INTERNATIONAL ENERGY AGENCY

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

**IEA R&D Wind Task 11 - Topical Expert Meeting**

# "Challenges on Wind Energy Deployment in Complex Terrain"

University of Stuttgart, Stuttgart, Germany

November 12th and 13th 2013


Scientific Co-ordination: Félix Avia Aranda

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# 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, 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 (RP) for wind turbine testing and evaluation for each topic needing recommended practices. In June 2011 was edited the RP on “Consumer Label for Small Wind Turbines”. A new RP about “Performance and Load Conditions of Wind Turbines in Cold Climates” is expected to be edited this year.

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 68 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**

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| COUNTRIES PRESENTLY PARTICIPATING IN THE TASK 11 | |
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| **COUNTRY** | **INSTITUTION** |
| Denmark | Danish Technical University (DTU) - Risø National Laboratory |
| Republic of China | Chinese Wind Energy Association (CWEA) |
| Finland | Technical Research Centre of Finland - VTT Energy |
| Germany | Bundesministerium für Umwelt , 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 | The National Renewable Energy Centre (NAREC) |
| United States | The U.S Department of Energy -DOE |

## CONTENTS



## PRESENTATIONS

# 1. INTRODUCTORY NOTE

## Wind Energy Deployment in Complex Terrain

Po Wen Cheng, Thorsten Lutz, Andreas Rettenmeier, Martin Hofsäß

Wind energy had gone through a period of expansions and currently wind energy contributes to ca. 2.5 % of the worldwide electricity production. The wind turbines in the developed markets have been installed primarily in sites that have very good wind resources and are easy accessible with simple or flat terrains. However, those sites are becoming scarcer as the wind energy market matures. For the wind energy to continue to expand it is necessary to explore sites that were not developed in the past due to the difficulty of the terrains which has been an obstacle for the development of wind energy in many countries and regions with complex terrain characteristic.

Often the complex terrain sites are also closer to the center of electricity consumptions and by using wind resources close to the center of consumption the investment cost related to the transmission can be reduced, which makes wind energy in complex terrain competitive if the technical challenges can be overcome. But there are many technical challenges associated with the utilization of wind energy in complex terrain and here we will name a few of them that will be discussed in this topical expert meeting

1- Wind resource: the wind resource across the complex terrain is not very easy to be determined using current flow models. The differences in the wind energy potential from turbine site to turbine site in a complex terrain can be significantly different. The localized measurements by using wind met mast that can only give localized information about the wind resource is not sufficient to estimate the wind resource of a wind park. Extrapolation of wind condition from one turbine position to another can have significant uncertainties.

2- Power performance and noise propagation: in a complex terrain as the flows are very complex it is difficult to verify the power performance of the wind turbines using standard procedures that have been applied in the wind industry in the past 20 years. This is an important aspect because the economic feasibility of wind farms in a complex terrain depends on the accurate prediction of the energy production. Therefore it is necessary to look at the wind turbine performance verification from a very different perspective with a common understanding of the measurement procedure. It is possible to consider the use of technologies that haven't been used in the past for wind turbine performance verification such aslidar and CFD in a wider range. The noise propagation of the wind turbine in complex terrain faces the same problematic as power performance prediction and verification. The current acoustic model has its limitations when applied to complex terrain, therefore it is necessary to develop more accurate acoustic models to predict the impact of noise on the surrounding.


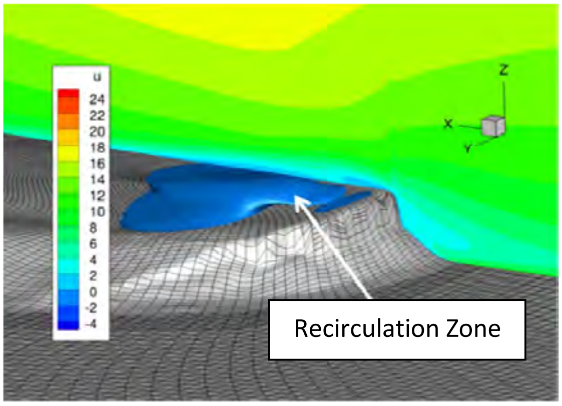


*Fig 1: Scanning Lidar system at a complex site in Southern Germany [SWE, University of Stuttgart]*

*Fig 2: CFD-Simulations of a complex terrain site [IAG, University of Stuttgart]*

3- Loads: For the wind turbine manufacturer the complex terrain poses new technological challenges in that the loads on the wind turbine are very different than those of a flat terrain. The changes in the wind direction are more frequent, the turbulence intensity is higher as well as the wind shear profile is different or can even show reverse flow. All these can cause extreme loads and stronger load fluctuations on the wind turbine and can lead to premature damage of the wind turbine components due to increased fatigue. A more detailed prediction of loads in the future wind turbine development will be needed.

4- Logistics: the logistics associated with a complex terrain is not a trivial challenge as the wind turbine grows larger and the rotor diameter becomes bigger, transporting those giant components to a site in complex terrain is not an easy task. Therefore having the right technical solutions for the logistics is essential to make exploitation of wind energy in complex terrain feasible and keep the cost of energy in an acceptable that make the use of wind energy economical.

5- Application of CFD models: Numerical simulations are a mean to improve the understanding of the atmospheric inflow in complex terrain and to verify site assessment and simplified power and load calculations. A coupling of meso- and microscale models can thereby generate site-specific information about the atmospheric boundary layer and turbulence characteristics and thus support the site assessment and reduce investment risks. Simulations of fully meshed wind turbines in complex terrain can help to predict power and loads of future wind turbines under consideration of the aerodynamic interaction between the atmospheric boundary layer, the wind turbine and its wake.

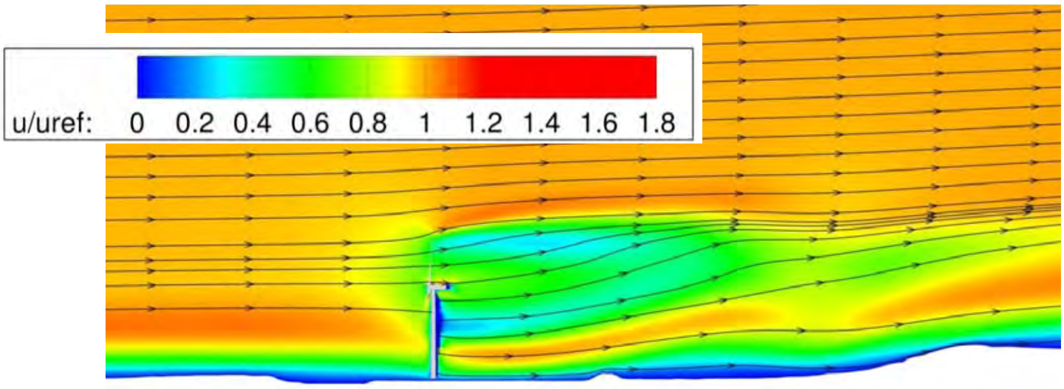


*Fig 1: Inflow, rotor and wake CFD-simulations of a turbine [IAG, University of Stuttgart]*

## Objectives

A primary goal of the meeting is to give the participants a good overview of the challenges encountered in wind energy application in complex terrains. A summary and assessment of issues will be a part of the finalizing discussion.

As a starting point for the potential participants, a list of topics and issues encountered on complex terrains has been given here below.

- Measurement procedure for characterization of wind field in complex terrain
- Meteorology in complex terrain
- Advances in measurement technologies, Lidar, Sodar, UAVs
- Experimental measurement of complex terrain models in atmospheric wind tunnels
- High fidelity modeling of wind field, interaction with the turbine and detailed load analysis (CFD)
- Wind resource assessment in complex terrain (Meso-scale model)
- Optimization of wind farm layout in complex terrain
- Design conditions for wind turbines in complex terrain (external conditions)
- Measurement of power curve in complex terrain
- Impact on loads and load mitigation strategy or control
- Feed-forward and model predictive control of wind turbines
- Acoustic modeling of noise propagation in complex terrain
- Logistic challenges and solutions in complex terrain
- Load and energy optimization

# 2. AGENDA

## Tuesday 12th November

*>09:00* **Registration**. Collection of presentations

*>09:20* **Introduction by Host**

*>09:40* **Recognition of Participants**

*>09:45* **Introduction by Task 11 Operating Agent.**
*Felix Avia, Operating Agent Task 11 IEAWind R&D*

*>10:10* **Wind Energy in Complex Terrain: State of the Art**
*Dr. Po Wen Cheng, Stuttgart Wind Energy (SWE), Germany*

***●10:40 Coffee Break (20 minutes)***

## 1st Session Individual Presentations:

*>11:00* **Quantifying terrain complexity**
*Dr. PJM Clive, SgurrEnergy Ltd, Scotland*

*>11:25* **Complex Terrain Test Site with 200m Met Mast at Fraunhofer IWES**
*Tobias Klaas, IWES, Germany*

*>11:50* **The Alaiz test site in complex terrain for site-assessment model evaluation**
*Dr. Javier Sanz Rodrigo, CENER, Spain*

*>12:15* **Wind tunnel aeroelastic models in complex terrains**
*Filippo Campagnolo, TUM, Germany*

*>12:40* **CFD of wind turbines in complex terrain**

*Christoph Schulz, IAG University of Stuttgart, Germany*

## ●*13:00 Lunch*

**2nd Session Individual Presentations:**

*>14:30* **Improving layouts in complex terrain using CFD-based constraint maps**

*Benjamin Martinez, Vattenfall, Denmark*

*>14:55* **Validations of Large-Eddy Simulations with the Weather Research and Forecasting Model using Askervein Hill experiment data**

*Dr. Branko Kosovic, National Center for Atmospheric Energy, USA*

*>15:20* **FNWP interpolation of wind measurements and implications for spatial uncertainty and wake losses**

*Dr James R. McCaa, 3TIER, Inc. USA*

*>15:45* **Experiences of different measurement techniques in Finland.**

*Merja Paakkari, Hafmex Oy, Finland*

## ●*16:10 Coffee Break*

*>16:30* **In-situ turbulence measurement with the UAV MASC for wind site evaluation.**

*Norman Wildmann, Centre for Applied Geo-Science, Univ. of Tübingen, Germany*

*>16:55* **Validation of CFD wind resource mapping based on performance data from 50 operational wind farms**

*Dr Gregory Oxley, Vestas Wind Sistems A/S, Denmark*

*>17:20* **A hybrid model adapted for wind energy applications**

*Mary C. Bautista, École de Technologie Supérieure, Canada*

***●17:45 End of the Tuesday meeting***

***●19:30** Dinner*

## Wednesday 13th November

### 3rd Session Individual Presentations

*>09:00* **Towards the consistent two-equation closure modeling of atmospheric flows**

*Dr. Andrey Sogachev, Technical University of Denmark, Denmark*

*>09:25* **Measured (by SODAR) vertical profiles of Weibull parameters over a hill**

*Dr. Stefan Emeis, Karlsruhe Institute of Technology, Germany*

*>09:50* **Loading conditions in complex terrains and load alleviation strategies**

*Vlaho Petrovic, TUM, Germany*

*>10:15* **Research Project Lidar complex**

*Martin Hofsäß, SWE, University Stuttgart, Germany*

***●10:30 Coffe Break***

*>10:50* **Wind Resource Assessment in Complex Terrain**

*Nicolas E. Veneranda, Lahmeyer International GmbH, Germany*

*>11:15* **Benchmarks of CFD simulation in complex terrain**

*Dr Yuko Ueda, Wind Energy Institute of Tokyo Inc, Japan*

*>11:40* **Wind field analysis and characterization of sound immission in the vicinity of wind turbines in topologically structured terrain**

*Dr J. Tessmer , DLR German Aerospace Center, Germany*

*>12:05* **A Landscape Character Assessments on Windfarms in populated complex landscapes on the example of Southern**

*Dr. Schoebel, Germany*

*>12:30* **Presentation 21**

*Dr Shreyas Anantha, Department of Energy, USA*

## *●13:00 Lunch*

*>14:00* **Discussion**

*>14:45* **Summary of Meeting**

*>15:00* **End of the meeting**

# 3. LIST OF PARTICIPANTS

The meeting was attended by 28 participants from 8 countries. Table 1 lists the participants and their affiliations.

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**Table 1 Participants in IEA Wind TEM on "Challenges on Wind Energy Deployment in Complex Terrain"**


TECHNISCHE HOCHSCHULE STUTTGART
Universität Stuttgart

Twenty two presentations were given:

*1.* **Wind Energy in Complex Terrain: State of the Art.** *Dr. Po Wen Cheng, Stuttgart Wind Energy (SWE), Germany*

*2.* **Quantifying terrain complexity.** *Dr. PJM Clive, SgurrEnergy Ltd, Scotland ...........*

*3.* **Complex Terrain Test Site with 200m Met Mast at Fraunhofer IWES.** *Tobias Klaas, IWES, Germany*

**4. The Alaiz test site in complex terrain for site-assessment model evaluation.** *Dr. Javier Sanz Rodrigo, CENER, Spain*

*5.* **Wind tunnel aeroelastic models in complex terrains.** *Filippo Campagnolo, TUM, Germany*

*6.* **CFD of wind turbines in complex terrain.** *Christoph Schulz, IAG University of Stuttgart, Germany*

**7. Improving layouts in complex terrain using CFD-based constraint maps.** *Benjamin Martinez, Vattenfall, Denmark*

*8.* **Validations of Large-Eddy Simulations with the Weather Research and Forecasting Model using Askervein Hill experiment data.** *Dr. Branko Kosovic, National Center for Atmospheric Energy, USA*

*9.* **FNWP interpolation of wind measurements and implications for spatial uncertainty and wake losses.** *Dr James R. McCaa, 3TIER, Inc. USA*

***10.*** **Experiences of different measurement techniques in Finland.** *Merja Paakkari, Hafmex Oy, Finland*

*11.* **In-situ turbulence measurement with the UAV MASC for wind site evaluation.** *Norman Wildmann, Centre for Applied Geo-Science, Univ. of Tübingen, Germany*

*12.* **Validation of CFD wind resource mapping based on performance data from 50 operational wind farms.** *Dr Gregory Oxley, Vestas Wind Sistems A/S, Denmark*

*13.* **A hybrid model adapted for wind energy applications.** *Mary C. Bautista, École de Technologie Supérieure, Canada*

*14.* **Towards the consistent two-equation closure modeling of atmospheric flows.** *Dr. Andrey Sogachev, Technical University of Denmark, Denmark*

**15. Measured (by SODAR) vertical profiles of Weibull parameters over a hill.** *Dr. Stefan Emeis, Karlsruhe Institute of Technology, Germany*

*16.* **Loading conditions in complex terrains and load alleviation strategies.** *Vlaho Petrovic, TUM, Germany*

*17.* **Research Project Lidar complex.** *Martin Hofsäß, SWE, University Stuttgart, Germany*

*18.* **Wind Resource Assessment in Complex Terrain.** *Nicolas E. Veneranda, Lahmeyer International GmbH, Germany*

*19.* **Benchmarks of CFD simulation in complex terrain.** *Dr Yuko Ueda, Wind Energy Institute of Tokyo Inc, Japan*

**20. Wind field analysis and characterization of sound immission in the vicinity of wind turbines in topologically structured terrain**

*Dr J. Tessmer , DLR German Aerospace Center, Germany*

*21.* **A Landscape Character Assessments on Windfarms in populated complex landscapes on the example of Southern.** *Dr. Schoebel, Germany*

*22.* **Presentation 21.** *Dr Shreyas Anantha, Department of Energy, USA*

# 4. SUMMARY

A primary goal of the meeting was to give the participants a good overview of the challenges encountered in wind energy application in complex terrains (CT). A summary and assessment of issues will be a part of the finalizing discussion.

Following the presentations, the floor was opened and a general discussion took place among the participants. Topics selected for the discussion were:

1. Challenges associated with the Wind Resource assessment on CT.
2. Use of Remote Sensors on CT.
3. Aplication of CFD models in CT.
4. Power Performance and AEP prediction on CT.

## 1. Challenges associated with the Wind Resource assessment in C.T.

One of the challenges to effective sitting of wind turbines is the ability to make reliable and accurate predictions of the wind power resource. There are a number of commercial wind resource assessment programs that have been developed in order to give estimates of site wind speed at potential wind farm sites. Such models produce reasonable results when the terrain is fairly flat with only gentle hills. However, if the wind farm is to be situated in mountainous terrain the results become less reliable. Wind resource assessment in complex terrain is not very easy to be determined using current flow models.

Use of a wind met mast that can only give localized information about the wind resource, but it is not sufficient to estimate the wind resource of a wind park. Extrapolation of wind condition from one turbine position to another can have significant uncertainties.

Numerical simulations are a mean to improve the understanding of the atmospheric inflow in complex terrain and to verify site assessment and simplified power and load calculations.

Recent research has been carried out using more complete Navier-Stokes solvers. These models uses the computational fluid dynamics (CFD) solvers. There is a clear improvement in accuracy over the commonly used linear models by using CFD models

## 2. Use of Remote Sensors in C.T.

Important wind farm development decisions are based on the accurate measurement of a variety of atmospheric variables. Traditionally, sensors mounted on meteorological masts have been used to characterize local wind regimes in advance of constructing a large wind farm development.

In recent years LIDAR (LIght Detection and Ranging) technologies have emerged as a potentially useful wind resource assessment tool. This technology is poised to change traditional wind resource measurement by offering physical measurements at several heights across the turbine rotor plane from a compact, ground-based system. The increasing trends in height and rotor diameter size of modern wind turbines have further encouraged the development and conditional acceptance of these measurement devices by the meteorological community.

An increasing number of studies have demonstrated that remote sensing technology is suitable for commercial use in the wind energy industry and interest in the technology is growing quickly in the global wind power community. However, mechanical cup anemometers are the current industry standard for measuring wind speed at wind farm sites and these instruments will continue to play a significant role in resource measurement campaigns. If implemented properly, the careful deployment of LIDAR remote sensing combined with traditional cup anemometer devices may provide wind project developers with useful information that can be used to reduce the costs associated with wind data collection at heights in excess of 60-80 meters. A well-planned and properly implemented wind resource measurement campaign involving a diverse suite of measurement techniques may also contribute to the overall reduction of uncertainty in a formal wind energy production assessment. In response to the growth of commercially available remote sensing technologies and the potential benefits of such devices, the need for information regarding the future use of LIDARs in formal energy production assessments (EPA) has been established.

IEA Wind Recommended Practice on “Ground-Based Vertically profiling Remote Sensing for Wind Resource Assessment” was edited in January 2013. This document includes recommended practices for the characterization, verification, installation, operation and maintenance, and data analysis of a remote sensing device for the purposes of wind energy assessments.

This document is limited to vertically probing, ground-based LIDAR systems that are designed for wind resource assessment. It should be noted that many of the recommendations provided below apply equally to SODAR remote sensing, but the scope of this document is specific to LIDAR technology only commercially available CFD software packages have recently attracted attention for applications where complex terrain conditions iºnitially cause poor agreement between LIDAR and in-situ measurements. In limited examples, these software packages have demonstrated an encouraging ability to model the flow distortion that is caused by local terrain or forestry features. These preliminary results suggest that measurement bias associated with non-uniform flow over the LIDAR probe volume may be removed. While these software packages may potentially offer another useful tool for wind resource practitioners to utilize, they should be further investigated for accuracy and repeatability before results are quantitatively used for formal applications.

## 3. <u>Aplication of CFD models in C.T.</u>

Flow modeling using Computational Fluid Dynamics (CFD) software packages and other tools have been used to estimate the flow distortion caused by complex terrain or by changes in land cover. Studies suggest that measurement bias introduced to the remote sensing data may be removed in some cases in post processing, but for the time being there are limited peer-reviewed studies of the accuracy of such tools or the resulting AEP.

Further investigations of accuracy and repeatability are required before these tools can be recommended for the correction of RSD data.

Some guidelines to standarize the flow modelling in ComplexTerrain are celarly required.

### 4. Power Performance and AEP prediction on C.T.

In a complex terrain it is difficult to verify the power performance of the wind turbines using standard procedures that have been applied in the wind industry in the past 20 years.

Therefore it is necessary to look at the wind turbine performance verification from a very different perspective with a common understanding of the measurement procedure. It is possible to consider the use of technologies that haven't been used in the past for wind turbine performance verification such as LIDAR and CFD in a wider range.

The noise propagation of the wind turbine in complex terrain faces the same problematic as power performance prediction and verification. The current acoustic model has its limitations when applied to complex terrain, therefore it is necessary to develop more accurate acoustic models to predict the impact of noise on the surrounding.

## 5. CONCLUSIONS AND FUTURE ACTIONS UNDER THE UMBRELLA OF IEA WIND IMPLEMENT AGREEMENT

The main part of the discussion was focused on the analysis and interest in establishing a new IEA Wind task on Challenges of Wind Energy in Complex Terrain.

It was commented that on the ongoing IEAWind Task there is already research activities related to specific issues of Complex Terrain Sites. For instant in Task 31 Wakebench there is a specific activity on model comparison on complex terrain sites.

It will be required to get information from all the operating agents of IEAWind Tasks to get a full overview on the ongoing research under the umbrella of the IEA Wind Implement Agreement related to Complex Terrain. However this action requires work time to go ahead.

It was remarked that it will be very useful to stimulate the coordination between different tasks, action that was required in the last ExCo meeting of the IEA Wind in Beijing.

One option commented was the possibility to launch a task to coordinate these research activities on different task related to Complex Terrain sites, but for the time being there are not previous experiences of this kind of task.

The general consensus was that is better to lunch one task focussed in one specific issue, for instance “Uncertainty Analysis of CFD models in Complex Terrain”, than launch one task with a more general scope, covering several issues of the Wind Energy in Complex Terrain.

Also it was commented the necessity that manufacturers and wind farm promoters will be involved from the beginning in these kind of research activities.

In the frame of Task 31 there are already plans for a follow-up Task (2015-2017) that would look into a wider scope of flow modelling, not only dealing with microscale wind farm flow models but also mesoscale and downscaling models as well as near wake rotor models. This extended scope makes it possible to interrelate all the relevant scales of wind power meteorology from different modelling perspectives. This framework also allows a comprehensive approach towards uncertainty assessment. This can be linked with project risk assessment which is one of the main challenges of wind power financing nowadays.

Instead of opening a new Task specific to complex terrain, this topic shall be considered as a working group inside Task 31 extension. Task 31 O.A. will circulate a questionnaire to ask potential participants about the areas of interest for this new Task and, based on these inputs, a draft proposal will be presented preliminary at the IEA ExCo73 in Spring 2014 to obtain expressions of interest and integrate a full proposal to be voted at ExCo74 in Autumn 2014.

iea wind

# PRESENTATIONS

WINDFORS
Windenergie
Forschungsnetzwerk

# IEA Topical Expert Meeting

**Wind Energy in Complex Terrain**
**12 November 2013, University of Stuttgart**

**Po Wen Cheng**

**Institute of Aircraft Design**
**WindForS –University of Stuttgart**

WindForS Windenergie Forschungsnetzwerk

## Challenges Created by Energy Transition

- **More pressure to drive the cost of energy down, especially offshore wind energy**
- **Urgency to expand the transmission capacity and interconnection to link the producers with the consumers**
- **Increase wind energy penetration in medium-low wind speed area with complex wind flow and complex terrain**
- **Ability in the turbine and the system to deal with fluctuations in renewable energy production**
- **Need to rethink how to increase social acceptance as wind turbines grows larger and becomes more of a prominent part of the landscape**

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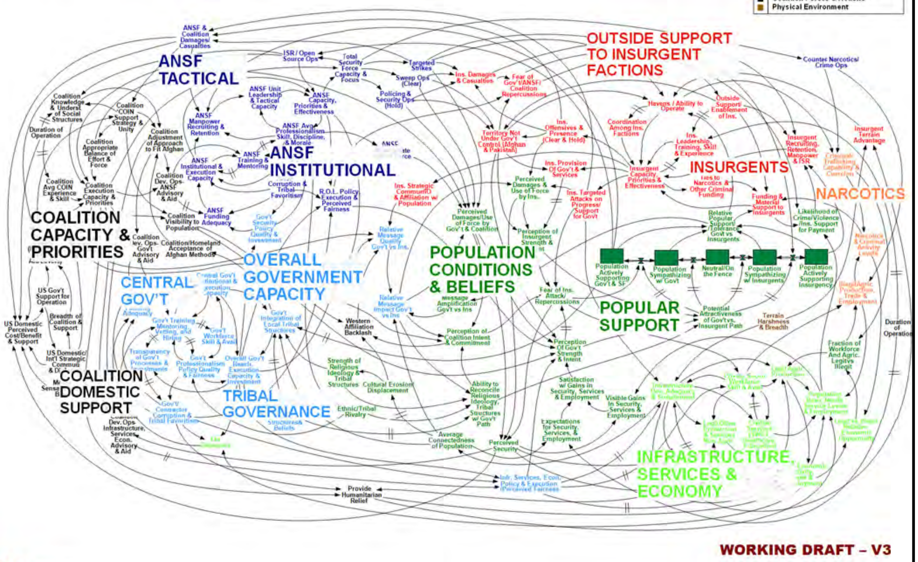
## Why Research on Wind Energy in Complex Terrain

- **It helps reduce the cost of energy because onshore wind is still cheaper than offshore wind and it has lower economic and technical risks.**
- **Reduce the need for the grid expansion as the power is produced where it is consumed**
- **Balancing the energy system together with the continuous expansion of photovoltaic**
- **Complex inflow condition leads to a difficult prediction of the power output with the current modeling and measurement techniques**
- **Complex load situation arises due to complex inflow that can lead to premature failure of the components**

**Afghanistan Stability / COIN Dynamics**

—//— = Significant Delay

- Population/Popular Support
- Infrastructure, Economy, & Services
- Government
- Afghanistan Security Forces
- Insurgents
- Crime and Narcotics
- Coalition Forces & Actions
- Physical Environment




WORKING DRAFT – V3

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## How Do We Define Complex Terrain?

- **Is there an objective characterization of the terrain complexity**
- **How can we decide when we need complex flow model**
- **Noise propagation model in complex terrain (size of the rotor blade, influence of the terrain)**
- **How to model complex inflow condition (model scale, computational efficiency, model uncertainty, improve performance in wind farm, wind farm layout)**
- **How to model the complex load situation arises due to complex inflow that can lead to premature failure of the components**

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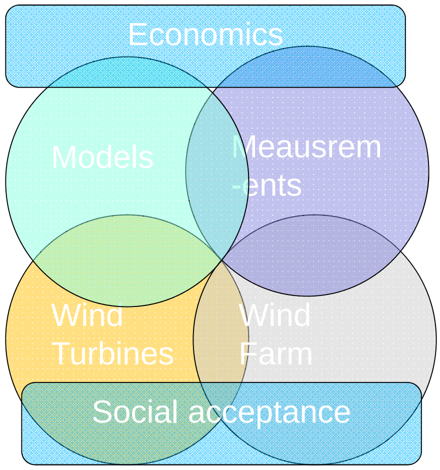
## Main Issues with Wind Energy in Complex Terrains

Mesoscale
LES
CFD

Dynamic
Response
Performance
Control




Uncertainties
Logistics

Wake
Wind Profile
Turbulence

Efficiency
Park Control

Landscapes
Conservation
Noise

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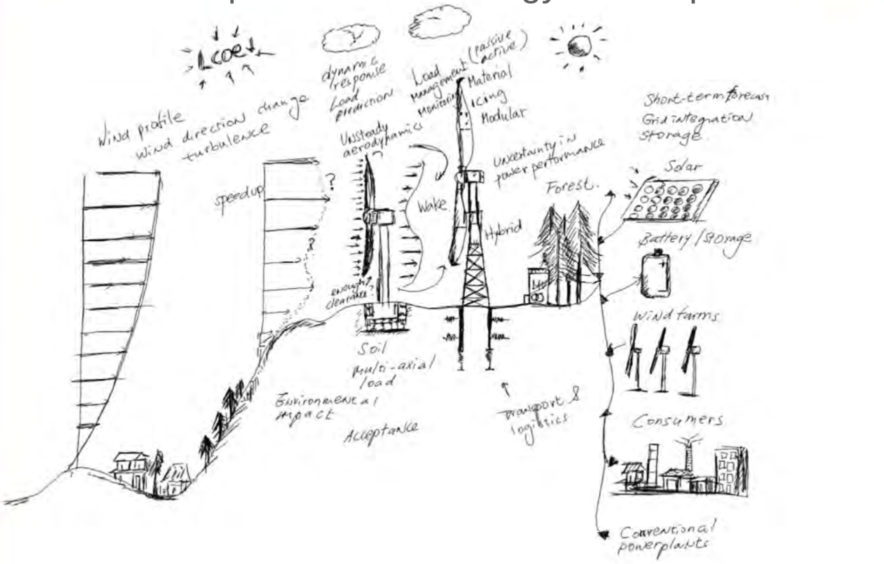
## Research Topics of Wind Energy in Complex Terrain



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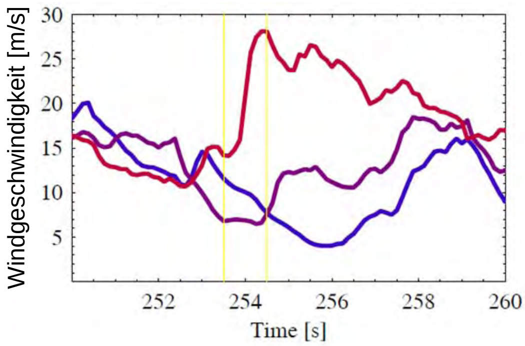
## Wind Shear and the Consequence



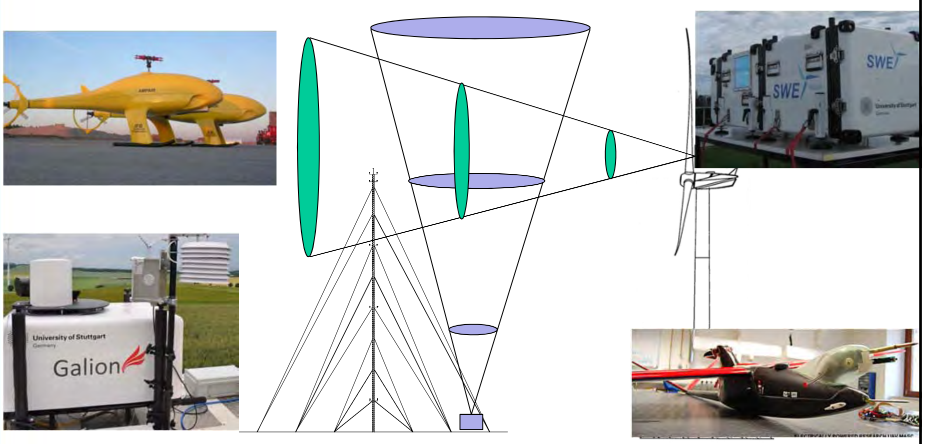

- 19m ---------
- 31m ---------
- 42m ---------

Source: Jacob Mann DTU

WINDFORS Windenergie Forschungsnetzwerk

## Measurement Campaign for Complex Terrain

- **Mobile measurements: UAV- Helicopter and Plane**
- **Fixed point measurement: metmast 80 meters**
- **LiDAR measurements: long-range and short-range**




Source: Jens Bange Univ. Tübingen

## Wind Modeling and Wind Tunnel Testing

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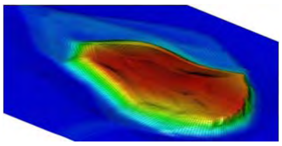
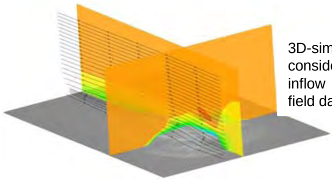
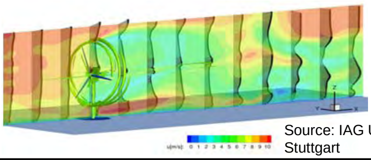
- Investigations on inflow influences and numerical parameters
- Implementation of further parameters of the ABL and an improved roughness consideration



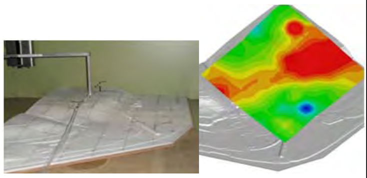


3D-simulation considering inflow field data

- Seven-hole probe measurements in Boundary Layer Wind Tunnel
  - Turbulent BL inflow generated by roughness elements
  - Alignment of BL to model scales



Source: IAG Univ. Stuttgart



## Model Scale and Model Complexity

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- Different scales serve different purposes, scale gaps are really that relevant ?
- Increase in model complexity needs to be justify by increase added value (significantly better performance, improved component design)
- Increase model complexity means more variances in the parameterization, strong influence of the users
- Are complex models really better models, offer more physical insights?
- Do not neglect engineering models for practical daily uses
- Are we getting the value out of HPC?

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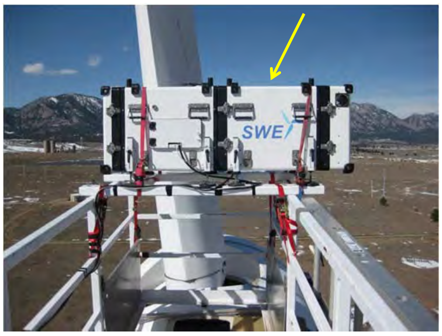
www.uni-stuttgart.de/windenergie

## LiDAR Feed-forward Controls Field Test

**First LIDAR feed-forward controller field tests successfully demonstrated (May 2012)**

University of Stuttgart (SWE) LIDAR - CART2




Catch the Wind
LIDAR – CART3

13

University of Stuttgart
Germany

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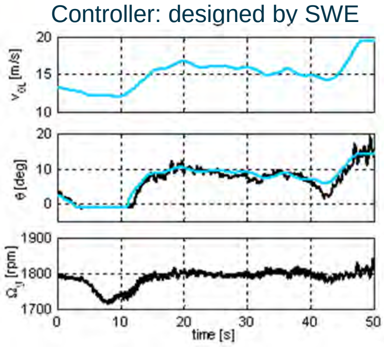
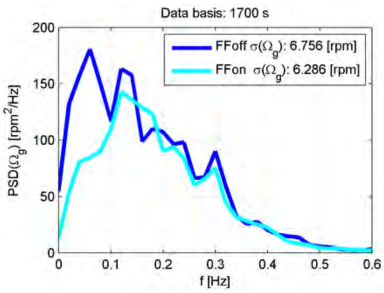
## Feed-forward Controls Field Test

Turbine: CART2
Lidar: SWE Lidar Scanner
Controller: designed by SWE




- Top: rotor effective wind speed from LIDAR
- Center: feed-forward pitch angle (blue) and applied pitch angle (black).
- Bottom: Generator speed .

Turbine: CART3
Lidar: Catch the Wind Vindicator
Controller: designed by SWE




- Feed-forward control reduces low frequency rotor-speed Power Spectral Density (psd)
- Feed-forward control improves speed regulation
- More test data needed

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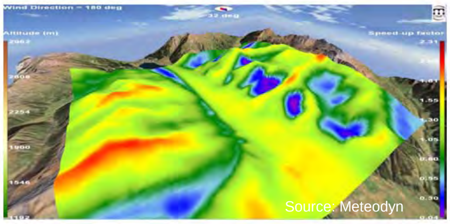
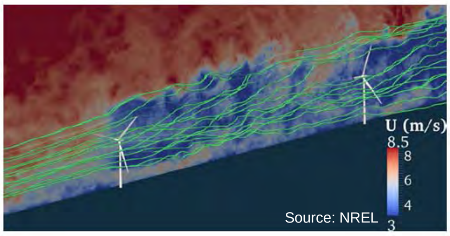
## Modeling of Wind Farm in Complex Terrains


Source: Meteodyn

- Understand the interaction between the flow, terrains and the wind turbines for siting purposes
- Determine the suitability of the wind turbine for the site



Source: NREL

- Understand the influence of the control strategy on the wind turbine performance and loads
- Derive wind farm control strategy to maximize turbine output, maximize turbine utilization

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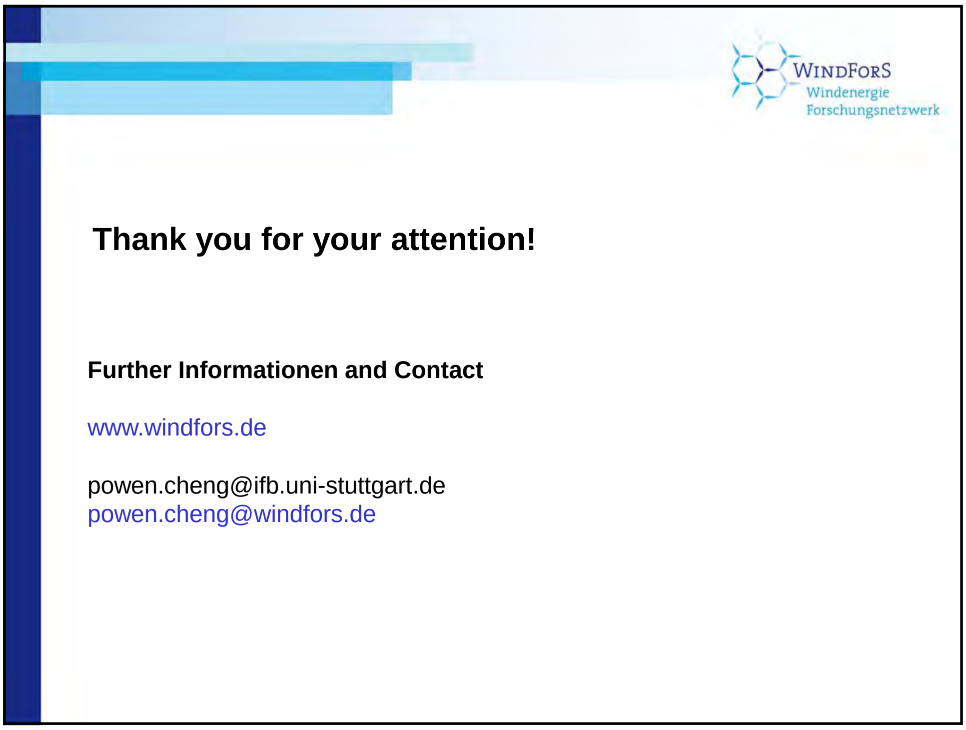
## Visual Impacts and Logistics of Wind Farm in Complex Terrains


Credit: ALAMY


Credit: Janna Nichols

- The size of wind turbines for complex terrains (low wind speed sites) can have significant visual impact
- Arrangement of the wind turbines not only based on performance but also on visual perception
- Difficult logistics for large components, blade and tower


Credit: WPD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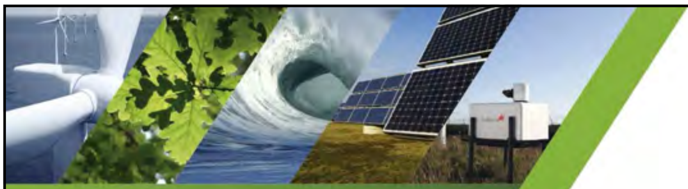
Thank you for your attention!
Further Informationen and Contact
www.windfors.de
powen.cheng@ifb.uni-stuttgart.de
powen.cheng@windfors.de



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Sustainable Engineering Worldwide

# Quantifying terrain complexity

Peter Clive
IEA R&D Wind Task 11 Topical Expert Meeting 75
University of Stuttgart, 12-13 November 2013

## Contents

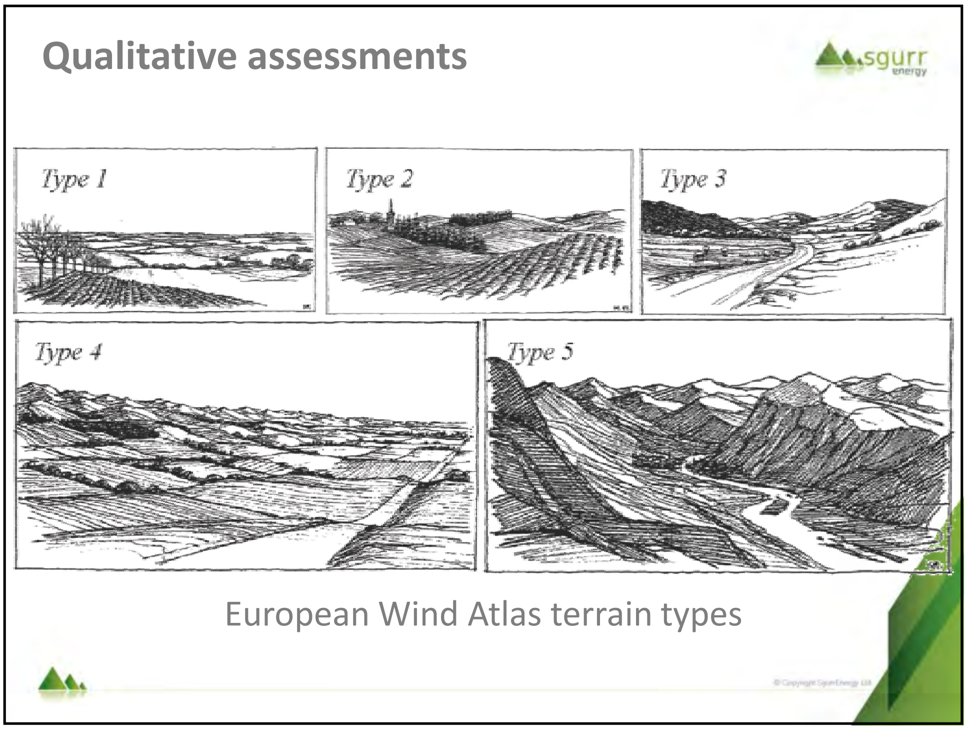
- Why do we need to? Decision support and the need to assess terrain complexity
- Assessing terrain complexity
  - Qualitative methods
  - Operational Methods
  - Quantitative methods
- Lidar use cases and terrain complexity
- Conclusions
  - Quantitative objective methods for assessing terrain complexity lead to repeatable procedures with inter-comparable results when making measurements or using models in complex terrain

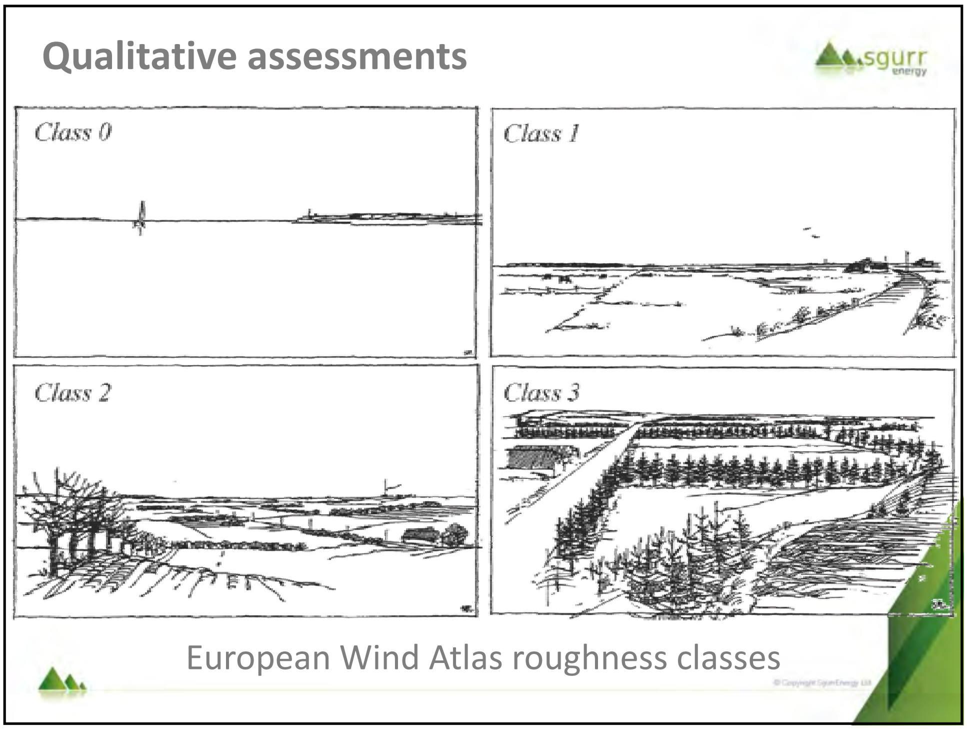
## Decision support

- Key decisions regarding wind power plant development are supported by information about terrain complexity, e.g.
  - Wind farm layouts
  - Wind resource assessment
  - Site suitability and classification
  - Turbine technology selections
- Decisions may be based on information from wind flow models, whose uncertainty may be assessed in relation to complexity metrics such as
  - Delta RIX between masts and turbines
  - Height difference between masts and turbines
  - Detachment, flow separation and recirculation
  - Distance of turbine from mast

