Offshore deployment and operation
- Wind farm optimisation
- Common themes
- Education
- Safety
- Environment
- Test facilities and infrastructure

MNOK 240 (M€ 26, MUSD 37) over 8 yrs



DEMO 2020 => ~3BNOK

Challenges

- Onshore wind energy : ~0.75 NOK/kWh
- Offshore -fixed : ~1.25 NOK/kWh
- Offshore floating : ~2.? NOK/kWh

(Norwegian prices)

Price on electricity - at best: ~0.6NOK/kWh

Bridging the gap by:

- Selecting better locations for wind parks
- Predicting wind parks energy output

uni Research

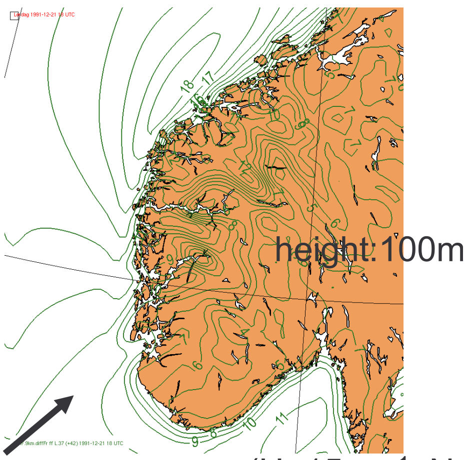
Mission:

To understand the important physical mechanisms effects in order to tailor a model system in the most suitable way

uni Research

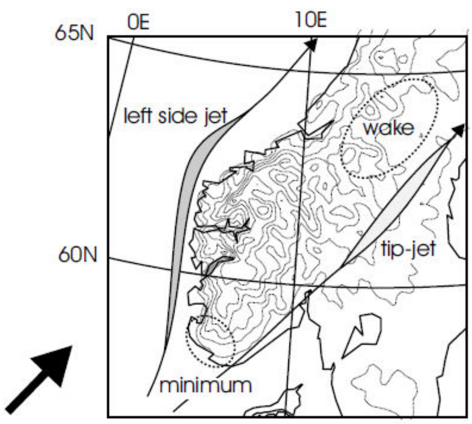
Mountain effects

Ideal atmosphere- real terrain



(U=15ms^{-1}, N=0.012s^{-1})

Schematic



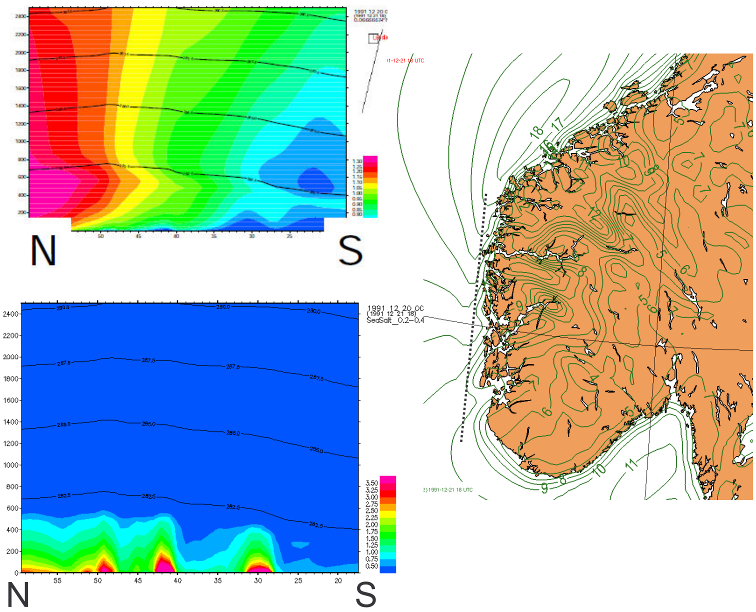
Barstad (2002)

uni Research

Mountains' influence on PBL

wind speed / isentropes

TKE / isentropes

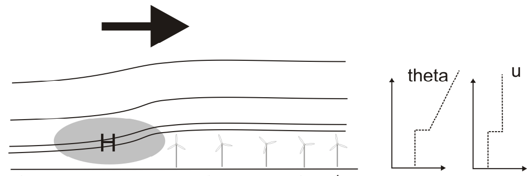


uni Research

Self-induced effects

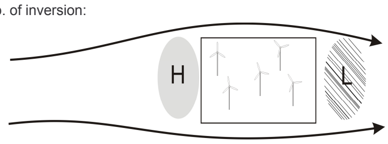
(Smith (2009)

$$U_b \frac{du_b}{dx} = -\frac{dp}{dx} - C_b u_b + C_t u_b + F_x$$

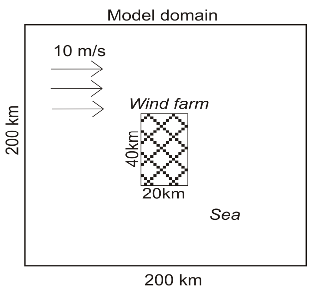


Pressure perturb. of inversion:

$$\hat{p} = -\frac{i|U|}{N}\frac{g\Delta\theta}{\theta_0}$$



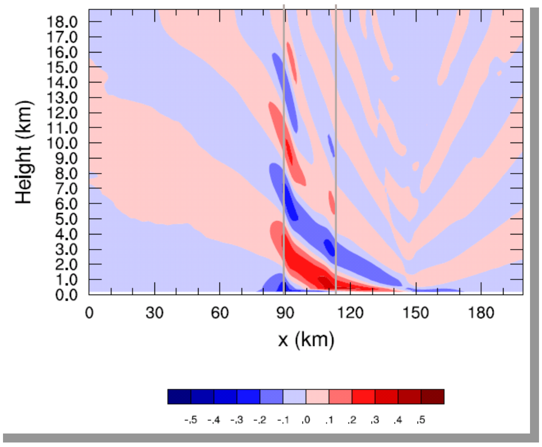
Idealised set-up:



uni Research

Self-induced effects

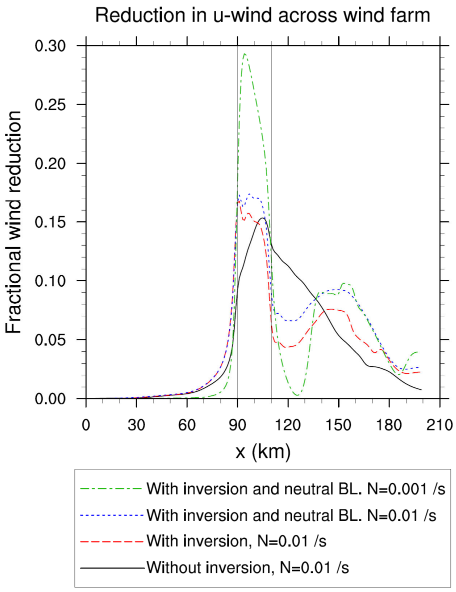
Gravity waves are being produced due to convergence/lifting of air



(Anna Fitch, Uni Research)

uni Research

Self-induced effects



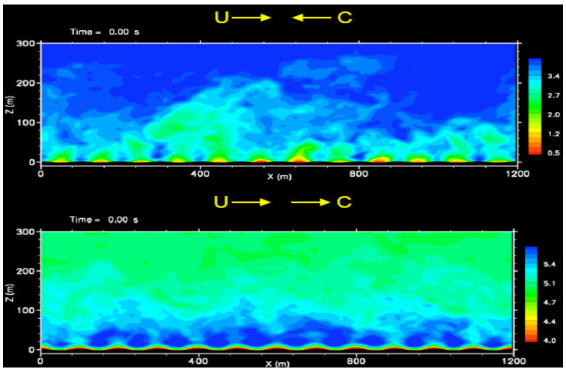
Idealised tests show:
- up to 30% reduction in the farm
- gravity wave signal in the lee

(Anna Fitch)

uni Research

Wave effects

- •Importance of sea waves
- - on larger scales
- - on smaller scales



(Sullivan)

uni Research

We will have to capture:

- Jets
- Lee waves (nonhydrostatic effects; big scale wakes)
- Self-induced effects (small scale wakes)
- Turbulence
- => high resolution -both vertically and horizontally
- => multi-scale approach
- Surface wave effects
- => subgrid scale parametrisation

uni Research

Model relevant scales (to capture the relevant effects)

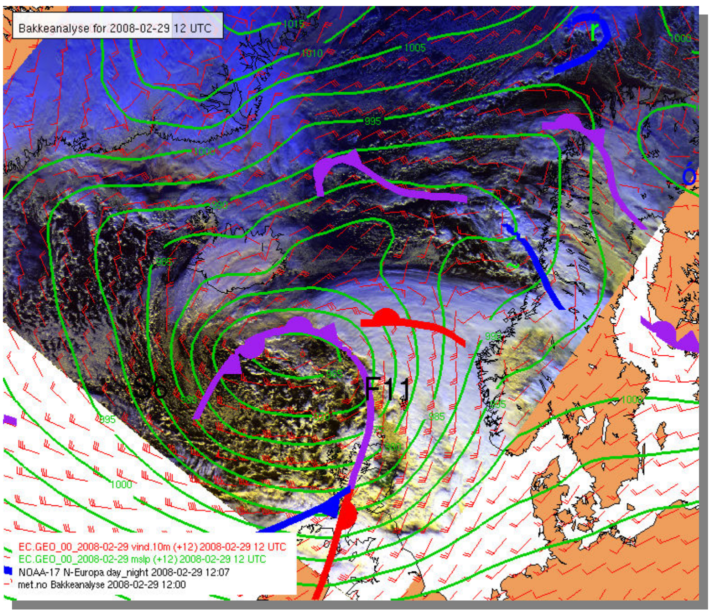
Comprehensive model tools taking into account relevant effects influencing large offshore wind parks

→ Next-generation mesoscale model - WRF+

uni Research

Examples from the coupled system

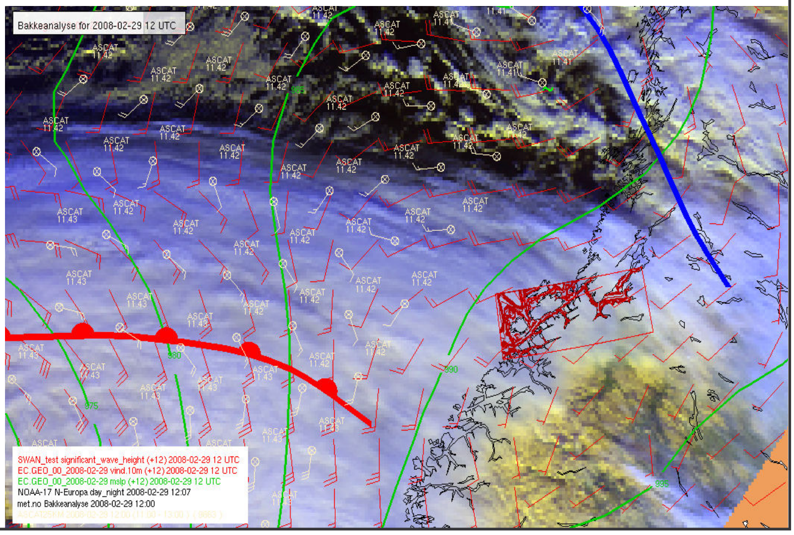
- A typical weather situation



uni Research

...and zooming in

- A closer look:



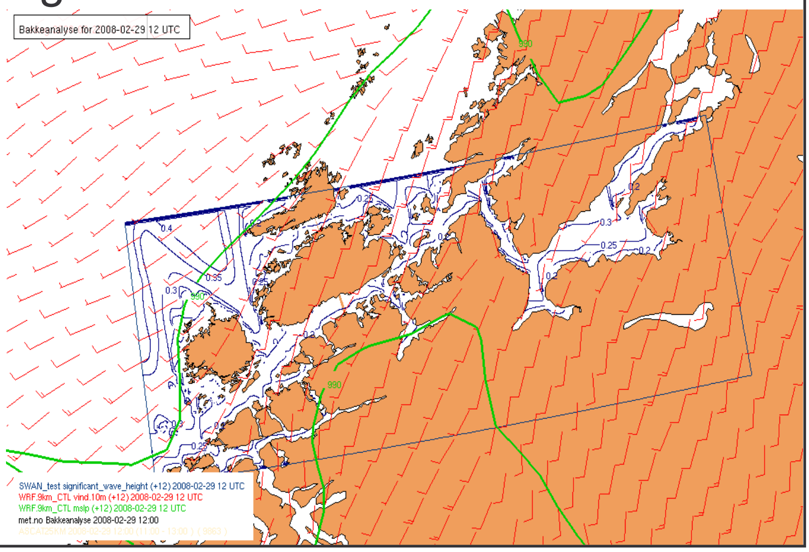
uni Research

...and a coupled wave model

(Alastair Jenkins, Uni Research)

- 416x156 grid points

Significant wave height



uni Research

WP1 - NORCOWE

(Headed by Idar Barstad @ Uni Research)

Coupled numerical model system (scale: 100km-10m):

- Mesoscale model – larger & medium scales
- Wave model for ocean waves
- Computational Fluid Dynamics
  (RANS/LES) model for microscale

An integrated system describing geophysical conditions vital for offshore wind energy.

- produce reliable estimates of forces acting on the wind park constructions.
- enable studies and increase understanding the geophysical off-/near-shore environment
- assist in production of reliable estimates of energy output.

GL Garrad Hassan

Wake effects within and between large wind projects:

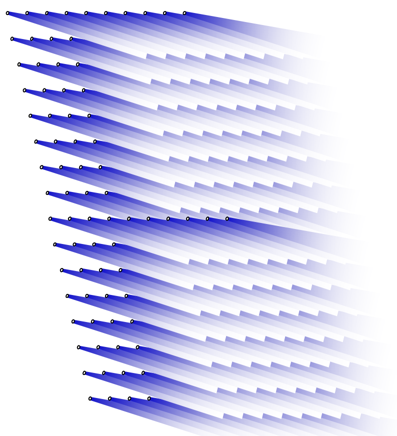
The challenge of scale, density and neighbours – onshore and offshore

6 May 2010

J Phillips, S Cox, A Henderson and J Gill

GL Garrad Hassan

Contents



GL Garrad Hassan

Background and Motivation

- Majority of R&D to date focused on single wakes
- High uncertainties when predicting for large arrays
- How big a problem (**or opportunity!**) is this ?........a worked example

> - Project X is a 500MW offshore wind development
> - Securing pre-construction non-recourse debt-finance
> - Bank's Technical Advisors conduct independent energy calculation
> - With today's wake modelling uncertainties ($\sigma_{array\ eff.}$≈6%) P90 / P50 = 87%
> - But with improved modelling ($\sigma_{array\ eff.}$ ≈3%) P90 / P50 = 89%
> - Assume the 2% improvement in P90 / P50 leads to a 2% leverage increase
> - ➔ Under these conditions the improvement of NPV for Project X is ~€15M

- If we scale this up to a 100GW future industry, the opportunity is huge (~€3Bn)
- There are other benefits to improving modelling too (WTG and layout design)

GL Garrad Hassan

What is the State of the Art ?

Summary of past, present and future model development

	Historical	The Art	R&D
Turbine representation	Empirical	Empirical	Numerical
Wake propagation	Empirical 2D	Numerical 2D	Numerical 3D
Wake interaction	Empirical	Empirical	Numerical

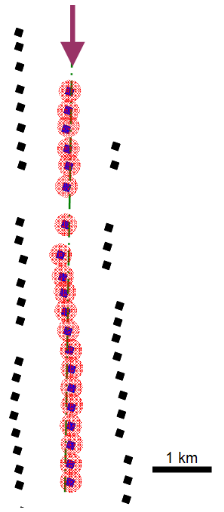
➔ New empirical data has always pushed advances in modelling

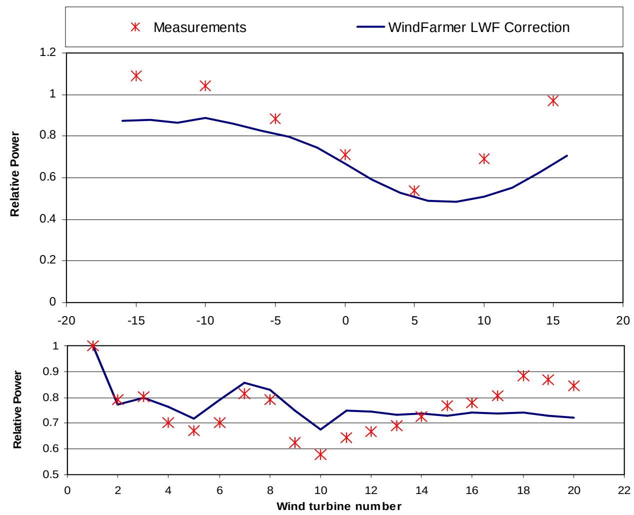
GL Garrad Hassan

Wakes – just an offshore problem ?

Climate & Renewables

19-wake investigation: US Onshore Project, data courtesy of E.on Climate and Renewables





GL Garrad Hassan

Specifying a ‘holy grail’ wake model

Requirement Specification

RANGE OF VALIDITY

Accurate results need for….

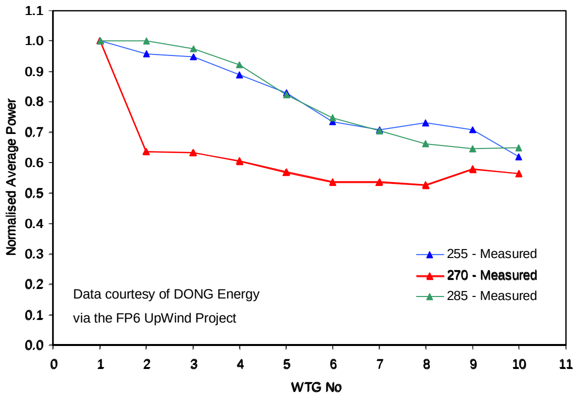
► Ambient Turbulence:	*Low (4% @ 15m/s)*	*High (15% @ 15m/s)*
► WTG Rotor Diameter:	*Small (50m)*	*Large (150m)*
► WTG Ct:	*Aggressive*	*Relatively passive*
► WTG Density:	*Dense (1.5D spacing)*	*Sparse (15D spacing)*
► Location:	*Onshore*	*Offshore*
► Project Scale:	*Small (5MW)*	*Huge (2GW)*
► Atmos. Stability:	*Very stable*	*Very unstable*
► Neighbouring effects:	*Close (2km)*	*Distant (30km)*

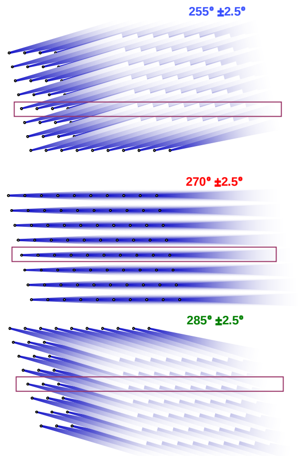
A single model for this entire envelope ? or specialist models ?

GL Garrad Hassan

Getting the right answer (in the right places)

Empirical evidence from Horns Rev





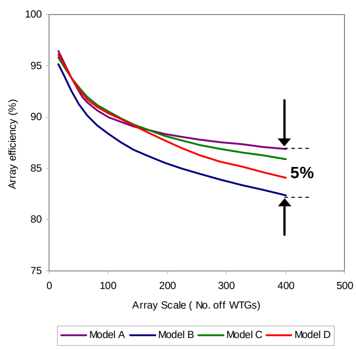
➔ Perhaps the classic 'plateau' is just a special case

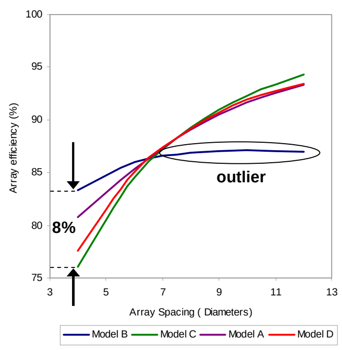
GL Garrad Hassan

The challenge of scale and density

A theoretical example….

- A square regular array, scale varied: 16 WTGs (4x4) ➔ 400 WTGs (20x20)
- WTG density varied: 4Dx4D ➔ 12Dx12D
- 4 offshore wind wake models applied





GL Garrad Hassan

The challenge of scale and density

Degree of uncertainty justifies an 'ensemble' approach

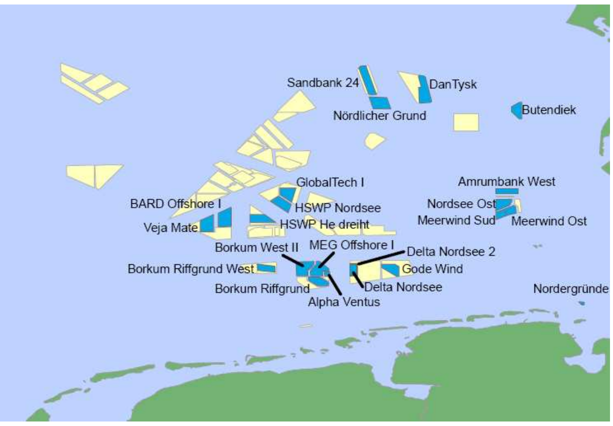
- Certainty weighted average array efficiency
- Worked example….