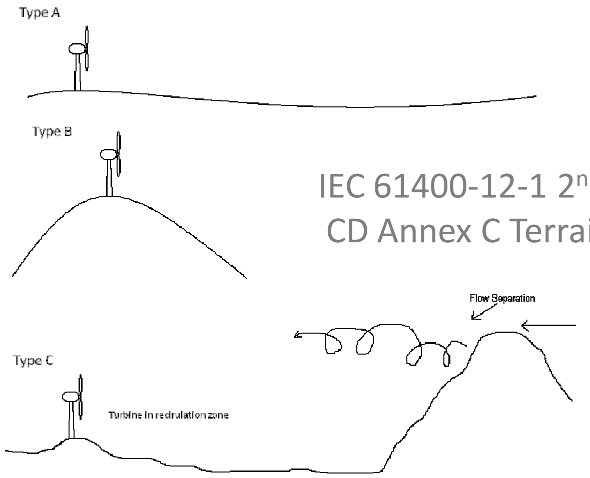
## Decision support

- Decisions regarding the design and implementation of measurement campaigns depend on assessments of terrain complexity, e.g. (non-exhaustive list)
  - The adoption of appropriate lidar use cases suited to
    - The purpose of the measurements
    - The circumstances in which the measurements take place
    - The measurement methodology adopted
  - Power Performance Assessments
    - Is a site calibration necessary?
- Quantitative assessments of terrain complexity are essential to
  - Eliminate subjectivity associated with qualitative methods
  - Facilitate the development and adoption of assessment procedures with repeatable and inter-comparable results
  - Enable transparent and comprehensive methods in wind power with respect to decision support in complex terrain


Qualitative assessments
sgurr energy
Type 1
Type 2
Type 3
Type 4
Type 5
European Wind Atlas terrain types


Qualitative assessments
sgurr energy
Class 0
Class 1
Class 2
Class 3
European Wind Atlas roughness classes

## Qualitative assessments




IEC 61400-12-1 2nd Edition
CD Annex C Terrain Types

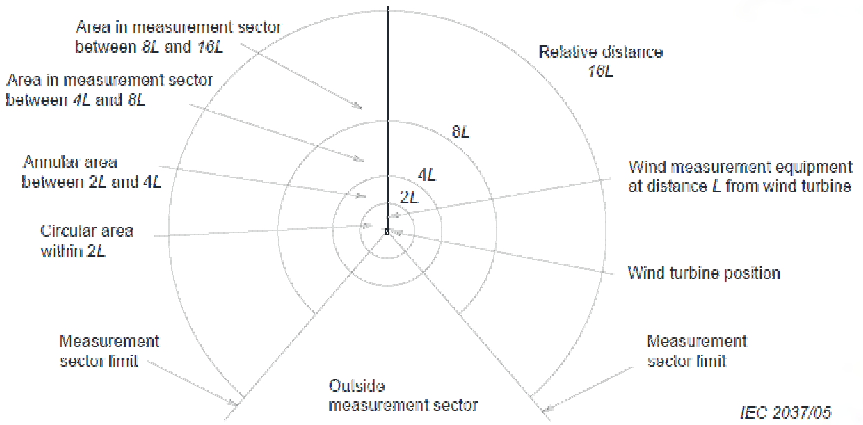
Qualitative assessments are too imprecise and subjective

## Operational assessments

| Wind Speed Definition | Hub-Height Wind Speed | | Rotor Equivalent Wind Speed | |
|---|---|---|---|---|
| Terrain Type | Non-Complex | Complex | Non-Complex | Complex |
| Hub Height Met Mast | X | X | | |
| Hub height mast in conjunction with remote sensing | X | | X | |
| Remote sensing in conjunction with short mast | X | | X | |
| Met Mast above Hub Height | X | X | X | X |

IEC 61400-12-1 2nd Edition
2CD measurement methods

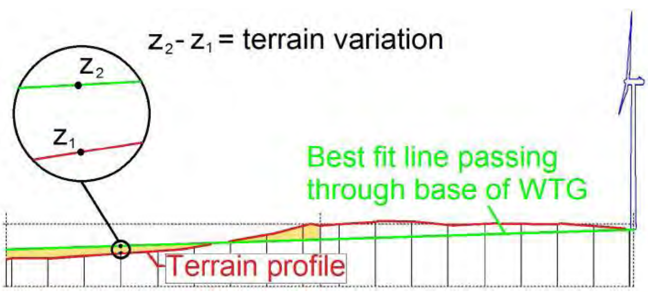
## Operational assessments




IEC 61400-12-1 2nd Edition 2CD Annex B

## Operational assessments

| Distance | Sector* | Maximum slope % | Maximum terrain variation from plane |
|---|---|---|---|
| <2 L | 360° | <3** | <1/3 (H-0.5 D) |
| ≥2 L and < 4 L | Measurement sector | <5** | <2/3 (H-0.5 D) |
| ≥2 L and <4 L | Outside measurement sector | <10*** | Not applicable |
| ≥4 L and <8 L | Measurement sector | <10** | < (H-0.5 D) |
| ≥8 L and <16 L | Measurement sector | <10*** | Not applicable |



## Operational assessments

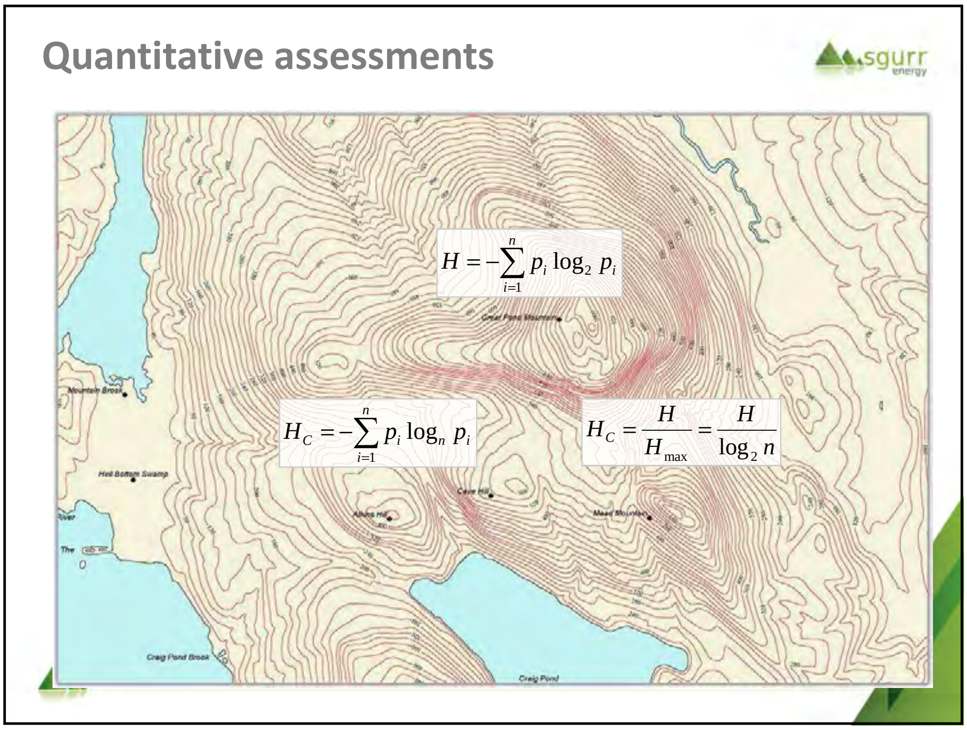
IEC 61400-1 3rd Edition

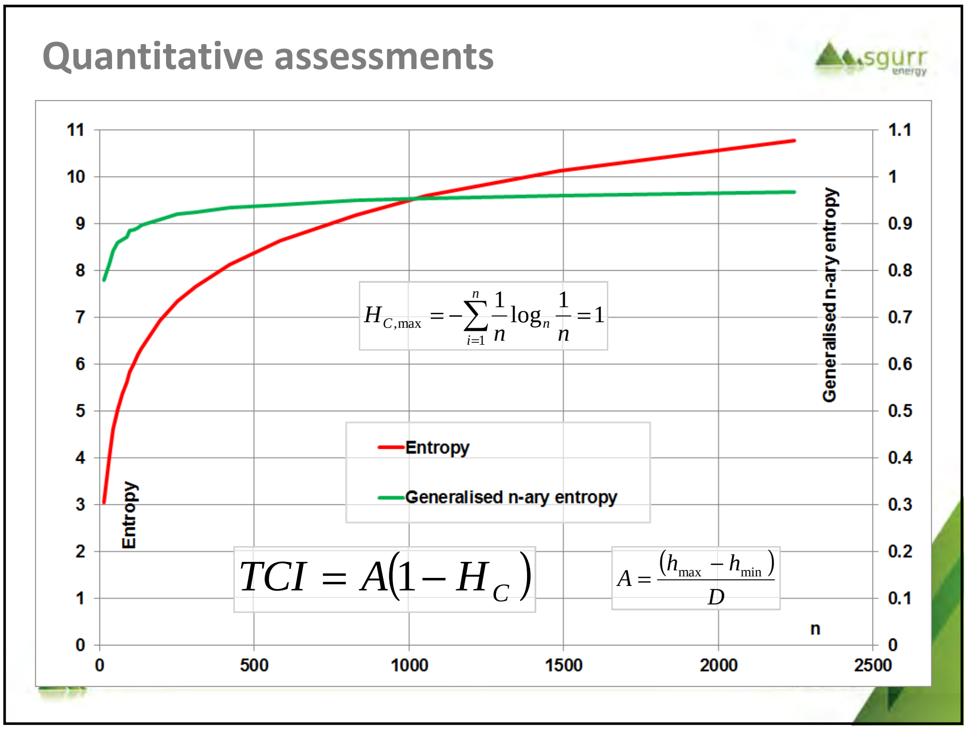
| Distance range from wind turbine | Max slope of fitted plane | Maximum terrain variation |
|---|---|---|
| < 5 $z_{hub}$ | <10° | < 0.3 $z_{hub}$ |
| < 10 $z_{hub}$ | | < 0.6 $z_{hub}$ |
| < 20 $z_{hub}$ | | < 1.2 $z_{hub}$ |

IEC criteria provide definitions of flatness or thresholds for a binary distinction between complexity and simplicity rather than a useful quantitative gradation of complexity

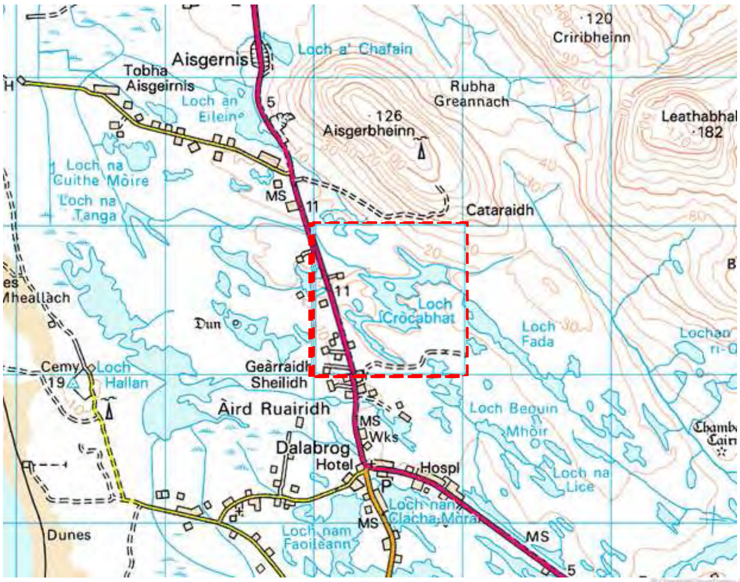
## Quantitative assessments

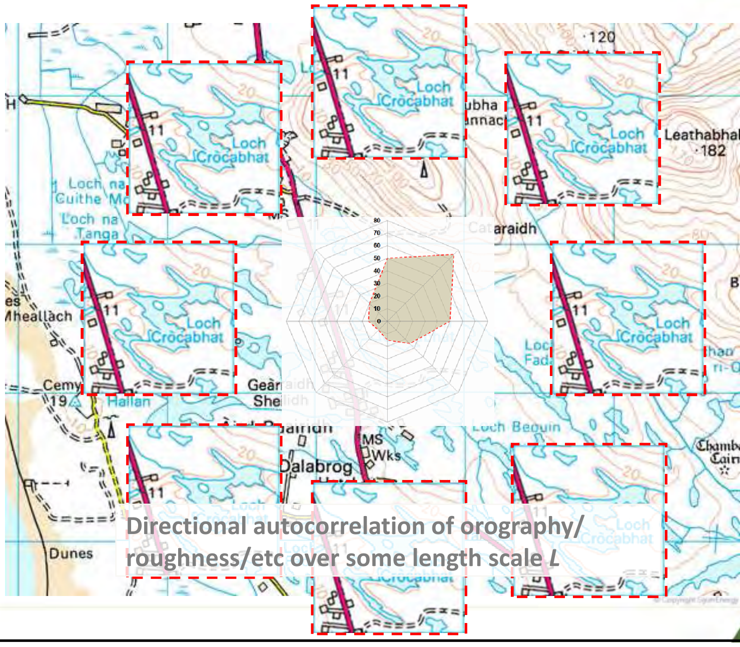
- Statistics of terrain parameters (non-exhaustive list)
  - Variance or standard deviation of elevation data (Hsu 2002, Zhang *et al*. 1999)
  - Autocorrelation of elevation data (Li and Zhu 2003)
  - Relief: $h_{max} - h_{min}$ (Gao 1998)
  - Contour density: $L_c/A_p$ (Byers 1992)
- Geometrical indices
  - Rugosity: $A_s/A_p$ (Hobson 1967, 1972)
  - Shape complexity: $L_c/\sqrt{(A_o/\pi)}$ (Hengl *et al*. 2003)
  - Fractal box dimension (Zhou and Long 2006)
- Multivariate approaches, e.g. wavelength, magnitude, kurtosis (homogeneity), skewness (massiveness, asymmetry) (Evans 1990), elevation, slope, curvature, etc.
- Compound terrain complexity indices


Quantitative assessments
sgurr energy
$H = -\sum_{i=1}^{n} p_i \log_2 p_i$
$H_C = -\sum_{i=1}^{n} p_i \log_n p_i$
$H_C = \frac{H}{H_{max}} = \frac{H}{\log_2 n}$

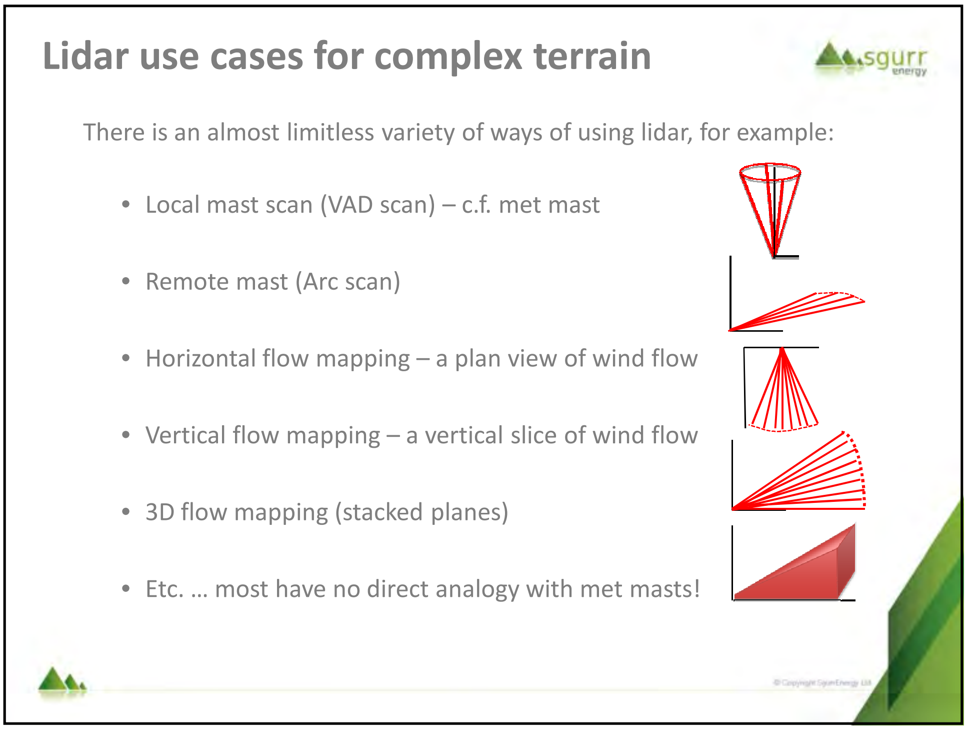

Quantitative assessments
sgurr energy
Entropy
Generalised n-ary entropy
n
$H_{C,max} = -\sum_{i=1}^{n} \frac{1}{n} \log_n \frac{1}{n} = 1$
Entropy
Generalised n-ary entropy
$TCI = A(1 - H_C)$
$A = \frac{(h_{max} - h_{min})}{D}$

## Exposure rose




Directional autocorrelation of orography/ roughness/etc over some length scale *L*


Lidar use cases for complex terrain
sgurr energy
There is an almost limitless variety of ways of using lidar, for example:
• Local mast scan (VAD scan) – c.f. met mast
• Remote mast (Arc scan)
• Horizontal flow mapping – a plan view of wind flow
• Vertical flow mapping – a vertical slice of wind flow
• 3D flow mapping (stacked planes)
• Etc. … most have no direct analogy with met masts!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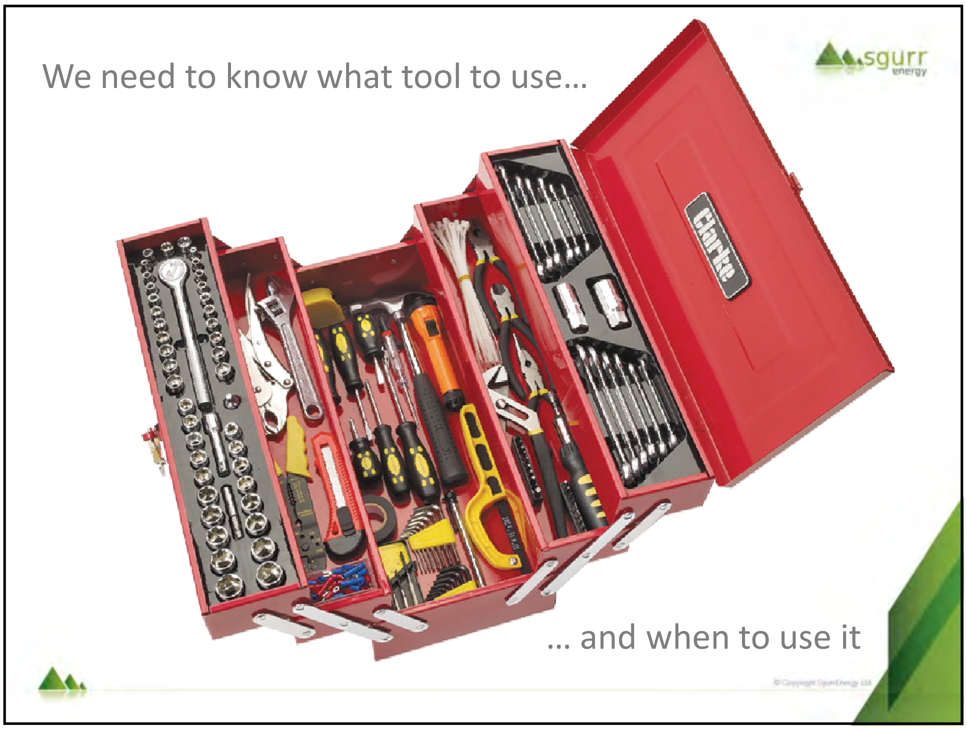
Hammers are useful …


Hammers are useful …
sgurr energy
Clarke
… but not everything
is a hammer …

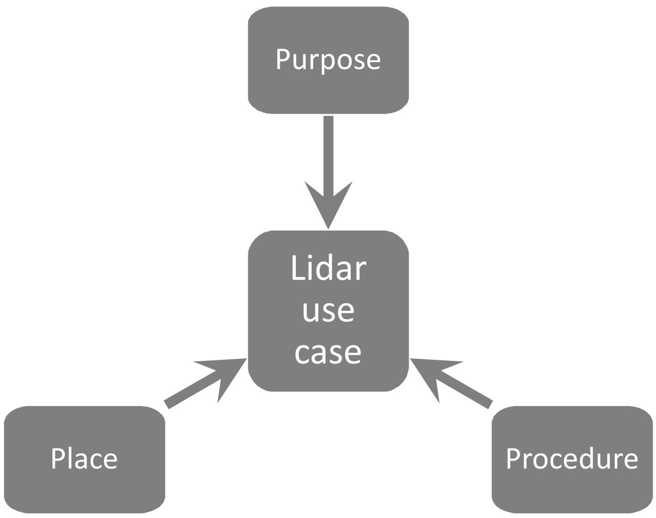

We need to know what tool to use…
sgurr energy
Clarke
… and when to use it

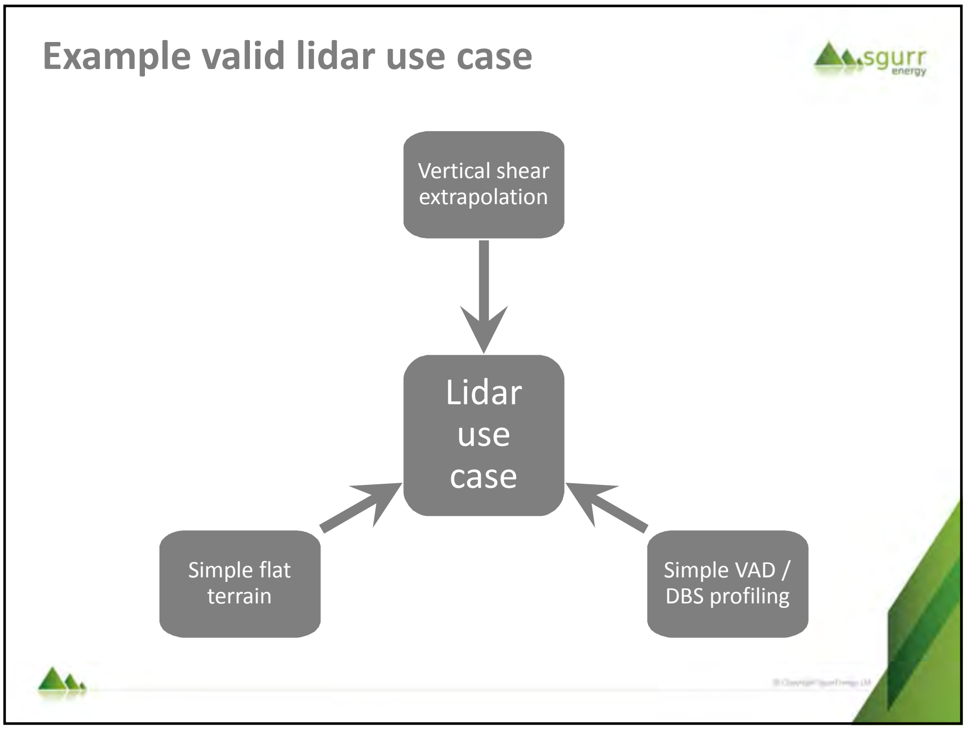
## The three P's

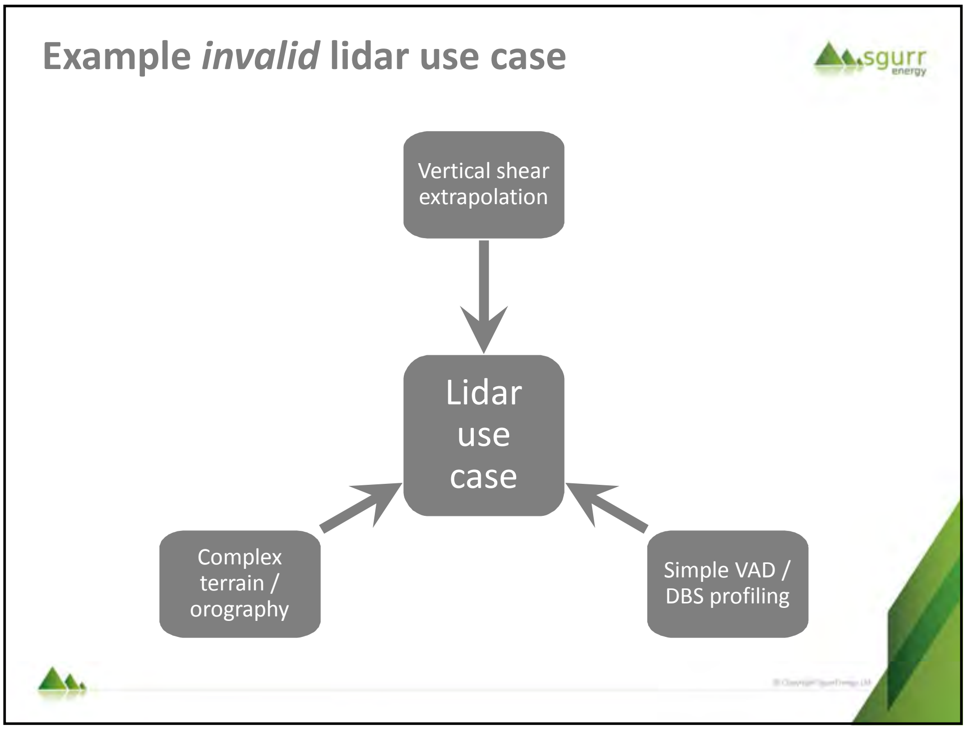
To define a lidar use case, consider the three "P's"

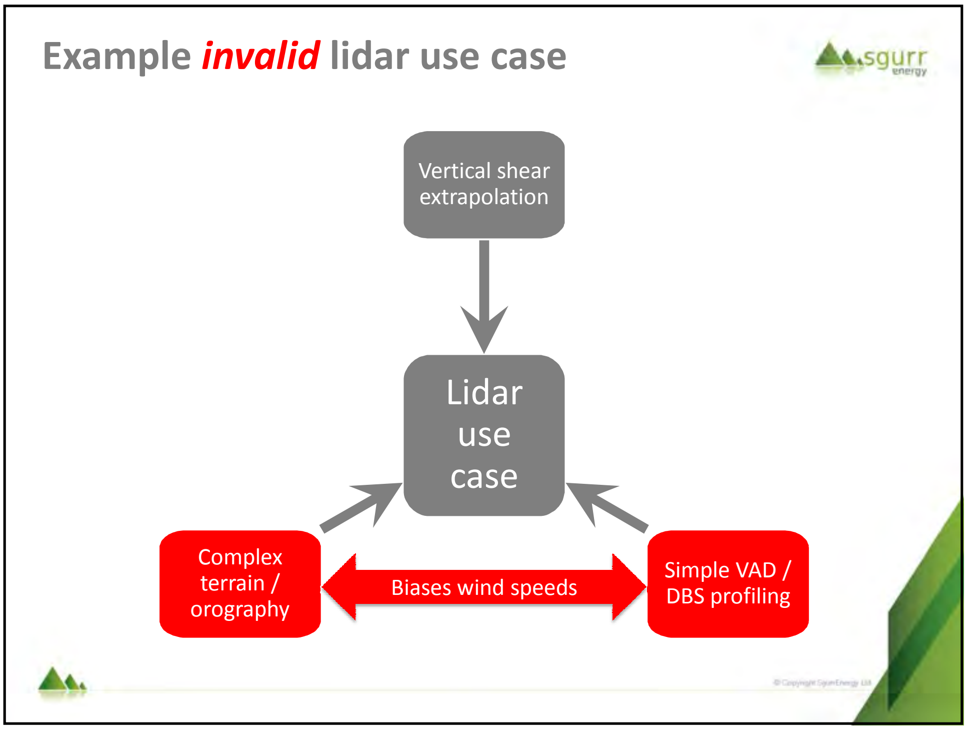
- **Purpose** - why to use lidar
  - What can you find out of value to your wind project that would otherwise be impossible or exceptionally difficult?
  - What is the lidar application you are implementing: what problem are you trying to solve; what question are you trying to answer?
- **Place** - when and where to use lidar
  - Under what circumstances do the kind of problems that lidar can solve arise, and under what circumstances are the particular applications of lidar that provide solutions valid?
  - What are the conditions in which the lidar is being used, and is the performance of the lidar in those conditions adequately understood?
- **Procedure** - how to use lidar
  - What techniques should you adopt to successfully implement the various applications of lidar and obtain the benefits that accrue as a result?
  - What lidar method is being used to implement a particular application under a particular set of circumstances – and is this combination of application, circumstances and method valid?

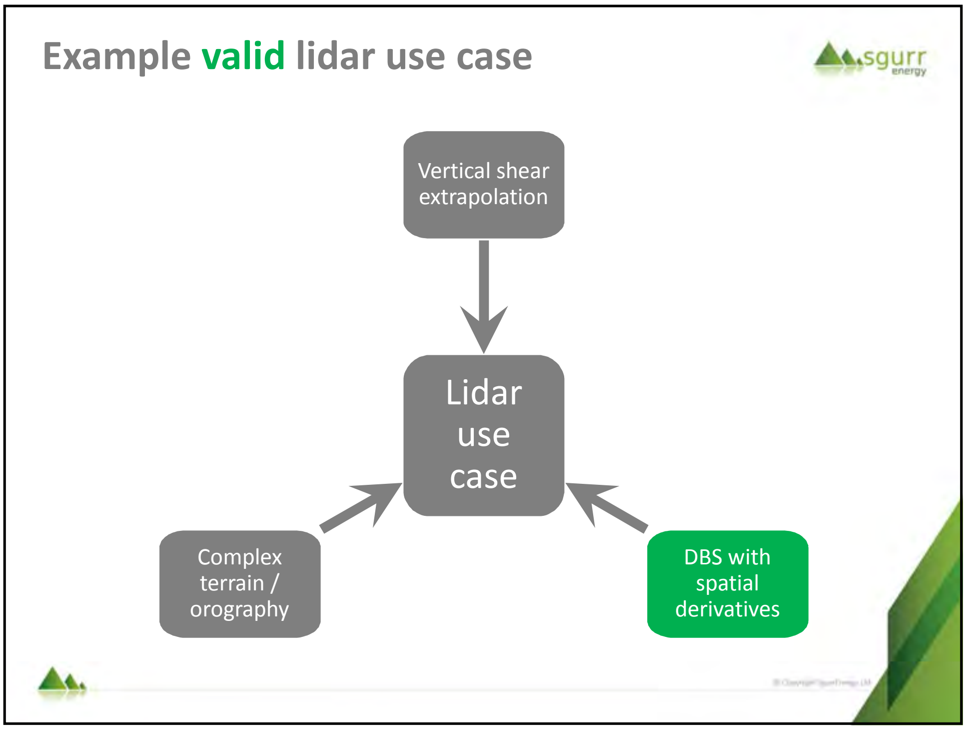
## Lidar use case diagram

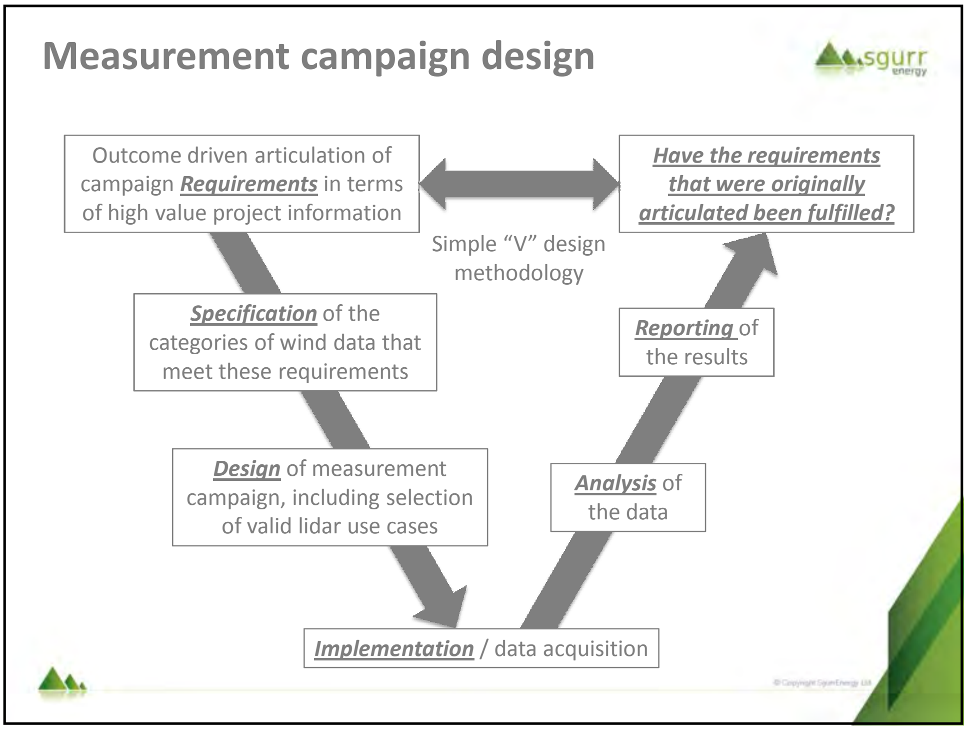


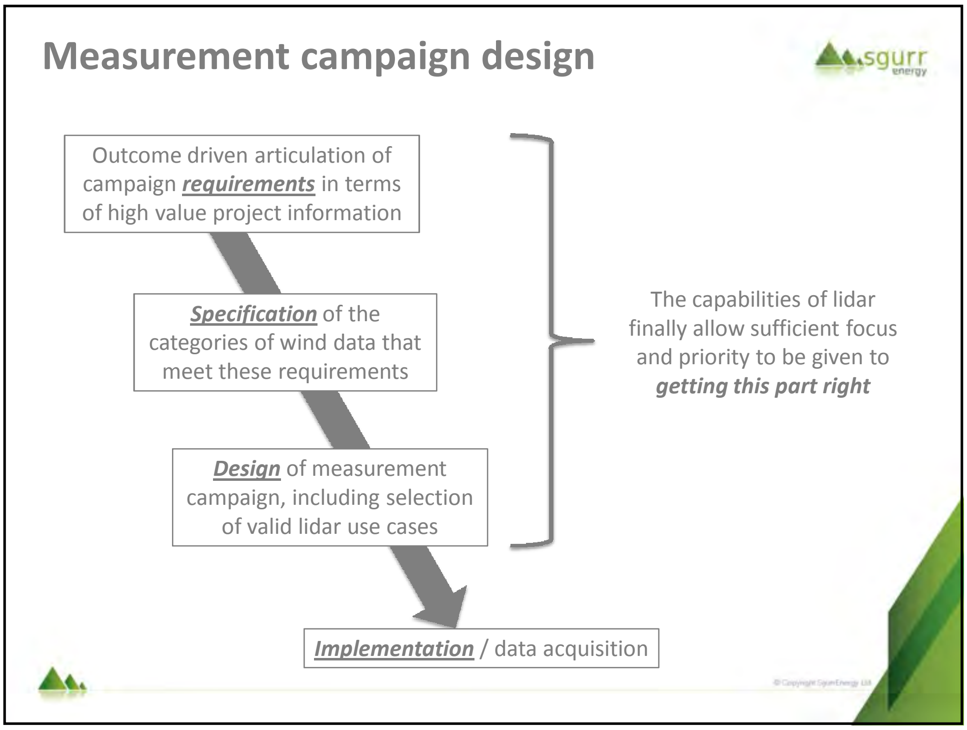

Example valid lidar use case
sgurr energy
Vertical shear extrapolation
Lidar use case
Simple flat terrain
Simple VAD / DBS profiling

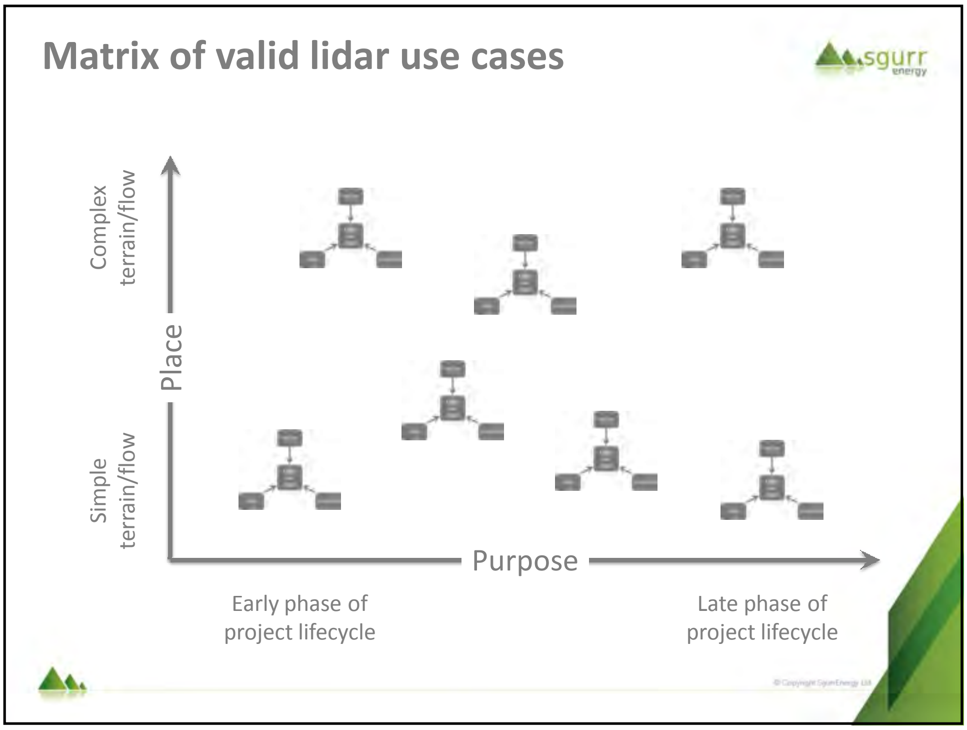

Example *invalid* lidar use case
sgurr energy
Vertical shear extrapolation
Lidar use case
Complex terrain / orography
Simple VAD / DBS profiling

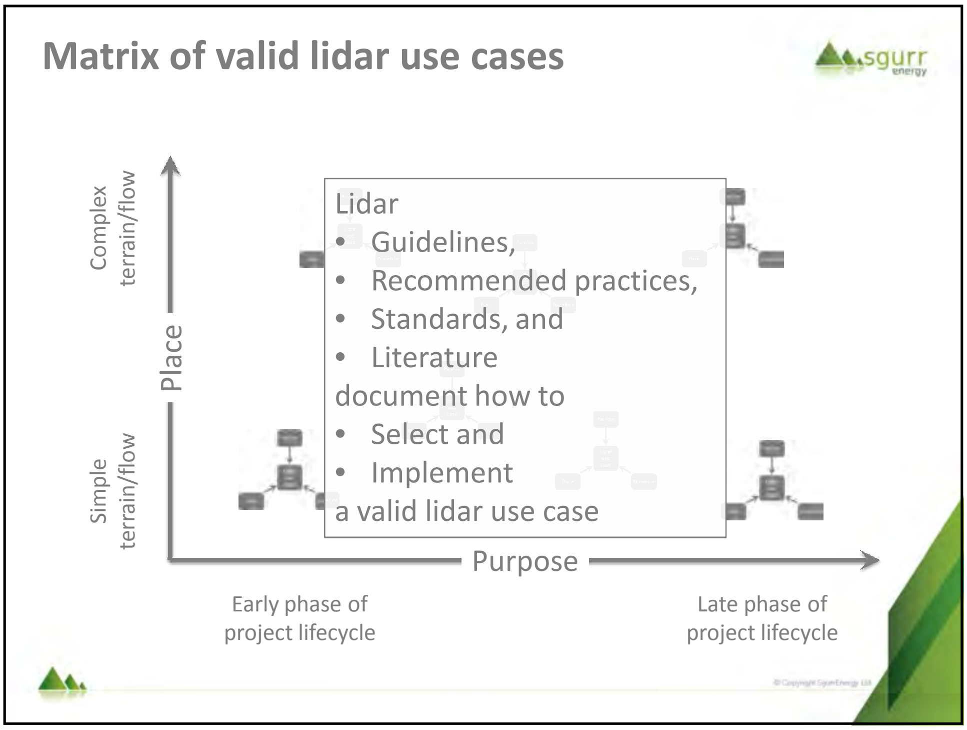

Example invalid lidar use case
sgurr energy
Vertical shear extrapolation
Lidar use case
Complex terrain / orography
Biases wind speeds
Simple VAD / DBS profiling

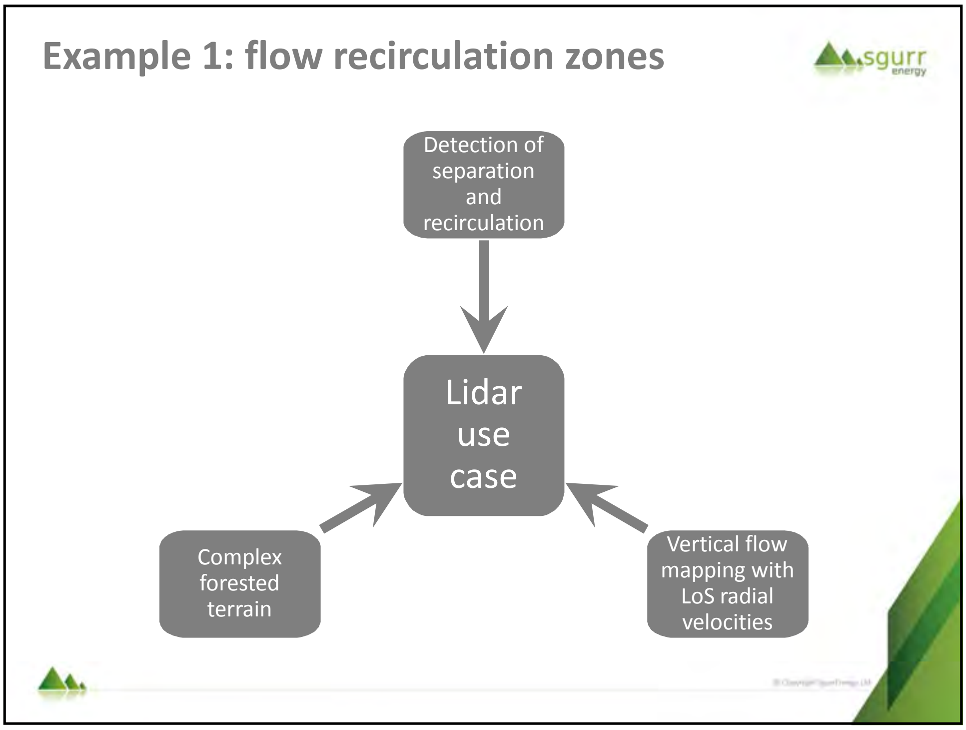

Example valid lidar use case
sgurr energy
Vertical shear extrapolation
Lidar use case
Complex terrain / orography
DBS with spatial derivatives

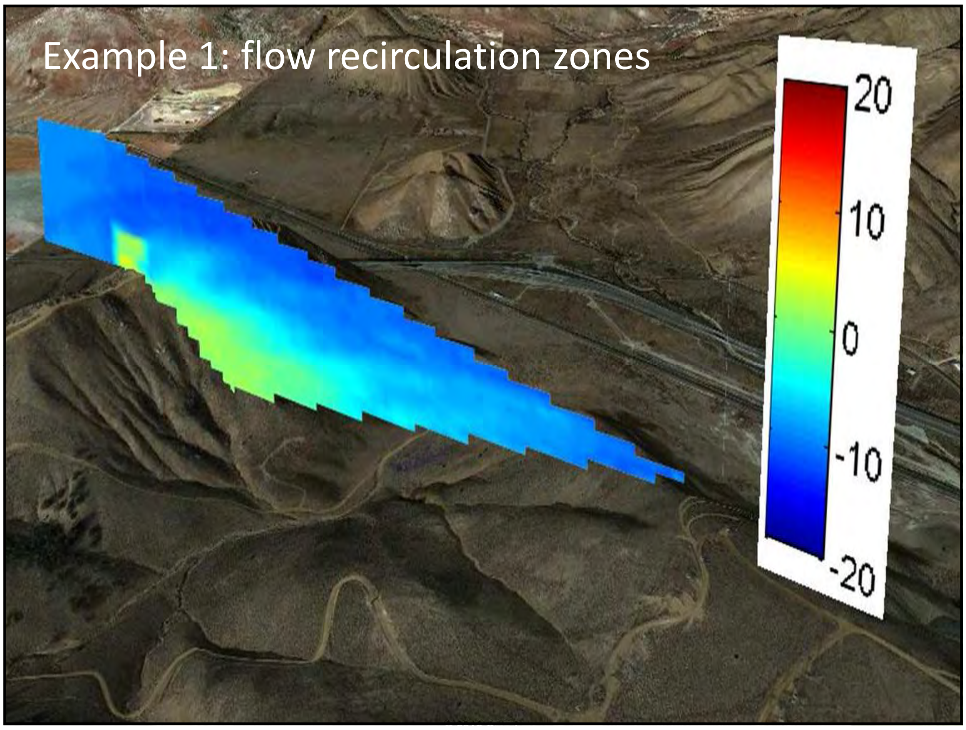

Measurement campaign design
sgurr energy
Outcome driven articulation of campaign Requirements in terms of high value project information
Have the requirements that were originally articulated been fulfilled?
Simple "V" design methodology
Specification of the categories of wind data that meet these requirements
Reporting of the results
Design of measurement campaign, including selection of valid lidar use cases
Analysis of the data
Implementation / data acquisition