	Confidence Factor	Array Efficiency
Model A	50%	92.5%
Model B	30%	91.0%
Model C	20%	93.0%
Total	**100%**	**92.2%**

GL Garrad Hassan

Nuisance neighbours

Development activity in the German Bight



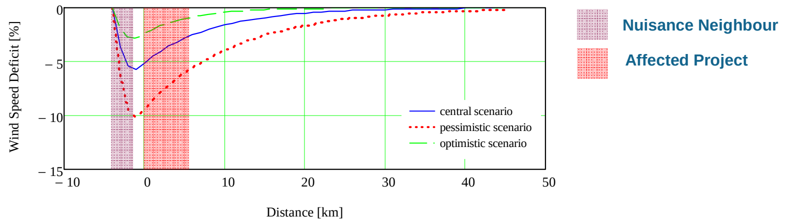
A very busy scene…..

GL Garrad Hassan

Nuisance neighbours

Making sense of the limited available evidence

- Literature provides limited but **valuable** evidence
  - Altamont Pass, Horns Rev and Nysted (Nierenberg, Jensen, Christiansen, Hasager, Frandsen *et al*)
- Collective wisdom distilled in to a simple empirical model by GH
  - Defined by 4 parameters, derived from literature review :
    1. Deficit at front of neighbouring wind farm
    2. Deficit development through neighbouring wind farm (exponential development)
    3. Maximum deficit at exit of neighbouring wind farm
    4. Recovery distance (exponential recovery assumed)



GL Garrad Hassan

Nuisance neighbours
(a couple of Danish case studies…)

N.B. Project data from public domain sources

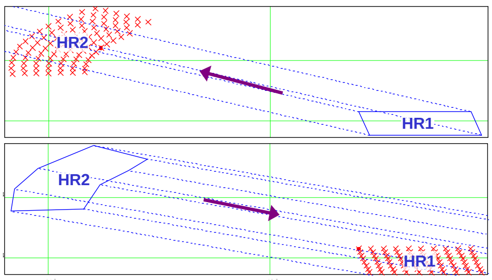
N.B. Nominal assumptions made where necessary

HR1➔HR2: 0% - 0.1%

Horns Rev 1&2

Separation distance ~15 km

HR2➔HR1: 0% - 0.3%

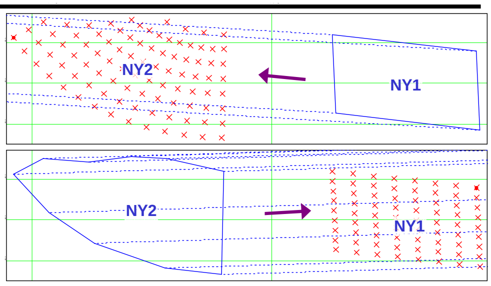


NY1➔NY2: 0.1% - 0.9%

Nysted 1&2

Separation distance ~5 km

NY2➔NY1: 0.5% - 2.7%

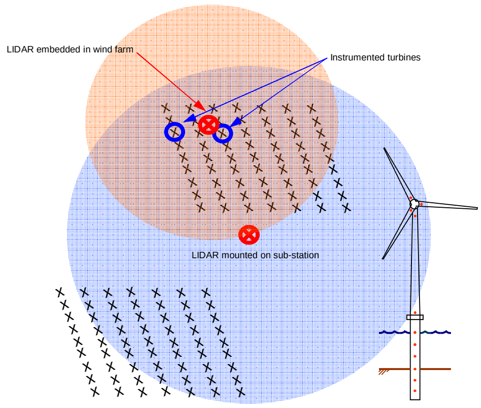


GL Garrad Hassan

Looking forward to a more certain future

Lack of data is critical

- Potential for a targeted Joint Industry Project ?



GL Garrad Hassan

Concluding remarks

- Huge potential to add value to industry
- Progress towards full numerical modelling
- Leading current generation model performs well in 19 wake case onshore...

  …some way from a 'holy grail' wake model
- High uncertainty when scaling up offshore….

  ….and so an ensemble modelling approach is sensible
- Valuable (if limited) empirical data on nuisance neighbours.….

  ….allows empirical modelling approach over many kilometres
- We look forward to a more certain future….

  …. but new measurements are needed to

  ➔ Improve models

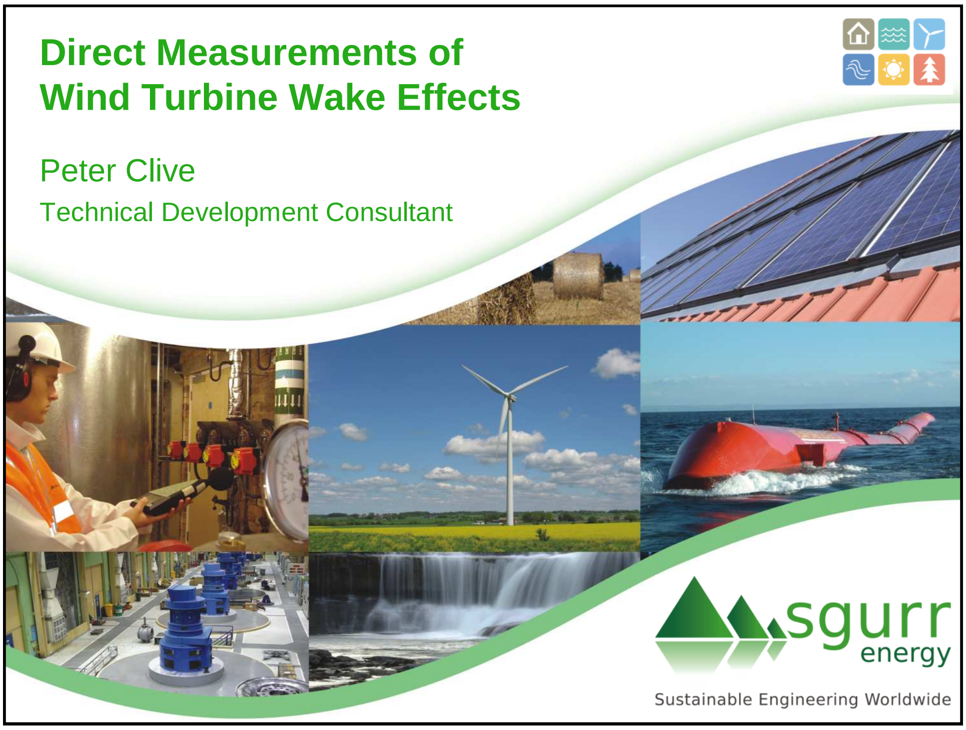
  ➔ Drive down uncertainty

GL Garrad Hassan

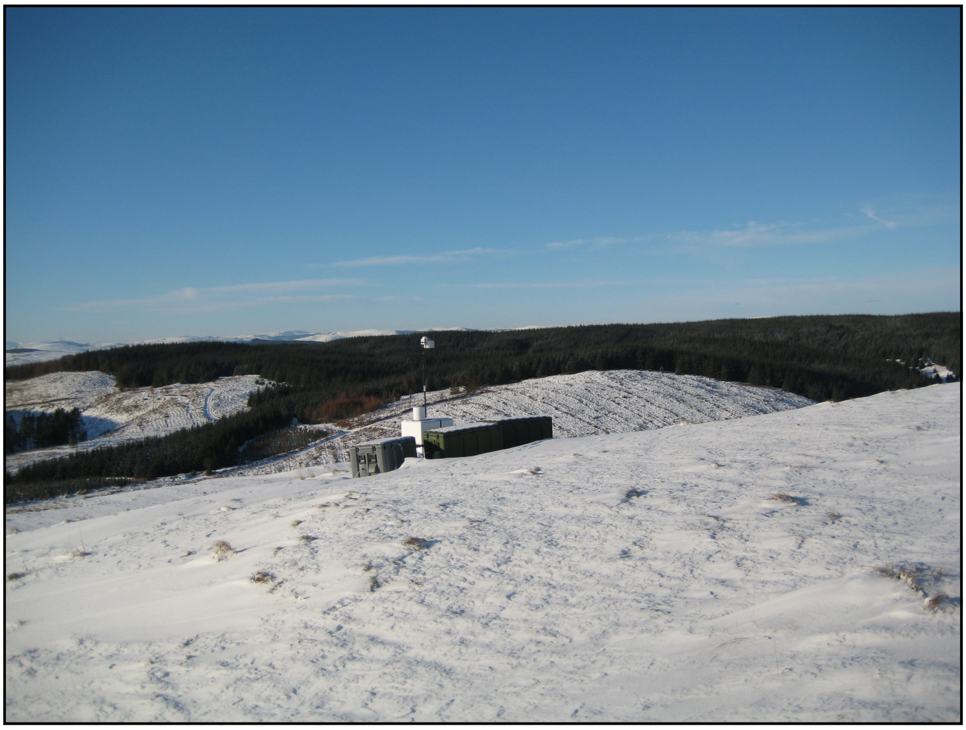
Acknowledgements

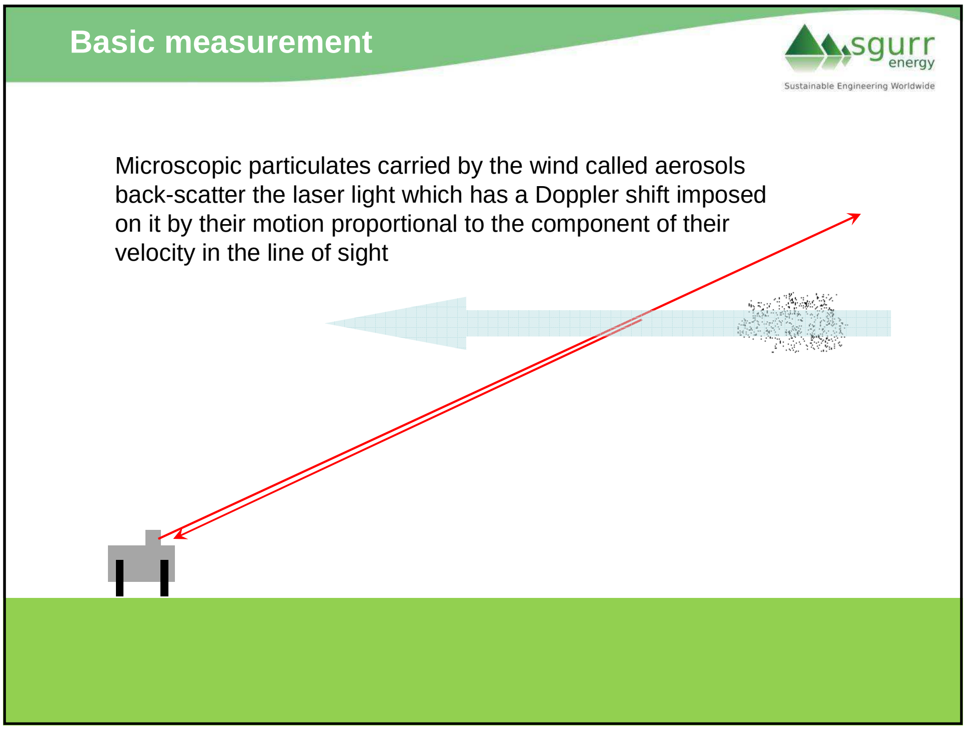
The authors would like to acknowledge and thank the following parties for their kind provision of data and results