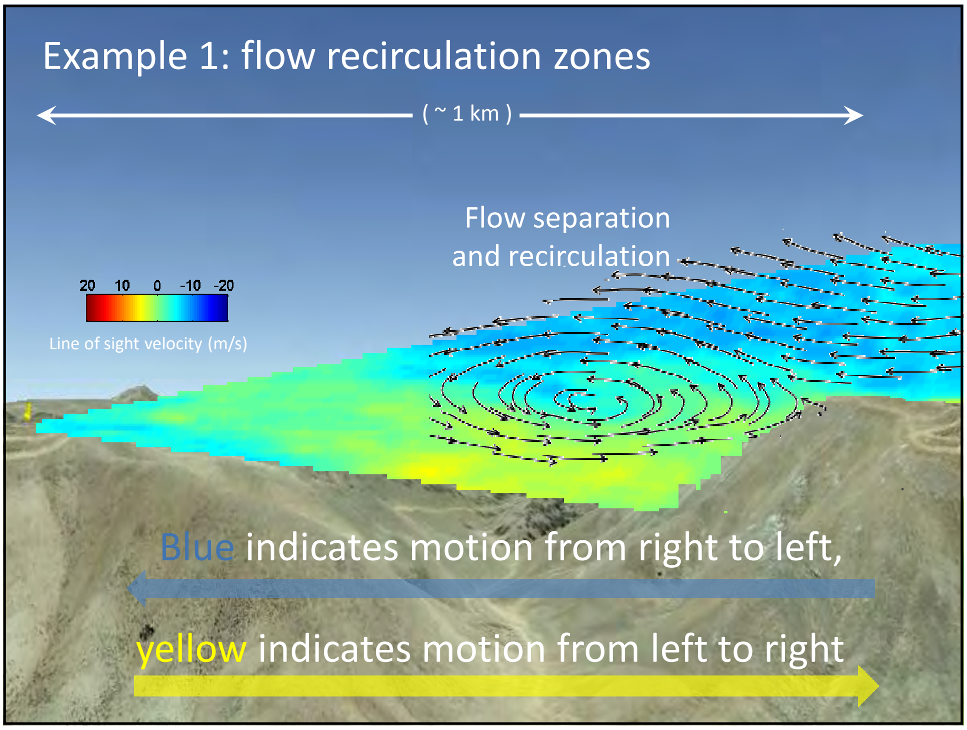

Measurement campaign design
sgurr energy
Outcome driven articulation of campaign requirements in terms of high value project information
Specification of the categories of wind data that meet these requirements
Design of measurement campaign, including selection of valid lidar use cases
The capabilities of lidar finally allow sufficient focus and priority to be given to getting this part right
Implementation / data acquisition

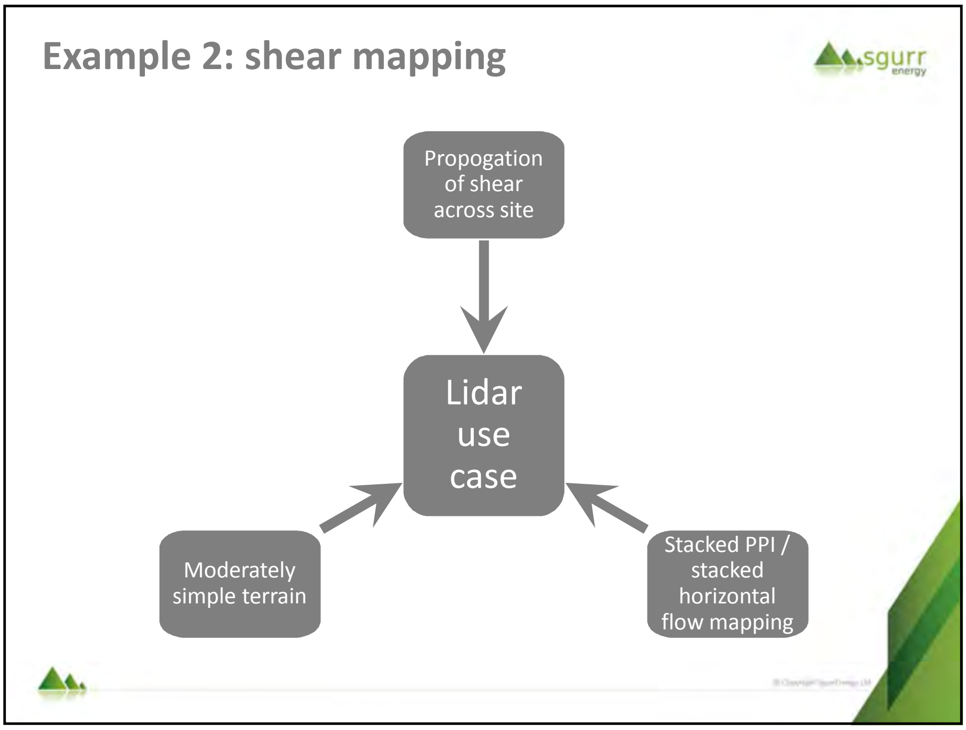

Matrix of valid lidar use cases
sgurr energy
Complex terrain/flow
Place
Simple terrain/flow
Purpose
Early phase of project lifecycle
Late phase of project lifecycle


Matrix of valid lidar use cases
sgurr energy
Complex terrain/flow
Place
Simple terrain/flow
Lidar
• Guidelines,
• Recommended practices,
• Standards, and
• Literature
document how to
• Select and
• Implement
a valid lidar use case
Purpose
Early phase of project lifecycle
Late phase of project lifecycle


Example 1: flow recirculation zones
sgurr energy
Detection of separation and recirculation
Lidar use case
Complex forested terrain
Vertical flow mapping with LoS radial velocities

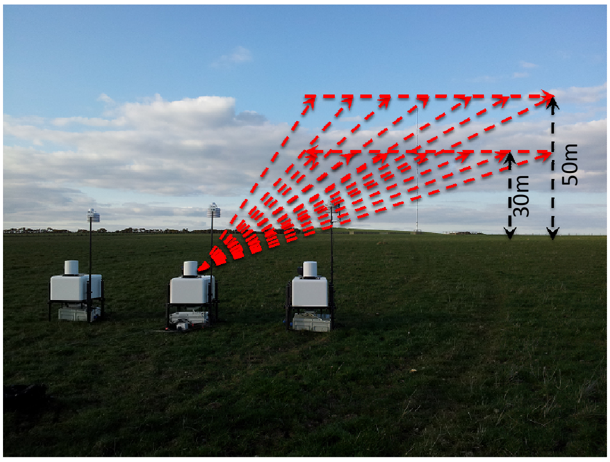

Example 1: flow recirculation zones
20
10
0
-10
-20


Example 1: flow recirculation zones
( ~ 1 km )
Flow separation
and recirculation
20 10 0 -10 -20
Line of sight velocity (m/s)
Blue indicates motion from right to left,
yellow indicates motion from left to right

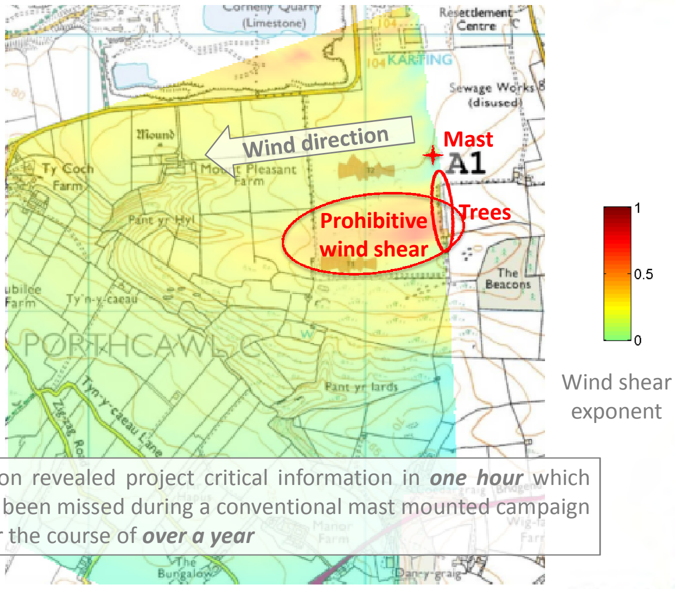

Example 2: shear mapping
sgurr energy
Propogation of shear across site
Lidar use case
Moderately simple terrain
Stacked PPI / stacked horizontal flow mapping

## Example 2: shear mapping

- Arc scans can be stacked to acquire wind speed data at more than one height at distant locations to assess wind shear …




## Example 2: shear mapping




Galion revealed project critical information in ***one hour*** which had been missed during a conventional mast mounted campaign over the course of ***over a year***

## Conclusions

- The difficulty in characterising terrain complexity should not obscure the fact that there is an urgent need for quantitative assessments of terrain complexity
- A variety of quantitative metrics of terrain complexity are possible
  - Here we have focussed on orography
  - Other features of terrain such as roughness can be represented in similar or analogous ways
- More work is necessary relating particular complexity metrics to specific wind energy concerns

## Conclusions

Going forward, a clear course of action is required

1. Further develop a variety of quantitative metrics that represent different aspects of terrain complexity (a vector or tensor representation may be required)
2. Identify sites exhibiting these characteristics
3. Calculate terrain complexity metrics and indices
4. Acquire measurements and run models that allow complex flow and influence of terrain to be assessed
5. Compare measured influence to complexity indices and metrics
6. Identify what metrics best predict the influence of the terrain on the outcome

## Thank you for listening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- Tel: +44 14 12 27 17 24
- Cell: +44 77 39 90 90 40
- Web: http://www.sgurrenergy.com

# Complex Terrain Test Site with 200m Met Mast at Fraunhofer IWES

Fraunhofer IWES, Kassel | November , 12th 2013
Tobias Klaas



Fraunhofer IWES

## Group Onshore Site Assessment

### Research Topics


Wind conditions at inland sites

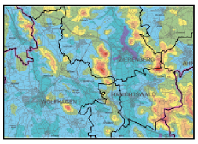
LiDAR measurement technology

Inland wind power potential

### Services

LiDAR wind measurements

Wind energy development potential



Test Center for wind sensors

 2

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## Group Onshore Site Assessment
### Test Center for Wind Measurements in Complex Terrain

Our hardware:

- 200 m met mast (2012)
- Five lidar systems (2011)
- Wind measurement network – 30 sites (1992)
- Test site for small wind tubines (2004)

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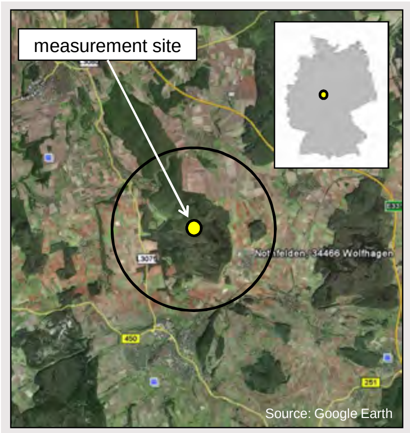
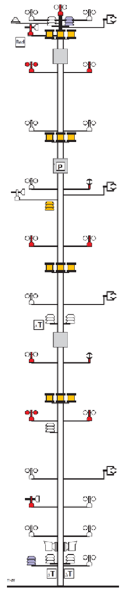
## Group Onshore Site Assessment
### Wind conditions at inland sites




- 200 m wind measurement mast in complex forested terrain
- Typical wind farm location in central / south Germany
- IEC conform booms
- 13 measurement heights
- Co-located LiDAR measurements



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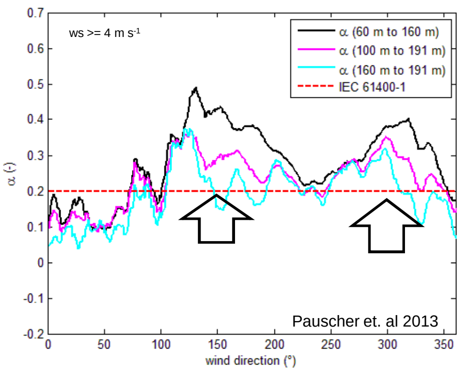
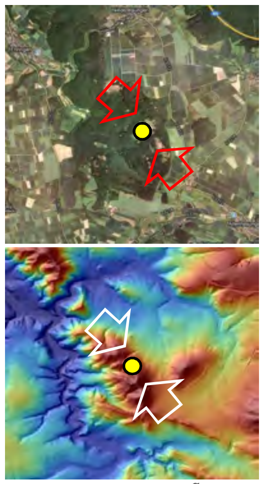
## Test Center for Wind Measurements in Complex Terrain
### Example: Wind shear



- Terrain influence decreases with height
- Shear coefficient ‚over rotor' slightly dercreases with height for most sectors

$$V_z = v_{z_r}(\frac{z}{z_r})^{\alpha}$$

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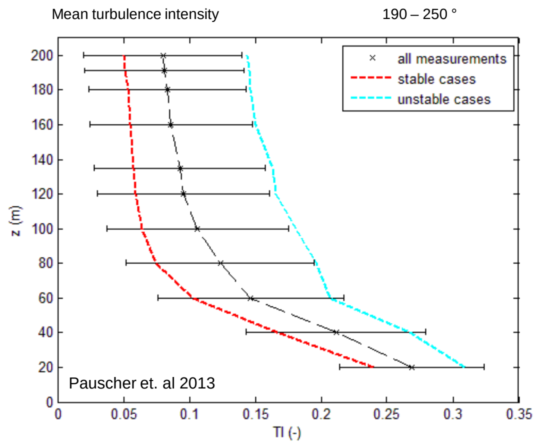
## Test Center for Wind Measurements in Complex Terrain Example: Turbulence intensity




- Forested fetch of ~ 2km
- Very high turbulence intensities close to the forest canopy
- Rapidly decreasing up to heights of about 100 – 120 m
- Stability is key driving factor for turbulence intensity

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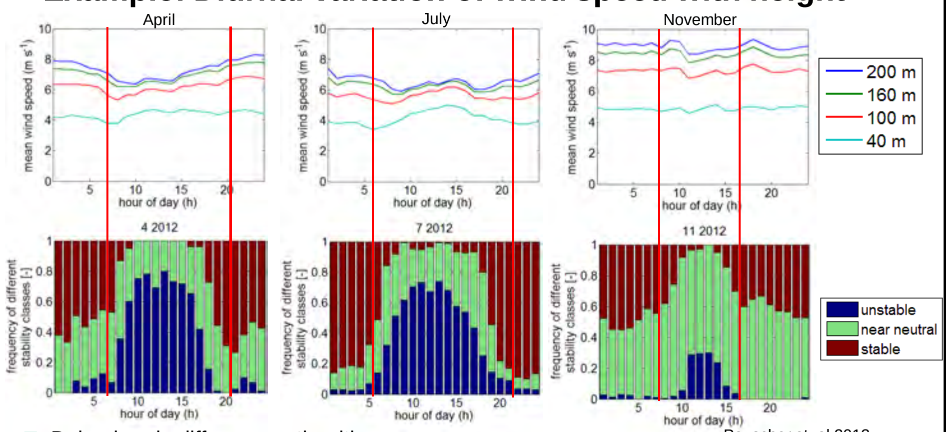
## Test Center for Wind Measurements in Complex Terrain Example: Diurnal variation of wind speed with height




- Duirnal cycle differes greatly with season
  → Strong differences in spring and summer
- Smaller variation in winter

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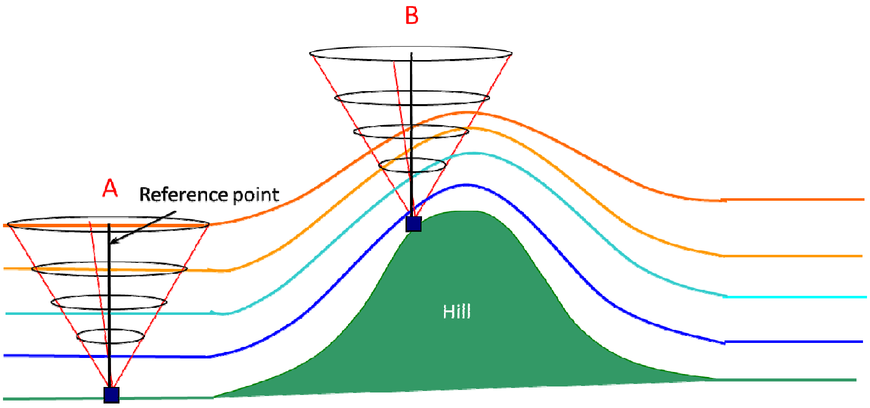
## LiDAR errors in complex terrain




- A: Homogeneous flow assumption valid → Good performance of LiDAR
- B: Homogeneous flow assumption not valid → LiDAR errors

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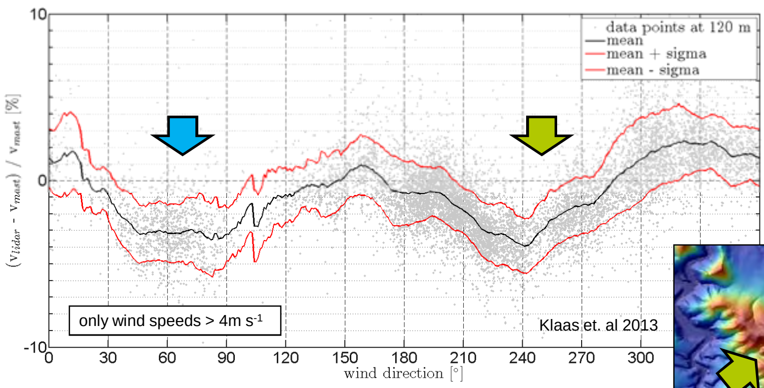
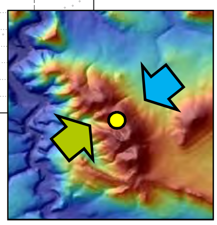
## LiDAR errors in complex terrain



- Lidar measurement errors at 120m
- Error depends on orography effects on flow

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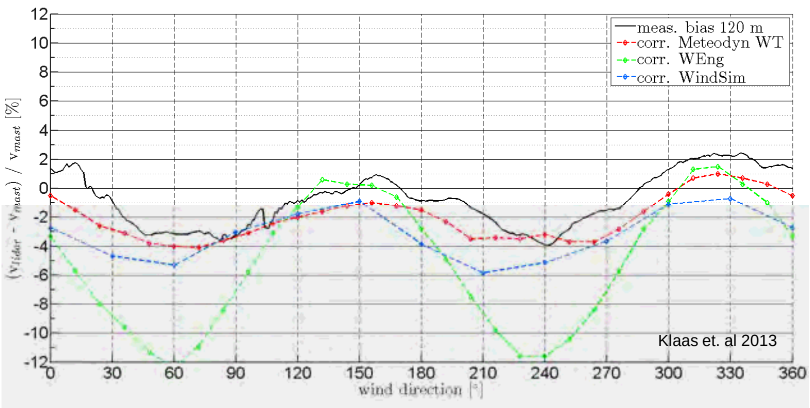
## LiDAR corrections with flow models




- Comparison of different correction tools (Weng, Meteodyn WT, WindSim) at 120m
- WEng estimation is much too high
- CFD tools fit much better

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## LiDAR error map at „Rödeser Berg“

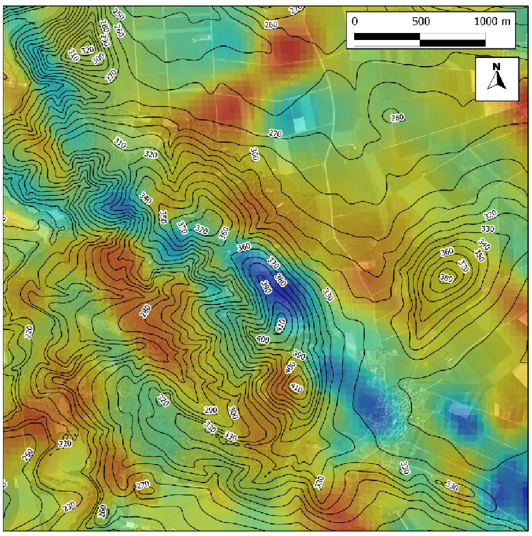
- Blue: under-estimation of lidar (up to -4 %)
- Red: over-estimation of lidar (up to +4 %)
- Green: close to 0 %

Height: 140 m

Resolution: 50 x 50 m²

Size: 4 x 4 km² (6400 cells)

CFD tool: Meteodyn WT

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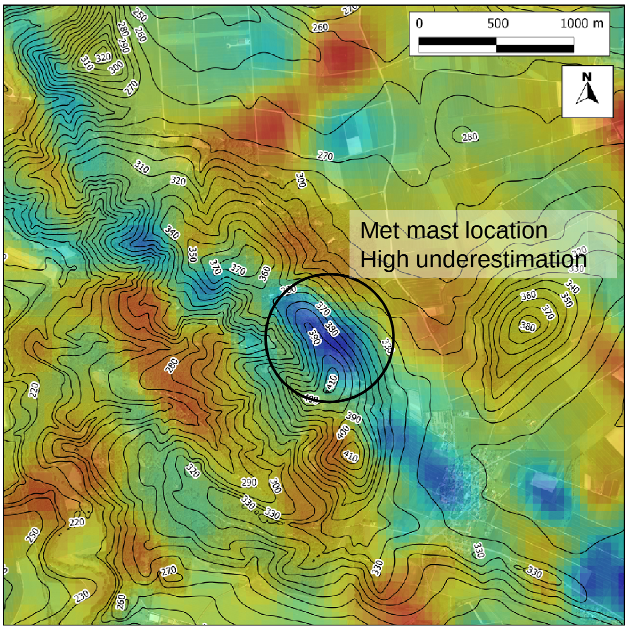
**Lidar error map**

Avoid high-underestimation

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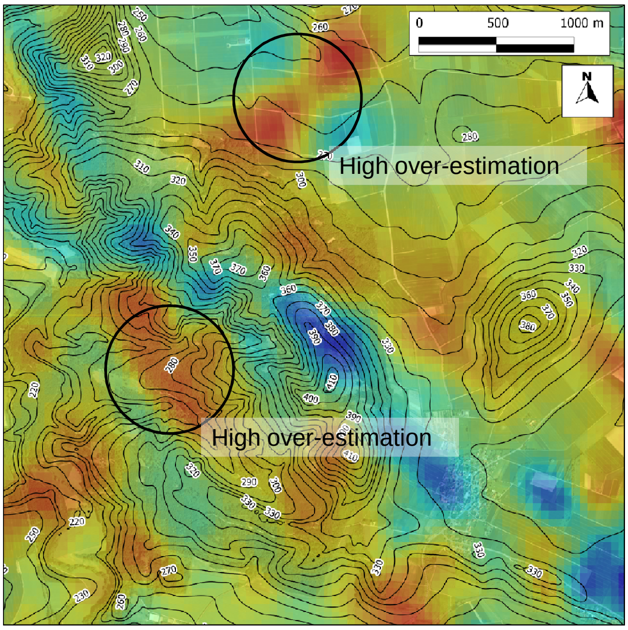
**Lidar error map**

Avoid high over-estimation

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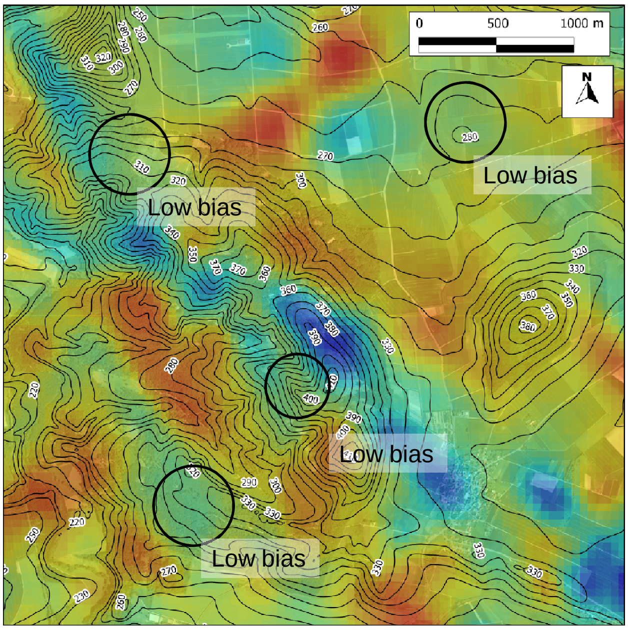
**Lidar error map**

Identify areas of low bias

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## The Alaiz test site in complex terrain for site-assessment model evaluation

IEA Topical Expert Meeting #75 on "Complex Terrain"

Javier Sanz Rodrigo, and all the WAUDIT "Alaiz fellows" (*)

Stuttgart, 12 November 2013

(*) Javier Sanz Rodrigo[1], Sergio Lozano Galiana[1], Pedro M. Fernandes Correia[1], Elena Cantero Nouqueret[1], Bibiana García Hevia[1], Christos Stathopoulos[1], Fernando Borbón Guillén[1], Roberto A. Chávez Arroyo[1], Pawel Gancarski[1], Tilman Koblitz[2], Nicolas Barranger[3], Boris Conan

[1] CENER; [2]DTU; [3]NKUA; [4]VKI

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## Context: The WAUDIT Initial Training Network

**WAUDIT**: Marie Curie Initial Training Network for the development of wind resource assessment techniques

- ❑ 4 M€, Oct-2009 to Sep-2013
- ❑13 partners (+ 17 associate institutions)
- ❑ 23 fellows from 20 different nationalities
- ❑15 Phd thesis, 120+ publications
- ❑ Training programme under the umbrella of the EAWE

• "**Alaiz secondment**": hosted by CENER, it gathered a group of researchers to work on Alaiz as a common test case and exchange experiences about the use of different experimental and numerical approaches, notably:

- ❑ Characterization of wind conditions vs atmospheric stability
- ❑ Numerical modelling from mesoscale to microscale
- ❑ Lidar flow-correction algorithms for complex terrain
- ❑ Wind tunnel modelling

PEOPLE MARIE CURIE ACTIONS WAUDIT Wind resource assessment audit and standardization

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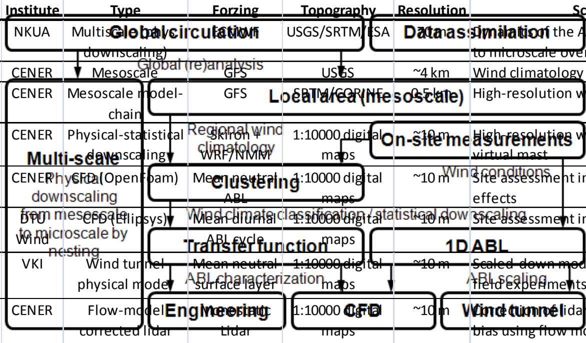
## State-of-the-art

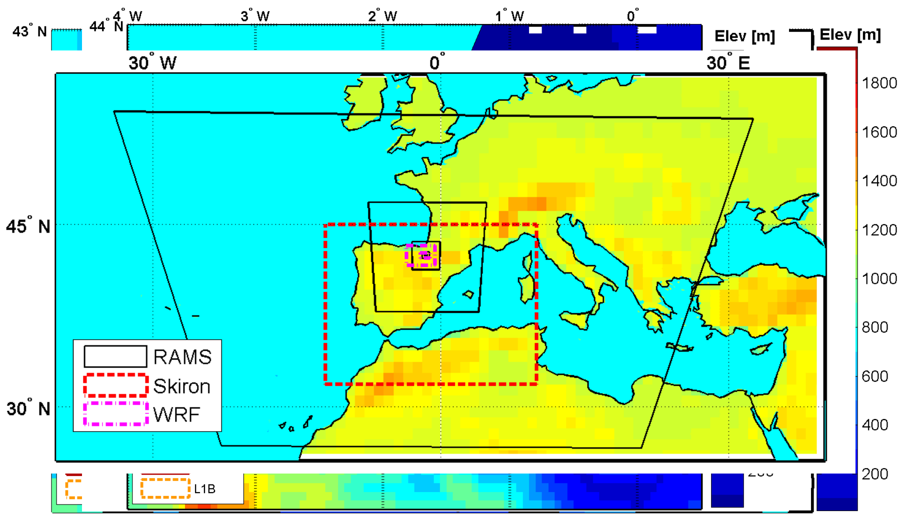
The **"model-chain"** from global to microscale models based on…

Physical-statistical downscaling
+ On-site measurements
+ Complementary measurements (RS, wind tunnel) for model evaluation

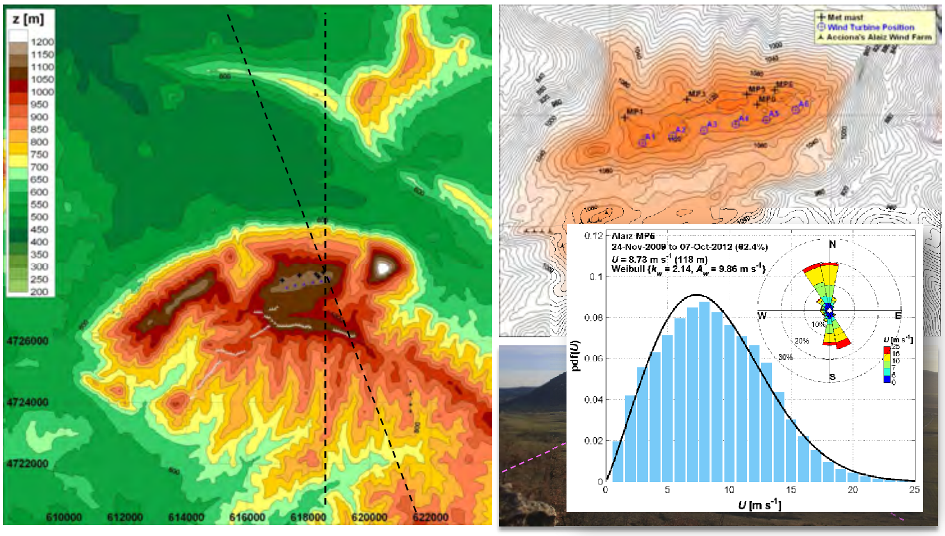
| Model | Institute | Type | Forzing | Topography | Resolution | Scope |
|---|---|---|---|---|---|---|
| RAMS | NKUA | Multiscale (phys. downscaling) | ECMWF | USGS/SRTM/ESA | [illegible] | Dynamics of the ABL from mesoscale to microscale over a few days |
| Skiron | CENER | Mesoscale | GFS | USGS | ~4 km | Wind climatology |
| Skiron + WRF/NMM | CENER | Mesoscale model-chain | GFS | SRTM/CORINE | 0.5 km | High-resolution wind climatology |
| Skiron + WRF + WAsP | CENER | Physical-statistical downscaling | Skiron + WRF/NMM | 1:10000 digital maps | ~10 m | High-resolution wind mapping, virtual mast |
| CFDWind | CENER | CFD (OpenFoam) | Mean neutral ABL | 1:10000 digital maps | ~10 m | Site assessment including forest effects |
| Ellipsys3D ABL | DTU Wind | CFD (Ellipsys) | Mean diurnal ABL cycle | 1:10000 digital maps | ~10 m | Site assessment including stability |
| L1-B | VKI | Wind tunnel physical model | Mean neutral surface layer | 1:10000 digital maps | ~10 m | Scaled-down model to complement field experiments for validation |
| Lidar + CFDWind | CENER | Flow-model corrected lidar wind profiler | [illegible] Lidar | 1:10000 digital maps | ~10 m | Correction of lidar mean wind speed bias using flow modelling. Complement mast measurements |




## Modelling Domains



## Alaiz test site: topography

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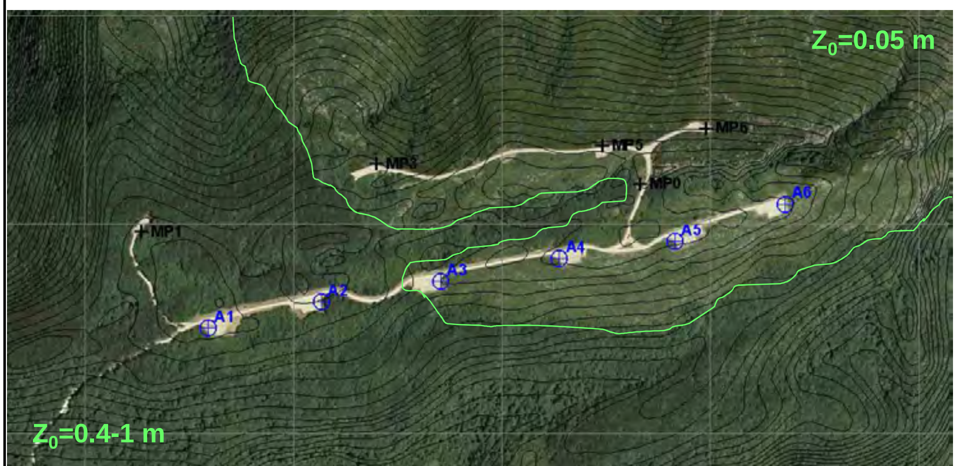
## Alaiz Test Site: roughness conditions

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## Alaiz Site: view from MP5 towards North


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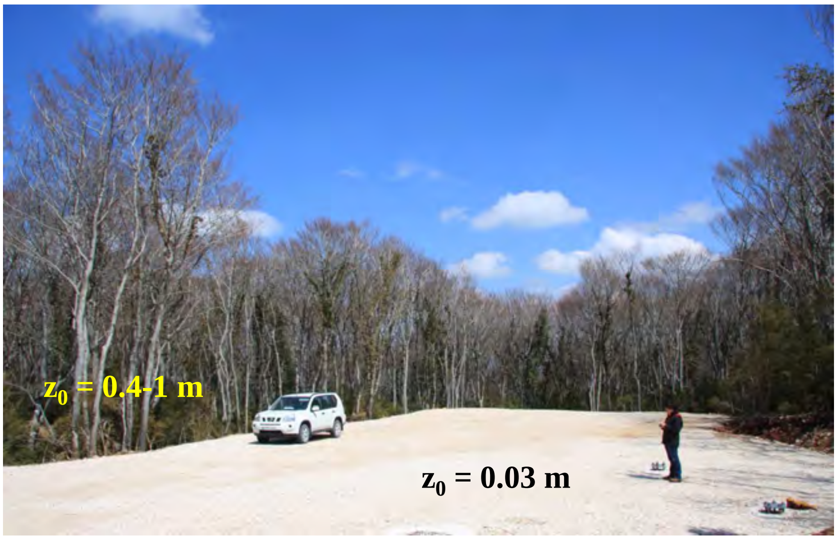
## Alaiz Site: forest canopy at MP1, to be characterized

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## Alaiz Site: view of Acciona's wind farms to the South


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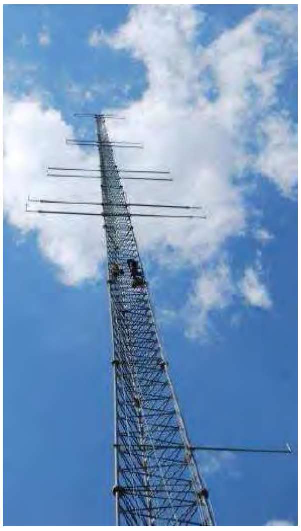
## Alaiz test site: instrumentation

- IEC compliant mast instrumentation
- MEASNET cup-anemometer calibrations
- MP5 reference mast
  - ❑ $RIX_N$ = 22.4%, $RIX_S$ = 9.9%
  - ❑ Mast distortion (N,S) < 2.5%
  - ❑ Flow inclination (N,S) W/U < 0.15

| | *D d* [m] | *D RIX$_N$* [%] | *D RIX$_S$* [%] | *U* levels [m] | *WD* levels [m] | *T/RH* levels [m] |
|---|---|---|---|---|---|---|
| MP1 | 1125 | 2.1 | -3.3 | 40, 78, 90, 102, 118 | 78, 90, 102, 118 | 81, 97, 113 |
| MP3 | 544 | -2.6 | -0.9 | 40, 78, 90, 102, 118 | 78, 90, 102, 118 | 81, 97, 113 |
| MP5 | 0 | 0.0 | 0.0 | 40, 78, 90, 102, 118 | 78, 90, 102, 118 | 2[1], 38[1], 81, 97, 113 |
| MP0 | 129 | 0.7 | 0.8 | 40, 78, 90, 102, 118 | 78, 102, 118 | 81, 97, 113 |
| MP6 | 253 | 0.7 | 1.3 | 40, 78, 90, 102, 118 | 78, 90, 102, 118 | 81, 97, 113 |
| A1 | 1043 | -1.0 | -3.8 | 78, 90, 102, 118 | 78, 90, 102, 118 | 81, 97, 113 |
| A2 | 771 | -1.3 | -1.3 | 40, 78, 90, 102, 118 | 40, 78, 90, 102, 118 | 81, 97, 113 |
| A3 | 506 | -2.0 | -0.9 | 78, 90, 102, 118 | 78, 90, 102, 118 | 81, 97, 113 |
| A4 | 290 | 1.5 | -0.1 | 40, 78, 90, 102, 118 | 78, 90, 102, 118 | 81, 97, 113 |
| A5 | 288 | 1.0 | 0.6 | 40, 78, 90, 102, 118 | 78, 90, 102, 118 | 81, 97, 113 |
| A6 | 462 | 0.9 | 0.6 | 78, 90, 102, 118 | 78, 90, 102, 118 | 81, 97, 113 |

[1] operational since 18/01/2011



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## Wind climate distribution

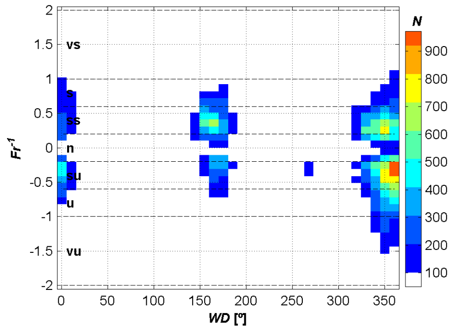
- Stability based on Froude number:

$$Fr = \frac{\pi U}{N_{bv} W_T}$$

$\Delta\Theta = \Theta_{97} - \Theta_{81}$
$U = U_{118}$
$W_T = 1000m$

$$N_{bv} = sign\left\{\frac{\partial\Theta}{\partial z}\right\}\sqrt{\frac{g}{\Theta_0}\left|\frac{\partial\Theta}{\partial z}\right|}$$

- Classification:
  - very stable (vs): $1 < Fr^{-1} \le 2$
  - stable (s): $0.6 < Fr^{-1} \le 1$
  - slightly stable (ss): $0.2 < Fr^{-1} \le 0.6$
  - neutral (n): $-0.2 < Fr^{-1} \le 0.2$
  - slightly unstable (su): $-0.6 < Fr^{-1} \le -0.2$
  - unstable (u): $-1 < Fr^{-1} \le -0.6$
  - very unstable (vu): $-2 < Fr^{-1} \le -1$




**TAB3(*WD*, *U*, $Fr^{-1}$)**
3D wind climate distribution

- Wind direction bin width = 30º
- Wind speed bin width = 2 m/s

$$AEP = \sum_{1}^{N_d}\sum_{1}^{N_u}\sum_{1}^{N_s} TAB3(i,j,k) \times P(U) \times 8760$$

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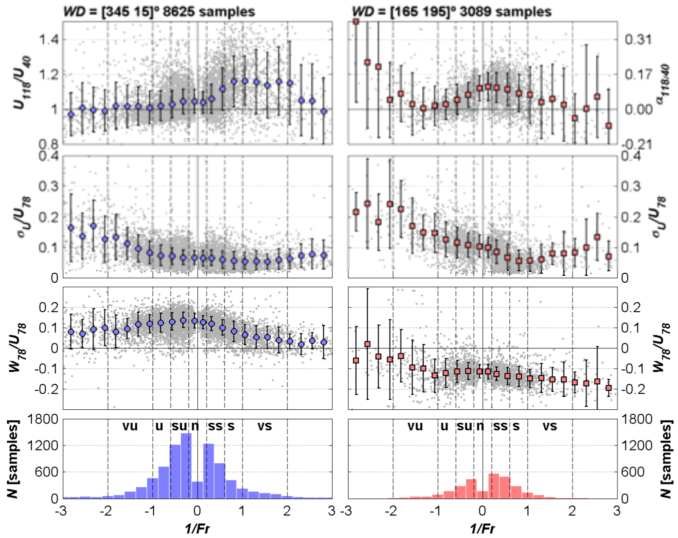
## Wind conditions vs stability

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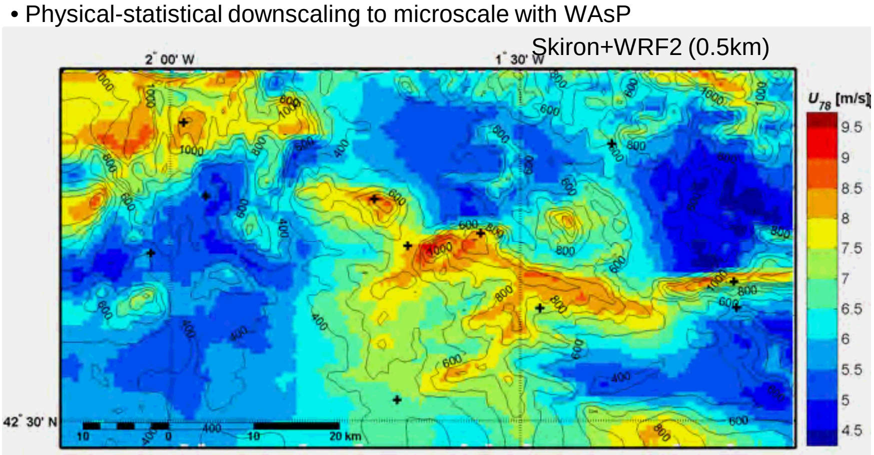
## Wind mapping

P.M.F. Correia, S. Lozano, C. Stathopoulos (CENER)

- Evaluation period of 1 year
- One-way nesting: Skiron (4km) > WRF (1.7km) > WRF (0.5km)
- Physical-statistical downscaling to microscale with WAsP

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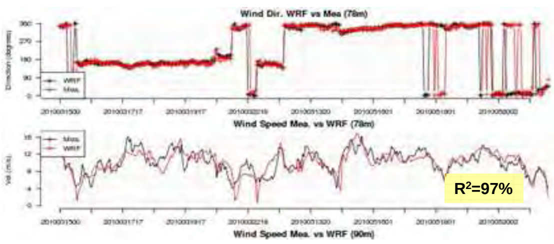
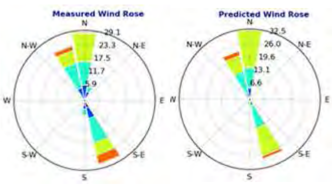
## Preliminary Results of Mesoscale Model-Chain (*)

- SKIRON (4 km) + WRF-NMM (1.67km/0.55km)
  - ❑ SRTM topo / CORINE land-use (90m)
  - ❑ One-way nesting

| MAE | Error (%) Dom1 | Error (%) Dom2 | Error (%) SKIRON |
|---|---|---|---|
| Vel78 | 10,45 | 6,53 | 17,5 |
| Vel90 | 10,1 | 6,63 | 18,3 |
| Vel102 | 8,83 | 5,68 | 17,6 |
| Vel118 | 7,34 | 4,74 | 16,9 |
| T81 | 3,95 | 1,2 | |
| T97 | 4,56 | 1,63 | |
| T113 | 7,95 | 6,18 | |


(*) Correia P, Lozano S, Chavez R, Loureiro Y, Cantero E, Benito P, Sanz Rodrigo J (2013) Wind Characterization at the Alaiz – Las Balsas Experimental Wind Farm using high-resolution simulations with mesoscale models. Development of a "low cost" methodology that address promoters needs. *EWEA-13 proceedings*, Vienna, February 2013

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## Microscale modelling

- Modelling issues:
  - ❑ Influence of upstream fetch (VKI wind tunnel)
  - ❑ Stability (Ellypsis3D ABL)
  - ❑ Forestry (CFDWind)

- Preliminary results (for north wind direction) with focus on feasibility and sensitivity analysis

- Benchmarking ongoing in the frame of IEA Task 31 Wakebench
  - ❑ Sensitivity analysis and blind comparison in neutral conditions (2013)
  - ❑ Blind comparison in stable conditions (2014)

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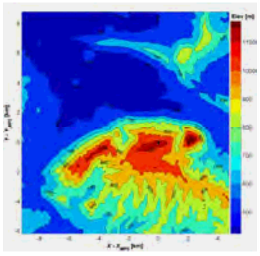
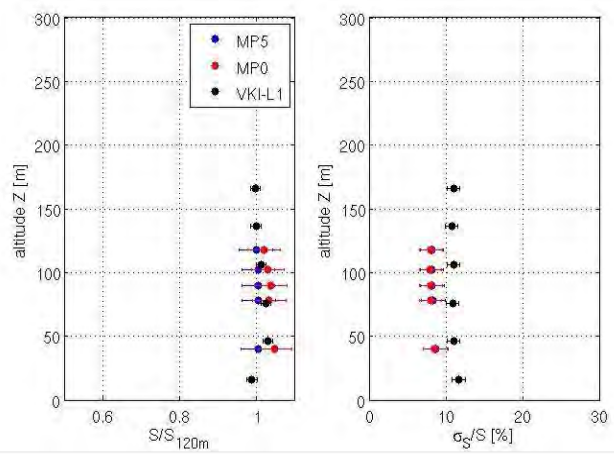
## Microscale modelling: VKI L1-B wind tunnel