- E.on Climate and Renewables
- Dong Energy A/S
- The Crown Estate
- The FP6 UpWind Project (Work Package 8)


Direct Measurements of
Wind Turbine Wake Effects
Peter Clive
Technical Development Consultant
sgurr
energy
Sustainable Engineering Worldwide

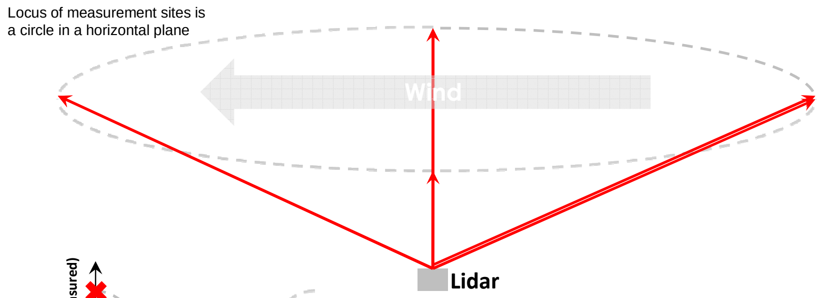

Galion

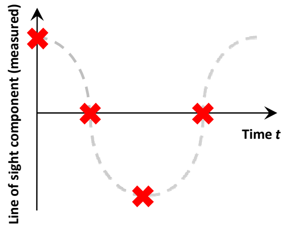



Basic measurement
sgurr energy
Sustainable Engineering Worldwide
Microscopic particulates carried by the wind called aerosols back-scatter the laser light which has a Doppler shift imposed on it by their motion proportional to the component of their velocity in the line of sight

VAD

VAD scan geometry

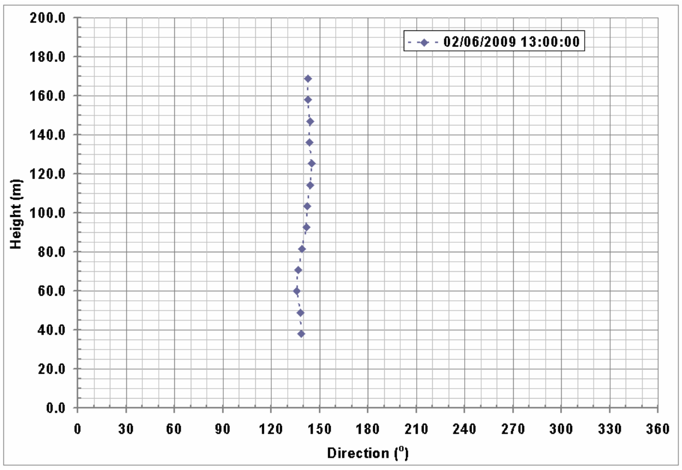


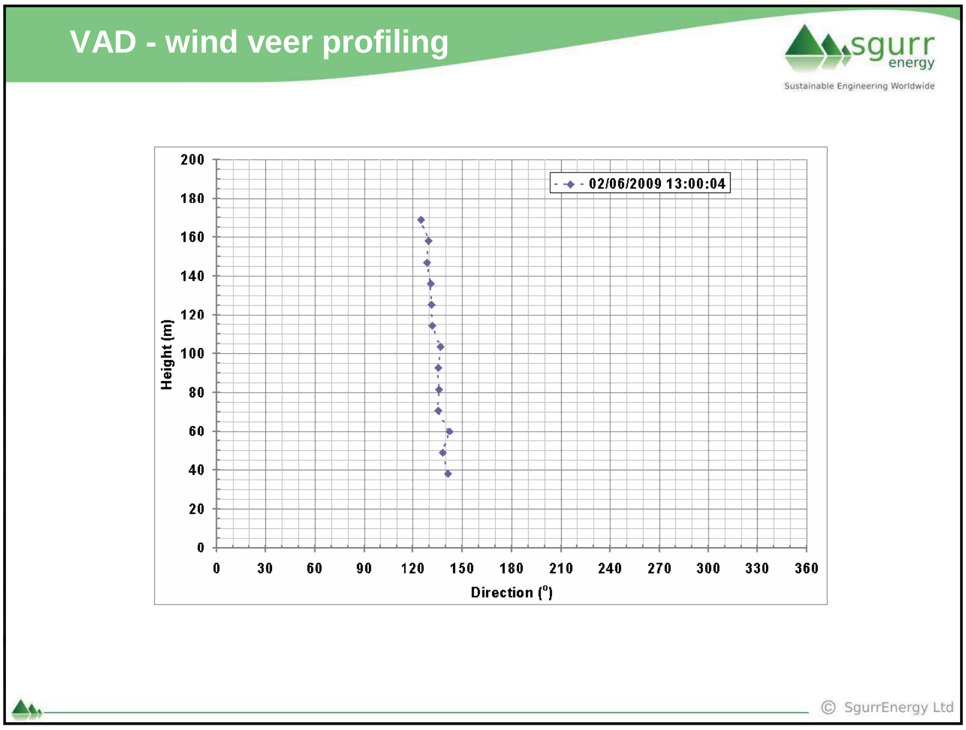


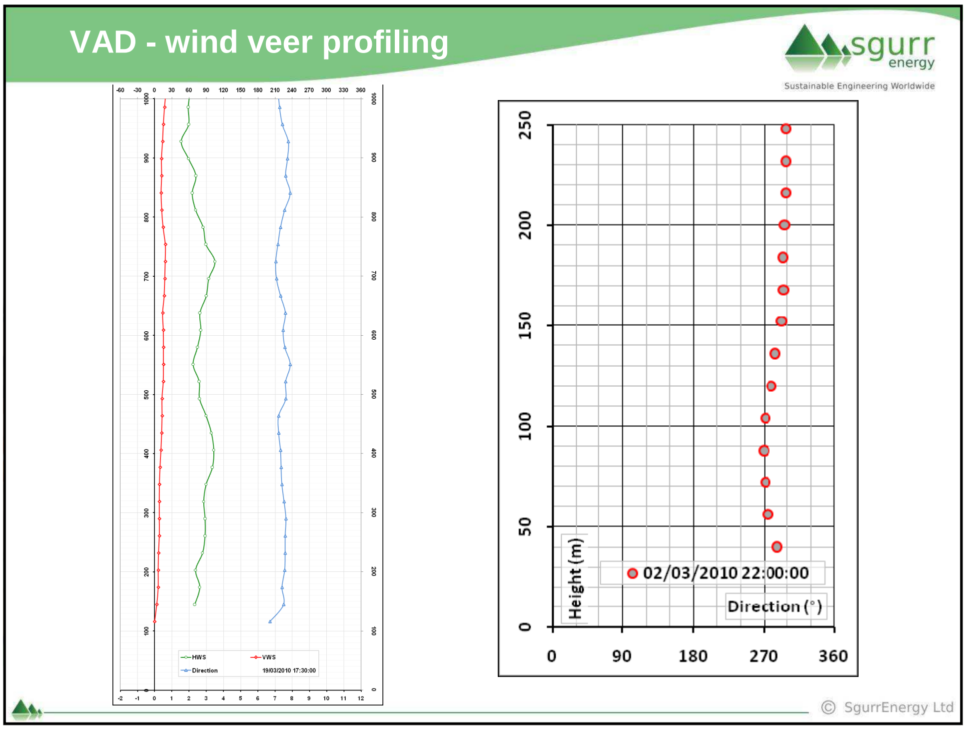
$x = A \sin(\omega t + B) + C$

A gives horizontal wind speed
B gives wind direction
C gives vertical wind speed

VAD - wind veer profiling

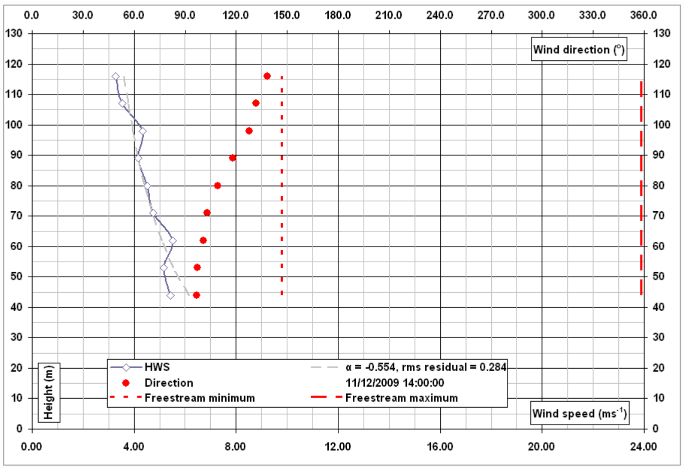



VAD - wind veer profiling
sgurr energy
Sustainable Engineering Worldwide
02/06/2009 13:00:04
Height (m)
200
180
160
140
120
100
80
60
40
20
0
0 30 60 90 120 150 180 210 240 270 300 330 360
Direction (°)
© SgurrEnergy Ltd


VAD - wind veer profiling
sgurr energy
Sustainable Engineering Worldwide
250
200
150
100
50
0
Height (m)
02/03/2010 22:00:00
Direction (°)
0 90 180 270 360
© SgurrEnergy Ltd