Boris Conan (VKI)

- 3-m wide, 15-m long test section configured with rough incoming ABL
- Scale: 1/5257
- $Re_h \sim 10^5$
- PIV fields



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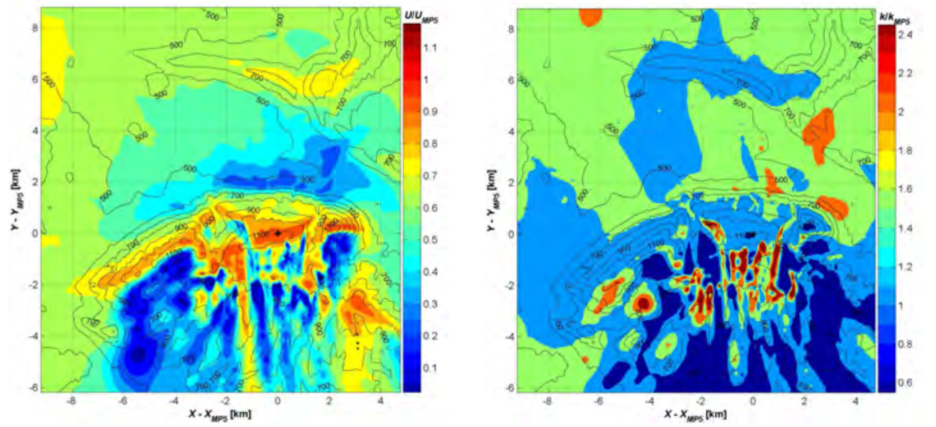
## Microscale modelling: Ellypsis3D ABL

Tilman Koblitz (DTU)

- Unsteady RANS, limited-length-scale k-ε model
- Koblitz et al., 2013, accepted for publication in *Wind Energy*
- Validation to come in *Wakebench* blind test



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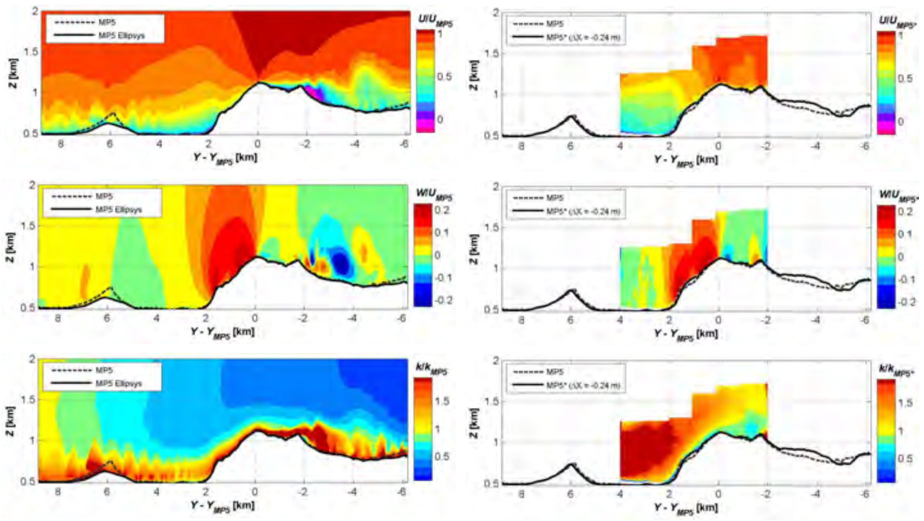
## Microscale modelling: CFD vs Wind Tunnel



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## Conclusions/ Outlook

- Preliminary results show good potential for the development of "model-chain" site-assessment methodologies based on:
  - ❑ Wind climate modelling from mesoscale models (statistics)
  - ❑ Site-assessment models based on CFD (local wind conditions)
  - ❑ Downscaling methods + on-site measurements (blend of meso-micro outputs)
  - ❑ Uncertainty-chain to be defined!
- Wind tunnel modelling looks very challenging at large scaling factors. Further testing may be conducted (UPM, Hamburg University)
- Alaiz will host a large-scale experiment in the frame of the ERA-Net+ New European Wind Atlas (NEWA) project.
  - ❑ Suitable site for the evaluation of meso-micro downscaling approaches
  - ❑ Focus on hill-mountain interaction and N-S wind direction
  - ❑ Instrumentation based on met-mast arrays and long-range RS
  - ❑ Wind energy case-studies based on operational wind farms
  - ❑ Aim for a site-assessment standard

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Technische Universität München
Wind Energy Institute

# Wind Tunnel Aeroelastic Models in Complex Terrains

F. Campagnolo, C.L. Bottasso
Technische Universität München , Germany

IEA R&D Wind Task 11 – Topical Expert Meeting on "WIND ENERGY IN COMPLEX TERRAIN"

12th November 2013, Stuttgart

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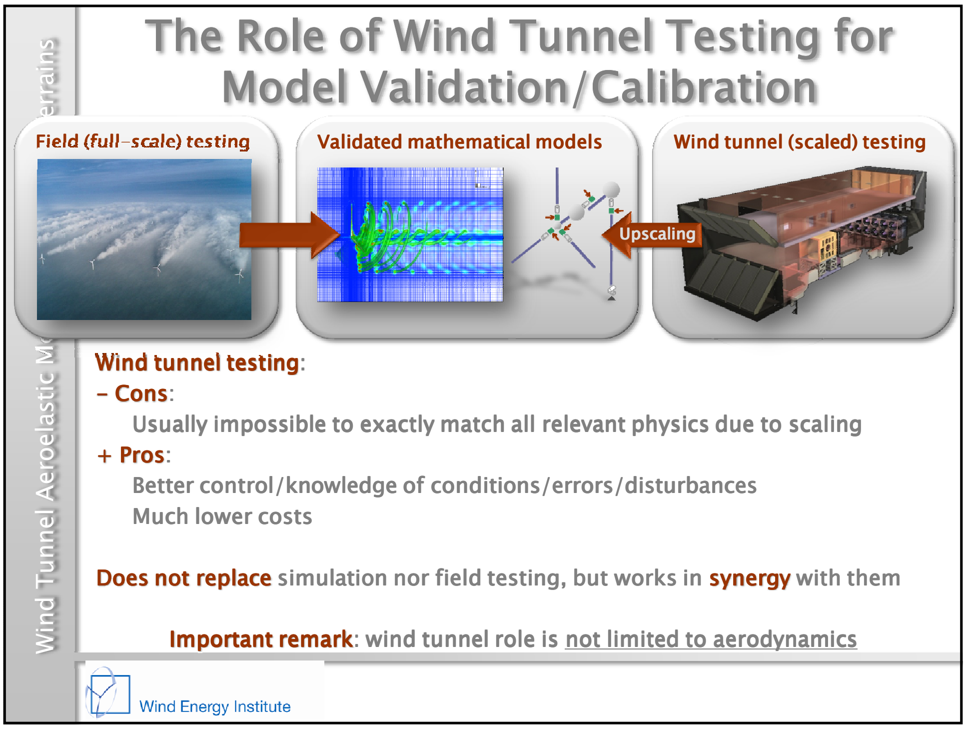
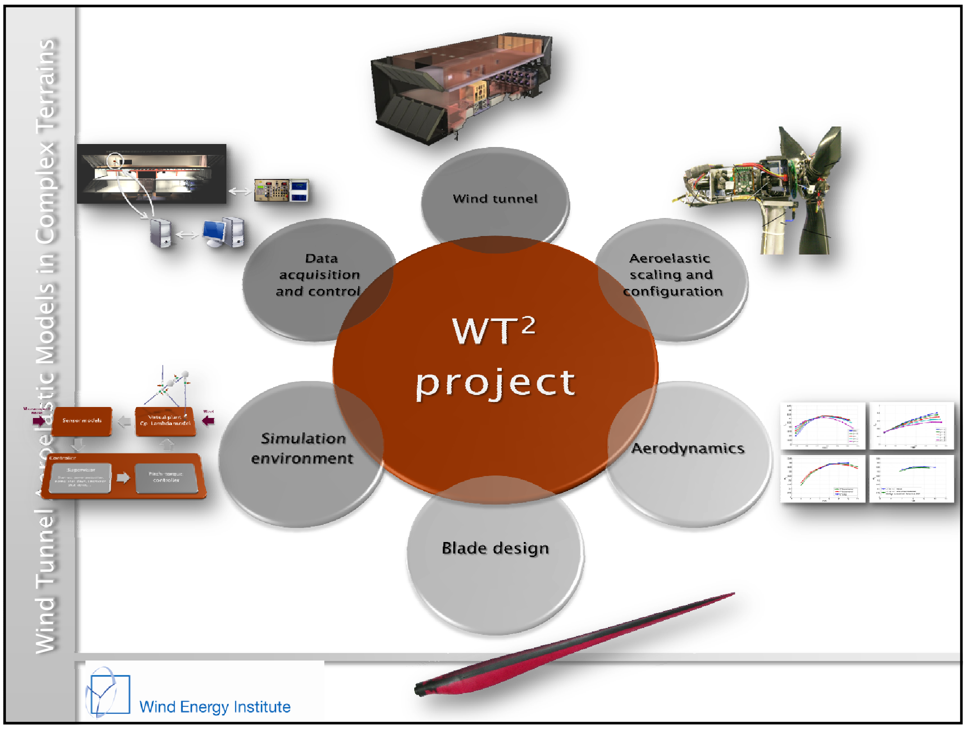
Wind Tunnel Aeroelastic Models in Complex Terrains

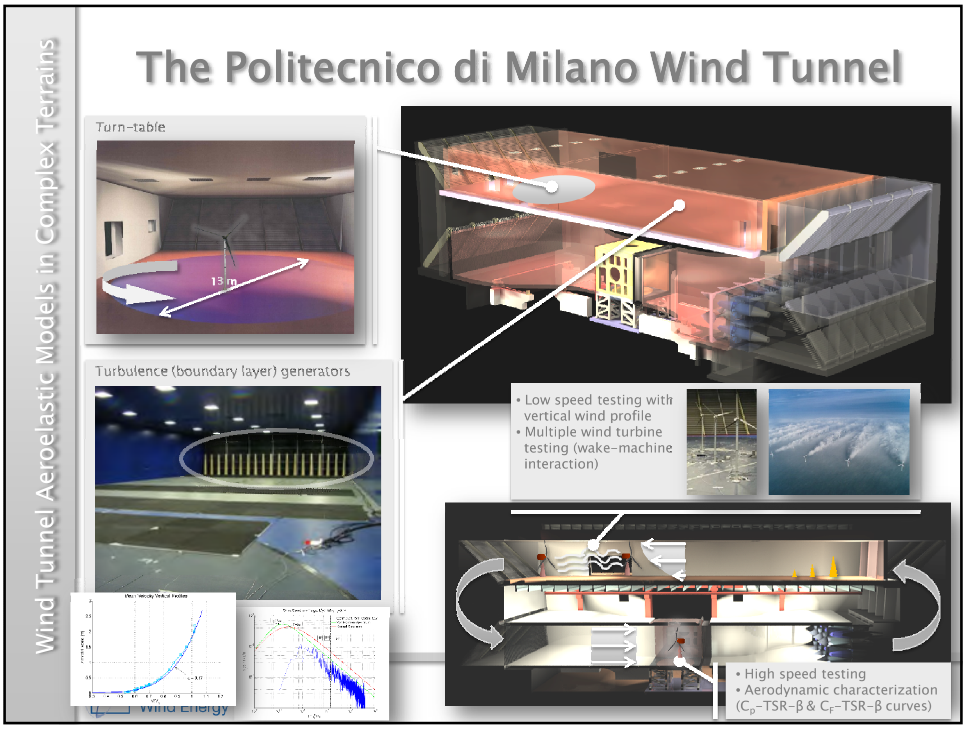
## Presentation Outline

- Wind tunnel testing: motivation and goals
- Model design and technology
- Applications
- Outlooks
- Conclusions

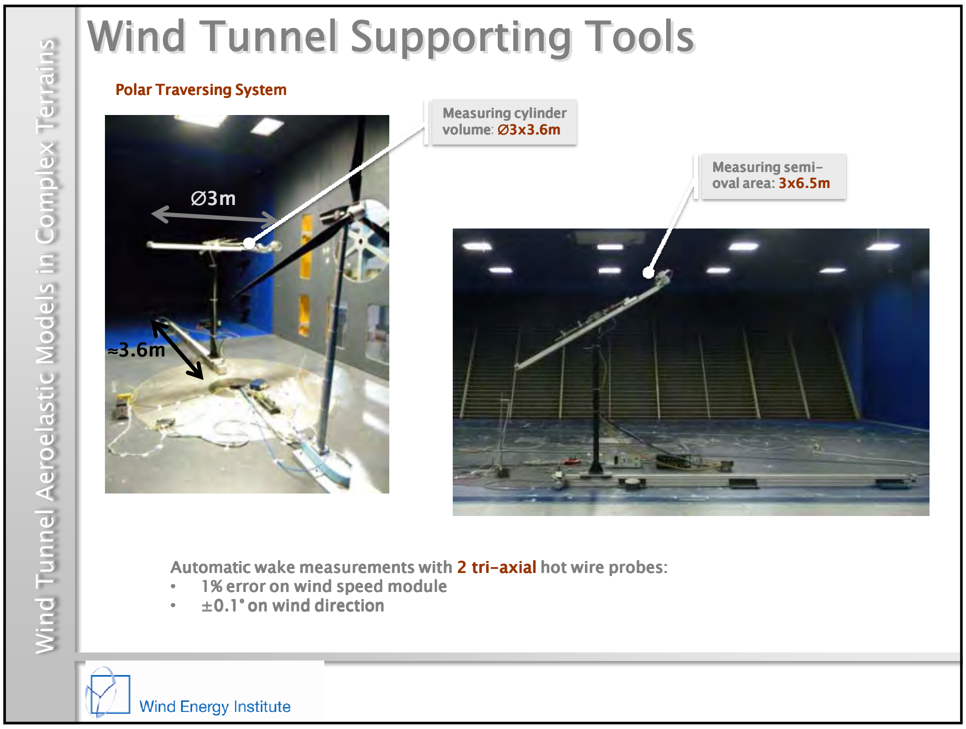
Wind Energy Institute


The Role of Wind Tunnel Testing for Model Validation/Calibration
Field (full-scale) testing
Validated mathematical models
Wind tunnel (scaled) testing
Upscaling
Wind tunnel testing:
– Cons:
Usually impossible to exactly match all relevant physics due to scaling
+ Pros:
Better control/knowledge of conditions/errors/disturbances
Much lower costs
Does not replace simulation nor field testing, but works in synergy with them
Important remark: wind tunnel role is not limited to aerodynamics
Wind Energy Institute

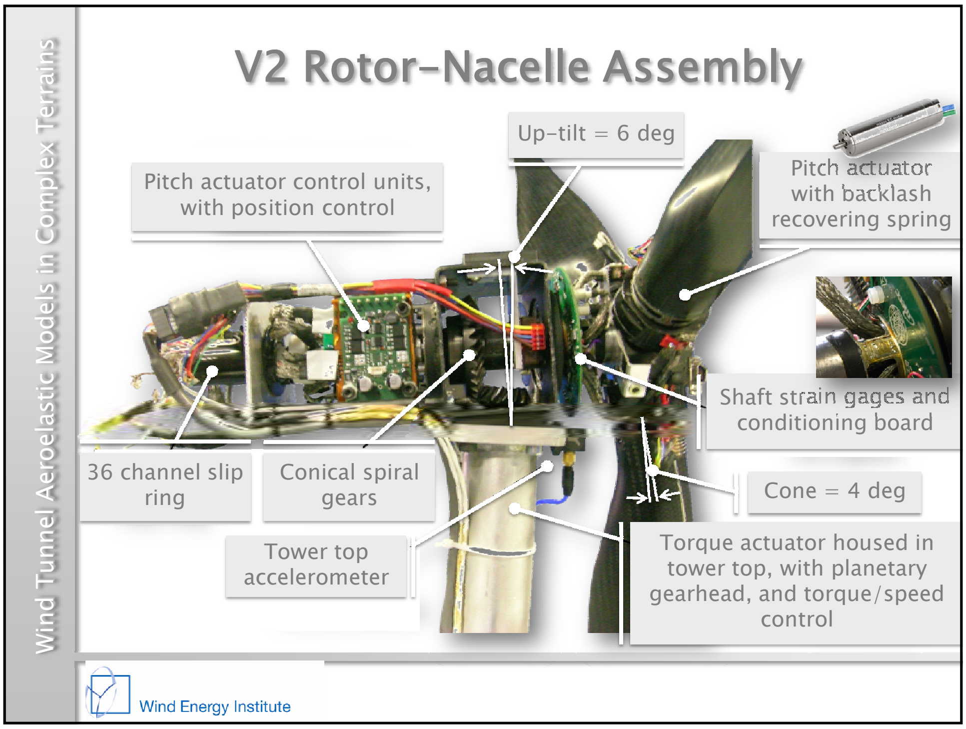

Wind tunnel
Data acquisition and control
Aeroelastic scaling and configuration
WT² project
Simulation environment
Aerodynamics
Blade design
Wind Energy Institute


The Politecnico di Milano Wind Tunnel
Wind Tunnel Aeroelastic Models in Complex Terrains
Turn-table
13 m
Turbulence (boundary layer) generators
• Low speed testing with vertical wind profile
• Multiple wind turbine testing (wake-machine interaction)
• High speed testing
• Aerodynamic characterization ($C_p$–TSR–β & $C_F$–TSR–β curves)


The Politecnico di Milano Wind Tunnel
Wind Tunnel Aeroelastic Models in Complex Terrains
Wind Energy Institute


Wind Tunnel Supporting Tools
Polar Traversing System
Measuring cylinder volume: Ø3x3.6m
Measuring semi-oval area: 3x6.5m
Ø3m
≈3.6m
Automatic wake measurements with 2 tri-axial hot wire probes:
• 1% error on wind speed module
• ±0.1° on wind direction
Wind Tunnel Aeroelastic Models in Complex Terrains
Wind Energy Institute


WT², the Wind Turbine in a Wind Tunnel
The V2: wind tunnel model of the Vestas V90 wind turbine
• Aeroelastically-scaled
• Real-time individual blade pitch and torque control
Height = 1.78 m
Radius = 1m
6 dof balance
Wind Tunnel Aeroelastic Models in Complex Terrains
Wind Energy Institute




Wind Tunnel Aeroelastic Models in Complex Terrains

## V2 Aeroelastic Scaling Laws

**Criteria for definition of scaling** (using Buckingham Π Theorem):

- **Exactly matched quantities**: TSR, Lock number, relative placement of frequencies wrt rev harmonics (same Campbell diagram)
- Best compromise between:
  - **Reynolds mismatch** (quality of aerodynamics)
  - **Speed-up of scaled time** (avoid excessive increase of control bandwidth)

| Quantity | Scaling factor |
|---|---|
| Length Ratio | 1/45 |
| Time Ratio | 1/22.84 |
| Velocity Ratio | 1/1.97 |
| Power Ratio | 1/15477 |
| Rotor Speed Ratio | 22.84 |
| Torque Ratio | 1/353574 |
| Reynolds Ratio | 1/88.64 |
| Froude Ratio | 11.6 |
| Mach Ratio | 1/1.97 |

| | V2 | V90 |
|---|---|---|
| Rotor Diameter | 2 [m] | 90 [m] |
| Hub Height | 1.78 [m] | 80 [m] |
| Rotor Speed | 367 [rpm] | 16 [rpm] |
| Nominal Power | 193.8 [W] | 3 [MW] |
| Nominal Torque | 5.06 [Nm] | 1790 [KNm] |
| Average Reynolds | ≈ 5÷6 e4 | ≈ 4÷5 e6 |

**Reynolds mismatch**:
- Low-Re airfoils (AH79 & WM006) to minimize aerodynamic differences
- Keep same chord distribution as original V90 blade, but
- Adjust blade twist to optimize axial induction factor

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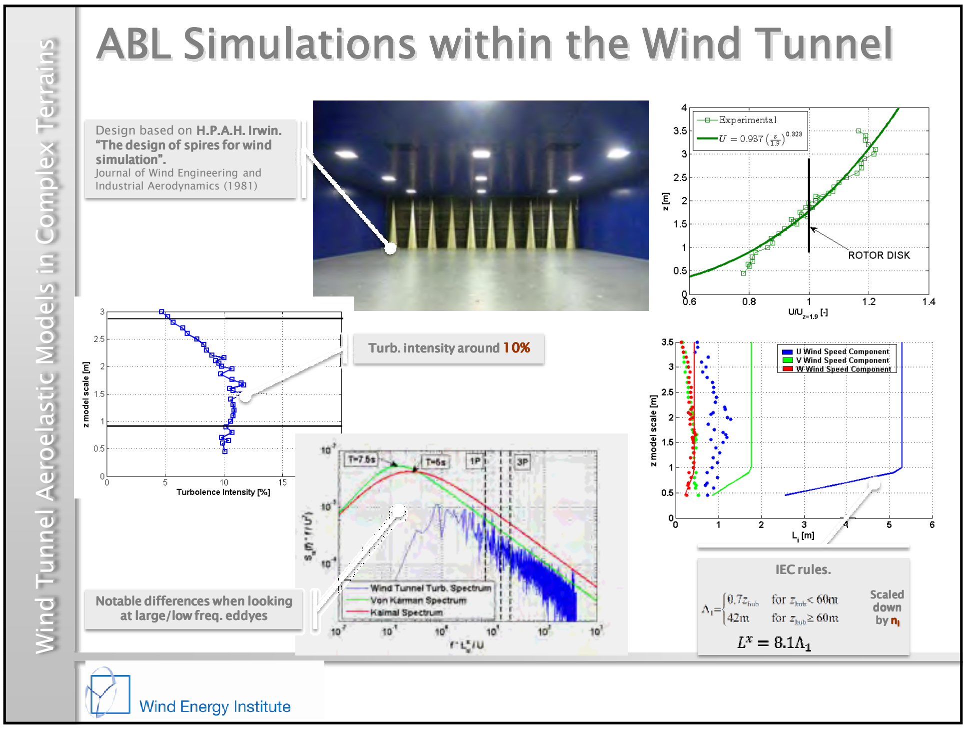
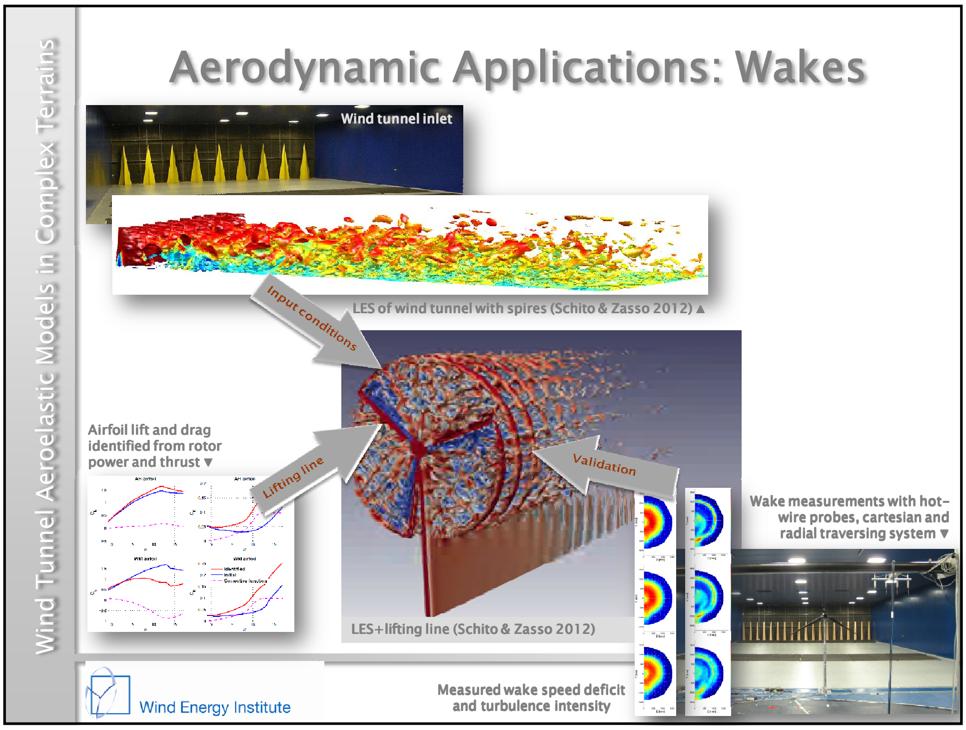
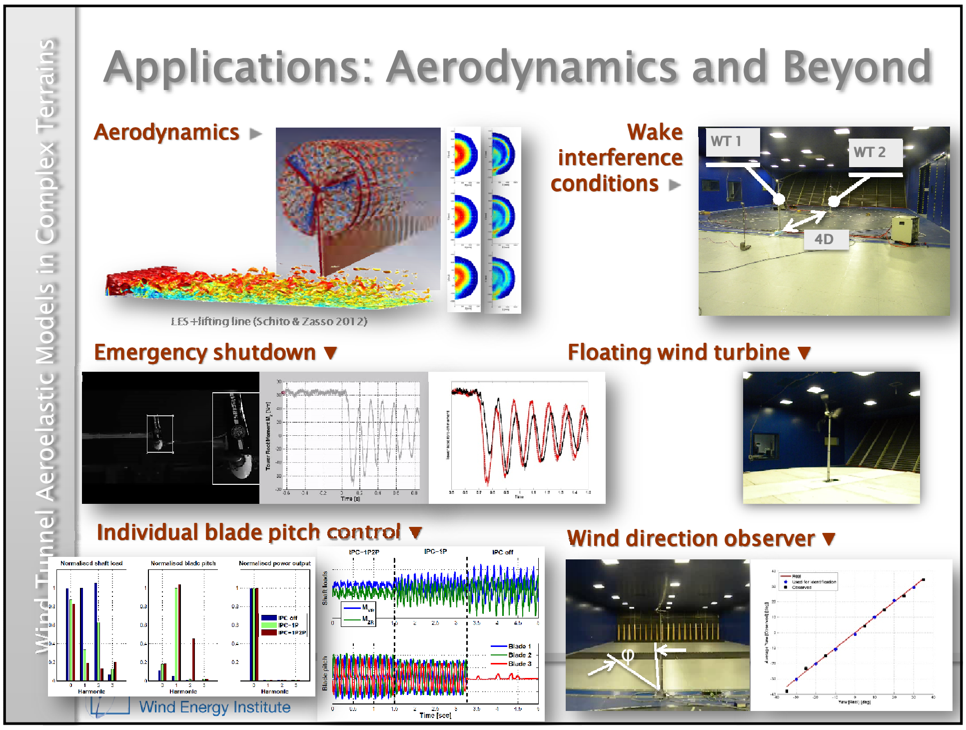

Wind Tunnel Aeroelastic Models in Complex Terrains
ABL Simulations within the Wind Tunnel
Design based on H.P.A.H. Irwin. "The design of spires for wind simulation". Journal of Wind Engineering and Industrial Aerodynamics (1981)
Experimental
ROTOR DISK
Turb. intensity around 10%
U Wind Speed Component
V Wind Speed Component
W Wind Speed Component
Turbolence Intensity [%]
Wind Tunnel Turb. Spectrum
Von Karman Spectrum
Kaimal Spectrum
Notable differences when looking at large/low freq. eddyes
IEC rules.
Scaled down by n
Wind Energy Institute


Wind Tunnel Aeroelastic Models in Complex Terrains
Aerodynamic Applications: Wakes
Wind tunnel inlet
LES of wind tunnel with spires (Schito & Zasso 2012) ▲
Input conditions
Airfoil lift and drag identified from rotor power and thrust ▼
Lifting line
Validation
Wake measurements with hot-wire probes, cartesian and radial traversing system ▼
LES+lifting line (Schito & Zasso 2012)
Measured wake speed deficit and turbulence intensity
Wind Energy Institute




Wind Tunnel Aeroelastic Models in Complex Terrains

## Outlook: Beyond the Individual Wind Turbine

Many problems/applications:

- Wind farm **layout** optimization
- Wind farm **control** (optimize power output, fatigue and loading distribution)
- Effects of **complex terrains** on single wind turbine and wind farm output and loading
- …

Applicable not only to new wind farms, but also already **existing ones**

**Many challenges**: lower atmosphere dynamics, turbulence, wakes, …

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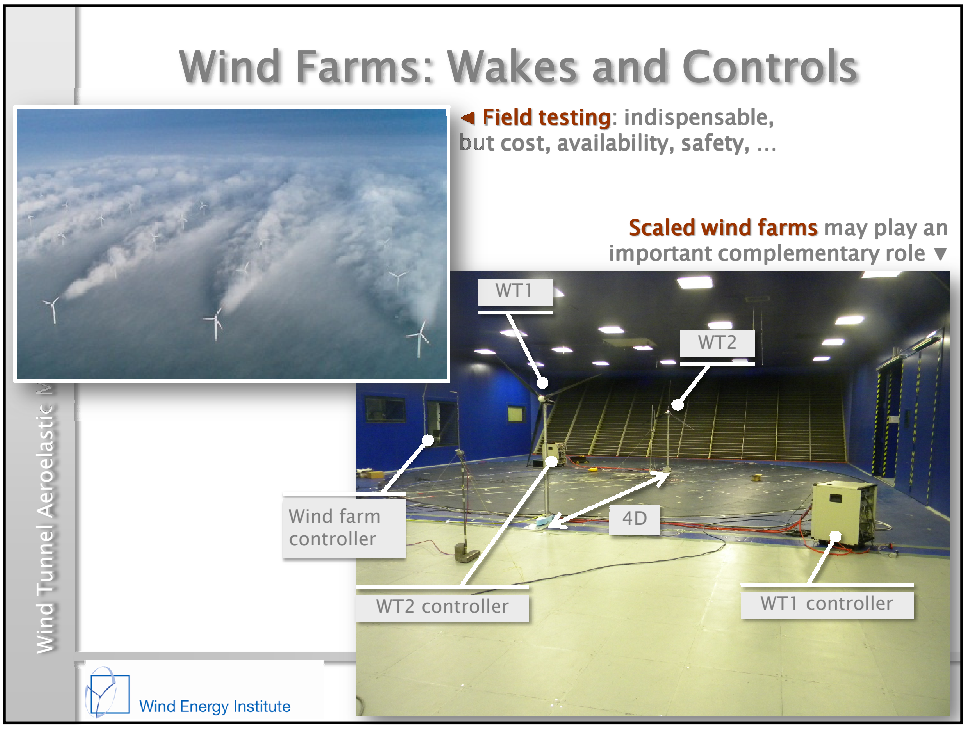
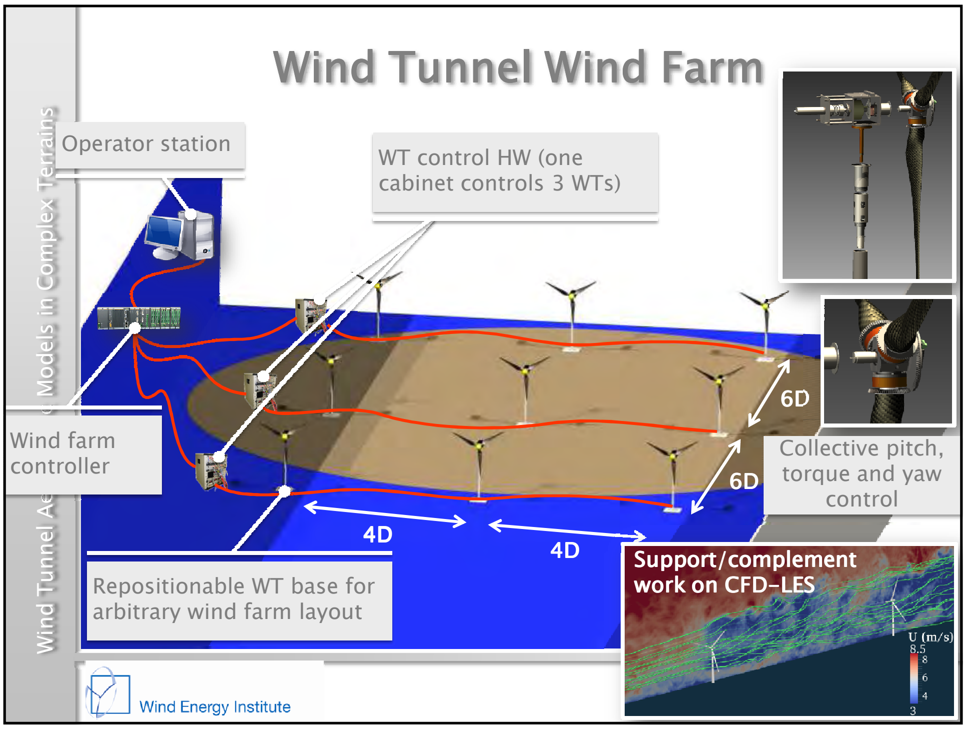
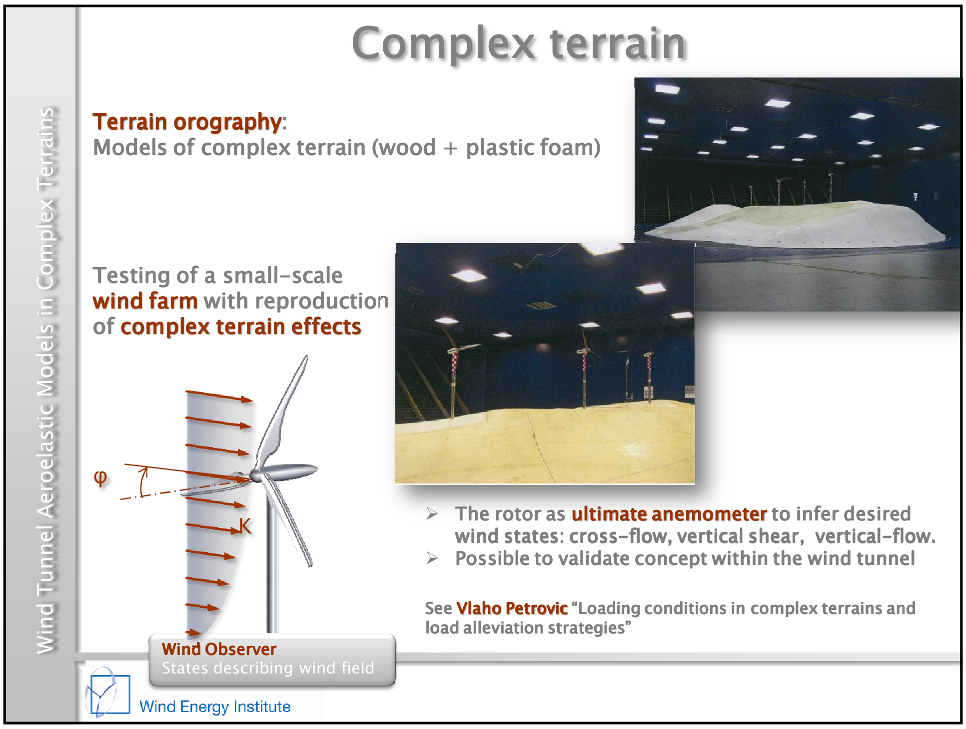

Wind Farms: Wakes and Controls
◀ Field testing: indispensable,
but cost, availability, safety, ...
Scaled wind farms may play an
important complementary role ▼
WT1
WT2
Wind farm
controller
4D
WT2 controller
WT1 controller
Wind Tunnel Aeroelastic M
Wind Energy Institute


Wind Tunnel Wind Farm
Operator station
WT control HW (one
cabinet controls 3 WTs)
Wind farm
controller
6D
6D
Collective pitch,
torque and yaw
control
4D
4D
Repositionable WT base for
arbitrary wind farm layout
Support/complement
work on CFD-LES
Wind Tunnel Ae
Models in Complex Terrains
Wind Energy Institute


Complex terrain
Wind Tunnel Aeroelastic Models in Complex Terrains
Terrain orography:
Models of complex terrain (wood + plastic foam)
Testing of a small-scale wind farm with reproduction of complex terrain effects
φ
K
Wind Observer
States describing wind field
The rotor as ultimate anemometer to infer desired wind states: cross-flow, vertical shear, vertical-flow.
Possible to validate concept within the wind tunnel
See Vlaho Petrovic "Loading conditions in complex terrains and load alleviation strategies"
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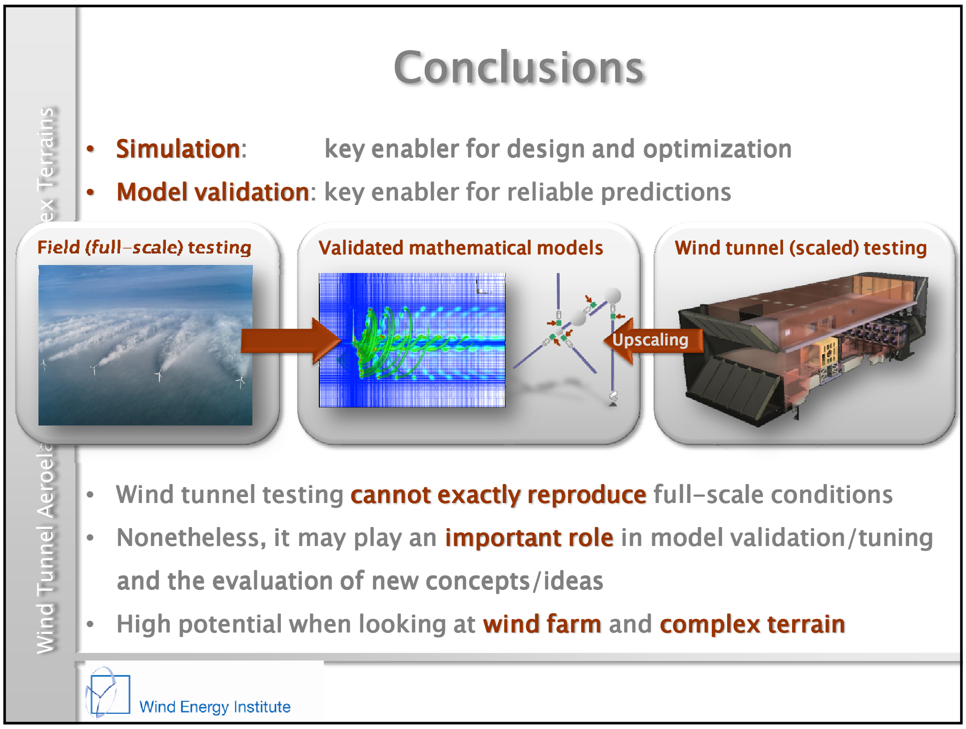
Conclusions
Simulation: key enabler for design and optimization
Model validation: key enabler for reliable predictions
Field (full-scale) testing
Validated mathematical models
Wind tunnel (scaled) testing
Upscaling
Wind tunnel testing cannot exactly reproduce full-scale conditions
Nonetheless, it may play an important role in model validation/tuning and the evaluation of new concepts/ideas
High potential when looking at wind farm and complex terrain
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Wind Tunnel Aeroelastic Models in Complex Terrains

## Acknowledgements

Research developed while at the Politecnico di Milano

Work in collaboration with:
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$WT^2$ Project, funding provided by:
**Vestas Wind Systems A/S**
Partial support provided by:
**Bachmann GmbH** (real-time control hardware)
**US DoE** (for development of wind observers)

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Wind Tunnel Aeroelastic Models in Complex Terrains

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Topical Expert Meeting #75 on

# Wind Energy in Complex Terrain

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WindForS
The Southern German Wind Energy Research Alliance

Christoph Schulz, Thorsten Lutz
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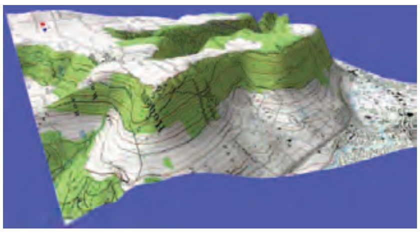
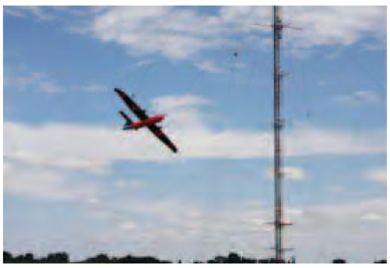
## Current research funding

**LiDAR Complex**

- BMU funded project of different WindForS partners and others
  - Uni Stuttgart, Uni Tübingen, KIT, FGW, Kenersys
  - LiDAR and UAV measurements in different terrains
  - Wind tunnel measurements
  - Numerical simulations
  - load and power evaluation ➔ improvement of predictions



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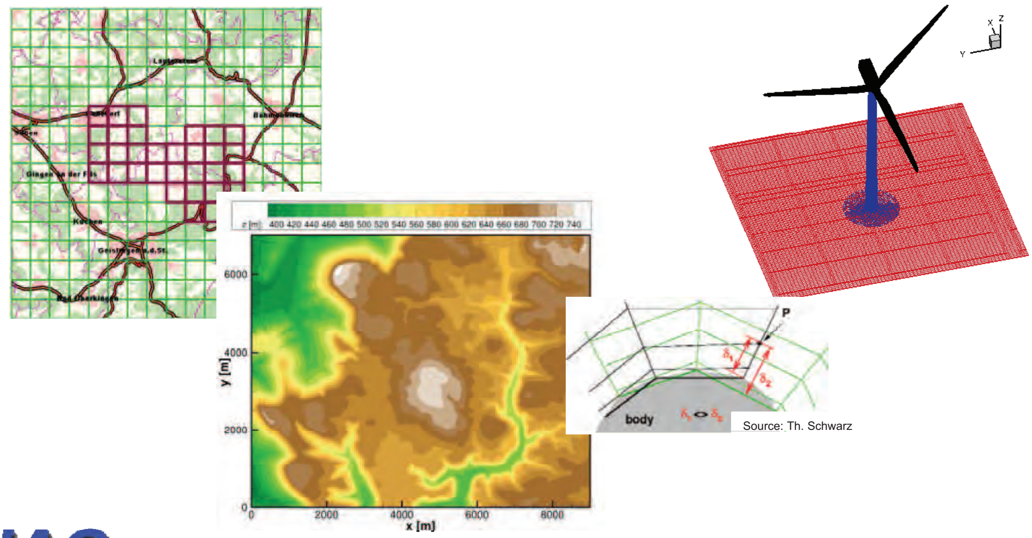
## Surface Generation and Preparation

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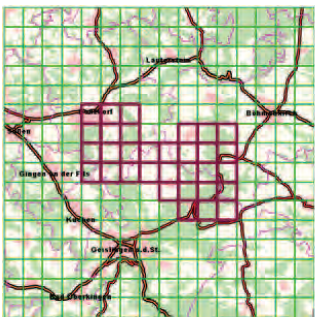
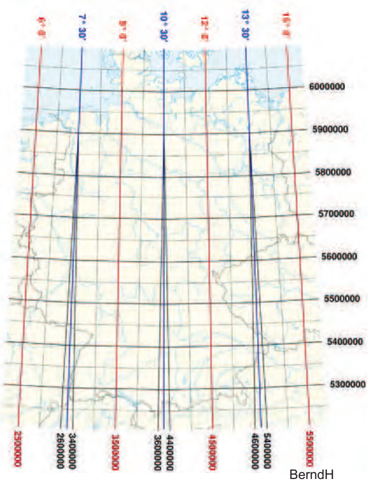
## Surface Generation

### Input data

LGL

- LGL (Landesamt für Geoinformation und Landentwicklung) has a digital terrain model database




- Data stored in ASCII files with Gauss Krüger coordinates
  - different resolutions available
  - transformation to other database formats possible

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## Surface Generation

### Transformation into database formats

LGL

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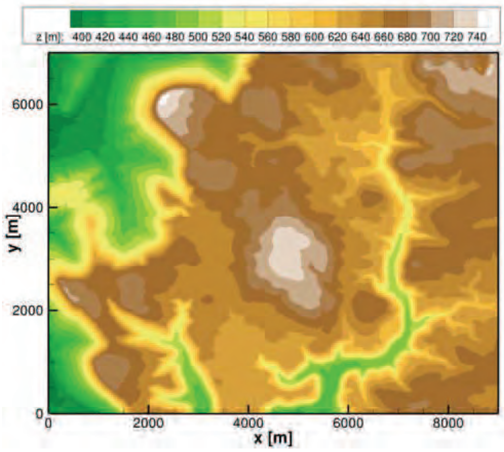
- Data are transformed to a Pointwise/Gridgen readable format