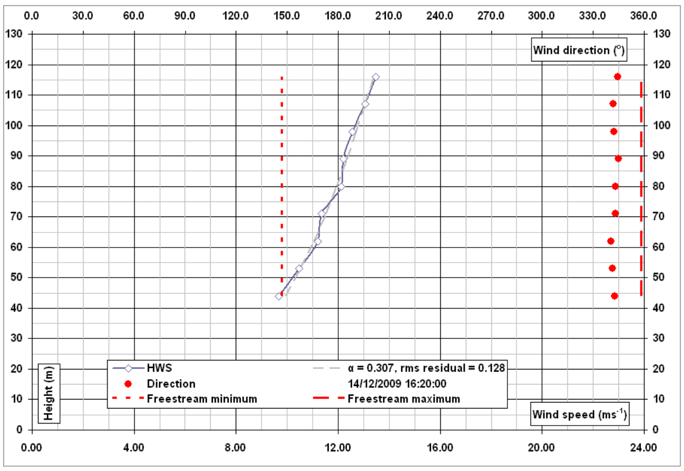
VAD - wind shear profiling

sgurr energy
Sustainable Engineering Worldwide

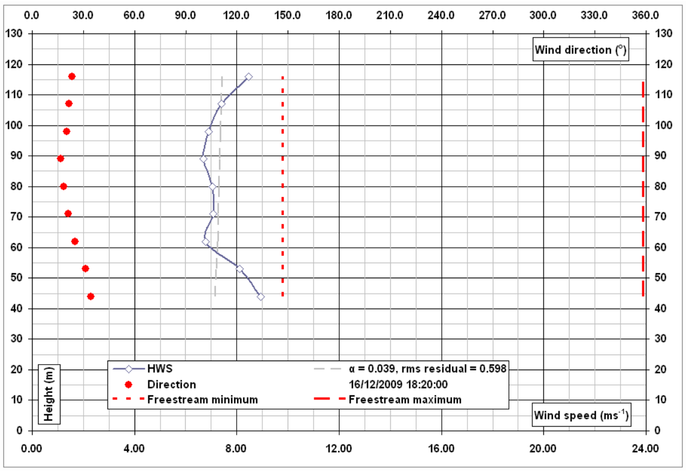


VAD - wind shear profiling

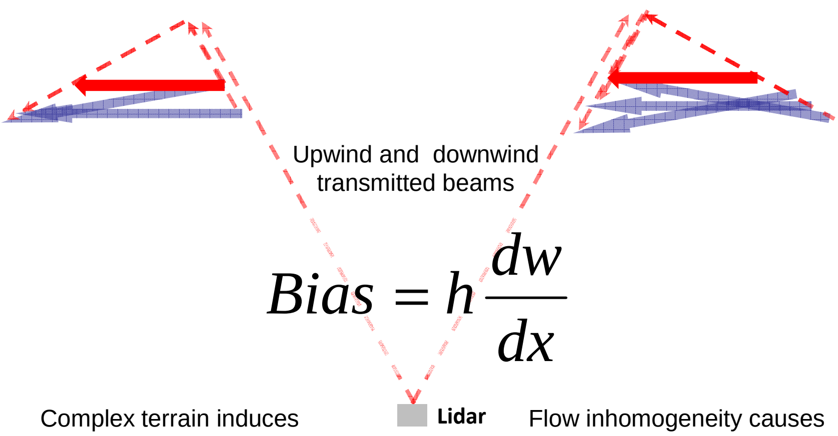
sgurr energy
Sustainable Engineering Worldwide



VAD - wind shear profiling



Complex flow



$$Bias = h\frac{dw}{dx}$$

Complex terrain induces flow inhomogeneity

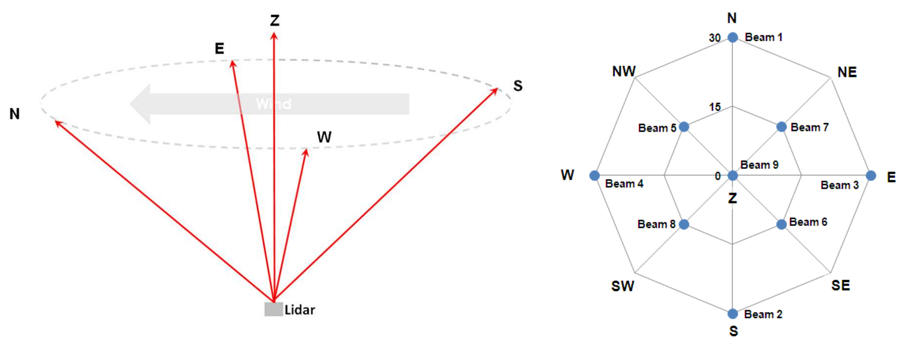
Flow inhomogeneity causes bias in VAD results

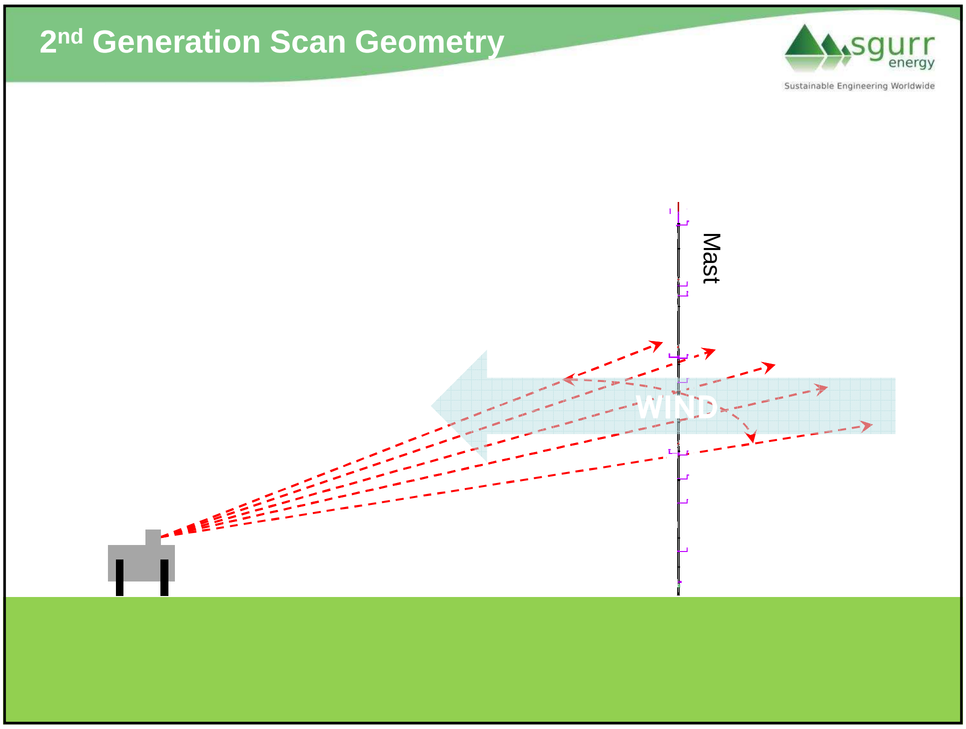
1st and 2nd Generation

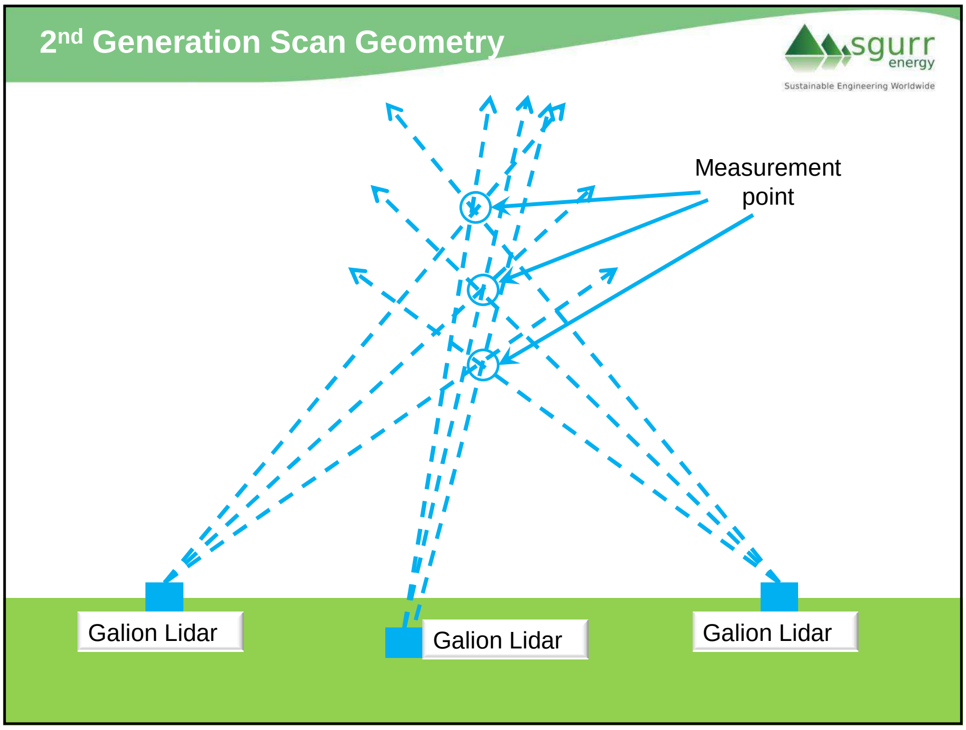
Table 1: 1st and 2nd Generation Characteristics

Characteristic	1st Generation Devices	2nd Generation Devices
Degrees of freedom	1: typically azimuth	2: azimuth and elevation
Scan geometry	A single "virtual mast" approach, either VAD or DBS	All-sky scanning enables use of any scan geometry
Range	~200m vertically upwards	Multiple km in any direction
Distance resolution	Time of flight or focussing methods	Time of flight methods only

2nd Generation Scan Geometry



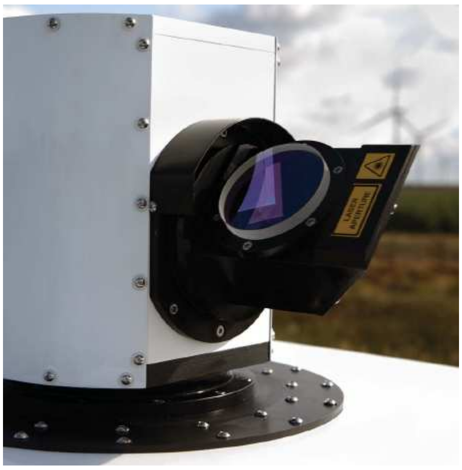

2nd Generation Scan Geometry
sgurr energy
Sustainable Engineering Worldwide
Mast
WIND


2nd Generation Scan Geometry
sgurr energy
Sustainable Engineering Worldwide
Measurement point
Galion Lidar
Galion Lidar
Galion Lidar

Galion

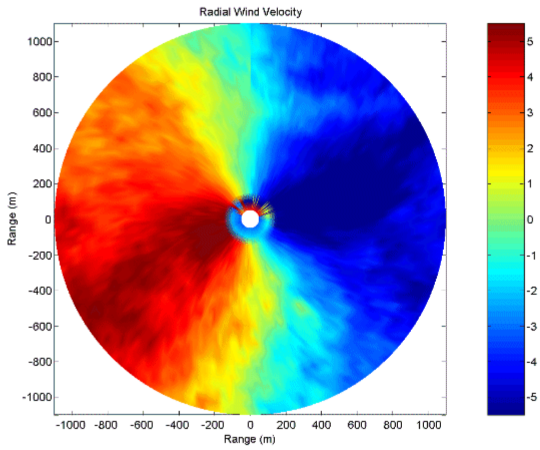
sgurr energy
Sustainable Engineering Worldwide

Galion™



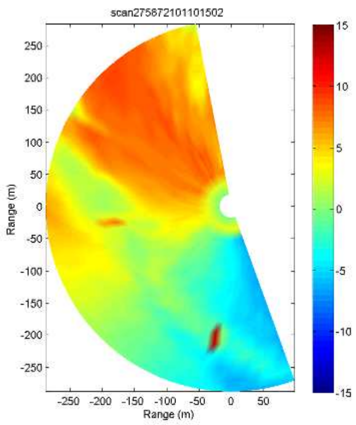
PPI

sgurr energy
Sustainable Engineering Worldwide



PPI

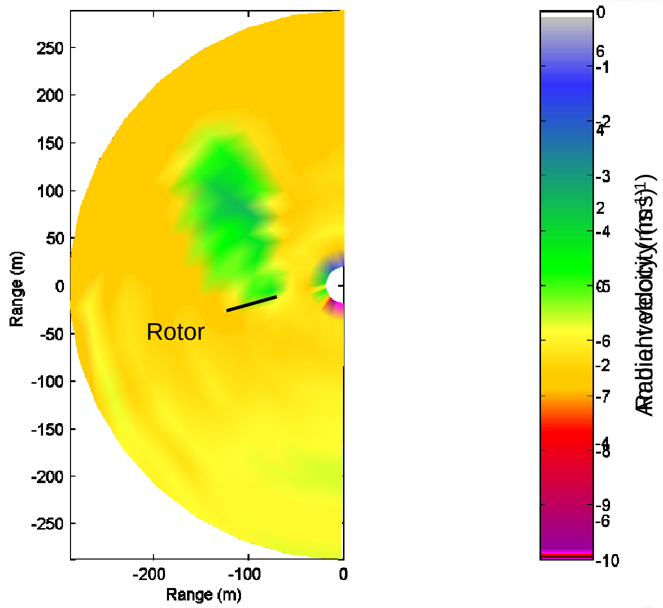
sgurr energy
Sustainable Engineering Worldwide



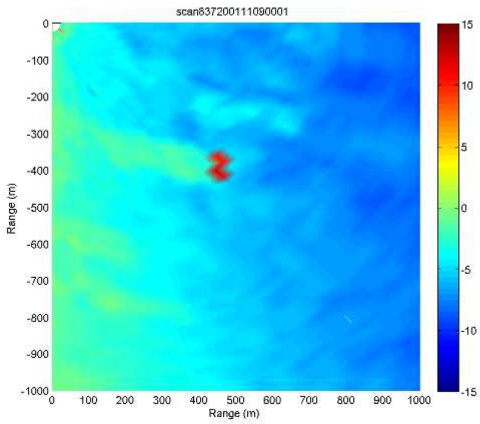
Galion installed at (0,0)
Radial velocities/line-of-sight data
Velocity deficits seen where turbine wakes intersect PPI

PPI

sgurr energy
Sustainable Engineering Worldwide

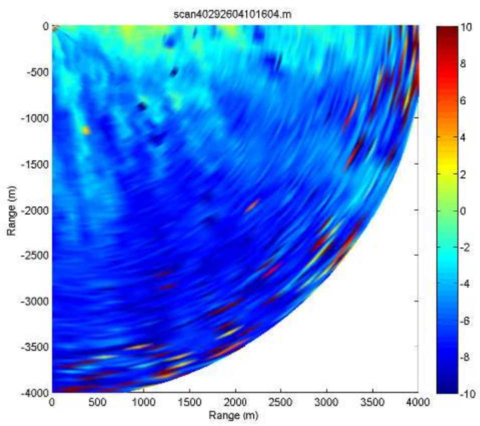


PPI



Galion installed at (0,0)
Radial velocities/line-of-sight data
Velocity deficits seen where turbine wakes intersect PPI

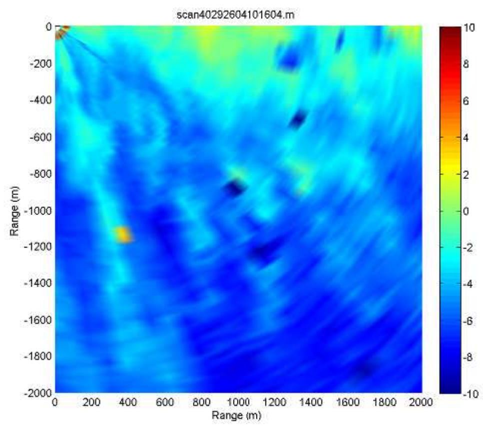
PPI



Galion installed at (0,0)
Radial velocities/line-of-sight data
Velocity deficits seen where turbine wakes intersect PPI

PPI

sgurr energy
Sustainable Engineering Worldwide

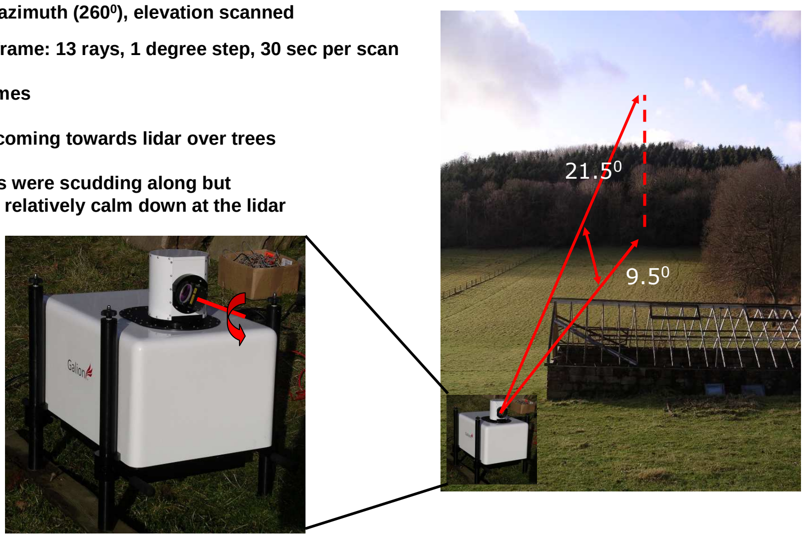


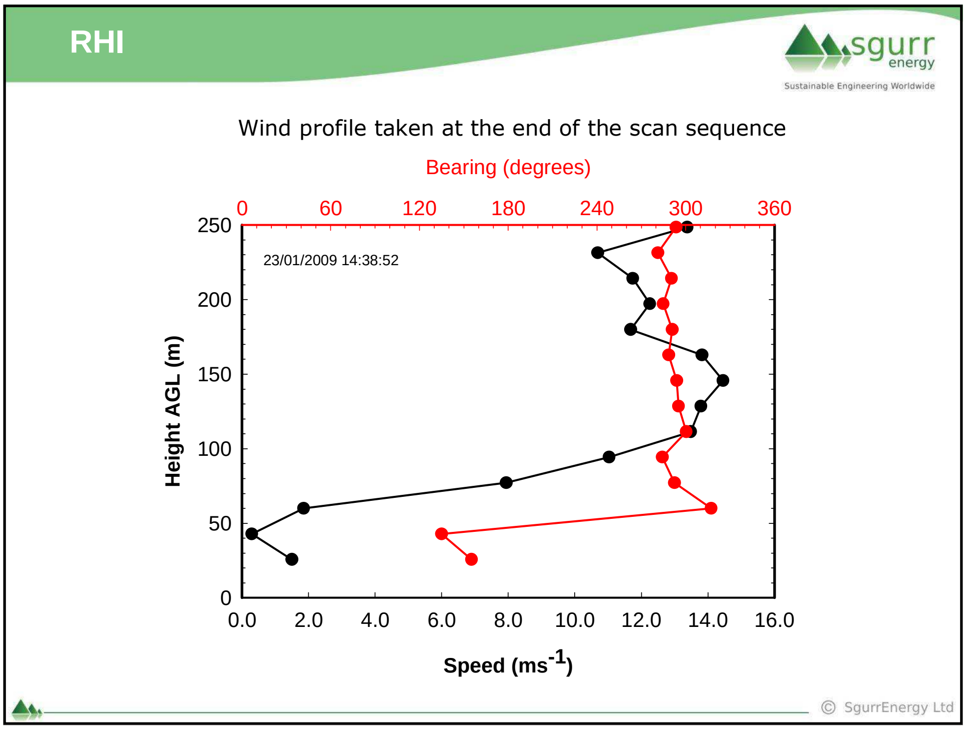
Galion installed at (0,0)
Radial velocities/line-of-sight data
Velocity deficits seen where turbine wakes intersect PPI