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## Surface Generation

### Chimera Issues

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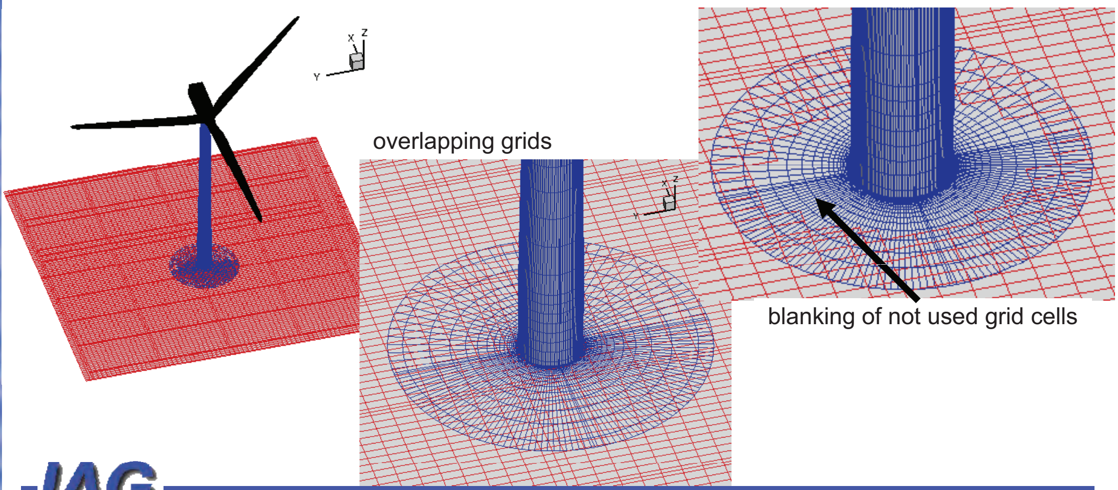
- Chimera between background and tower
  - Identical surfaces needed due to wall distance computations

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## Surface Generation
### Chimera Issues

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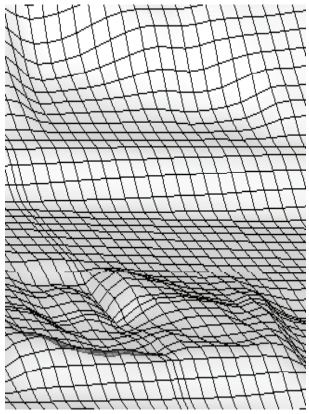
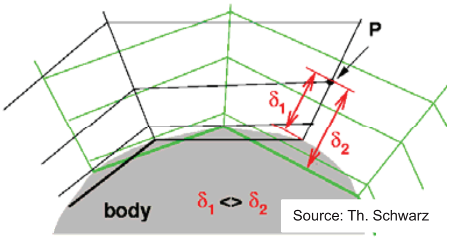
- Chimera overlap between background and tower
  - Identical surfaces needed due to wall distance computations
  - Two overlapping surfaces with different meshes
    - 1 point can have varying wall distances in these meshes
    - Interpolation data are taken from locations with different wall distances
    - Even possible that point is inside other structure
    - Interpolation may become impossible

➔ Can be solved to some extend by interpolation algorithm
➔ Nevertheless a good surface overlap of the grids avoids several problems



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## Surface Generation
### Chimera Issues

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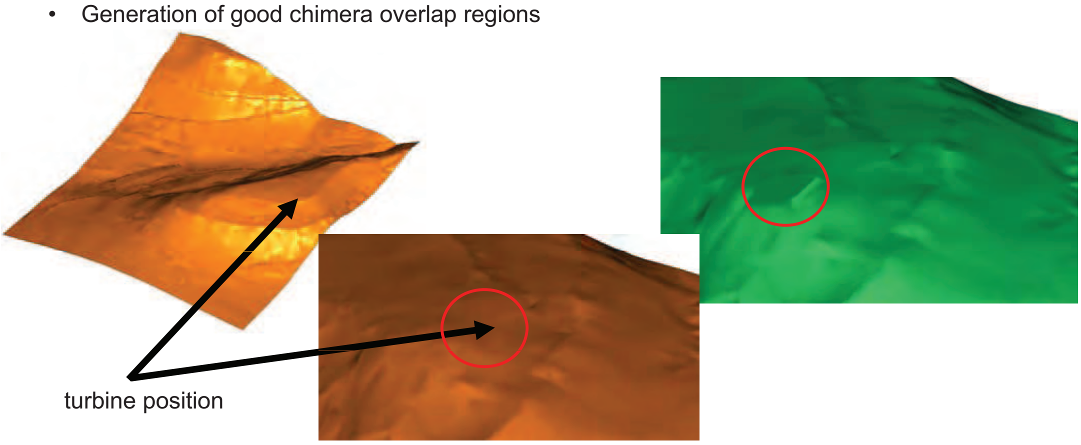
- Surface adaption needed for tower ground connection
  - Plane on surface must be created
  - Programme to manipulate surface data at given points
  - Generation of good chimera overlap regions

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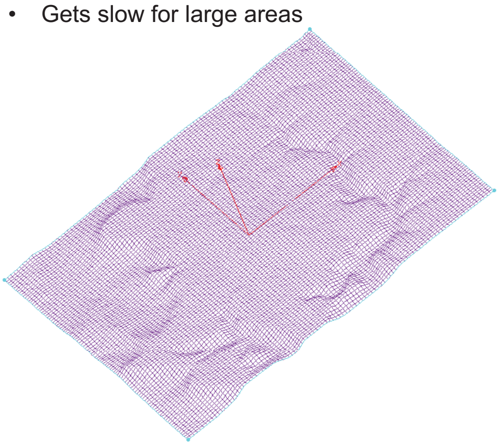
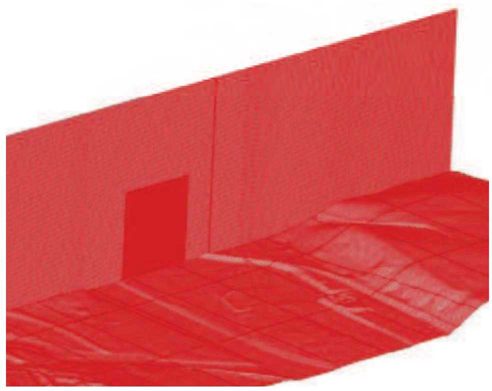
## Surface Generation

### Mesh Generation

- Automatization of mesh generation
  - Under further development (hanging grid nodes, independence from meshing software)
  - At the moment differnt scripts generate the mesh by defining resolution etc. in an input file
  - Gets slow for large areas





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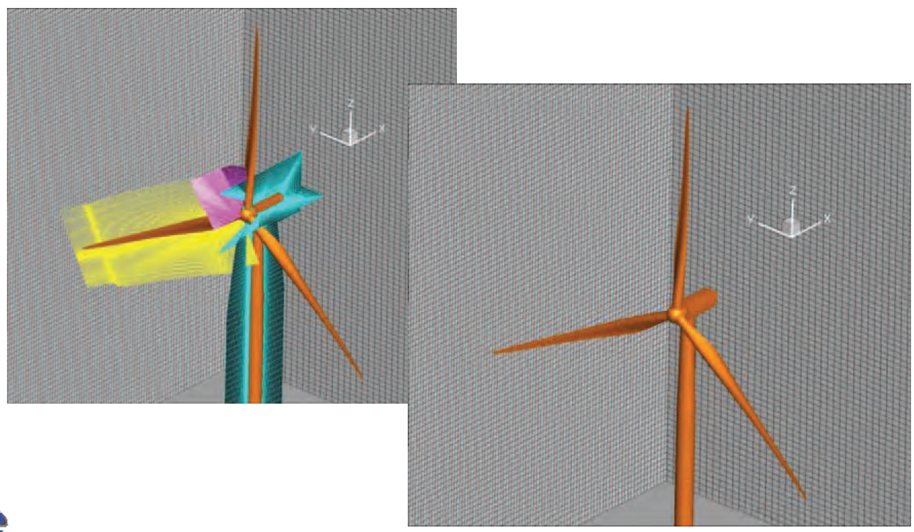
## Turbine Meshing and Simulation Setup



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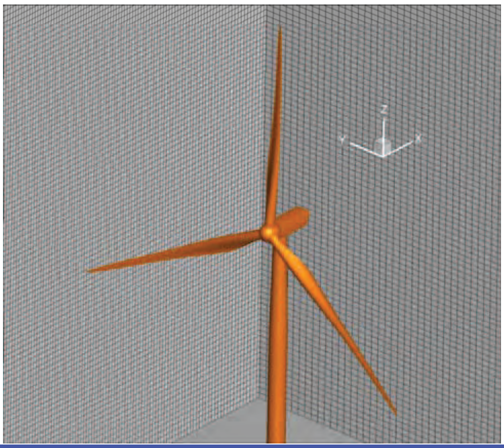
## Turbine Meshing and Simulation Setup

### Meshing

- Overall mesh consist of different components
  - Overlapped with Chimera technique
  - Depending on turbine different setups are chosen
  - In general background mesh



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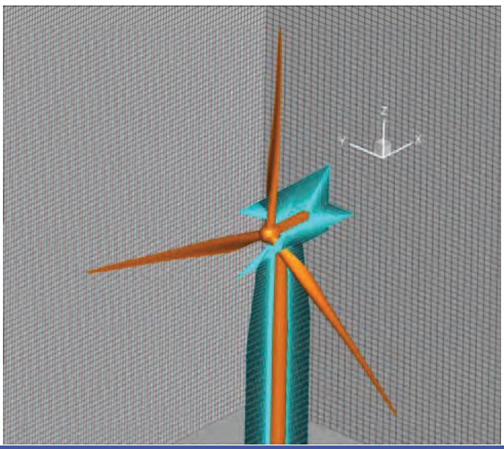
## Turbine Meshing and Simulation Setup

### Meshing

- Overall mesh consist of different components
  - Overlapped with Chimera technique
  - Depending on turbine different setups are chosen
  - In general background, tower and nacelle meshes



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## Turbine Meshing and Simulation Setup
### Meshing

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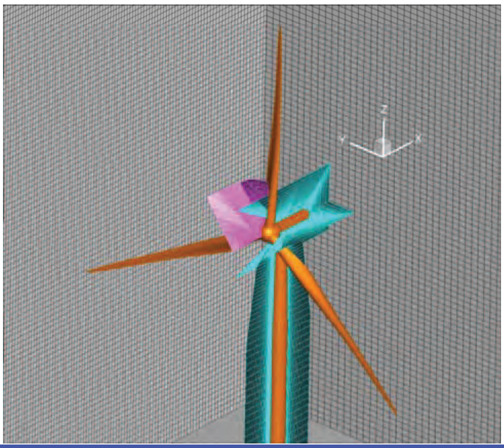
- Overall mesh consist of different components
  - Overlapped with Chimera technique
  - Depending on turbine different setups are chosen
  - In general background, tower, nacelle and hub meshes



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## Turbine Meshing and Simulation Setup
### Meshing

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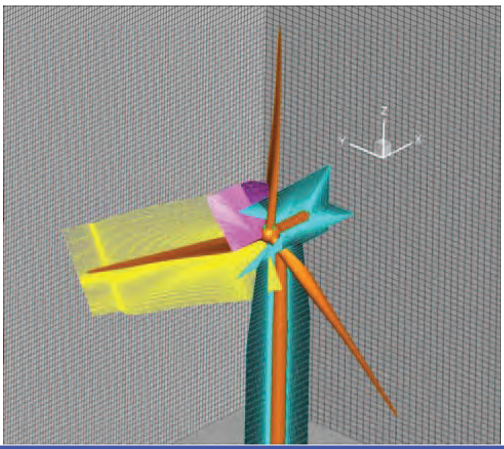
- Overall mesh consist of different components
  - Overlapped with Chimera technique
  - Depending on turbine different setups are chosen
  - In general background, tower, nacelle, hub and blade meshes



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## Turbine Meshing and Simulation Setup

### Simulation Setup

- Gridgen and Pointwise for mesh generation
- FLOWer (provided by DLR)
- Block structured flow solver
- Cell vertex
- Finite volume
- Unsteady computations, hybrid RANS/LES is possible
- Different turbulence models available
- Timestep and number of inner iterations are adapted to simulation case

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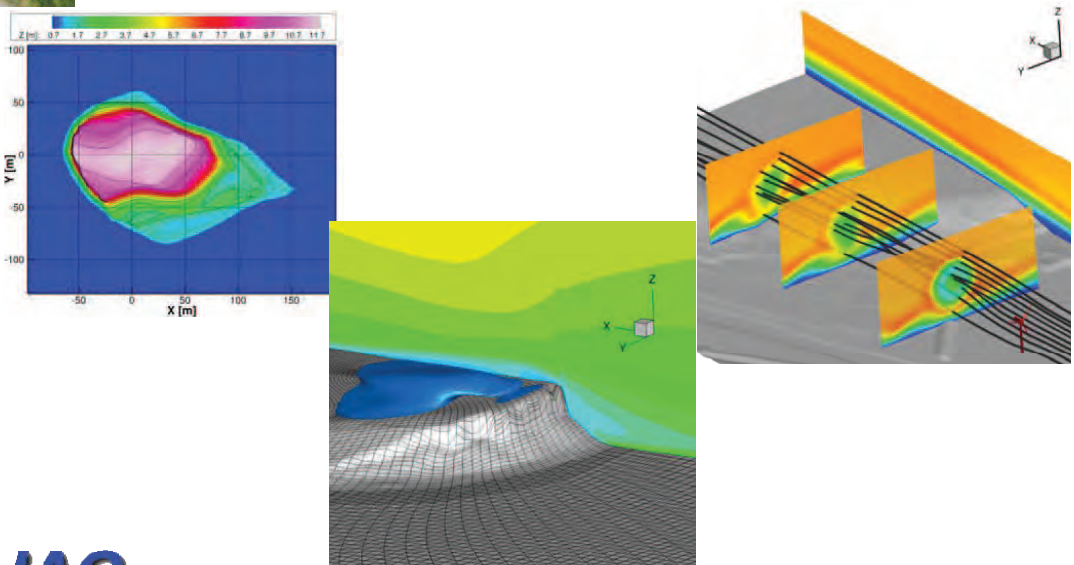
## Terrain Simulation

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## Terrain Simulation
**Bolund**

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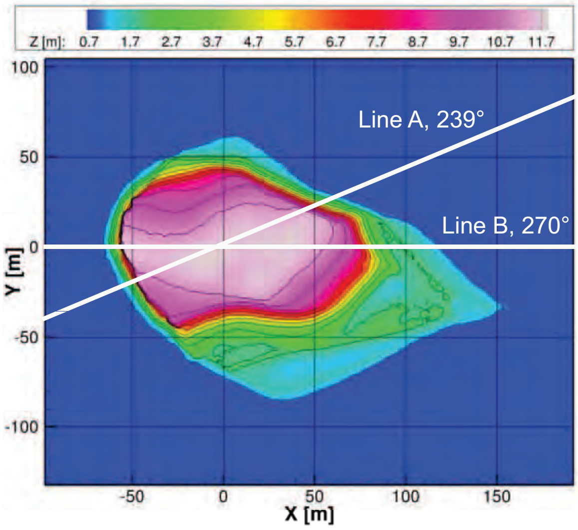
- Blind comparison performed by DTU
- 12m high, 130m long, 75m wide
- Re approx 1e7

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## Terrain Simulation
**Bolund**

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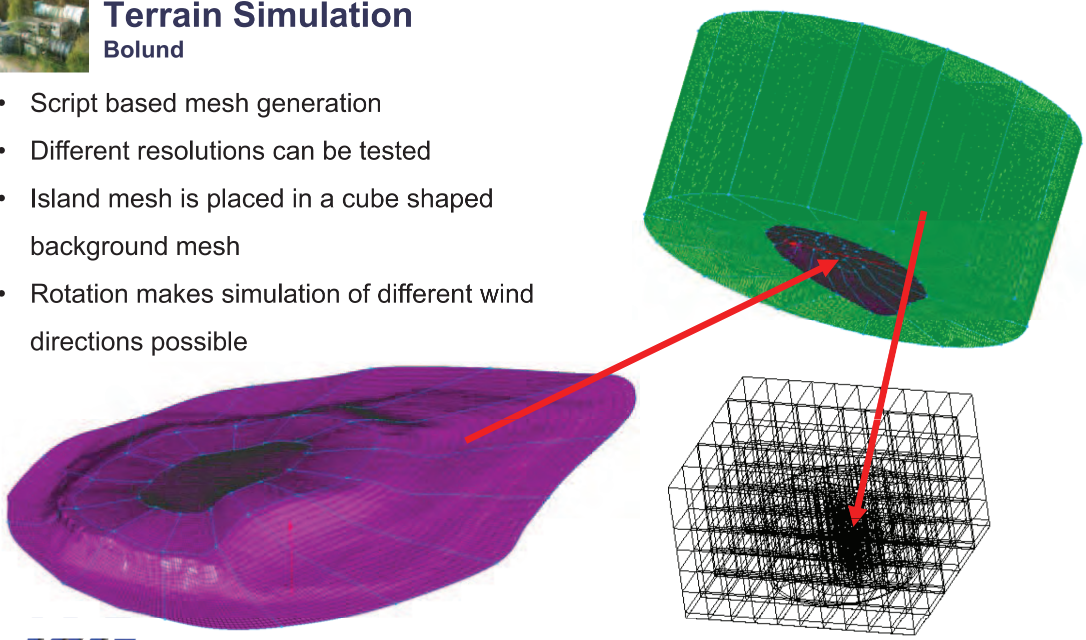
- Script based mesh generation
- Different resolutions can be tested
- Island mesh is placed in a cube shaped background mesh
- Rotation makes simulation of different wind directions possible



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## Terrain Simulation
### Bolund

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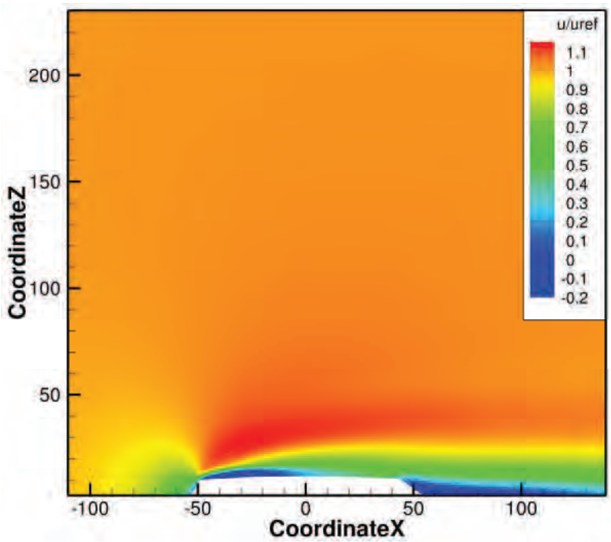
- Inflow in 239° direction
- Slice extracted at x=0 ➔ Line A
- Seperation at edge and downstream of Bolund is captured
- Speed up for higher z values

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## Terrain Simulation
### Bolund

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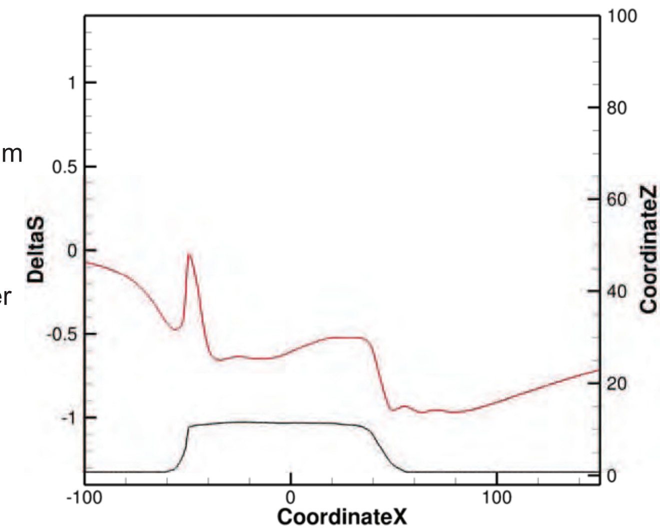
- Inflow in 239° direction
- Slice extracted at x=0 ➔ Line A
- Seperation at edge and downstream of Bolund is captured
- Speed up for higher z values
- Speed up at constant distance over surface shows same effects
- Large low speed region close to surface

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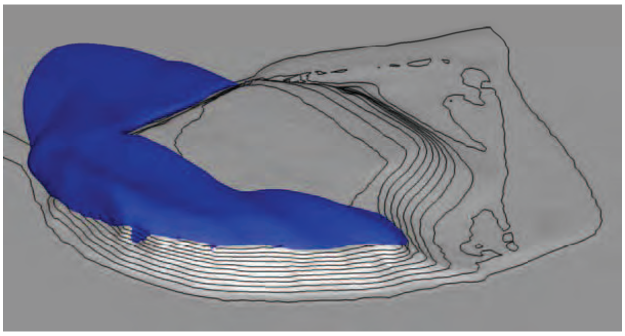
# Terrain Simulation
## Bolund

- Inflow in 239° direction
- Slice extracted at x=0 ➔ Line A
- Seperation at edge and downstream of Bolund is captured
- Speed up for higher z values
- Speed up at constant distance over surface shows same effects
- Large low speed region close to surface



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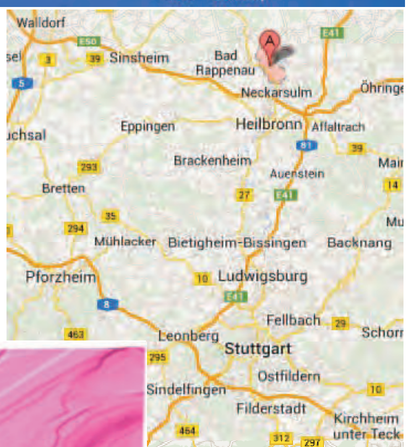
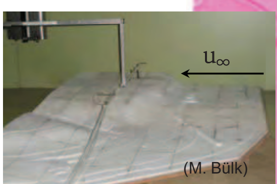
# Terrain Simulation
## Jagstfeld

- Free test data set provided by LGL
- Gauss Krüger coordinate ASCII files
- Process chain used for mesh generation
- Different simulations performed
- Wind tunnel tests done on terrain

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## Terrain Simulation
**Jagstfeld**

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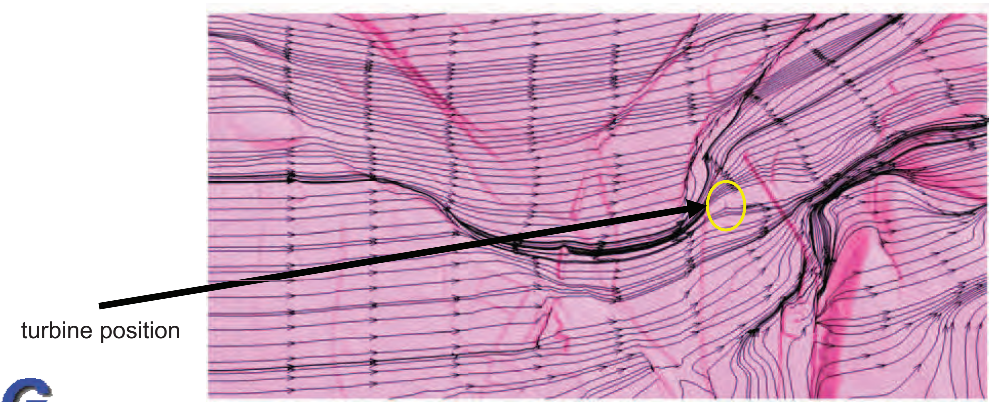
- Flow is strongly affected by mountain at lower right corner of the domain

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## Terrain Simulation
**Jagstfeld**

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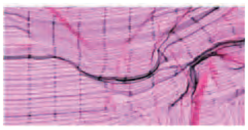
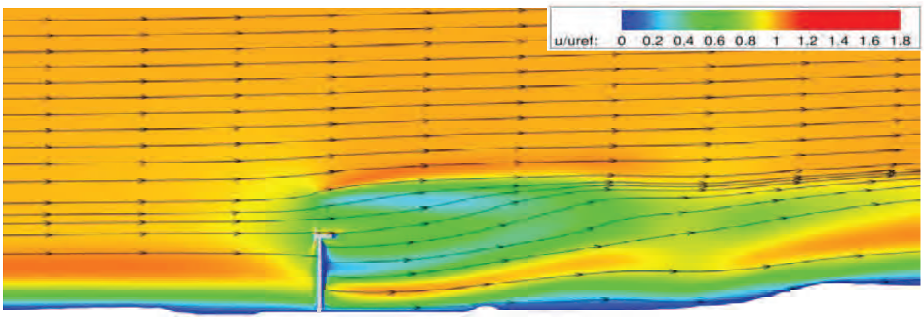
- Flow is strongly affected by mountain at lower right corner of the domain
- W component of flow influenced by terrain effects



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## Terrain Simulation
### Jagstfeld

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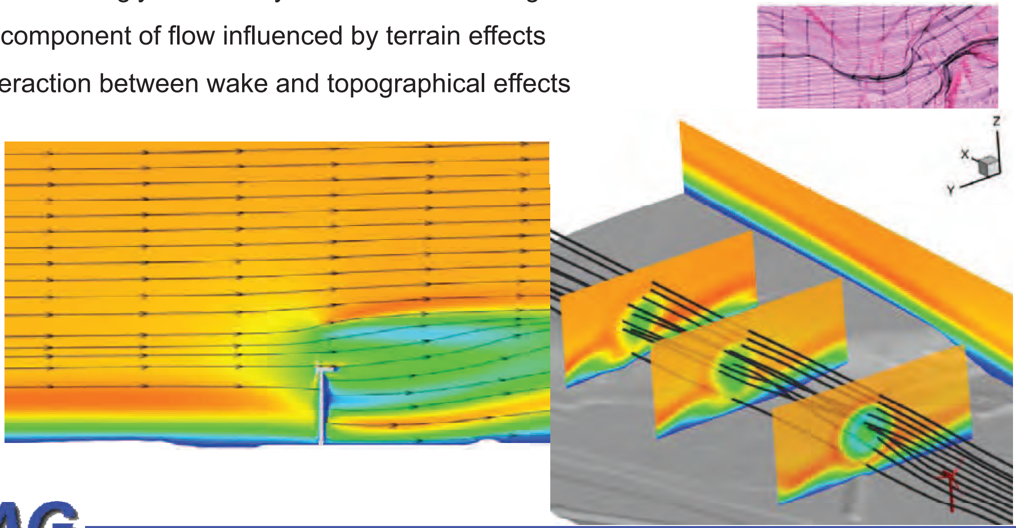
- Flow is strongly affected by mountain at lower right corner of the domain
- W component of flow influenced by terrain effects
- Interaction between wake and topographical effects

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## Terrain Simulation
### Jagstfeld

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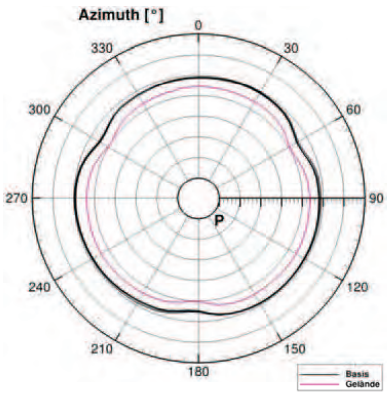
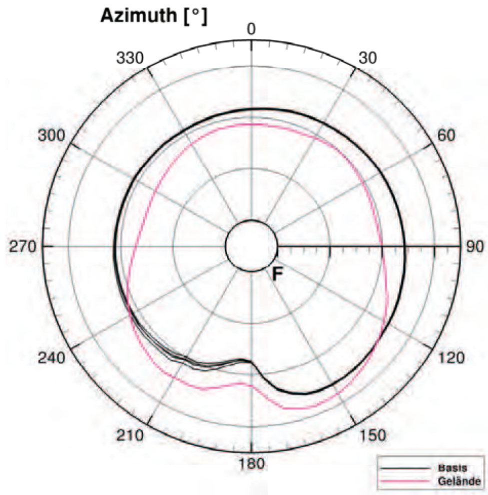
- Power reduced
- Variiying conclusion from loads
  - Further investigations needed

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# Terrain Simulation
## Jagstfeld/ Site Assessment

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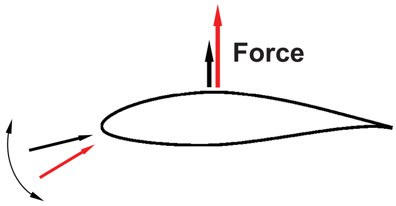
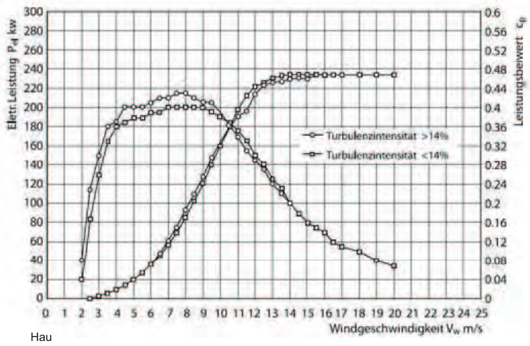
- Different evalutions of flow field in complex terrain without wind turbine
  - Turbulence intensity
  - Velocity distribution ➔ power estimations
  - Possible wake effects/ interactions

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# Terrain Simulation
## Jagstfeld/ Site Assessment

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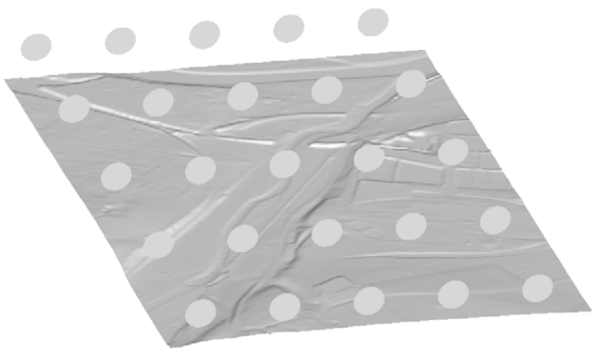
- Script for analysis of maximum power production inside terrain
  - Input values: hub height, radius, …
- Integration of wind speeds over circular area at different positions inside the domain
- Circular center is equal to hub height



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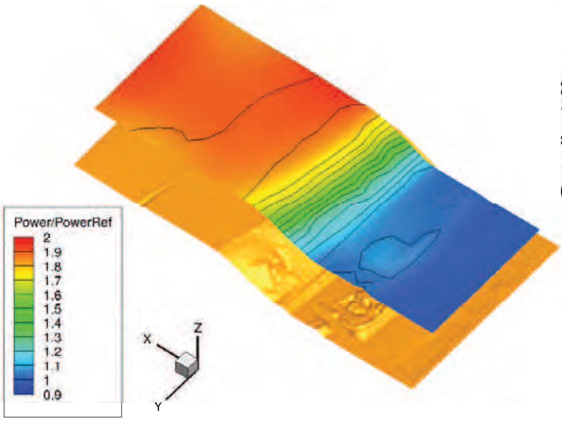
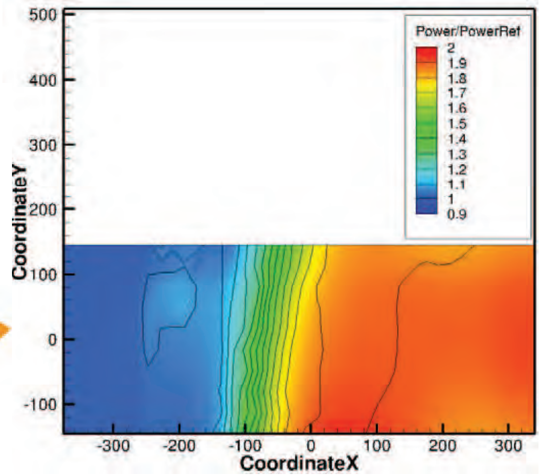
## Terrain Simulation

**Jagstfeld/ Site Assessment**

- Higher possible Power than on a flat plate possible
- Turbulence not evaluated so far
- Turbine interaction neglected so far

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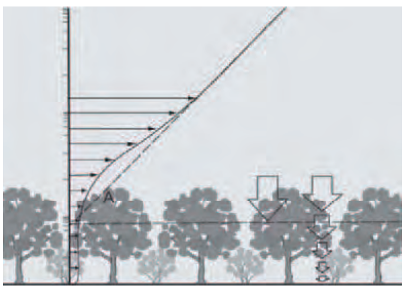
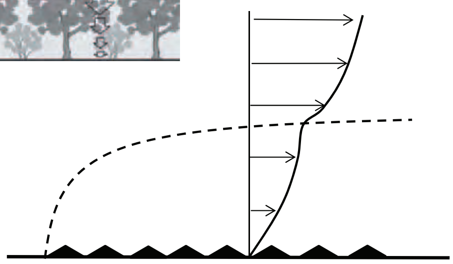
## Ongoing Implementations




Ayotte



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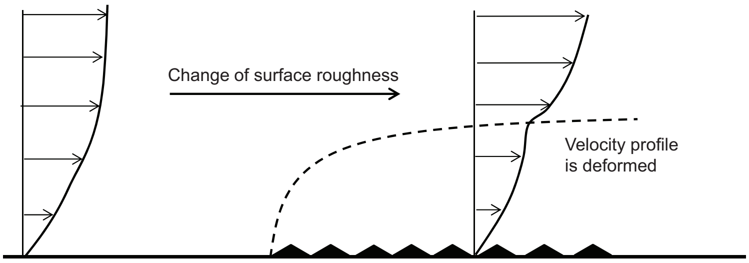
## Ongoing Implementations
### Surface roughness changes

- Standard FLOWer does not support different roughness at surfaces
- Currently new models are implemented to consider these effects
- Different vegetation etc. should be used in future

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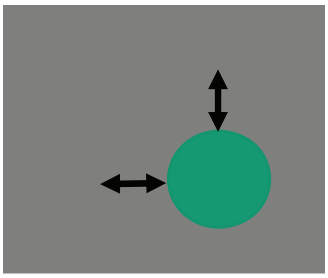
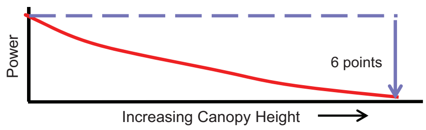
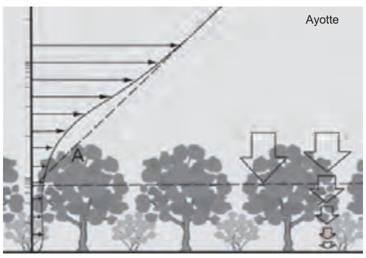
## Ongoing Implementations
### Canopy

- Consideration of forests by implementation of momentum effects etc.
- Forest areas are integrated into the computational domain via Chimera technique






Windatlas BaWü

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WindForS
The Southern German
Wind Energy Research Alliance
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# Improving layouts in complex terrain using CFD-based constraint maps

Ben Martinez, Vattenfall R&D Wind

TEM 75 Topic Expert Meeting, Stuttgart
12-11-2013

Confidentiality - Low (C2)

## Outline

1. Vattenfall onshore wind
2. In-house site prospecting / constraint tool based on RANS-CFD
    - Motivation
    - Input / Output
    - Wind climate extrapolation assumptions
3. Test case example: EWEA site (Dublin workshop)

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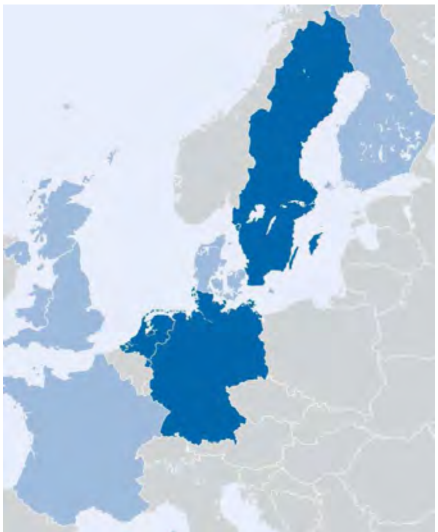
## This is Vattenfall



Vattenfall's main markets are
Nordics, Germany, Netherlands

Vattenfall also have operations in:
UK, France

Vattenfall's main products are
Electricity, Heat, Gas

Vattenfall works in all parts of the value chain
Production, distribution,
trading and sales

Vattenfall produces electricity and heat
from six energy source
Hydro, Nuclear, Coal, Wind,
Biomass and Gas

100%-owned by the Swedish state

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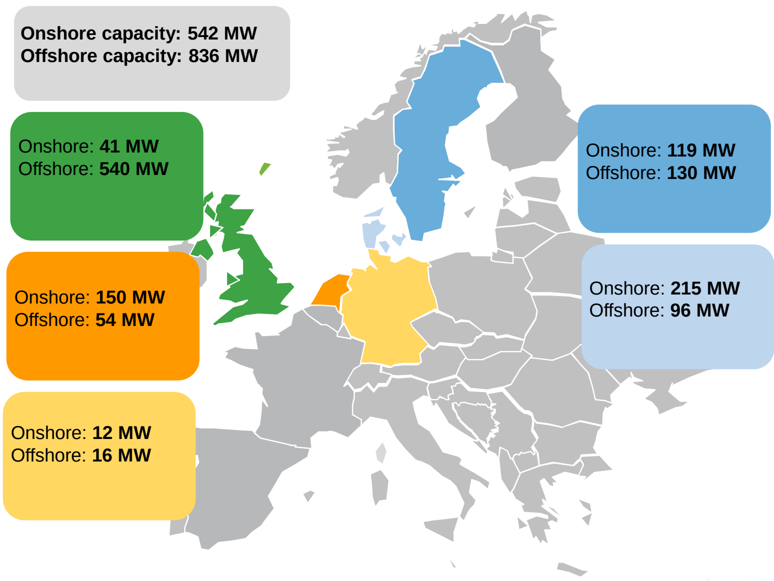
## 1. Wind power – Vattenfall wind assets (as per early 2012)

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## 1. Onshore wind: welcome to our world – it's full of trees, hills and ice !

- Growth in onshore wind power portfolio mainly in Sweden & UK
  - Areas affected by forest in complex terrain
  - Areas affected by severe icing (Running internal R&D icing program since 2011)
- Sweden has 60-65% forest cover
  - About 18% of all forest in Europe
  - Forest coverage in comparison:
    - Denmark: 11%
    - United Kingdom: 12% (Scotland 15%)
    - Germany: 31%
    - European average: 35-45%
- Need to understand better wind conditions in forest / complex terrain
  - 35 met masts and 20 SODAR systems in operation (mostly in southern Sweden)
  - High turbulence and wind shear
  - A matter of techno-economical risk mitigation


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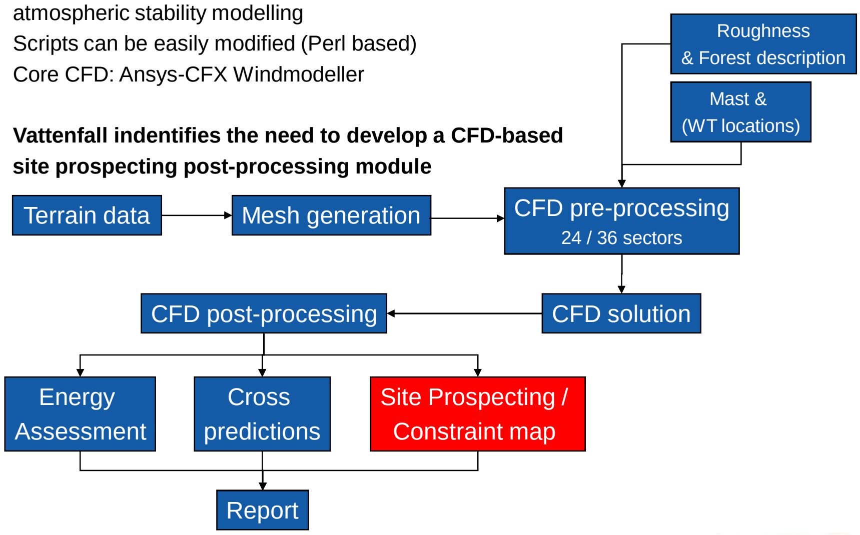
## 2. Motivation: Site prospecting / constraint map tool

- Vattenfall makes use of a fully automated RANS CFD workflow with wake & atmospheric stability modelling
- Scripts can be easily modified (Perl based)
- Core CFD: Ansys-CFX Windmodeller

→ **Vattenfall indentifies the need to develop a CFD-based site prospecting post-processing module**

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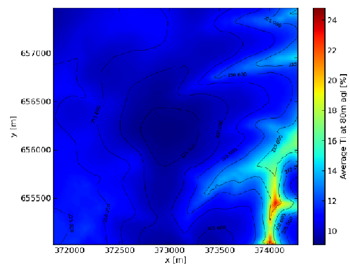
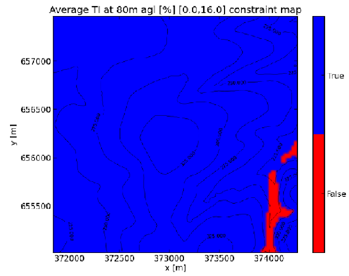
## 2. Motivation: Site prospecting / constraint map tool

- To Exclude areas with high loads via boolean constraint maps
- To Map shear / turbulence: extremely relevant in forested areas (Sweden, Scotland)
- To integrate the module in the GUI (Graphical user interfase)

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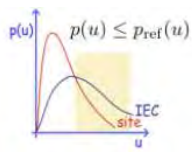
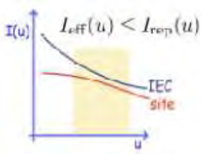
## 2. Motivation: Site prospecting / constraint map tool

- Constraint inputs linked with IEC 61400-1 Ed3 Standard (Project developer site assessment checklist)

| Wind turbine class | | I | II | III | S |
|---|---|---|---|---|---|
| $V_{ref}$ | (m/s) | 50 | 42,5 | 37,5 | Values |
| A | $I_{ref}$ (-) | 0,16 | | | specified |
| B | $I_{ref}$ (-) | 0,14 | | | by the |
| C | $I_{ref}$ (-) | 0,12 | | | designer |

1. **0 < Average shear coefficient < 0.2** ✓
2. **Abs(Flow inclination) < 8 deg (for any direction)** ✓
3. **Extreme Wind speed < Vref** ✓
4. **Wind distribution <= IEC design distribution** ✓ ✗
5. **Effective TI <= Representative TI** ✗

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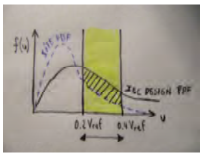
## 2. Motivation: Site prospecting / constraint map tool

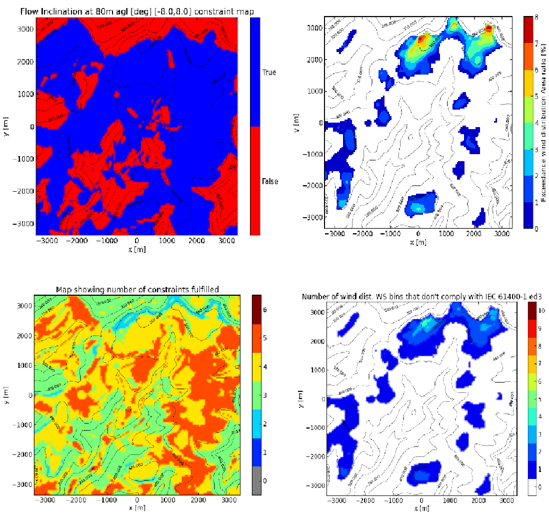
**INPUT: User defined site contraints on:**

- Ambient Turbulence intensity (average or at specific wind speed)
- Shear coefficient
- 50 year extreme wind speed
- Terrain inclination
- Flow inclination

**Output:**

- Individual boolean (True, False) .xyz maps for each constraint
- Combined boolean .xyz map for all constraints
- Constraint fullfilment .xyz map showing number of constraint fullfilled
- .xyz maps showing number of bins exceeding IEC Wind distribution
- .xyz maps showing % of Exceedance wind distribution area ratio



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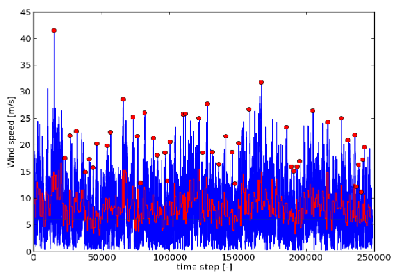
## 2. Wind climate extrapolation assumptions

- Wind speed, Shear coefficient , Flow Inclination → Reynolds number independence assumption with no stability or wakes
- Turbulence Intensity or Standard deviation → $\sigma_{grid\ point,\ pred} = \sigma_{mast,\ mast} * \sqrt{\frac{TKE_{grid\ point,\ sim}}{TKE_{mast,\ sim}}}$
- Extreme 10min 50 year Wind Speed →
  - Maximas obtained at mast using Method of Independent Storms (MIS) developed by Cook [1] and further developed by RI Harris [2]
  - Maximas extrapolated using directional speed-up factors to each grid point and fitted using a simple Least Square methodology.
  - Maximas fitted to a GEV – Fisher Typett Type 1 distribution; plotting positions from J P Palutikof [3]
  - Other fitting methods (Blue Lieblein, Modified Blue Lieblein or method of moments) were found difficult to converge / automate