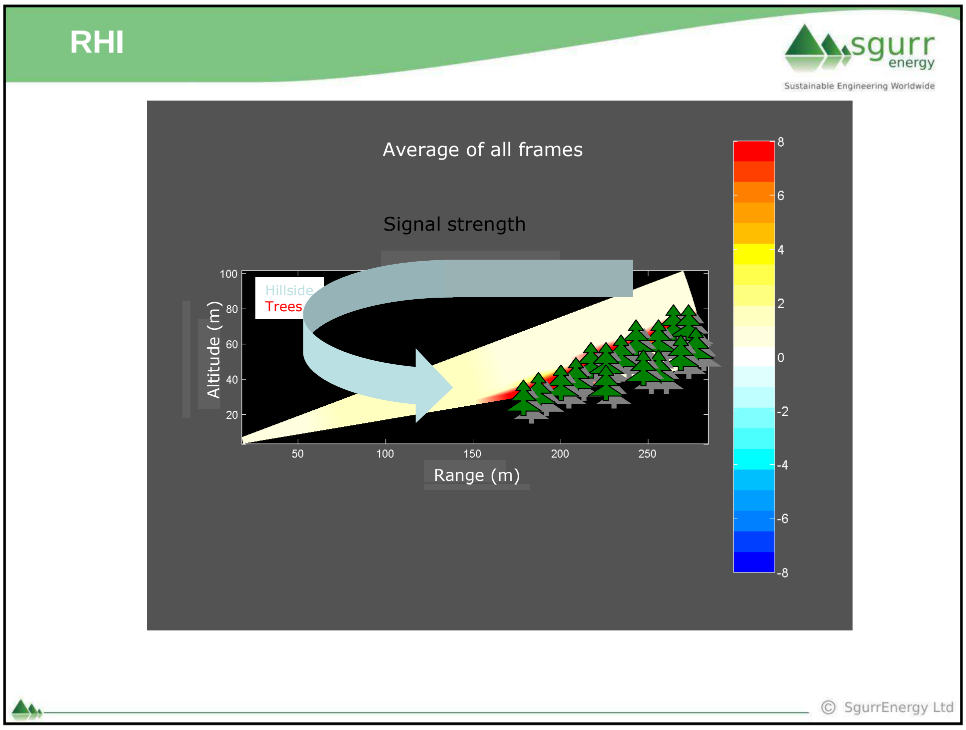
RHI

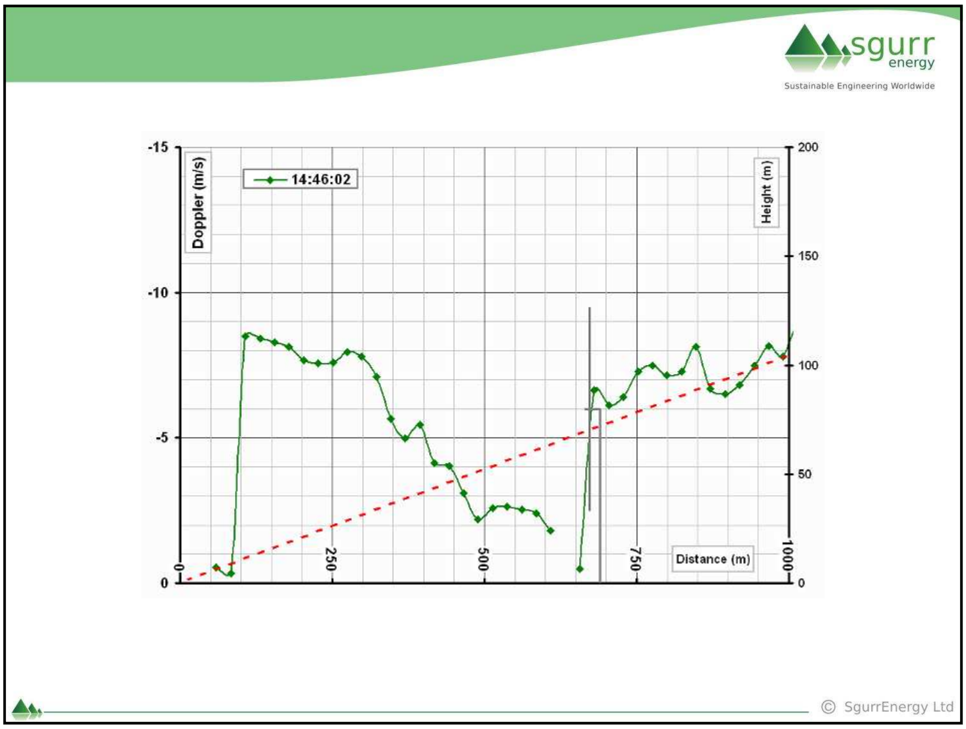
sgurr energy
Sustainable Engineering Worldwide

- **Fixed azimuth (260^0), elevation scanned**
- **Each frame: 13 rays, 1 degree step, 30 sec per scan**
- **16 frames**
- **Wind coming towards lidar over trees**
- **Clouds were scudding along but it was relatively calm down at the lidar**




RHI
sgurr energy
Sustainable Engineering Worldwide
Wind profile taken at the end of the scan sequence
Bearing (degrees)
0
60
120
180
240
300
360
250
200
150
100
50
0
23/01/2009 14:38:52
Height AGL (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Speed (ms-1)
© SgurrEnergy Ltd


RHI
sgurr energy
Sustainable Engineering Worldwide
Average of all frames
Signal strength
Hillside
Trees
Altitude (m)
100
80
60
40
20
50
100
150
200
250
Range (m)
8
6
4
2
0
-2
-4
-6
-8
© SgurrEnergy Ltd


sgurr energy
Sustainable Engineering Worldwide
14:46:02
Doppler (m/s)
Height (m)
Distance (m)
-15
-10
-5
0
0
250
500
750
1000
200
150
100
50
0
© SgurrEnergy Ltd

Conclusions

sgurr energy
Sustainable Engineering Worldwide

1) Complex flow in wakes within and between wind farms presents challenges to 1st generation wind Lidar measurement techniques;

2) 2nd generation devices can implement useful scan geometries for investigating wakes.

Any questions?

Email: peter.clive@sgurrenergy.com

Tel: 0141 227 1724
www.sgurrenergy.com

sgurr energy
Sustainable Engineering Worldwide

GARRAD HASSAN

A GL company

Large wind farm model

Presented at IEA wakes meeting, Pamplona May 2010

Renewable Energy Experts
worldwide

GARRAD HASSAN

A GL company

The problem

- Wake models were designed for modelling a single wake
- It is assumed that the wakes in a wind farm are independent and don't affect the flow itself

Large wind farm model

GARRAD HASSAN

A GL company

The problem

- Wind farms have evolved since and new challenges have arisen.
- The wind farm size has increased and wind farms with hundreds up to several thousands turbines are under development, onshore and offshore.
- For wind turbines more than 5 rows inside a large wind farm wake losses can be higher than predicted by standard models.

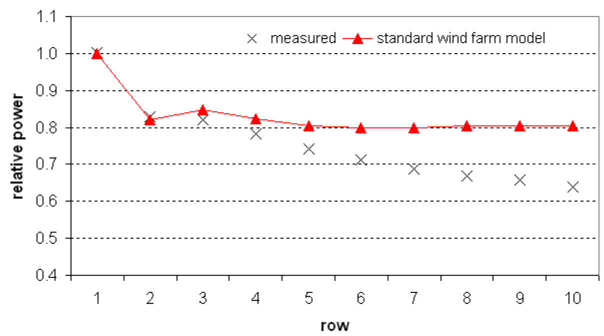
Large wind farm model

GARRAD HASSAN

A GL company

Horns Rev

wind speed 8 m/s
direction 255-285 deg



Large wind farm model

© 2010 Garrad Hassan and Partners Ltd

GARRAD HASSAN

A GL company

Model Assumptions

- The wind farm size has increased so that it now affects the free flow
- The wind farm can be treated as independent perturbation of the wind flow
- An increased roughness is assumed for the wind farm area to model the perturbation
- The wake model stays the same

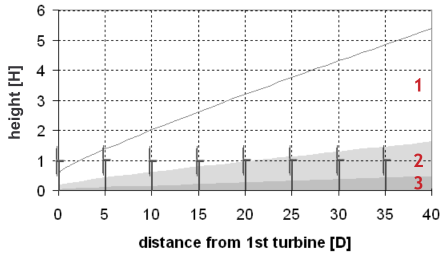
Large wind farm model

GARRAD HASSAN

A GL company

Large wind farm model

Correction of the free wind speed using an internal boundary model



Height of internal boundary layer

$$\frac{h}{z_0'}\left(\ln\frac{h}{z_0'}-1\right)=0.9\frac{x}{z_0'} \qquad h' = h+\frac{2}{3}H$$

Roughness settings

$$z_{02} = z_{01} + 0.03 \quad onshore$$
$$z_{02} = z_{01} + 0.02 \quad offshore$$

3 layer model

$$u(z)=\begin{cases} u_1(z) \quad for\ z' \geq 0.3h' & \mathbf{1} \\ \dfrac{u_1(z)}{ln\left(\frac{z'}{z_{01}}\right)}\left[\dfrac{ln\left(\frac{h'}{z_{01}}\right)}{ln\left(\frac{h'}{z_{02}}\right)}\cdot ln\left(\frac{0.09h'}{z_{02}}\right)\left\{1-\dfrac{ln\left(\frac{z'}{0.09h'}\right)}{ln\left(\frac{0.3}{0.09}\right)}\right\}+ln\left(\frac{0.3h'}{z_{01}}\right)\cdot\dfrac{ln\left(\frac{z'}{0.09h'}\right)}{ln\left(\frac{0.3}{0.09}\right)}\right] \quad for\ 0.09h' < z' < 0.3h' & \mathbf{2} \\ u_1(z)\left[ln\left(\frac{h'}{z_{01}}\right)\cdot ln\left(\frac{z'}{z_{02}}\right)\right] \Big/ \left[ln\left(\frac{h'}{z_{02}}\right)\cdot ln\left(\frac{z'}{z_{01}}\right)\right] \quad for\ z' \leq 0.09h' & \mathbf{3} \end{cases}$$

In the model

z'_0 is higher of z_{01} and z_{02}

z' is the lower tip height

Large wind farm model

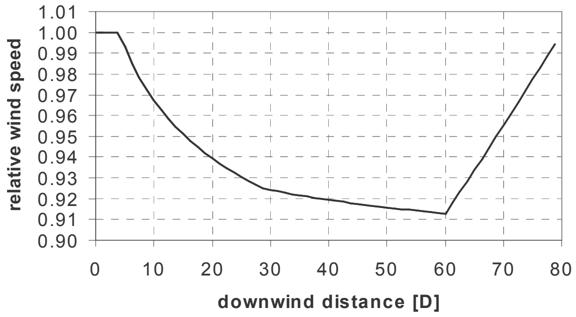
GARRAD HASSAN

A GL company

Large wind farm model

Wind speed correction

- Changes with downwind distance
- Includes linear recovery



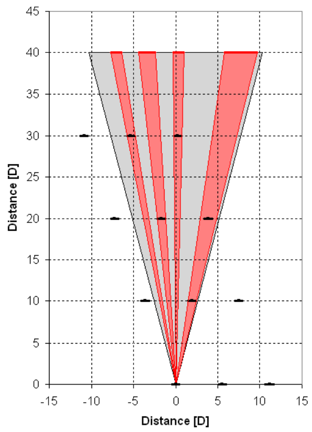
Large wind farm model

GARRAD HASSAN

A GL company

Large wind farm model

Turbine density



- The momentum extracted per given area increases with the number of wind turbines in that area
- Geometrical detection of sectors with upwind turbines
- Takes into account the turbine rotor diameter, D

Large wind farm model

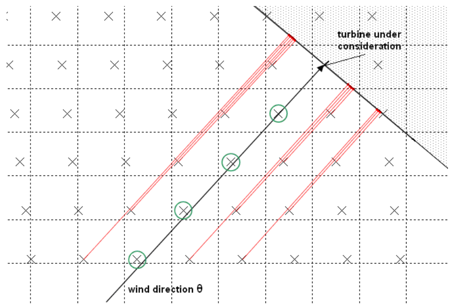
GARRAD HASSAN

A GL company

Large wind farm model

Row spacing

- Looking at distance to neighbouring rows perpendicular to the wind direction
- If it is more than 5D then the wakes are considered to develop independent from other rows and the large wind farm correction is not applied



Large wind farm model

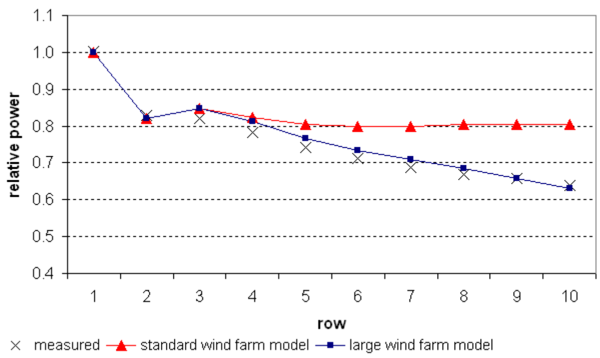
GARRAD HASSAN

A GL company

Validation

Horns Rev

- wind speed 8 m/s
- direction 255-285 deg

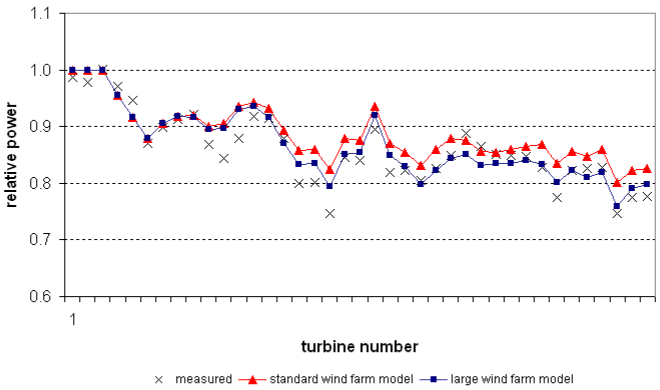


Large wind farm model

Validation

Onshore wind farm in flat terrain

- wind speed 8 m/s
- 30 deg sector



Large wind farm model

Examples

- Turbines arranged in a square layout
- 5 by 5 and 10 by 10 turbines
- Uniform wind rose
- Array efficiency in %

5 by 5 turbines array

Spacing [D]	standard model	large wind farm model	
		onshore	offshore
6	94.0	93.7	93.1
7	95.1	94.9	94.4
8	95.9	95.7	95.2
9	96.5	96.3	96.0
10	97.0	96.8	96.4

10 by 10 turbines array

Spacing [D]	standard model	large wind farm model	
		onshore	offshore
6	91.9	90.9	88.5
7	93.2	92.4	90.4
8	94.2	93.5	91.6
9	95.0	94.4	93.0
10	95.6	95.1	93.8

Large wind farm model

GARRAD HASSAN

A GL company

Summary

- Large wind farm model for improved modelling of a large array
- Reduction in net energy yield depends on layout, ratio of rotor diameter and hub height and roughness
- Reduction is bigger for offshore wind farms

Further validation of the model is required when data from more wind farms are available

Large wind farm model

GARRAD HASSAN

A GL company

For more information on the large wind farm modelling described in this presentation, see:

- Schlez W, Neubert A "New Developments in Large Wind Farm Modelling" Conf Procs EWEC09, Marseille 2009
- Johnson C et al "New Developments in Wake Modeling for Large Wind Farms" Conf Procs AWEA09, Chicago 2009

Contact: windfarmer@garradhassan.com

End

Large wind farm model

Summary of IEA RD&D Wind – 62th Topical Expert Meeting

Daniel Cabezón, Javier Sanz, Félix Avia, CENER

a) Participants

A total of 15 persons registered for this meeting. They represented the following countries: Denmark, Germany, Japan, Norway, Sweden, Netherlands, Spain, UK and the USA. A total of 13 presentations were given.

The participants represented a great variety of stakeholders related to the topic. Those were: research organizations, universities and consultants.

A total of 13 presentations were given:

1. Arno J. Brande, ECN Wind Energy, The Netherland
2. Michael Robinson, National Renewable Energy Laboratoy (NREL), USA
3. Daniel Cabezón, CENER, Spain
4. Anders Sommers, Vatenfall Vindkraft AB, Denmark
5. Jan-Ake Dahlberg, Vatenfall Vindkraft A, Sweden
6. Rodman Linn, Alamos National Laboratory, USA
7. Peter Stuart, RES, UK
8. Juan Jose Trujillo, Carl Von Ossieztky University of Oldenburg, Germany
9. Iida Makoto, The Univ. of Tokyo, Japan
10. Alla Sapronova, Uni Research, BCCS, Norway
11. Nick Baldock, Garrad Hassan, UK
12. Peter Clive, SgurrEnergy Ltd, UK
13. Cesar Castillo, Garrad Hassan Ibérica L.S.U., Spain

b) Discussion

Following the two days of presentations the floor was opened and a general discussion took place with the main target of reach conclusions derived from the presentation trying to identify priorities for new R&D activities, including specific actions to improve the present state of the art of this topic. A number of different points were handled.

In particular, the following topics were discussed, in order to decide which are the priorities:

- Necessity of new Wake codes
- Validation of Wake codes
- Data required for validation. LIDAR use for CFD models validation
- Stability
- Topography
- Future actions

- New Wake models and the necessity of codes validation.

The first topic under discussion was to analyse the necessity to develop new codes for wake modelling. There was a general consensus between the participants about the necessity to develop new codes, due to the limitations of the already existing wake codes.

Wind turbine wakes represent an important topic of research due to the need of new wake models as an alternative to engineering models and new data bases of specific measurements inside wind farms located at challenging environments such as offshore and complex terrain.

From the modelling point of view, several aspects not considered by traditional models must be solved such as the interaction with complex terrain, which has an important effect on the wake deficit and fatigue loading for the different spacing. For that purpose, more sophisticated models based on CFD technology are being developed in order to solve in detail the interaction between topographic features and wind turbine wakes.

Future trends focus on methods to measure and model the effect produced between big wind farms composed by huge wind turbines particularly at offshore sites and on how this effect can influence local wind climate. For this purpose, several upscaling hypothesis and a combination of mesoscale and microscale modelling could help to highlight some of these uncertainties.

-Validation of Wake Codes

A more formal wake model evaluation benchmarking is needed – likely in the framework of the IEA. The main objectives could be:

- ✓ To provide a universal set of benchmarks for wake model evaluation
- ✓ To evaluate current wind farm model performance
- ✓ To increase the availability and scope of detailed validation data.

These benchmarks should involve model intercomparisons and also comparisons to field data.

One of the main conclusions is that the validations should be done in several steps. For the beginning it is necessary to perform a comparison of the codes for some well defined cases.

A second step could be a validation exercise using measured data from an isolated wind turbine installed in a not very complex site. Last step of the validation process could be done using data form wind turbines installed in a wind farm, including cases of installations in complex terrain and with more complex meteorological conditions.

- Data required for validation. LIDAR use for CFD models validation

From the measurements point of view, new data bases are needed in order to understand the behaviour of flow at the near and far wake regions of wind turbines and also inside wind farms.

As a general conclusion, more wind farm data are needed from different environments. Discussion is needed to decide the data type and format adequate for the validation.

New LIDAR measurements techniques are very promising in order to characterise wind speed distributions at areas affected by the presence of wind turbines under certain conditions. Complementary data bases from Scada systems of wind farms are also really valuable in order to complement wind speed information and validate complete wind farm models.

- Stability

Offshore industry have experimented an important development during the last years and big wind farms are being installed for several kilometres along the coasts. As part of this development, new wind farm models based on CFD but also on revised analytical models are needed to take into account the thermal effects produced by the atmospheric stability especially predominant at offshore sites. This effect have a clear impact on the wind shear and ambient turbulent intensity, making the recovery distance of the flow and wake effects to be modified intensively inside wind farms and consequently energy production and fatigue loading of wind turbines between big wind farms. Nevertheless, stability of atmosphere is not easy to measure and classify so that some criteria are needed in order to homogenise this process.

These effects have some implications on wind farm and wind turbines design at offshore sites, where these special conditions make previous design criteria to be revised accordingly. Some new algorithms have started to be developed in order to optimize positions of big wind farms in terms of cost and output net production. Some aeroelastic codes are also being implemented as part of new wake models in order to estimate the influence of the disturbed flow on the wind turbine structures.

- Topography

In the previous TEM #59 about remote sensing, and TEM o#60 on Wind Farms in Complex Terrain, one of the topics under discussion was the definition of complex terrain (CT). There was also a general consensus between the participants about the necessity to have a clear definition of CT.

c) Future actions under the umbrella of IEA Wind

The development of a benchmarking framework for wind turbine wakes and wind farm modeling was proposed for some of the participants. The purpose is to gain insight into the benefits and drawbacks of a set of modeling assumptions for a wide range of applications. Much of this new task will involve benchmarking models of wakes against other models and verifications using good quality measured data.


cener
centro nacional de energías renovables

Participants List - TEM -Micro Meteorology inside Wind Farms and Wakes between Wind Farms

Name	Last Name	Job Center	Country	Phone/Fax	E-mail
Alla	**Sapronova**	Uni Research, BCCS	**NORWAY**	47 414 88 643/ 55 584 295	alla.sapronova@uni.no
Anders	**Sommers**	Vatenfall Vindkraft AB	**DENMARK**	45 278 75869	anders.sommer@vattenfall.com
Arno J.	**Brand**	ECN Wind Energy	**HOLLAND**	31 224 56 4775/8216	brand@ecn.nl
Cesar	**Castillo**	Garrad Hassan	**SPAIN**	34 976 435 155/28 01 17	cesar.castillo@garradhassan.com
Daniel	**Cabezón**	CENER	**SPAIN**	34 948 252 800	dcabezon@cener.com
Iida	**Makoto**	The Univ. of Tokyo	**JAPAN**	81 354 658 212	iida@cfdl.t.u-tokyo.ac.jp
Jan-Ake	**Dahlberg**	Vatenfall Vindkraft AB	**SWEDEN**	46 705 727142	jan-ake.dahlberg@vattenfall.com
Javier	**Sanz Rodrigo**	CENER	**SPAIN**	34 948 252 800	jsanz@cener.com
Juan Jose	**Trujillo**	Carl Von Ossieztky University of Oldenburg	**GERMANY**	49 441 36116 572/575	juan.jose.trujillo@forwind.de
Michael	**Robinson**	National Renewable Energy Laboratoy	**USA**	303 384 6947/6999	michael.robinson@nrel.gov
Nick	**Baldock**	Garrad Hassan	**UNITED KINGDOM**	44 119 972 9901	nick.baldock@garradhassan.com
Peter	**Stuart**	RES	**UNITED KINGDOM**	441 923 299238	peter.stuart@res-ltd.com
Peter	**Clive**	SgurrEnergy Ltd	**UNITED KINGDOM**	44141 227 1724	peter.clive@sgurrenergy.com
Rodman	**Linn**	Alamos National Laboratory	**USA**	505 665 6254/3415	rrl@lanl.gov
Lars	**Johansson**	Vatenfall Power Consultant	**SWEEDEN**	+46 46 286 4880	lars.e.johansson@vattenfall