$F(x) = \exp[-\exp(-y)]$ $\quad k = 0$

**MIS assumption for plotting positions:**

Ps(m) = ( m / N + 1) ** (annual_storm_rate)

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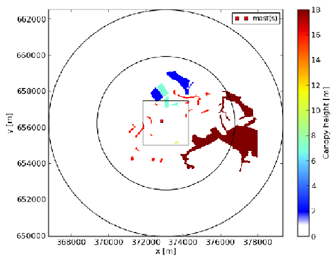
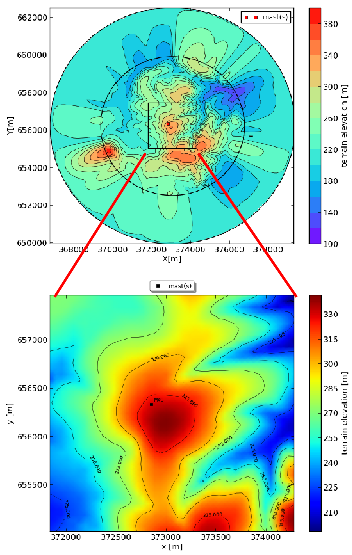
## 3. Test Case: CREYAP exercise 2 site (EWEA wind res. Dublin 2013)

Model settings:

- Approx. 7 millions cells
- RANS modified k-epsilon model
- 24 sectors run
- Coupled solver (5e-6 conv. criteria on RMS residuals)
- 25m horizontal resolution in target area (2.5 x 2.5 km)
- Constant roughness of 0.03
- Forest surrounding site → not too significant (constant LAD = 0.25 and Cd = 0.2)

→ Constraint / Field maps produced in target area

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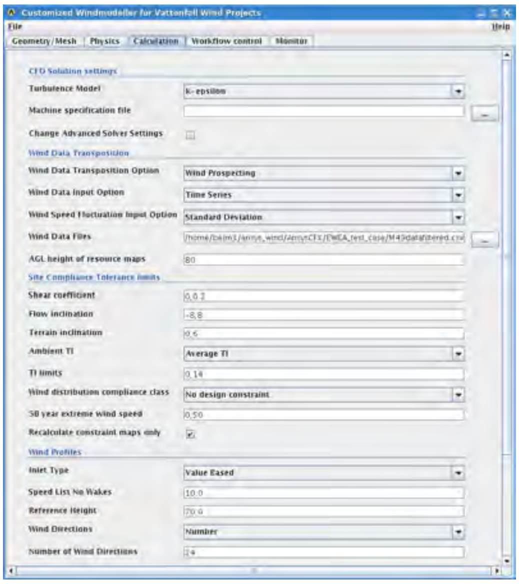
## 3. Test Case: CREYAP exercise 2 site (EWEA wind res. Dublin 2013)




**Constraint setup at 80 @ agl:**

1. **min: 0 max: 14** (Average Ambient TI)
2. **min: 0 max: 0.2** (Shear coefficient)
3. **min: 0 max: 50** (Extreme 50 year ws class I)
4. **min: 0 max: 6** (Terrain Inclination)
5. **min: -8 max: 8** (Flow inclination)
6. **wind distribution:** No design constraint

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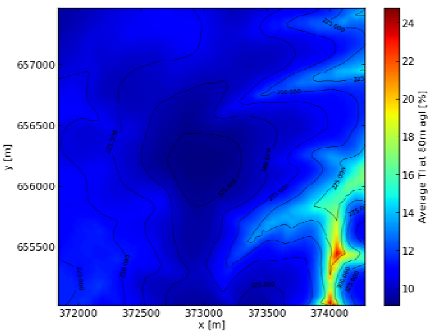
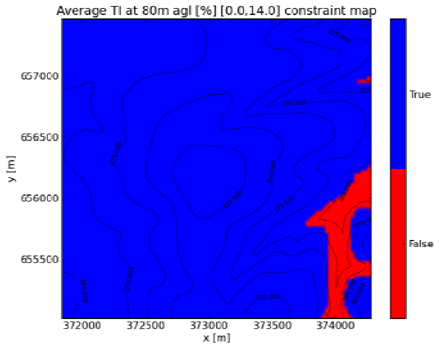
## 3. Results: CREYAP exercise 2 site (EWEA wind res. Dublin 2013)

- Average Ambient TI < 14 %



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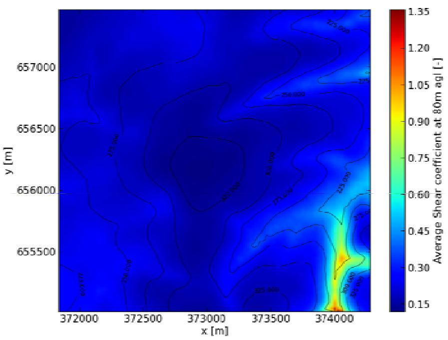
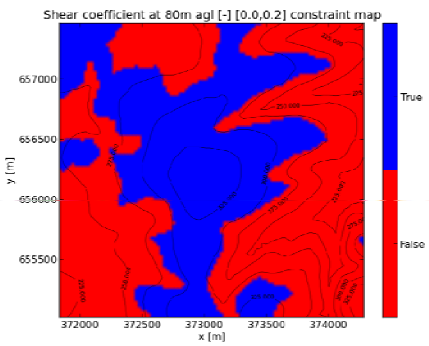
## 3. Test Case: CREYAP exercise 2 site (EWEA wind res. Dublin 2013)

- 0 < Average Shear coefficient < 0.2



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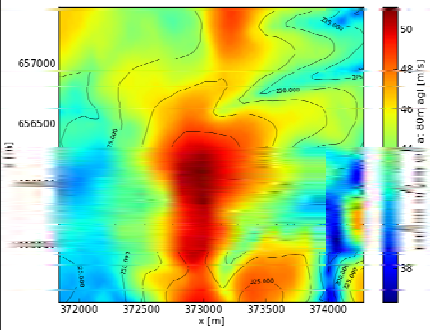
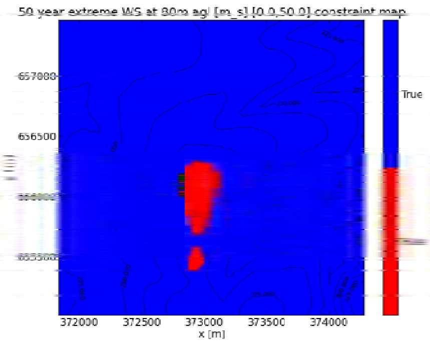
## 3. Test Case: CREYAP exercise 2 site (EWEA wind res. Dublin 2013)

- Extreme 50 year Wind speed < 50 m/s (Class I)

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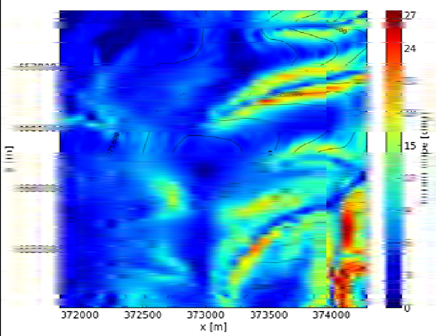
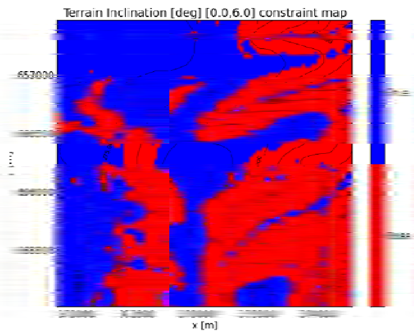
## 3. Test Case: CREYAP exercise 2 site (EWEA wind res. Dublin 2013)

- 0 < Terrain inclination < 6 deg

→ Terrain inclination calculation based on the '8th point neighboor methodology' and 3rd order finite differencing

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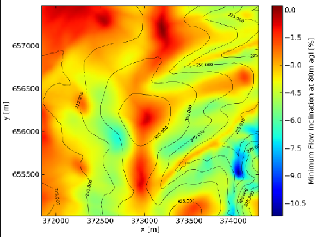
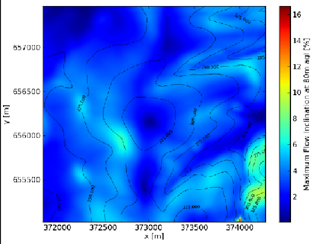
## 3. Test Case: CREYAP exercise 2 site (EWEA wind res. Dublin 2013)

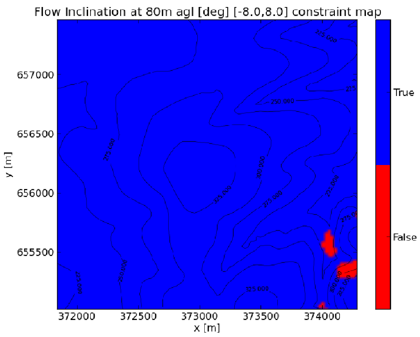
- Abs (Flow inclination) < 8 deg, for any direction



Min



Max

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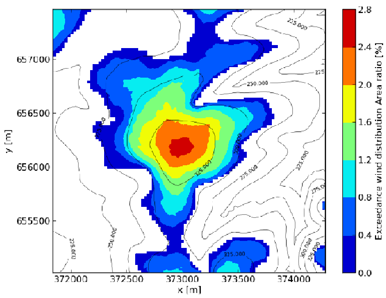
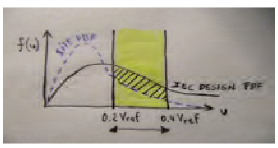
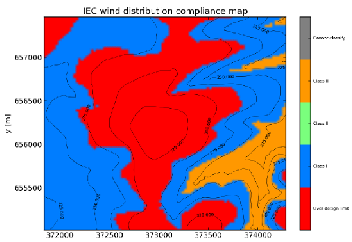
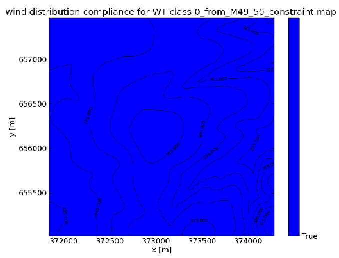
## 3. Test Case: CREYAP exercise 2 site (EWEA wind res. Dublin 2013)

- Wind Distribution: No design constraint considered
  → Barely over design limit of Class I



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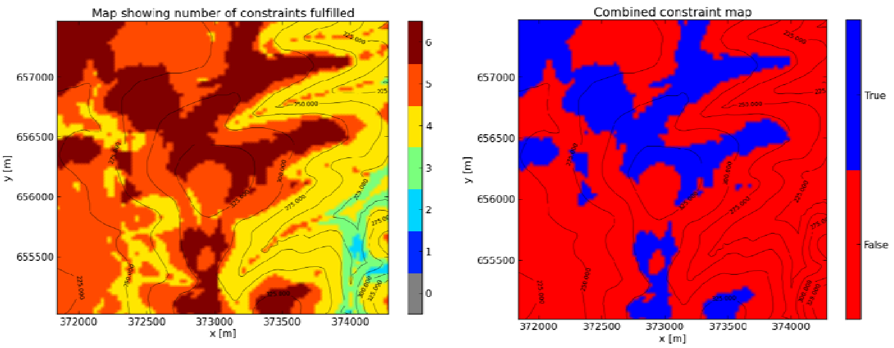
## 3. Test Case: CREYAP exercise 2 site (EWEA wind res. Dublin 2013)

- COMBINED CONSTRAINTS

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## Future work

- Systematic validation with mesurements
- Comparison with WAsP Engineering
- 50 year extreme wind cross-prediction tests and investigation of possible improvements for fitting method

References:
[1] Towards better estimates of Extreme wind speeds, Cook
[2] Improvements of the Method of Independent Storms, RI Harris
[3] A review of methods to calculate Extreme wind speeds, JP Palutikof et alt.

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## THANK YOU FOR YOUR ATTENTION !

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NCAR

# Validations of LES with the Weather Research and Forecasting Model using Askervein Hill experiment data

Branko Kosović[1]
Katherine A. Lundquist[2] and Jeffrey D. Mirocha[2]

[1] National Center for Atmospheric Research
[2] Lawrence Livermore National Laboratory

Acknowledgments: DOE EERE

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

## Toward Multiscale Modeling

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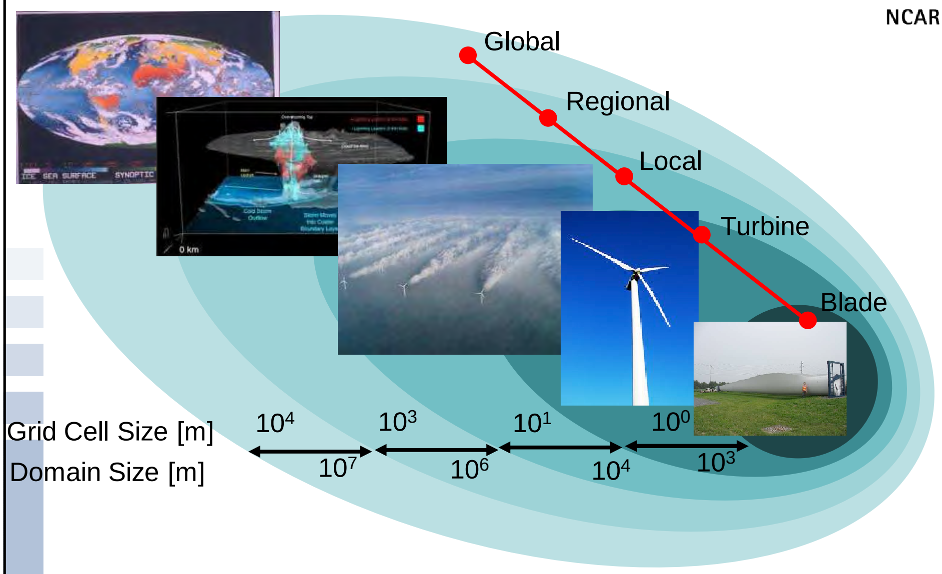



Adapted from Mike Robinson (DOE/NREL)

## We Validated WRF's LES Capability for Simulation of Flows Over Complex Terrain

NCAR

- Weather Research and Forecasting (WRF) model is developed by community and has a wide user base
- WRF model includes advanced LES capabilities and two subgrid turbulence models Smagorinsky and Nonlinear Backscatter Anisotropy (NBA):

$$\tau_{ij} \approx M_{ij} = -(C_s l)^2 \left\{ 2\left(2\tilde{S}_{mn}\tilde{S}_{mn}\right)^{\frac{1}{2}}\tilde{S}_{ij} \right. \quad \text{Smagorinsky}$$

$$+C_1\left(\tilde{S}_{ik}\tilde{S}_{kj} - \frac{1}{3}\tilde{S}_{mn}\tilde{S}_{mn}\delta_{ij}\right)$$

$$\left. + C_2\left(\tilde{S}_{ik}\tilde{R}_{kj} - \tilde{R}_{ik}\tilde{S}_{kj}\right) \right\} \quad \text{NBA}$$

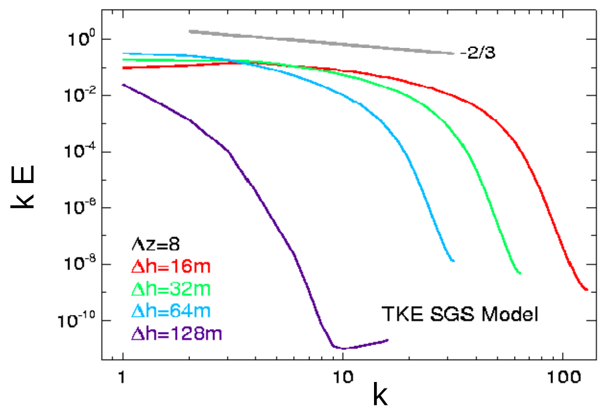
(Kosovic, JFM 1997; Mirocha et al., MWR 2010)

$$C_1 = C_2 = \frac{960^{\frac{1}{2}}C_b}{7(1+C_b)S_k} \qquad \tilde{S}_{ij} = \frac{1}{2}\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right) \qquad \tilde{R}_{ij} = \frac{1}{2}\left(\frac{\partial \tilde{u}_i}{\partial x_j} - \frac{\partial \tilde{u}_j}{\partial x_i}\right)$$

## Why Nest LES Within a Mesoscale Simulation? Why Couldn't We Use SGS Model at Mesoscale?

NCAR

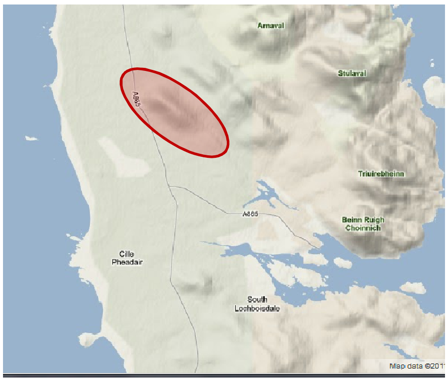
- Subgrid turbulence model in LES must accurately represent energy transfer in the inertial range
- PBL parameterizations in mesoscale model must represent larger scale turbulence effects.




LES must: fully resolve energy containing scales and partially resolve inertial range scales

## Askervein Hill Experiment Was Used for Validation of WRF

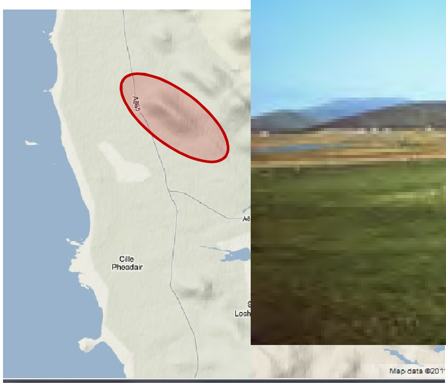
NCAR

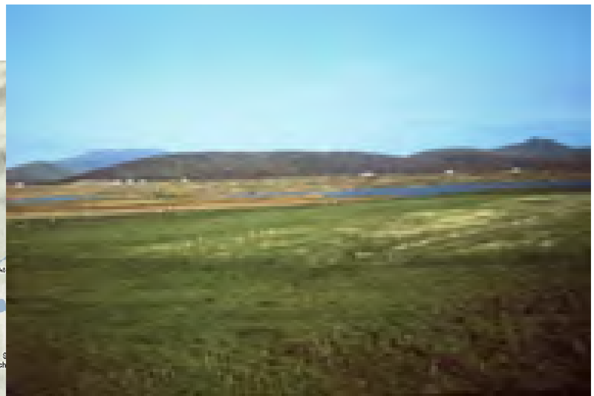



**Asker vein Hill experiment took place on the West side of South Uist island (Scotland) in 1983 (Taylor and Teunnisen, BLM 1987). Measurements were taken using cup anemometers mounted at 10m above the ground on 50 towers.**

## Askervein Hill Experiment Was Used for Validation of WRF

NCAR

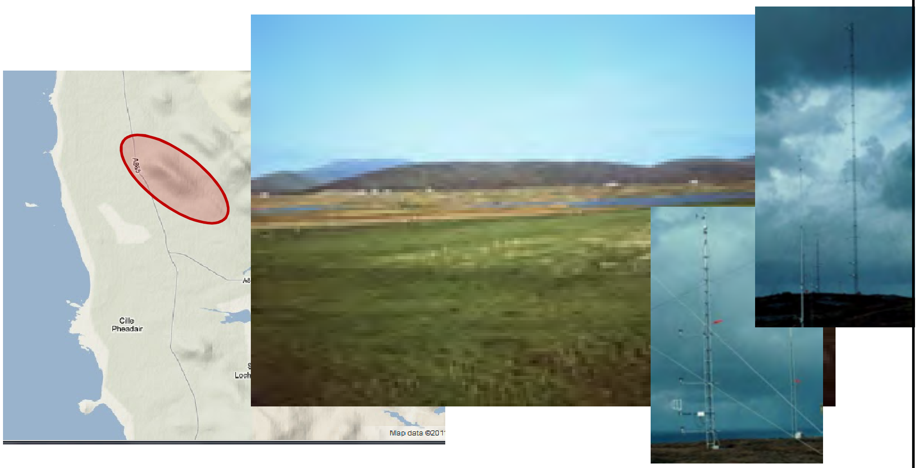


**Asker vein Hill experiment took place on the West side of South Uist island (Scotland) in 1983 (Taylor and Teunnisen, BLM 1987). Measurements were taken using cup anemometers mounted at 10m above the ground on 50 towers.**

## Askervein Hill Experiment Was Used for Validation of WRF

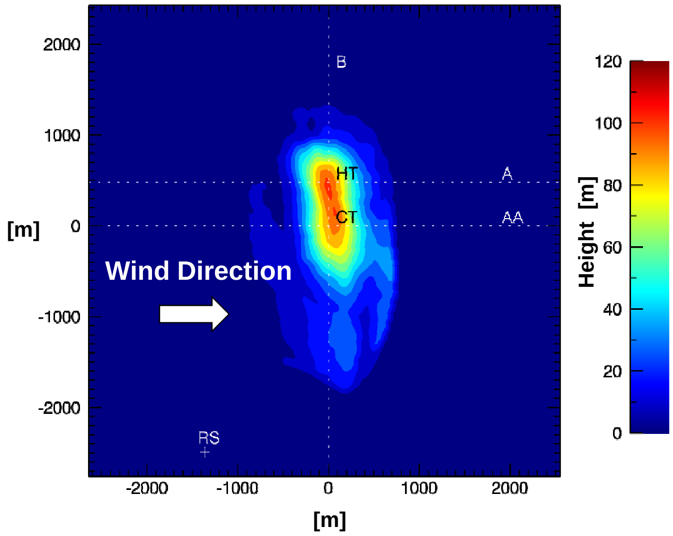
NCAR



**Asker vein Hill experiment took place on the West side of South Uist island (Scotland) in 1983 (Taylor and Teunnisen, BLM 1987). Measurements were taken using cup anemometers mounted at 10m above the ground on 50 towers.**

## Observations Were Made Along Three Lines Parallel to Major and Minor Axes

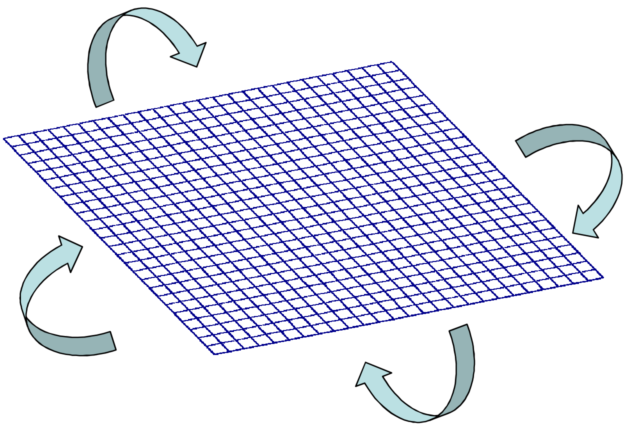
NCAR



## One Way Nesting Is Used for LES Over Complex or Heterogeneous Terrain

NCAR

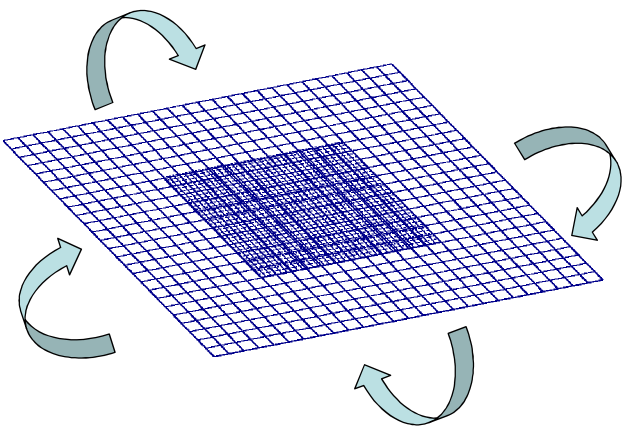
- Periodic boundary conditions are used on the outer domain to spin up realistic turbulent inflow
- Outer domain had 134x134x97 grid cells wind grid size 90m



## One Way Nesting Is Used for LES Over Complex or Heterogeneous Terrain

NCAR

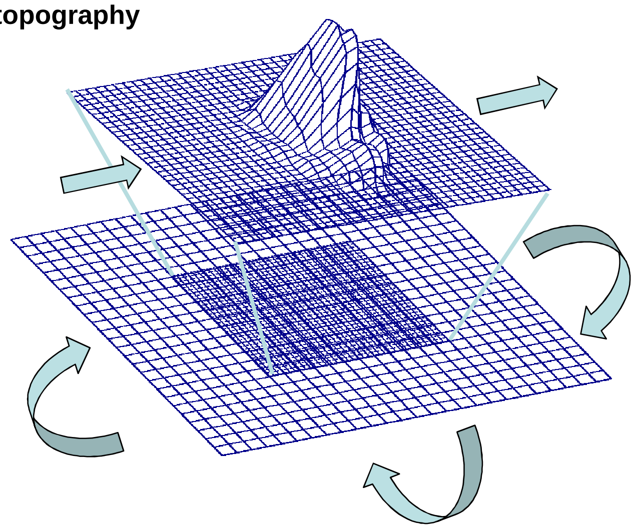
- Inner domain had 174x174x97 grid cells wind grid size 30m



## One Way Nesting Is Used for LES Over Complex or Heterogeneous Terrain

NCAR

- Only inner domain includes represenation of the Askervein Hill topography



## Vertical Velocity

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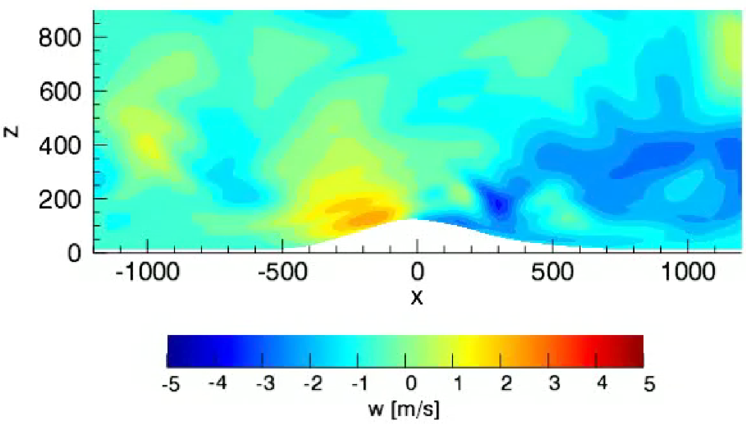
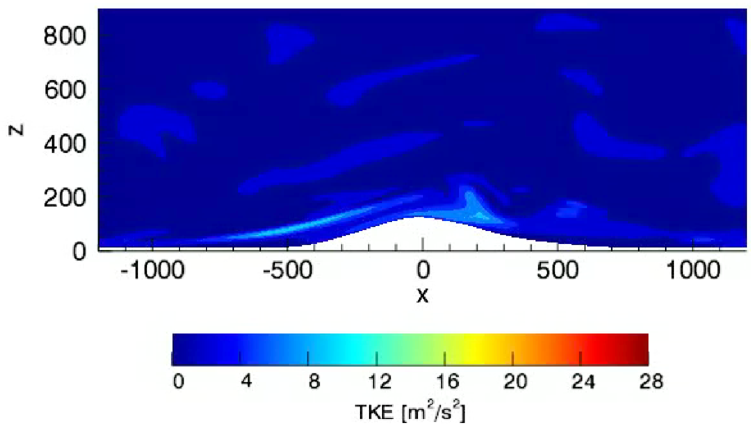


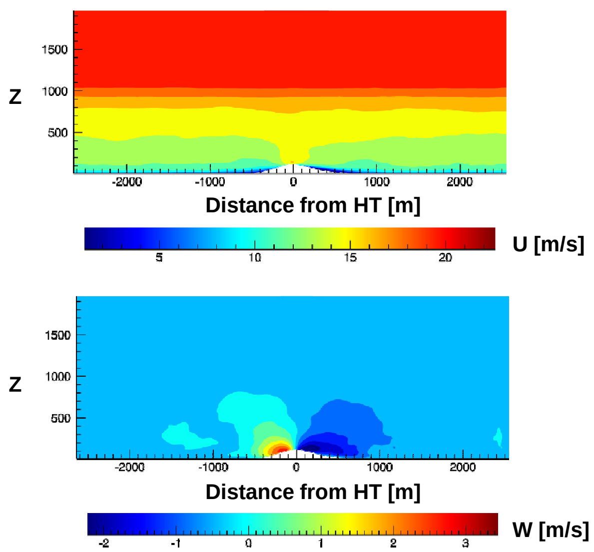
## Turbulent Kinetic Energy

NCAR

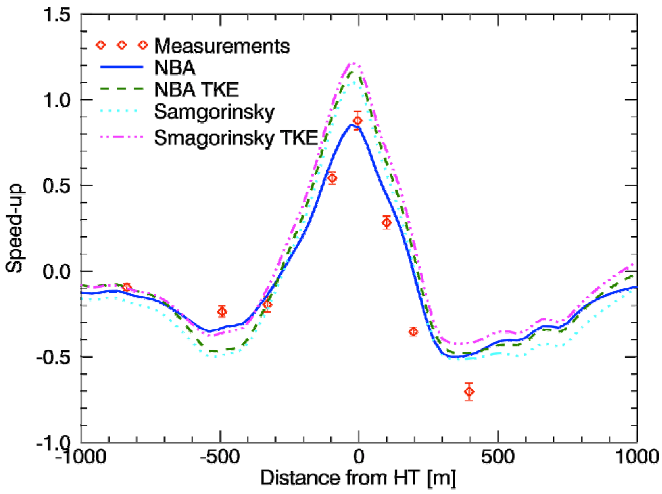



## LES Results Were Averaged Over 30 Minutes

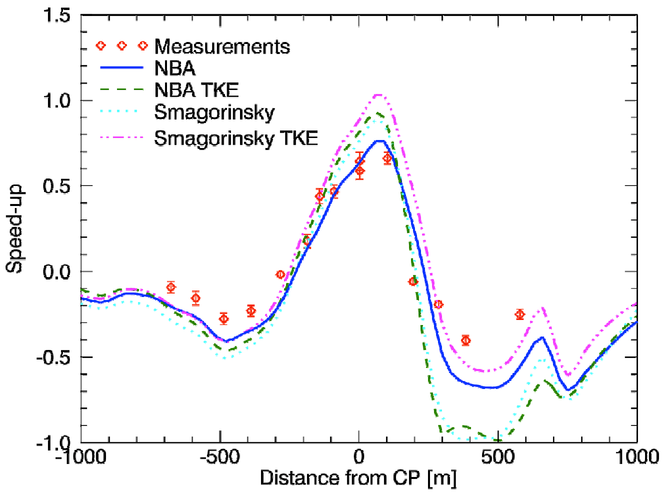
NCAR



## Speed-up along Line A

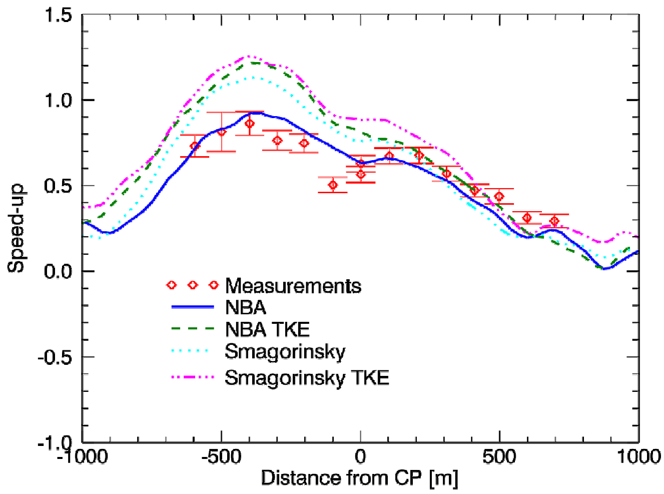



## Speed-up along Line AA



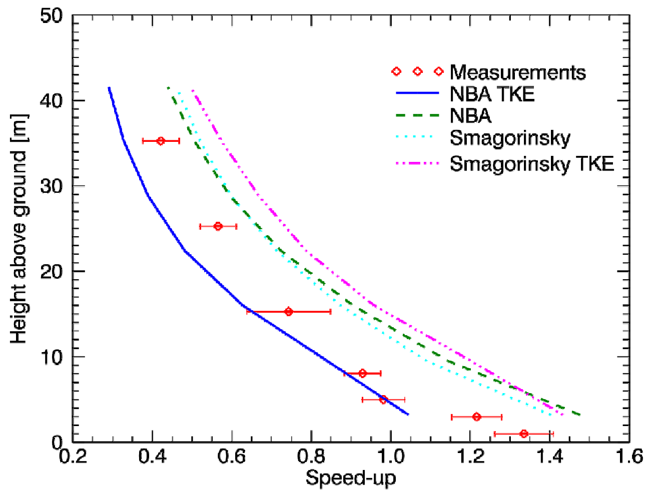
## Speed-up Along Line B

NCAR



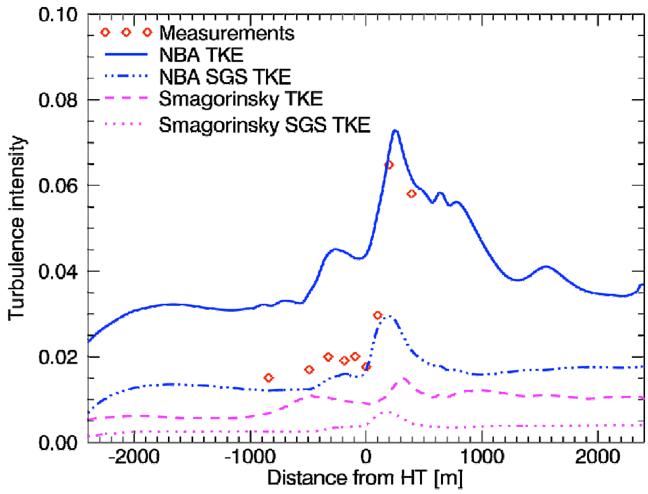

## Speed-up at the Tower HT

NCAR



## Turbulence Intensity along Line A

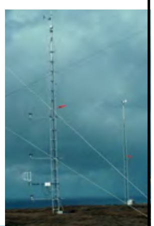
NCAR

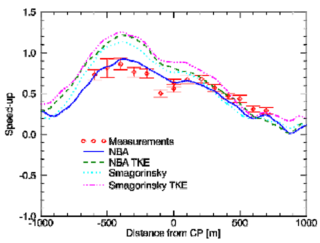


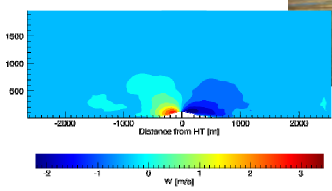

## Summary

NCAR

- Validation of WRF LES for flow over complex terrain is one step toward development of an effective multi-scale modeling capability
- We used data from Askervein Hill experiment to validate WRF LES
- We demonstrated good performance of WRF LES
- NBA model with prognostic equation for yields best accuracy





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## NWP use in complex terrain

October 8, 2013



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## Background

Accuracy is always the foremost goal, but…
there are some other influences:

- Time and budget pressure from financial institutions has led to a tiered approach to siting analysis:
  - Prescreening of sites requires sub-week delivery, whereas late stage analysis can go on for months
  - Changes in estimated production (and its uncertainty) should be incremental, not abrupt
- Widespread availability of remote sensing is making measurement campaigns more dynamic:
  - Increased need for model output early in the process
  - Discourages data assimilation
- We need either consistent processes for simple and complex terrain and land use, or clear criteria for when and how they are changed



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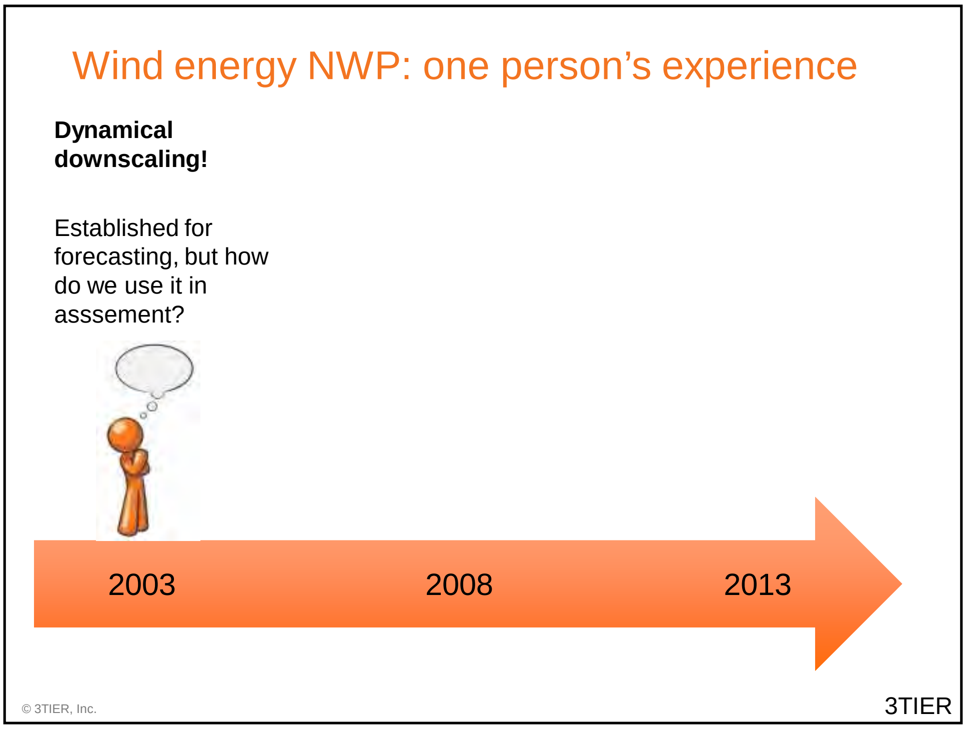
Wind energy NWP: one person's experience
Dynamical downscaling!
Established for forecasting, but how do we use it in asssement?
2003
2008
2013
© 3TIER, Inc.
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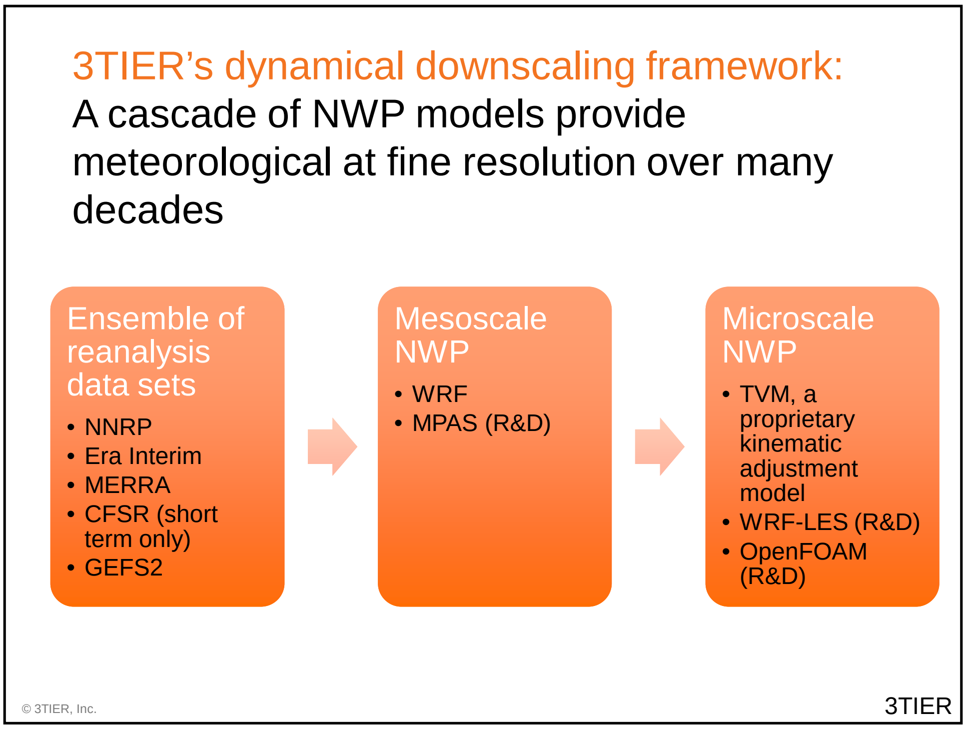
3TIER's dynamical downscaling framework:
A cascade of NWP models provide meteorological at fine resolution over many decades
Ensemble of reanalysis data sets
• NNRP
• Era Interim
• MERRA
• CFSR (short term only)
• GEFS2
Mesoscale NWP
• WRF
• MPAS (R&D)
Microscale NWP
• TVM, a proprietary kinematic adjustment model
• WRF-LES (R&D)
• OpenFOAM (R&D)
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## Wind energy NWP: one person's experience

**Dynamical downscaling!**

Established for forecasting, but how do we use it in asssement?

**Finer resolution!**

Bias (and uncertainty) reduction.




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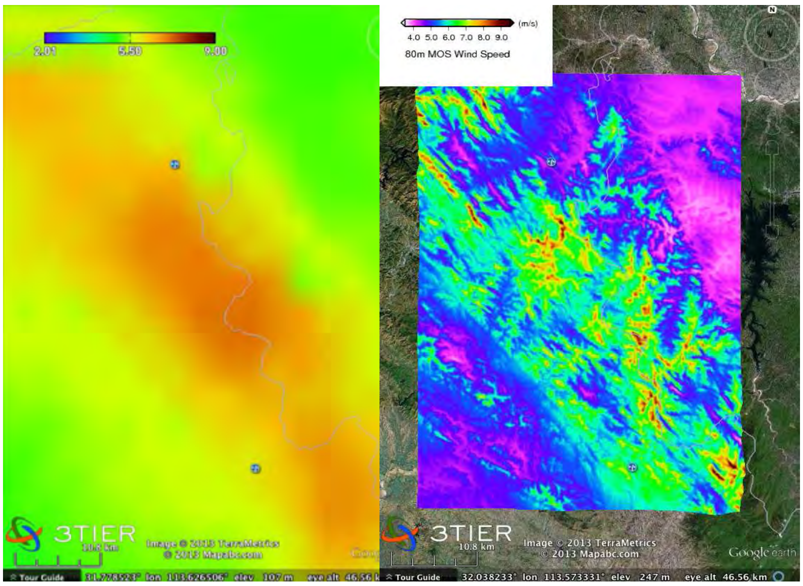
## NWP resolution matters in complex terrain



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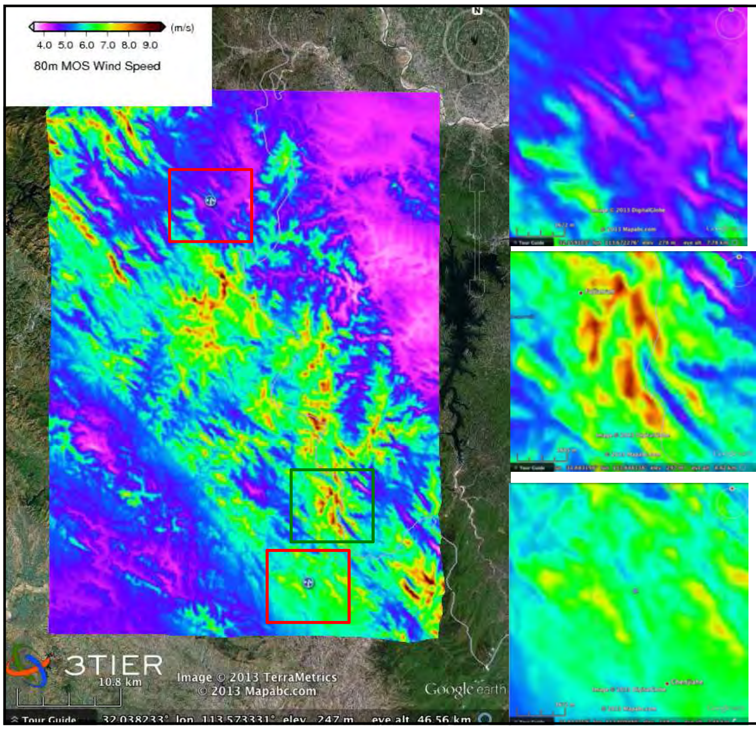
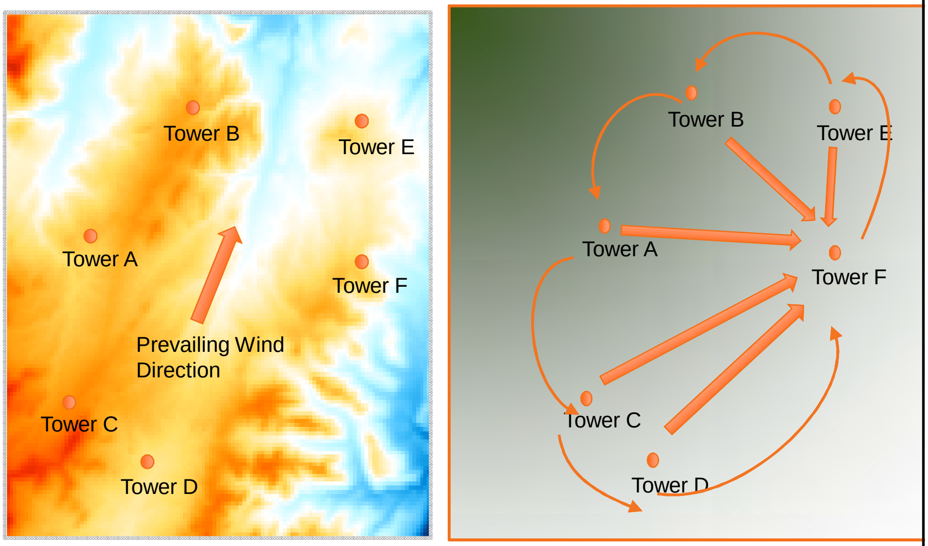



## Round robin analysis of uncertainty



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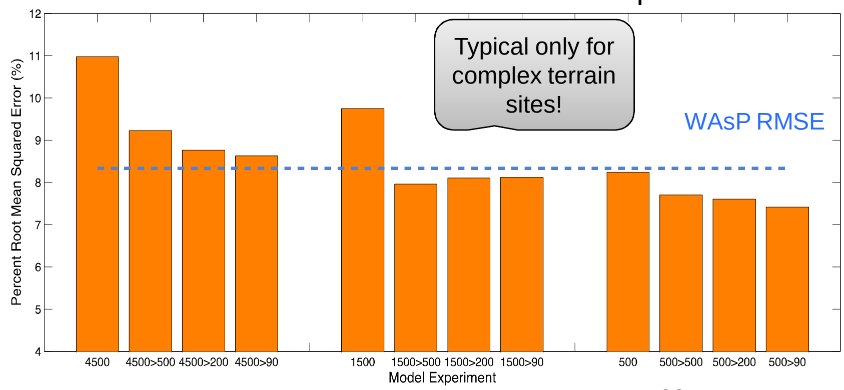
## Round robin analysis of uncertainty

Estimated RMSE error of mean annual production




**4.5 km WRF**
direct, plus downscaled with TVM to 500m, 200m, and 90m resolution

**1.5 km WRF**
direct, plus downscaled with TVM to 500m, 200m, and 90m resolution

**500 m WRF**
direct, plus downscaled with TVM to 500m, 200m, and 90m resolution



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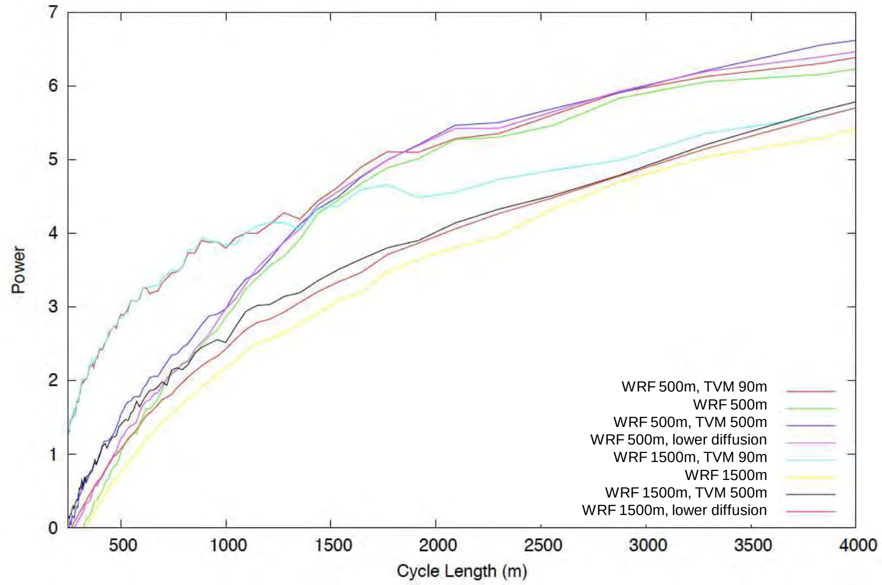
## A Fourier transform look at spatial complexity



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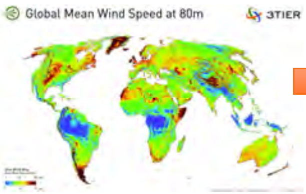
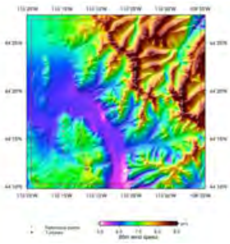
## Reducing uncertainty

Uncertainty = 20-25% | Uncertainty = 10-15% | Uncertainty = 5-7%



Before local observations are collected, NWP resolution and configuration have an influence on uncertainty.

Once observations are collected, the role of modeling is large reducing the uncertainty in the spaces between the observations.



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## Wind energy NWP: one person's experience

**Dynamical downscaling!**

Established for forecasting, but how do we use it in asssement?

**Finer resolution!**

Bias (and uncertainty) reduction.

**Time series analysis!**

It's been here along…




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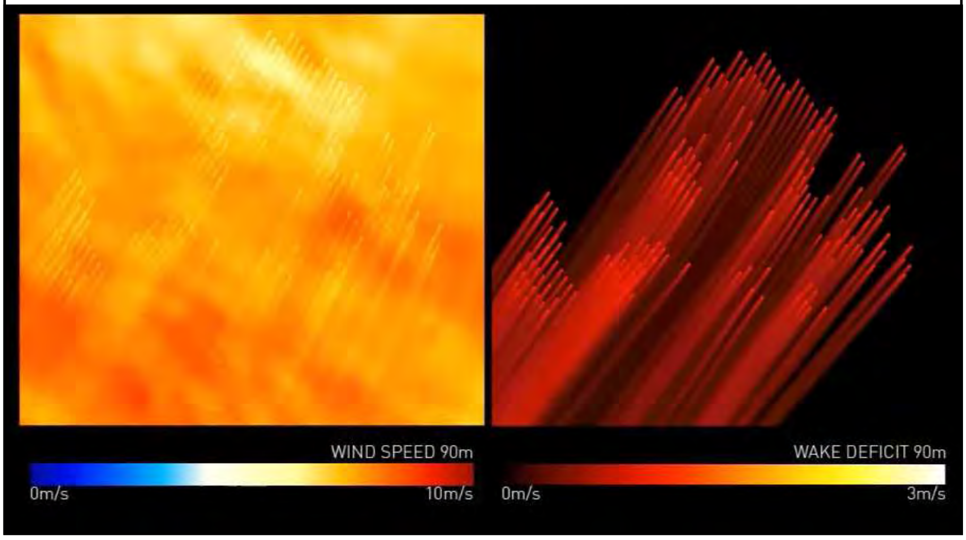
## An illustration of temporal complexity




## Statistics on the mean are no longer enough

**Fluctuating energy prices**

- Will the plant produce at times of high energy prices?

**Sophisticated control mechanisms**

- Time-dependent power curves
- More sophisticated sector management

**Integration Issues**

- Analysis of plant variability for large-scale projects
- What is the severity of ramp events?

**Post-construction operational analysis**

- Detection of underperforming assets

But how are these impacted in areas of complex terrain?



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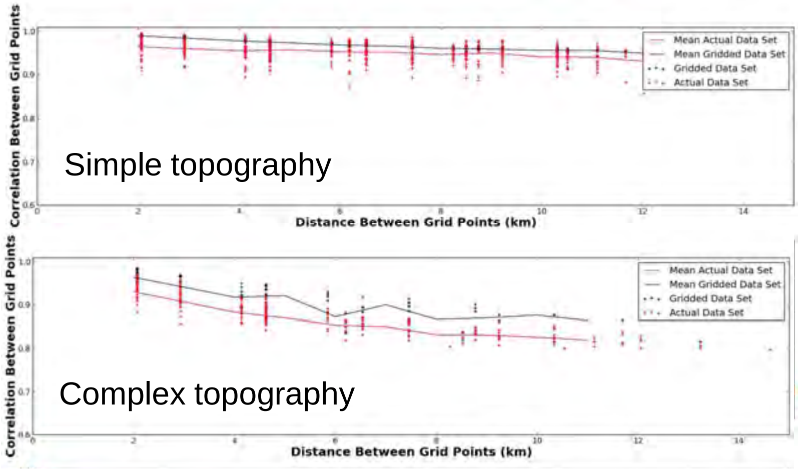
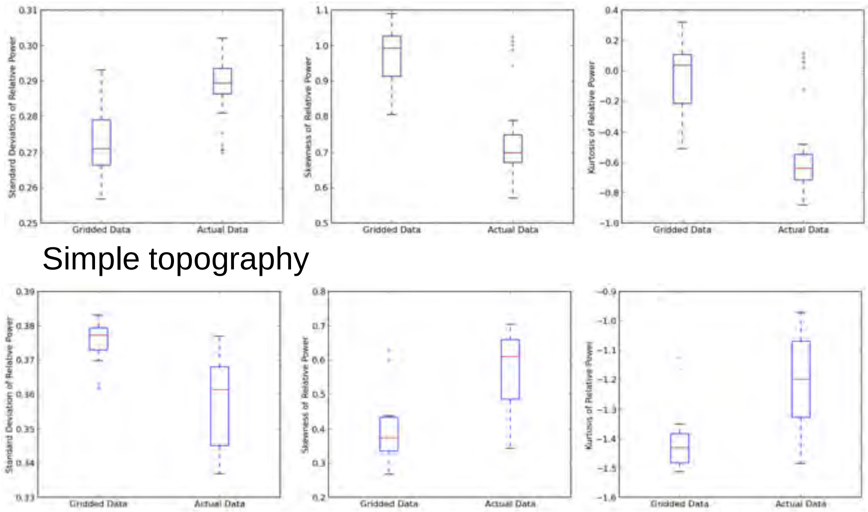
## Spatial covariance

Observed Production vs Simulated Production




## Standard deviation, skewness, kurtosis

Observed Simulated | Observed Simulated | Observed Simulated




Complex topography



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## Conclusions

- We will continue to see incremental improvements in modeling the 'spaces' between observations: but dramatic decreases in uncertainty will come from increasing the observational density
- We can not afford to give up temporal information in our quest for reducing spatial uncertainty



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# EXPERIENCES OF DIFFERENT MEASUREMENT TECHNIQUES IN FINLAND

MSc (Eng.), BSc (Env.) Merja Paakkari, Hafmex Oy

## Hafmex Oy

History

- Family company, founded 1939
- Started at wind sector 1999
- Agent of wind turbine manufacturer at Nordic and Baltic Countries until 2009
- Project development and construction of Högsåra wind farm
  - 3 x 2 MW Zephyros type turbines
  - Located in southwest archipelago of Finland
  - Hafmex Group owns 50% of the wind farm
  - In operation since 2007
  - Service and maintenance of the turbine since 2007
- Coordination of HISP (Högsåra Island Wind Energy Project) research project 2004-2007 that was part of EU's 6th framework programme

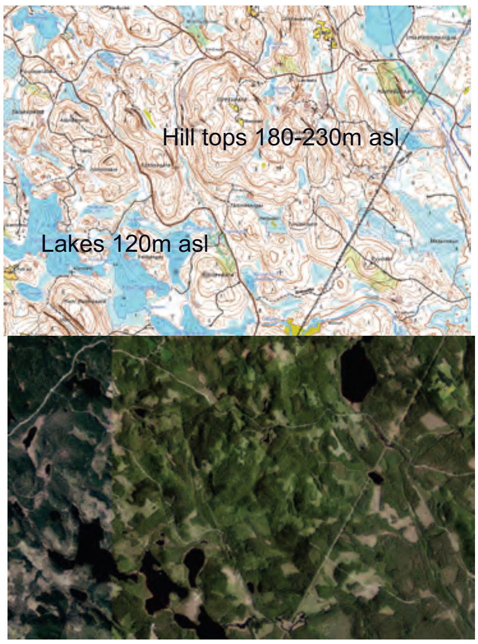
Current activities:

- Wind turbine service and maintenance
- Wind measurement planning, execution and operation: sodar, met masts, lidars
- Wind energy project consulting
- Project development as part of a joint venture

# Wind energy in Finland

- Population: 5.4 million
- Area: 338 434,73 km$^2$ (c.10% is lakes)
- Most of the coastline of sea and lakes are inhabited or have holiday houses
- Tendency is to go inland away from coastline
- Forested country with small field areas
- Currently installed turbines have high hub heights (>140m) and large rotor swept areas (>100m)
- Special weather and wind conditions
  - Icing during winter
  - Inversion is typical
  - Fogs are usual especially on coastal areas
  - High shear factors over the forests 0.3-0.4
- Measurements required from whole swept area to confirm the wind profile. This means that we need data from 200 meters and up.

# Example site




Maps: National Land Survey of Finland Topographic Database and NLS Orthophotos 08/2013

- Wind turbines planned at 140-200 m asl
- Hub height c.140 m
- Not big height differences c 100m but:
  - Undulating orography
  - Vegetation is forrest of different ages with open clearings (active forrestry means cut downs of trees)
  - According to icing atlas 6% production lost due to icing
- Challenging environment to make good measurements

# Met mast

- Usually on top of hill with mast height 120-140 m or more, so total height asl can be several hundred of meters
  - Definetly some icing will occur on top of the mast
  - Stronger mast required → more expensive
- Fully heated anemometers and vanes required
  - not according to IEC standards
  - Power consumption also higher - difficult to cope if grid is not available
- If both IEC approved anemometers and heated anemometers/ultrasonics are used, end up having lot of equipment up in the mast

# Sodar

- Based on sound pulses reflecting from small temperature variations moving with the wind
- Used widely in Finland and also as stand alone system even in forested and hilly areas
- Gives good data coverage
- Complex terrain can cause orographic deviation, but this can be corrected with specific calculation models but increases uncertainty
- Requires open areas with no source of echoes at the measurement distance usually 50-200m sometimes difficult to find good sites
- Experience on phased array sodar and sodar with three speakers/microphones

## Lidar

- Emitted laser beam is reflected by aerosols or particulates moving with the wind
- According to experience by VTT Technological Research Centre of Finland the bias due to complex terrain can be 5-10% compared to mast measurements (Tuulienergia 02/12). This can be corrected using specific calculation models.
- Especially on coastal areas fogs are very common creating data losses. Our experience is that data coverage can be -/+ 90% between 20 - 200m
- What about data coverage inland?
- Could short met mast be used together with lidar to estimate the bias if data loss is big?
- Not much experience in Finland especially inland

## Summary

- Tendency towards very high hub heights
- Icing and complex terrain are major issues
- Expencive to build high masts and in addition power consumption is high because of heated elements
- Because of high swept areas we should get measurements up to 200 m and more
- Remote sensing devices are used increasingly, but not approved as stand alone systems in complex terrain
- As met mast is also challenging to use in Finland it would be helpful to have RSD methods as stand alone or with short met mast c. 40-60m
- What to do with the data loss can the bias at high altitudes be estimated by short met mast?
- This requires more studies with RSD against high met mast in nordic complex terrain to be sure that possible bias is corrected the right way

# Thank you!

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www.hafmex.fi

# In-situ thermodynamic measurements with the RPA MASC for wind energy research

Norman Wildmann, Jens Bange

*Center for Applied Geosciences, Environmental Physics, Eberhard Karls University Tübingen*

12. November 2013, Stuttgart




## Outline

1. RPAS for Atmospheric Sciences
2. MASC RPAS at Tübingen
3. Lidar Complex, a wind energy experiment
   - test campaign in Schnittlingen
   - joint campaign in Grevesmühlen
   - wake measurements
   - turbulence characterisation

## Comparison manned aircraft / small UAV

- large payload
- large endurance
- large logistics (airport, crew, ...)
- large disturbance of atmospheric turbulence
- minimum altitude $>> 100$ m

- very small payload
- small endurance (e.g. 70 km, 1 h)
- very flexible and mobile (no runway, carried in car trunk)
- small disturbance of atmospheric turbulence
- minimum altitude $\approx 50$ m

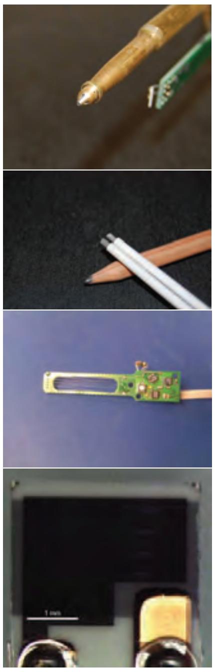




## RPAS MASC for Atmospheric Sciences

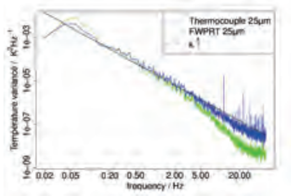
- $5 - 7$ kg
- 2.60 - 3.40 m wingspan
- max. 15-60 minutes endurance, depending on battery load
- electrical pusher motor
- take off with bungee launch system
- ROCS Autopilot, IFR Stuttgart

# MASC Sensor System



- sensor package:
  - thermocouple
  - fine wire resistance thermometer
  - capacitive humidity sensors
  - flow probe
  - inertial measurement unit
  - GNSS position and velocity
  - MEMS barometer
- Turbulence measurement up to 20 Hz
- Live data observation on ground-station computer
- 100 Hz on-board log to SD-card

**more information:** Wildmann, N., Mauz, M., and Bange, J.: Two fast temperature sensors for probing of the Atmospheric Boundary Layer using small Remotely Piloted Aircraft (RPA), Atmospheric Measurement Techniques, 6, 2101-2113, 2013.







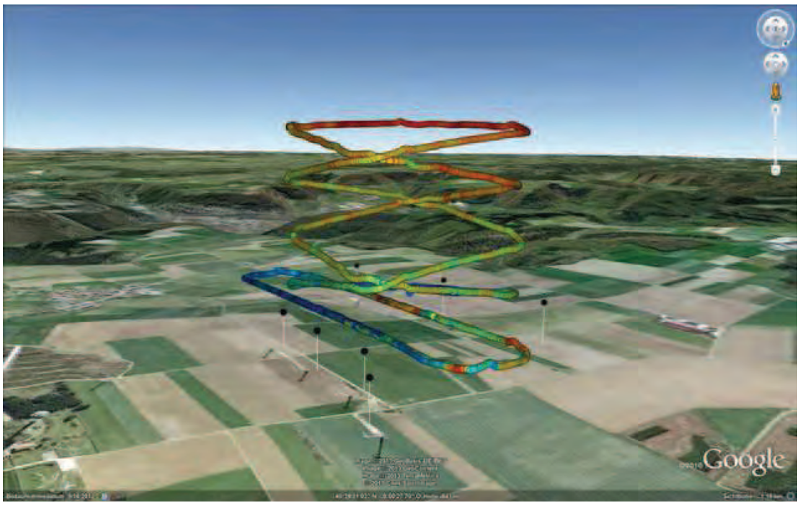

# ’Lidar Complex’ - A wind energy project


- First MASC proof of concept in May 2013, at test site Schnittlingen.
- First joint campaign with all project partners in October 2013.
- strategy: in-situ measurements + CFD + windtunnel model + lidar
- Project goal: Establish lidar technology in complex terrain.

→ **more information: Talk by Martin Hofsäss, tomorrow 3rd session, 10:15**

# ’Lidar Complex’ - A wind energy project

**Schnittlingen, May 2013**

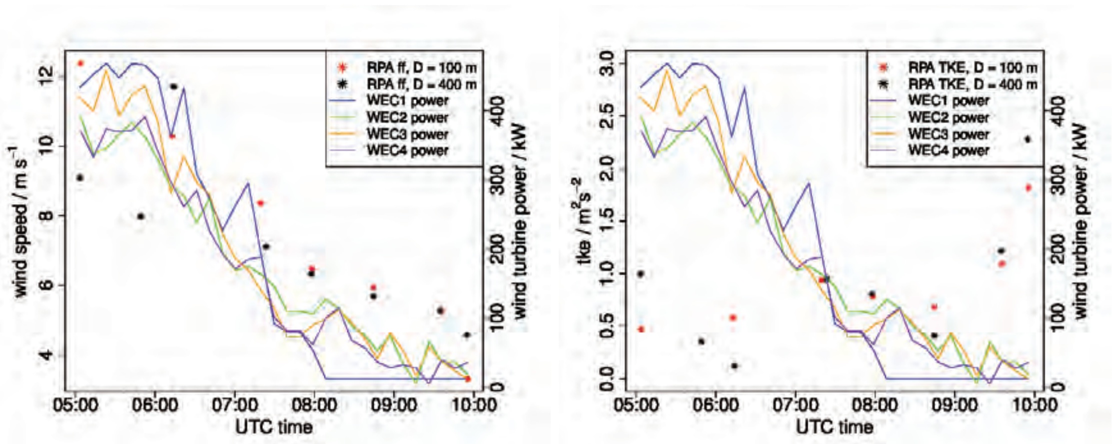



vertical profile and racetrack flight pattern. Path is color coded with potential temperature. Flights at 08. Mai 2013 between 07:00 and 11:00 local time.





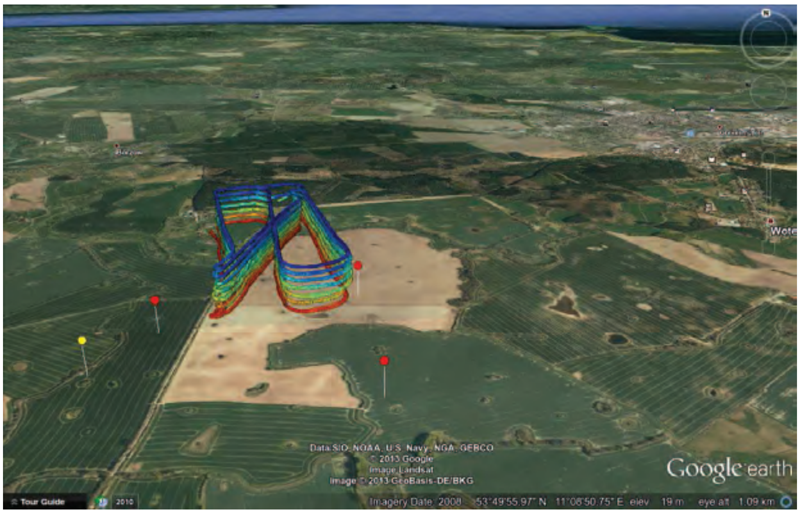
# ’Lidar Complex’ - Wind energy project




RPA measurements of wind speed (left) and turbulent kinetic energy (tke, right) measure upstream, compared to SCADA data of four Vestas V52 converters.

# 'Lidar Complex' - A wind energy project

**Grevesmühlen, October 2013**

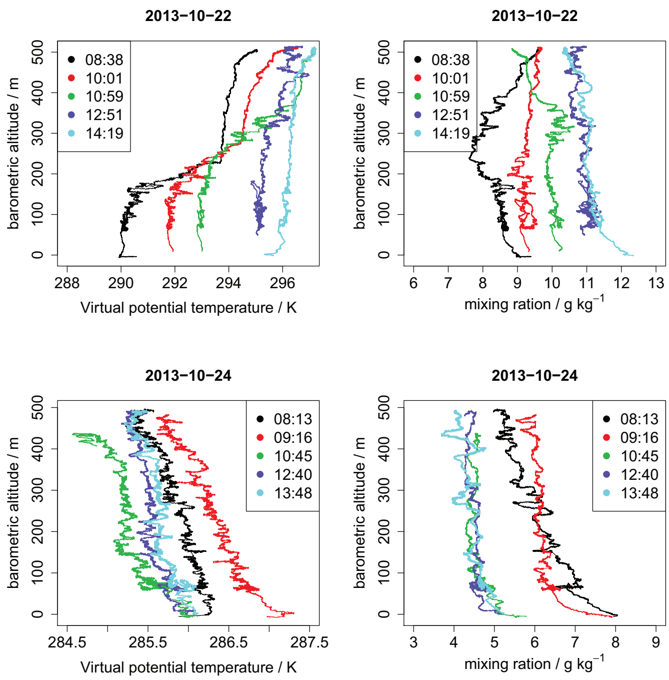



Flight pattern at the test site in Grevesmühlen. Path is color coded with measured temperature. Flights at 24 October 2013 in the afternoon.

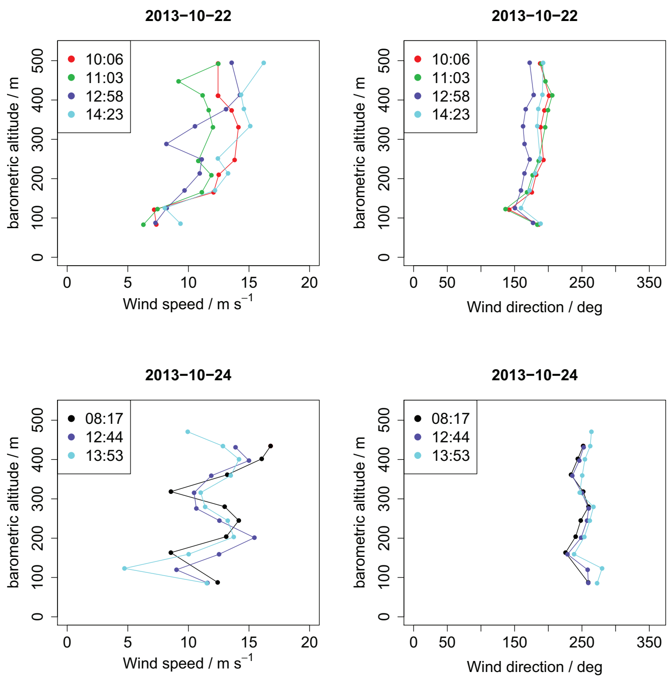




# Investigation of stratification of the atmosphere



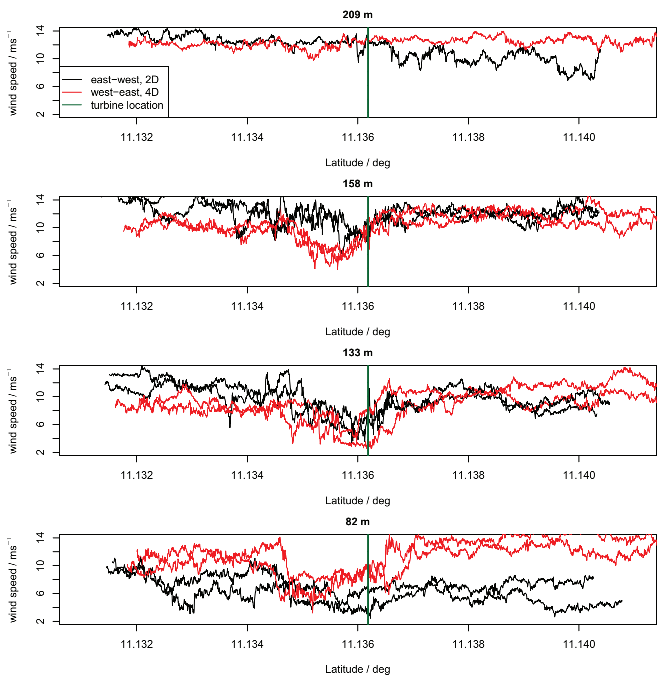
# Investigation of atmosphere stratification



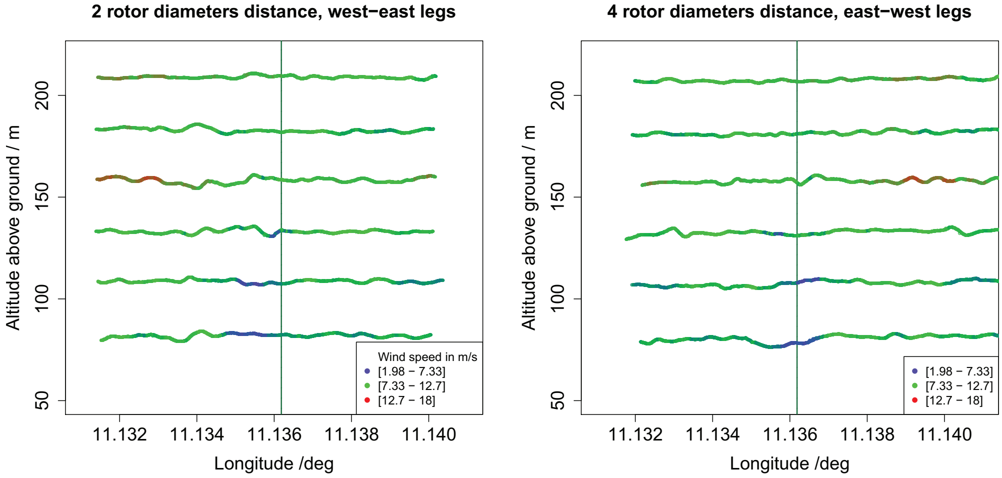





# Wind speed measurement in the wake



# Wind speed measurement in the wake

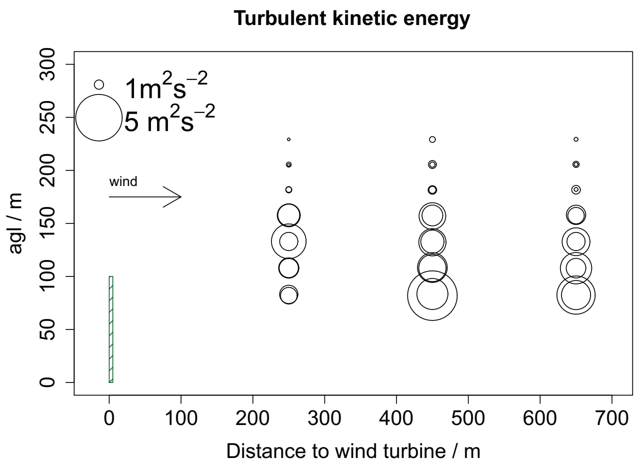



Two-dimensional wind field measurement behind a wind turbine in two distances.





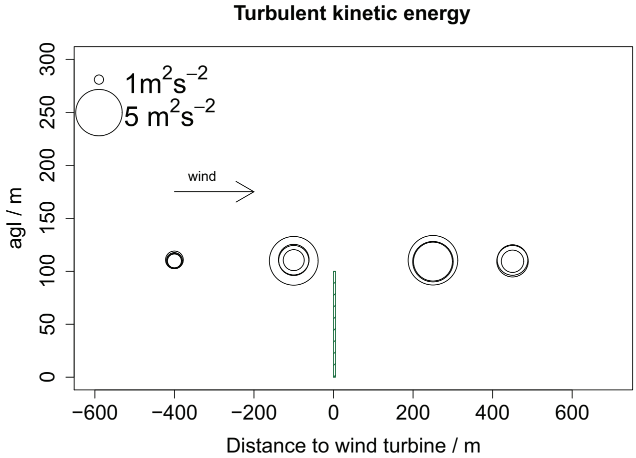
# Turbulent kinetic energy around wind turbine




Measurements of turbulence in the wake of a turbine.
24 October 2013, around 1430 UTC

$$\text{TKE} = \frac{1}{2}\left(\sigma_u^2 + \sigma_v^2 + \sigma_w^2\right)$$

# Turbulent kinetic energy around wind turbine




Measurements of turbulence upstream and downstream a turbine in comparison.
22 October 2013, around 1300 UTC

$$\text{TKE} = \frac{1}{2}\left(\sigma_u^2 + \sigma_v^2 + \sigma_w^2\right)$$





# Outlook

- Analysis of 2013 campaigns and data. Synthesis with lidar, helicopter and mast data, as well as comparison to CFD.
- Continuous improvement in sensor technology and aircraft performance (latent heat flux accuracy, endurance, etc. )
- Work on Boundary Layer Meteorology (morning/afternoon transition, heterogenity and flux analysis, etc.)
- Aerosol research (Aladina, cooperation with University of Braunschweig and IFT Leipzig) → **September / October 2013 first tests successfully performed, next campaign in Spring 2014**
- Wind energy research ('Lidar Complex', etc.) → **next campaign in Spring 2014 in Schnittlingen**
- ... and more

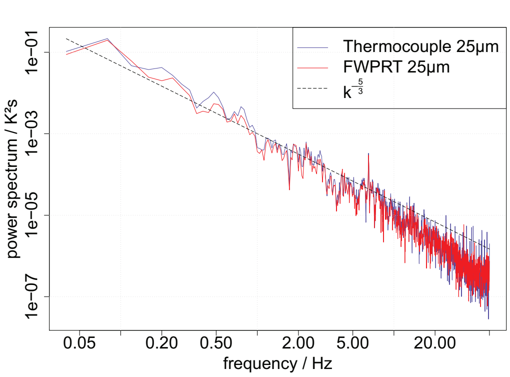
# Thank you

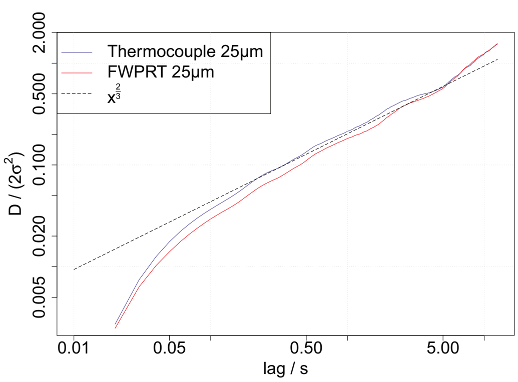
Acknowledgements: The Project 'Lidar complex' is funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) on the basis of a resolution of the German Bundestag. SCADA data of the four Vestas V52 wind converters in Stötten was provided by Windreich GmbH.
'Lidar Complex' was started as an initiative of the WindForS network (http://www.windfors.de).



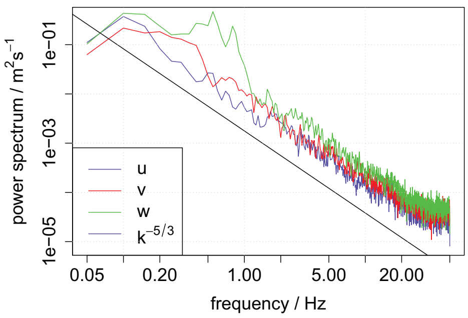


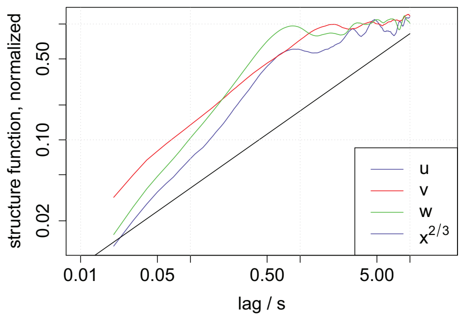
# Temperature spectra



# Wind spectra




# Validation of CFD Wind Resource Mapping Based On Performance Data From 50 Operational Wind Farms

**Dr. Gregory S. Oxley and Dr. Yavor V. Hristov**
Plant Performance and Modelling Group
Vestas Wind Systems A/S - Technology Service and Solutions

TEM75 - Nov. 11 2013 - Dr. Gregory S. Oxley - Plant Performance and Modelling - Vestas Wind Systems A/S

## OUTLINE

- **Introduction to Plant Performance and Modelling Group**
- **Summary of Vestas CFD wind and site activities:**
  - Level 1: Automated RANS
  - Level 2: Custom RANS
  - Level 3: DES
  - Level 4: Mesoscale-CFD coupling
  - Level 5: LES-ALM
- **CFD - Linear flow model AEP comparisons**
- **Improvements**:
  - Forest modelling
  - LTC with noise
  - WAKEBENCH best practices

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## Plant Performance and Modelling

**Tasks**

- New software and hardware tools
- Uniform calculation methods and reporting
- Siting and optimised production calculations
- Wind resource measurements / risk assessment
- Weather prediction

**Staff**

- CFD specialists
- Meteorologists
- Statisticians
- Engineers
- Software application developers
- Business analysts

**Firestorm**

- 14664 processors on 1222 hosts each with 2 Intel X5670 (hex core) processors and 24 GB memory
- 24 GPU's with 192 GB RAM and M2070Q graphic card 4xQDR (40Gbit) Infiniband network
- 2.6 PetaB fast parallel storage
- 150+ TFLOP/S
- Energy requirement 500 kW, cooling 10% of the power

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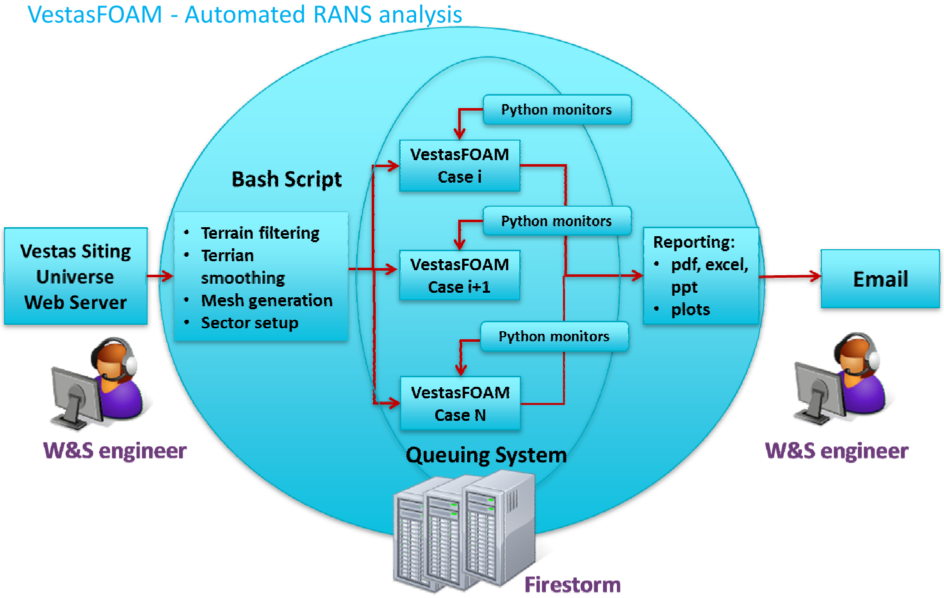
## CFD LEVEL 1

VestasFOAM - Automated RANS analysis

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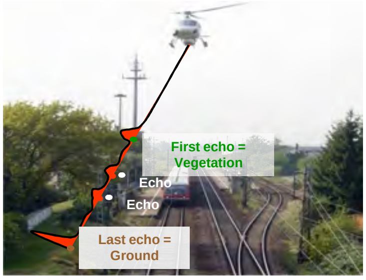
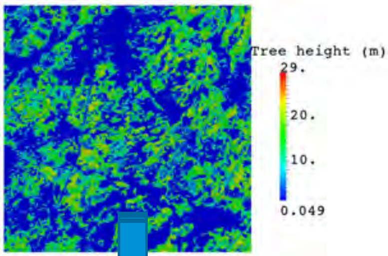
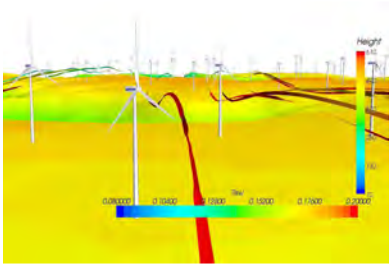
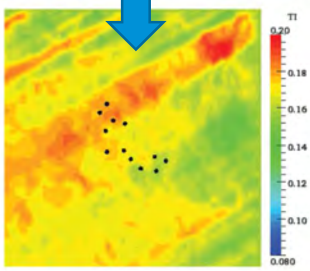
## CFD LEVEL 2

VestasFOAM RANS (k-ε) + forest/tricky terrain/custom analysis



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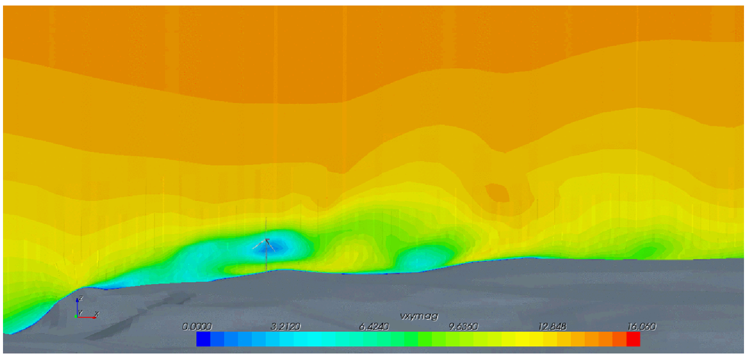
## CFD LEVEL 3

VestasFOAM Hybrid RANS-LES (k-ω SST)

- Transient flow features captured
- Compromise before full Large-Eddy Simulation (LES) – very expensive
- Statistical post-processing yields confidence intervals of adherence to IEC standards of wind shear and veer.



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## CFD LEVEL 3

VestasFOAM Hybrid RANS-LES (k-ω SST)

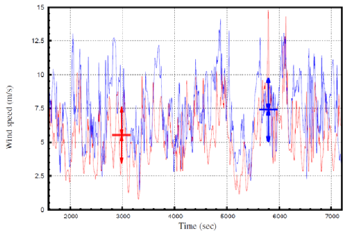


Figure A.53. Time histories of wind speed for WTG14: ——, rotor bottom; ——, rotor top. Horizontal bars and vertical arrows denote mean and standard deviation, respectively.

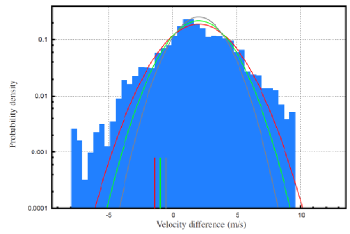


Figure A.54. Velocity-difference PDF between rotor top (140m) and bottom (28m) for WTG14: ——, IEC turbulence class A; ——, B; ——, C. Vertical lines denote the threshold values for *extreme* negative wind shear, which are based on the one-tailed significance level of 5%.

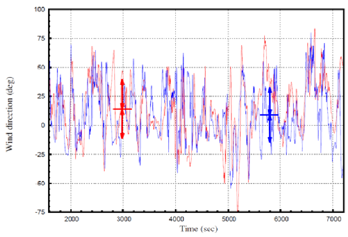


Figure A.55. Time histories of wind direction for WTG14: ——, rotor bottom; ——, rotor top. Horizontal bars and vertical arrows denote mean and standard deviation, respectively.

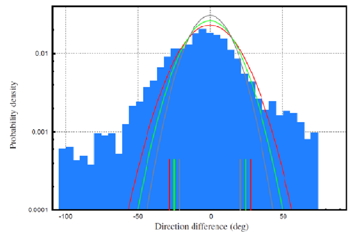


Figure A.56. Direction-difference PDF between rotor top (140m) and bottom (28m) for WTG14: ——, IEC turbulence class A; ——, B; ——, C. Vertical lines denote the threshold values for *extreme* wind veer, which are based on the one-tailed significance level of 5%.

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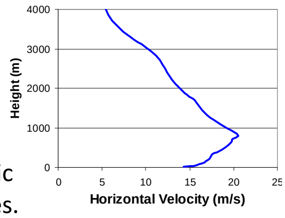
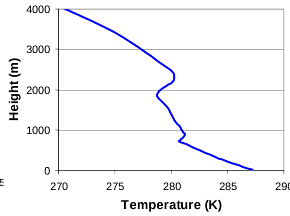
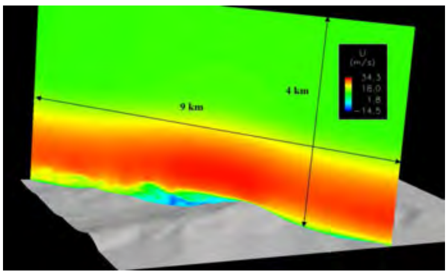
## CFD LEVEL 4

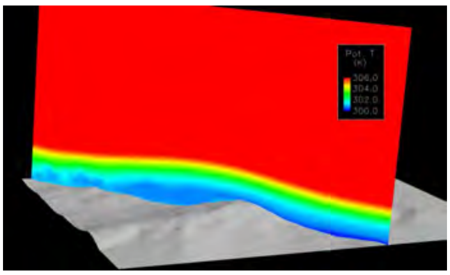
VestasFOAM WRF-CFD Coupling

- DES analysis
- “Real” wind considered as mesoscale profiles are interpolated to CFD boundaries
- Forensic analysis of problematic weather events on existing sites.



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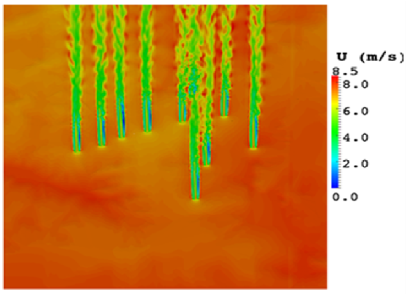
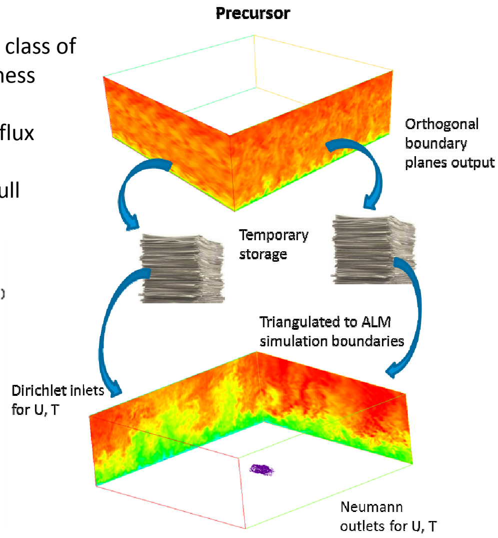
## CFD LEVEL 5

VestasFOAM Large-Eddy Simulation – Actuator Line Model Coupling

- "Real" fluctuating wind generation
- Proper turbulence statistics according to class of thermal stratification and surface roughness
- Flow now dependent on Richardson no.
- Geostrophically driven and surface heat flux imposed
- Precursor simulations serve as input to full activation of ALM model.

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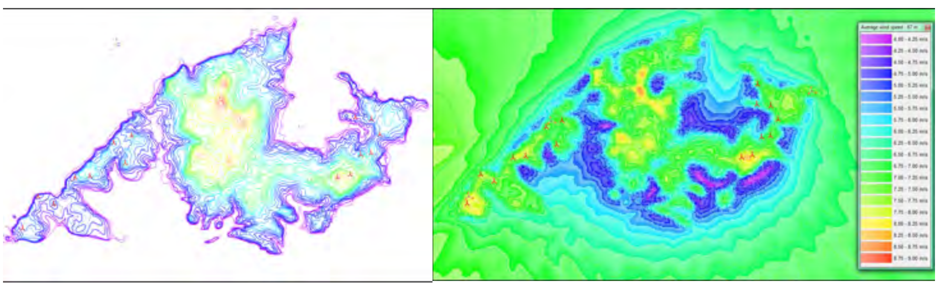
## CFD Resource Mapping

Procedure

- CFD-RANS, modified k-ε turbulence closure, neutral conditions, 36 sectors
- LTC met mast data with Vestas 13-year mesoscale WRF model data
- Extrapolation of mast data to hub height according to CFD predicted wind shear
- Scaling CFD wind velocity field to match measurements at mast positions
- Inverse distance weighting together with directional wind distribution frequencies for each met mast is used to calculate the Weibull parameters
- Resource file in RSF format with 25 m horizontal resolution is generated



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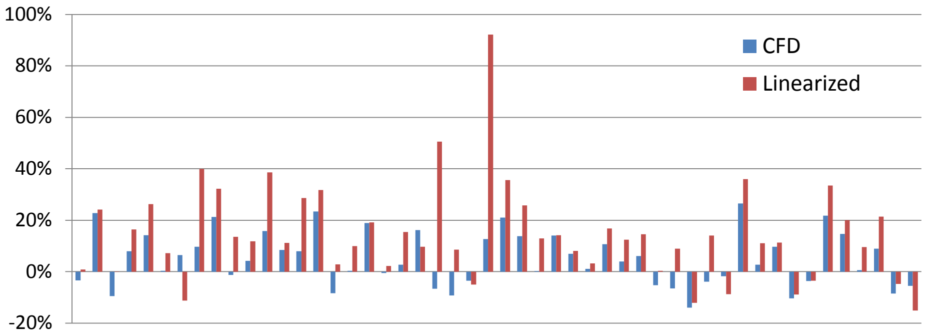
## CFD Resource Mapping

Validation based on 50 operational wind farms




| | CFD | Linearized model |
|---|---|---|
| BIAS | **5.14%** | **14.72%** |
| STDEV | **10.34%** | **18.50%** |

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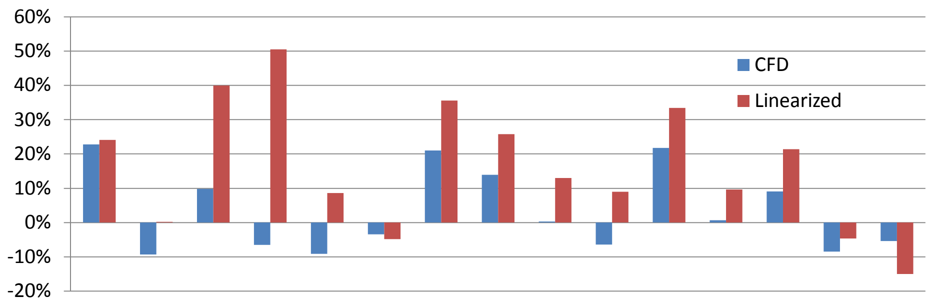
## CFD Resource Mapping

Complex terrain




| | CFD | Linearized model |
|---|---|---|
| BIAS | **3.37%** | **16.46%** |
| STDEV | **11.97%** | **18.67%** |

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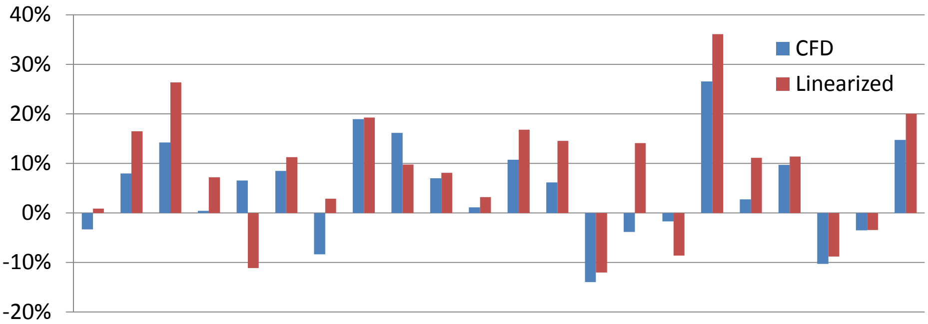
## CFD Resource Mapping

Semi-complex terrain




| | CFD | Linearized model |
|---|---|---|
| BIAS | **7.69%** | **23.38%** |
| STDEV | **9.03%** | **23.79%** |

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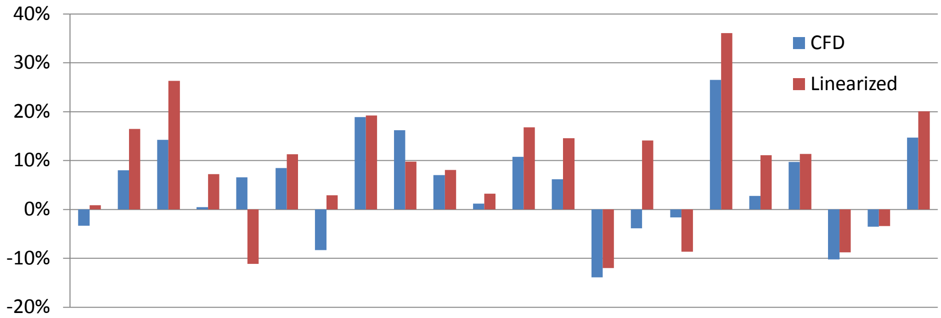
## CFD Resource Mapping

Non-complex terrain




| | CFD | Linearized model |
|---|---|---|
| BIAS | **4.85%** | **8.43%** |
| STDEV | **10.04%** | **12.36%** |

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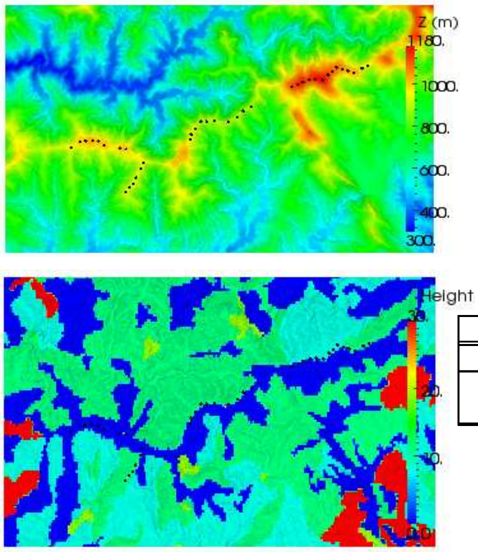
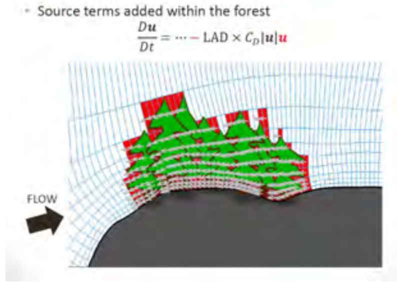
## CFD Resource Mapping Improvement

### Forest modelling




| AEP (GW/yr) | | | |
|---|---|---|---|
| **Actual** | **CFD** | **CFD w/ Forest** | **Linearized** |
| 271.6 | 324.0 | 309.3 | 341.7 |
| **Error** | **19.3%** | **13.9%** | **25.8%** |

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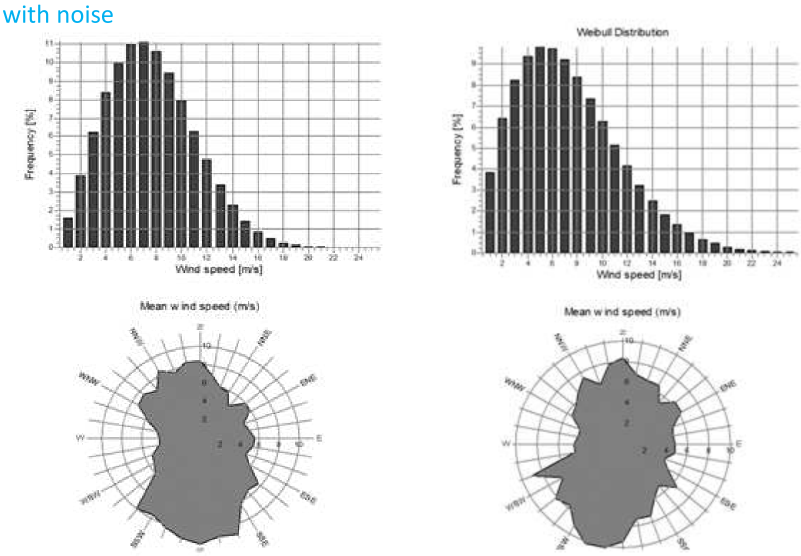
## CFD Resource Mapping Improvement

### LTC with noise




**Sector Linear Regression** **Sector Linear Regression w/ Noise**

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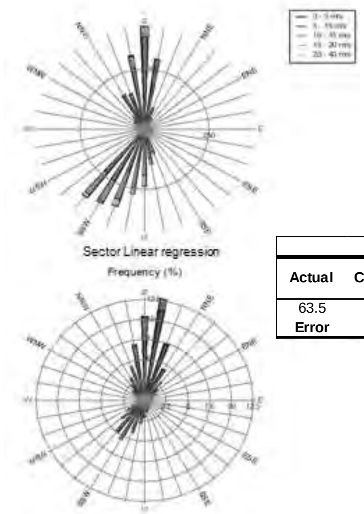
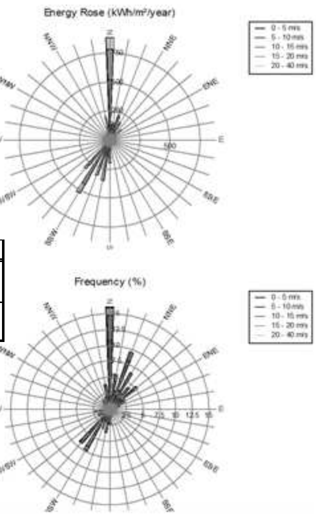
## CFD Resource Mapping Improvement

LTC with noise




| AEP (GW/yr) | | | |
|---|---|---|---|
| Actual | CFD LTC | CFD LTC w/ Noise | Linearized |
| 63.5 | 73.0 | 69.7 | 88.8 |
| Error | 15.0% | 9.8% | 39.8% |

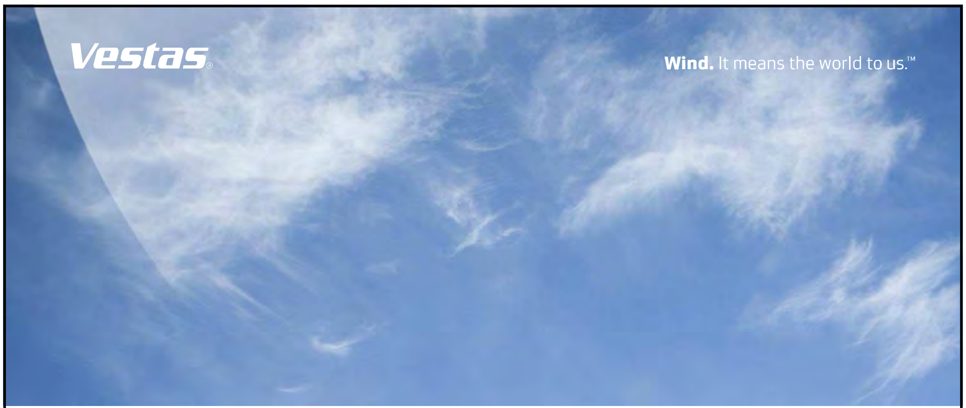



**Sector Linear Regression** **Sector Linear Regression w/ Noise**



## Conclusions

- CFD wind resource mapping method improves annual production prediction on average with 8-10 % compared to Linearized model standard approach
- Further flow modelling improvements can be achieved through:
  - Include atmospheric stability in the CFD simulations, sectorwise weighting according to WRF provided stability rose
  - Improved wake model
  - Variation in the power curve related to flow parameters (inflow, wind shear, wind veer)
  - Accounting for lost production due to some atmospheric phenomena (e.g. icing)
  - Improve procedure of mast data to turbine positions correction techniques
- IEA Task 31: WAKEBENCH – incorporation of best practices determined during this benchmarking project.




Thank you for your attention

# A hybrid model adapted for wind energy applications

Mary C. Bautista

PhD Student
École de Technologie Supérieure, Montreal, QC

*Supervisors :* Christian Masson and Louis Dufresne

Topical Expert Meeting 75
Challenges on Wind Energy Deployment in Complex Terrain

Universität Stuttgart, Nov 12th 2013

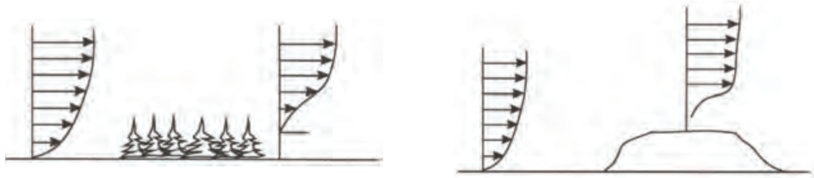




## Table of contents

## Atmospheric turbulence modelling

- The wind behavior on flat terrain is fairly well understood.



Images : Manwell (2002)

**As the flow complexity increases :**

- the computer **cost** increases
- the **accuracy** of the simulations diminishes greatly





## Atmospheric modelling - Current issues :

1. Turbulence models :
   - **RANS :** Incomplete description of the flow
   - **LES :** Too costly for wall-bounded flows
2. Turbulence theory is based on flat terrain studies
   - Wall-functions
     - To account for near-wall turbulence and surface roughness
     - Not valid for adverse pressure gradients or separation regions → but used in complex terrain !
3. Atmospheric stability, among others.

**The improvement of atmospheric flow simulations over complex terrain is crucial.**

## Atmospheric modelling - Some solutions :

1. **Hybrid models :** Compromise between accuracy and cost
2. Choose turbulence models that can bypass flat terrain assumptions
   - Promising models exist for aerodynamic flows
   - Extend their use to wind energy sector → very high Re and really rough surfaces

**To implement these solutions :**

$k-\omega$ SST SIDDES turbulence model
(Simplified Improved Delayed Detached Eddy Simulation)





## Proposed Model : $k-\omega$ SST-SIDDES (Gritskevich et al., 2012)

- **Hybrid approach :** Based on DES (Spalart et al.,1997)
- **RANS :** $k-\omega$ SST (Menter et al., 2003)
- **LES :** an eddy viscosity model
- Implemented in OpenFOAM®

$$\frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\nu + \nu_t)\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right)\right]$$

RANS-mode : $\overline{u}_i$ is the time-average velocity
LES-mode : $\overline{u}_i$ is the filtered velocity

## $k - \omega$ SST-SIDDES

$$\frac{\partial k}{\partial t} + ... = \tilde{P} - \underbrace{\frac{k^{3/2}}{\tilde{l}}}_{\epsilon}$$

$$\frac{\partial \omega}{\partial t} + ..$$

In the RANS-mode and LES-mode :

$$\nu_t = \frac{a_1 k}{\max(a_1 \omega, \mathcal{S} F_2)}$$

The length scale $\tilde{l}$ will determine the "mode" of the equations locally and varying in time





## Model advantages : SIDDES

- Reduces the cost of resolving the near-wall turbulence
  → but two equations are solved in the whole domain.
- Corrects the log-layer mismatch (LLM)
- Yields accurate results for aerodynamic flows
  → Low Re and smooth walls
  → Needs to be validated for atmospheric flows
  (i.e. high Re, rough wall, and LLM correction.)

## Model advantages : RANS

- In most RANS models, the surface roughness is accounted for by
  $\rightarrow$ A modification of the original equations
  $\rightarrow$ A wall-function

**$k - \omega$ SST :**

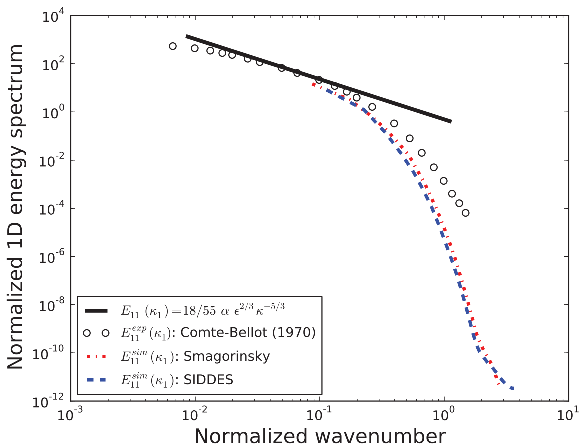
- Wall functions can be avoided because it can
  - be integrated down to the wall
  - account for rugosity with the boundary conditions

  but a proper mesh is needed $\rightarrow$ $z_1^+ \approx 0.3$ $\rightarrow$ Can be costly !
- Adverse pressure gradient and separation regions are well modelled $\rightarrow$ Widely used for aerodynamic flows





## Decaying isotropic turbulence - (LES-mode)



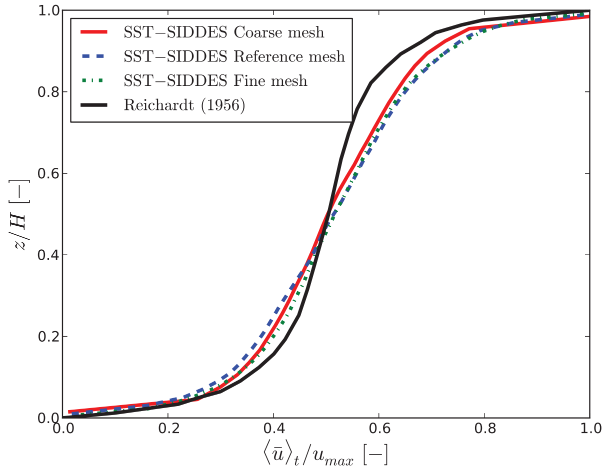

The implementation of the model is slightly too dissipative due to the chosen interpolations schemes.

Needs to be reviewed !

## Constant shear flow - (LES-mode)

Study the effect of mean shear without a wall

Confirms that the implementation of the model is too dissipative.








## Constant shear flow - (LES-mode)

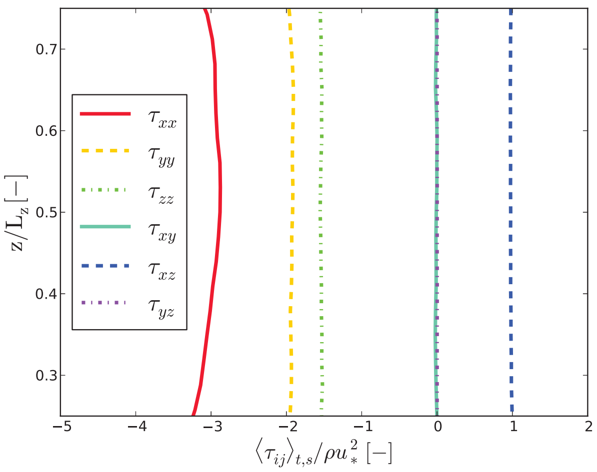
The atmospheric stresses :

$$\langle \tau_{xx} \rangle / \rho u_*^2 = -5.71$$

$$\langle \tau_{yy} \rangle / \rho u_*^2 = -3.69$$

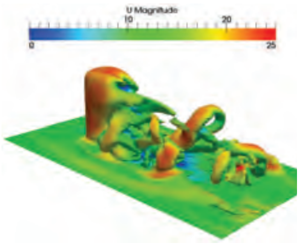
$$\langle \tau_{zz} \rangle / \rho u_*^2 = -1.56$$

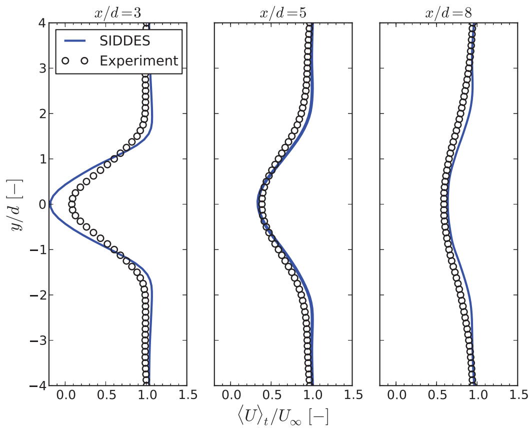
Slightly under-predicted but consistent with Jimenez et al. (2010)



# Wind-tunnel case (Low Re and smooth wall)

**Flow around a square-section cylinder**



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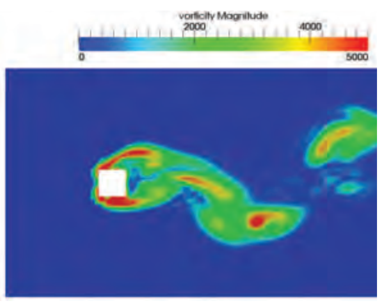
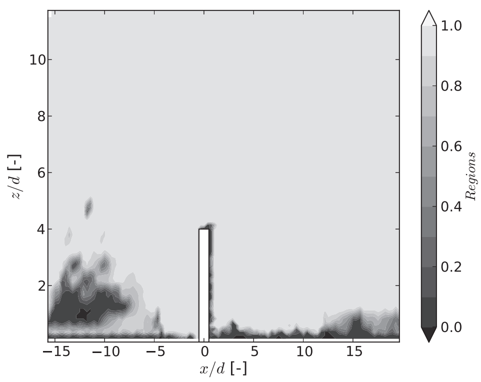
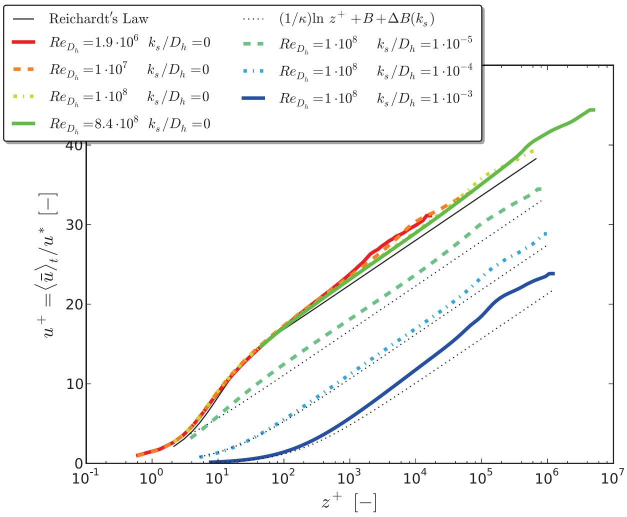
# Wind-tunnel case (Low Re and smooth wall)



## Channel flow




The model tested for :

- High Re
- High $z_0$
- LLM correction is still valid



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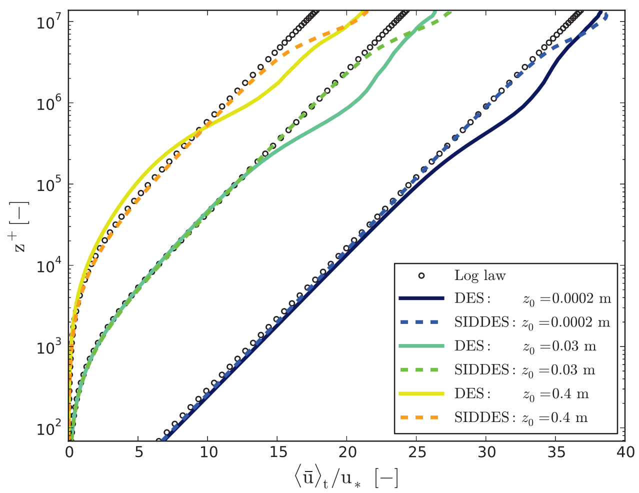
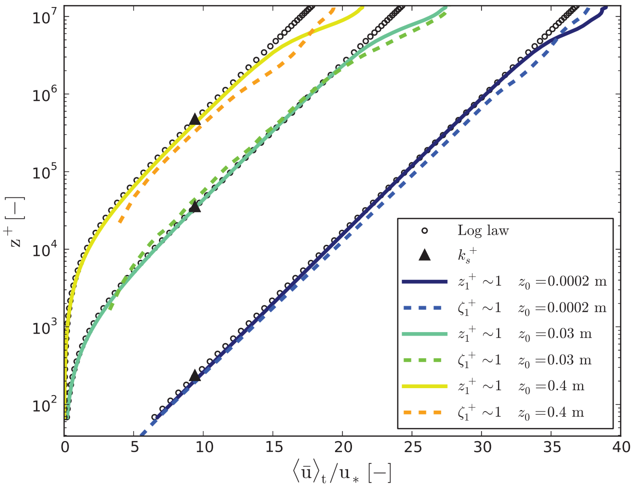
## Idealized atmospheric boundary layer




- Neutral
- No Coriolis
- SIDDES :
  - Log-law up to $\sim 0.1H$
  - No LLM
  - Improvement over DES

## Idealized atmospheric boundary layer




$$\zeta_1^+ = z_1/z_0$$
$$z_1^+ = u_* z_1/\nu$$

$$k_{s,ABL} \approx 30 z_0$$

The results below $k_s^+$ are not physical ! !





## Future work :

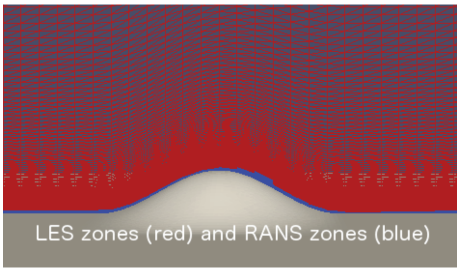
**Neutral atmospheric flow**

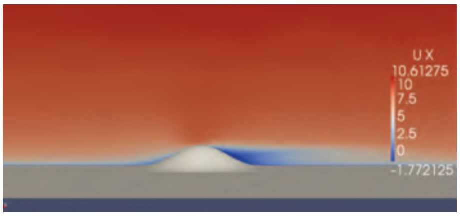
- Flat and rough terrain
- Including Coriolis effects
- Leipzing test case (Wakebench)
- Based on the measurement campaign by Lettau (1950)

## Future work :

**Simplified atmospheric flow over an ideal 3D hill**

- Based on Sullivan (2010)
- Preliminary results ! !








## Future work :

**Atmospheric flow over real terrain**

- Bolund case (Wakebench)

Images : www.bolund.risoe.dk

## Conclusion

**The $k-\omega$ SST-SIDDES :**

1. is a compromise between accuracy and computational cost
   $\rightarrow$ and eliminates the log-layer mismatch
2. avoids the use of **wall functions**

**The flat terrain analysis :**

- shows promising preliminary results
- is not based on "flat terrain assumptions"
  $\rightarrow$ Anticipates the forthcoming problems in complex terrain
- revels that the interpolations schemes need to be modified



# Danke schön !

Questions ?
mary.bautista.1@ens.etsmtl.ca

## Wind in complex terrain

Image : http ://chiefio.wordpress.com/2010/09/21

- Higher shear stress
- Higher turbulence
- Flow separation

**For the turbines this means :**

- Increase the risk of damage ($)
- Reduction in energy production ($)

**Reliable wind simulations are crucial for complex terrain.**



## Detached eddy simulation (DES) (Spalart et al., 1997)

- **Aim :** model flows with massively separated zones
  - RANS to solve the boundary layer
  - LES outside the boundary layer

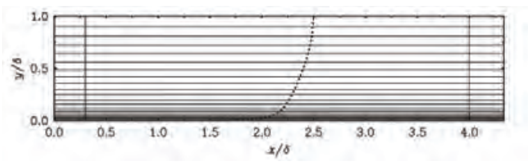
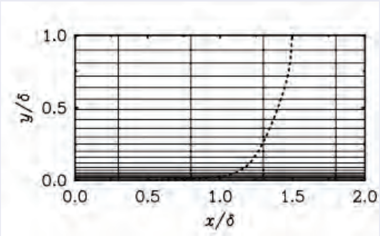



Image : Spalart et al. (2006)

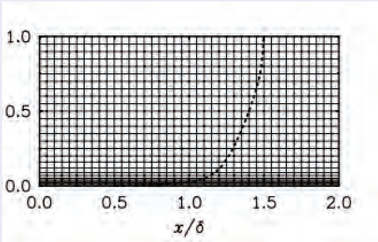
- **Problem :** In atmospheric flows, we are only interested in the boundary layer
- **Workaround :** Use another type of mesh

## DES approaches




- **Problem :** Grid-induced separation (GIS)
- **Solution :** DDES approach

Images : Spalart et al. (2006)




- Wall-Modelled LES
- **Problem :** Log-layer mismatch (LLM)
- **Solution :** IDDES approach



## The LES/RANS switch

The length scale determines the LES and RANS regions

$$l_{RANS} = \frac{\sqrt{k}}{\beta^* \omega} \qquad l_{LES} = C_{DES}\Delta$$

The DES switch is defined as :

$$\tilde{l}_{DES} \equiv min(l_{RANS}, l_{LES})$$

## DES Approaches

**Detached Eddy Simulation (DES)** Spalart et al. (1997)

$$\tilde{l}_{DES} \equiv min(l_{RANS}, l_{LES})$$

**Delayed Detached Eddy Simulation (DDES)** Spalart (2006)

$$\tilde{l}_{DDES} \equiv l_{RANS} - f_d max(0, l_{RANS} - l_{LES})$$

**Improved Delayed Detached Eddy Simulation (IDDES)**
Travin et al. (2006)

$$\tilde{l}_{IDDES} \equiv \tilde{f}_d l_{RANS} + (1 - \tilde{f}_d) l_{LES}$$

- A simplified version of $\tilde{f}_d$ exist (SIDDES) Gritskevich et al. (2012)



## Roughness extension (Knopp et al., 2009)

$k - \omega$ SST accounts for roughness simply through the boundary conditions

$$k|_{w,ABL} = \frac{u_*^2}{\sqrt{\beta_*}} \qquad \omega|_{w,ABL} = \frac{u_*}{\sqrt{\beta_*}\kappa z_0}$$

$$u_*^2 = (\nu + \nu_t)\left|\frac{\partial u}{\partial z}\right|_{z=0}$$

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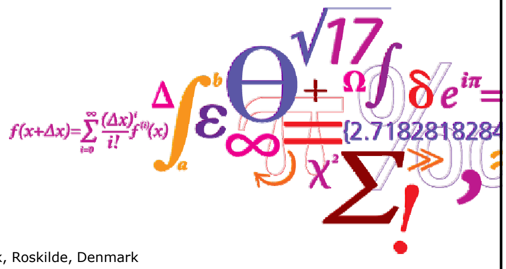
# Towards the consistent two-equation closure modelling of atmospheric flows

Andrey Sogachev



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Department of Wind Energy

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## Turbulence model: governing equations

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$$\frac{\partial \bar{U}_i}{\partial x_i} = 0. \qquad \frac{\partial \bar{U}_i}{\partial t} + \bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} + 2\varepsilon_{ijk}\Omega_j \bar{U}_k = -\frac{1}{\rho_0}\frac{\partial \bar{P}}{\partial x_i} - \frac{\partial \overline{u_j u_i}}{\partial x_j} \quad \text{with} \quad U_i = \bar{U}_i + u_i$$

$$\overline{u_i u_j} = \frac{2}{3}\delta_{ij} E - K\left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i}\right)$$

To close the system certain assumptions concerning *K* are needed

$$\frac{\partial E}{\partial t} + \bar{U}_j \frac{\partial E}{\partial x_j} - \frac{\partial}{\partial x_i}\left(\frac{K}{\sigma_E^{\varphi}}\frac{\partial E}{\partial x_i}\right) = P - \varepsilon \qquad \text{with} \quad \varphi \equiv \varepsilon, \omega$$

$$\frac{\partial \varphi}{\partial t} + U_j \frac{\partial \varphi}{\partial x_j} - \frac{\partial}{\partial x_i}\left(\frac{K}{\sigma_\varphi}\frac{\partial \varphi}{\partial x_i}\right) = \frac{\varphi}{E}\left(C_{\varphi 1} P - C_{\varphi 2}\varepsilon\right)$$

| | | | | |
|---|---|---|---|---|
| E-ε model | Jones and Launder (1972) | $K = C_\mu \frac{E^2}{\varepsilon}$ | $\ell = \frac{C_\mu^{3/4} E^{3/2}}{\varepsilon}$ | $C_{\varepsilon 1}$ = 1.44, $C_{\varepsilon 2}$ = 1.92, $\sigma_E$ = 1, and $\sigma_\varepsilon$ = 1.3. |
| E-ω model $(\omega = \varepsilon / E)$ | Kolmogorov (1942), Wilcox (1998) | $K = C_\mu \frac{E}{\omega}$ | $\ell = \frac{C_\mu^{3/4} E^{1/2}}{\omega}$ | $C_{\omega 1}$ = 0.52, $C_{\omega 2}$ = 0.8, $\sigma_E$ = 2., $\sigma_\omega$ = 2. |

(e.g. Pope 2000 )

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## Accounting for plant drag and buoyancy: the traditional way

$$\frac{\partial \bar{U}_i}{\partial t}+\bar{U}_j\frac{\partial \bar{U}_i}{\partial x_j}+2\varepsilon_{ijk}\Omega_j\bar{U}_k=-\frac{1}{\rho_0}\frac{\partial \bar{P}}{\partial x_i}-\frac{\partial \overline{u_ju_i}}{\partial x_j}+S_i \qquad S_i=-c_d\,A(z)\bar{U}_i|U|,$$

( Raupach and Shaw, 1982 )

$$\frac{\partial E}{\partial t}+U_j\frac{\partial E}{\partial x_j}-\frac{\partial}{\partial x_i}\left(\frac{K}{\sigma_E^{\varphi}}\frac{\partial E}{\partial x_i}\right)=(P-\varepsilon)+\left[B+S_p-S_d\right] \qquad B\equiv\frac{g}{\theta_v}\overline{w'\theta_v'}$$

$$\frac{\partial \varphi}{\partial t}+U_j\frac{\partial \varphi}{\partial x_j}-\frac{\partial}{\partial x_i}\left(\frac{K}{\sigma_\varphi}\frac{\partial \varphi}{\partial x_i}\right)=\frac{\varphi}{E}\left(C_{\varphi1}^{*}P-C_{\varphi2}\varepsilon\right)+\frac{\varphi}{E}\left[C_{\varphi3}B+C_{\varphi4}S_p-C_{\varphi5}S_d\right] \quad ?$$

$$C_{\varphi1}^{*}=C_{\varphi1}+(C_{\varphi1}-C_{\varphi2})(-\ell/\ell_e)$$

( Apsley and Castro 1997)

$$\ell_e=\begin{cases}\ell_B=0.00027G/f & \text{(Blackadar 1962)}\\ \ell_{MY}=0.075\int_0^\infty z\sqrt{E}dz\Big/\int_0^\infty\sqrt{E}dz & \text{(Mellor and Yamada 1974)}\end{cases}$$

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## Uncertainties: vegetation

$$\frac{\partial \varphi}{\partial t}+U_j\frac{\partial \varphi}{\partial x_j}-\frac{\partial}{\partial x_i}\left(\frac{K}{\sigma_\varphi}\frac{\partial \varphi}{\partial x_i}\right)=\frac{\varphi}{E}\left(C_{\varphi1}P-C_{\varphi2}\varepsilon\right)+\frac{\varphi}{E}\left[C_{\varphi3}B+C_{\varphi4}S_p-C_{\varphi5}S_d\right]$$

Wake production

$$S_p\approx\beta_p c_d\,A(z)|U|^3$$

Enhanced dissipation

$$S_d\approx\beta_d\,c_d\,A(z)|U|E$$

Different choices of coefficient sets

| Type | Model | $\beta_p$ | $\beta_d$ | $C_{\varphi4}$ | $C_{\varphi5}$ |
|---|---|---|---|---|---|
| $E$–$El$ | Analytical | 1.0 | 4.0 | 1.0 | 1.0 |
| | Yamada (1982) | 1.0 | 0.0 | 1.0 | 0.0 |
| $E$–$\varepsilon$ | Analytical | 1.0 | 4.0 | 1.5 | 1.5 |
| | Liu et al. (1996) | 1.0 | 4.0 | 1.5 | 0.6 |
| | Foudhil et al. (2005) | 0.8 | 4.0 | 1.875 | 0.81 |
| $E$–$\omega$ | Analytical | 1.0 | 4.0 | 0.5 | 0.5 |
| | Neary (2003) | 0.05 | 0.0 | 3.2 | 0.0 |
| $E$-$\varepsilon$ | Hiraoka and Ohashi (2008) | 1.0 | 4.0 | 0.01 | 0.01 |
| | Mochida et al. (2008) | 1.0 | 4.0 | 1.8 | 1.5 |
| | Palpé and Masson (2009) | 1.0 | 5.03 | 0.78, | 0.78 |

(after Sogachev and Panferov, 2006)

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## Uncertainties: buoyancy

$$\frac{\partial \varepsilon}{\partial t}+U_j\frac{\partial \varepsilon}{\partial x_j}-\frac{\partial}{\partial x_i}\left(\frac{K}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_i}\right)=\frac{\varepsilon}{E}\left(C_{\varepsilon 1}P-C_{\varepsilon 2}\varepsilon\right)+\frac{\varepsilon}{E}\left[C_{\varepsilon 3}B+C_{\varepsilon 4}S_p-C_{\varepsilon 5}S_d\right]$$

**Table 4.** Different Choices of $c_{\varepsilon 3}$ in the Literature

| Reference | $c_{\varepsilon 3}$ |
|---|---|
| *Gibson and Launder* [1976] | 0 |
| *Zeman and Lumley* [1976] | 1.3 |
| *Mellor and Yamada* [1982] | 1 |
| *Betts and Haroutunian* [1983] | -1.15 |
| *Rodi* [1985] | 0.2 |
| *McGuirk* [1988] | 0 |
| *Hunt et al.* [1988] | 0 |
| *Haroutunian and Launder* [1988] | 1.45 |
| *Mellor* [1989] | 1 |
| *Burchard and Baumert* [1995] | -1.4 |
| *Apsley and Castro* [1997] | -0.67 |

(after Baumert and Peters, 2000)

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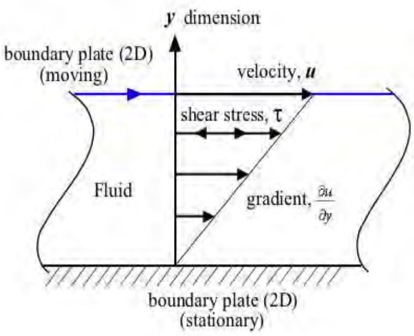
## Uncertainties: analysis of inconsistency

In addition to the canonical flow regimes of grid turbulence (gives $C_2$) and wall-bounded flow (gives $C_1$) we employ a homogeneous shear flow




The constant mean shear rate implies that the turbulence time scale $\tau = E/\varepsilon$ is also fixed.

$$\frac{\partial}{\partial t}\left(\frac{E}{\varepsilon}\right)=\frac{\partial \tau}{\partial t}=\left(C_{\varphi 2}-\gamma_\varphi\right)\left(\frac{\varepsilon}{\varepsilon}\right)-\left(C_{\varphi 1}-\gamma_\varphi\right)\left(\frac{P}{\varepsilon}\right)$$

($\gamma_\varphi = \{1, 0\}$ for $\varphi = \{\varepsilon, \omega\}$).

$$\frac{P}{\varepsilon}=\frac{C_{\varepsilon 2}-1}{C_{\varepsilon 1}-1}\approx\frac{C_{\omega 2}}{C_{\omega 1}}$$

But when $\frac{\partial E}{\partial t}=P-\varepsilon+X$ then $\frac{P+X}{\varepsilon+X_\varepsilon}\neq\frac{C_2}{C_1}$ ,however $K=C_\mu\frac{E^2}{\varepsilon}$

(Pope, 2000; Sogachev and Panferov., 2006)

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## Accounting for plant drag and buoyancy: the consistent way

$$\frac{\partial E}{\partial t}+U_j\frac{\partial E}{\partial x_j}-\frac{\partial}{\partial x_i}\left(\frac{K}{\sigma_E^{\varphi}}\frac{\partial E}{\partial x_i}\right)=P-\varepsilon+\left[B+\underbrace{0}_{(S_p-S_d)}\right] \qquad S_P\propto|U|^3$$

$$S_p=S_d\propto|U|E \qquad \text{(Seginer et al., 1976)}$$

$$\frac{\partial\varphi}{\partial t}+U_j\frac{\partial\varphi}{\partial x_j}-\frac{\partial}{\partial x_i}\left(\frac{K}{\sigma_\varphi}\frac{\partial\varphi}{\partial x_i}\right)=\frac{\varphi}{E}\left(C_{\varphi1}^{*}P-C_{\varphi2}\varepsilon\right)+\frac{\varphi}{E}\left[C_{\varphi3}B+C_{\varphi4}S_d-C_{\varphi5}S_d\right]$$

In consistent way 'extra' coefficients appearing in the supplementary equations have to be presented as

$$C_{\varphi i}=\alpha_i\left(C_{\varphi1}-C_{\varphi2}\right)+\gamma_\varphi \qquad (\gamma_\varphi=\{1,0\}\text{ for }\varphi=\{\varepsilon,\omega\})$$

Compare with $C_{\varphi1}^{*}=C_{\varphi1}+(C_{\varphi1}-C_{\varphi2})(-\ell/\ell_{MY})$ $\quad\alpha_1=-\ell/\ell_{MY}$ $\quad\alpha_2=0$

$$\alpha_3=\begin{cases}-(\ell/\ell_{MY})\left(C_{\varphi2}-\gamma_\varphi\right)/\left(C_{\varphi2}-C_{\varphi1}\right) & \text{for}\quad Ri\le0,\quad \varepsilon/B\to1\\ 1-\ell/\ell_{MY} & \text{for}\quad Ri>0,\quad P/\varepsilon\to1\end{cases} \qquad \text{(Sogachev et al., 2012 )}$$

$$S_d=12C_\mu^{1/2}c_d\,A(z)|U|E \qquad \alpha_4=0 \qquad \alpha_5=1 \qquad \text{(Sogachev and Panferov, 2006 )}$$

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## SCADIS (scalar distribution) model: overview

Basic equations:

momentum,
heat,
moisture,
scalars ($CO_2$, $SO_2$, $O_3$),
turbulent kinetic energy (*E*)

One-and-a-half-order turbulence closure
based on equations of *E* and *ε* (dissipation rate) : ( *E-l*, *E-ε*)
*E-ω* closure based on *ω* (*ε/E*) equation

Terrain-following coordinate system

Horizontal and vertical resolutions

(depending on a particular problem)

(Sogachev et al., 2002, 2004; Sogachev and Panferov, 2006; Sogachev 2009; Sogachev et al., 2012)

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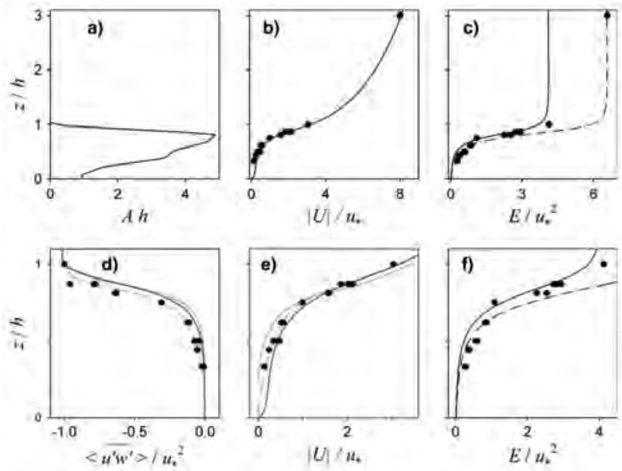
## Implementing plant drag: corn




Turbulence statistic within and above the Elora corn canopy (Wilson et al., 1982; Wilson, 1988)

(after Sogachev and Panferov, 2006)

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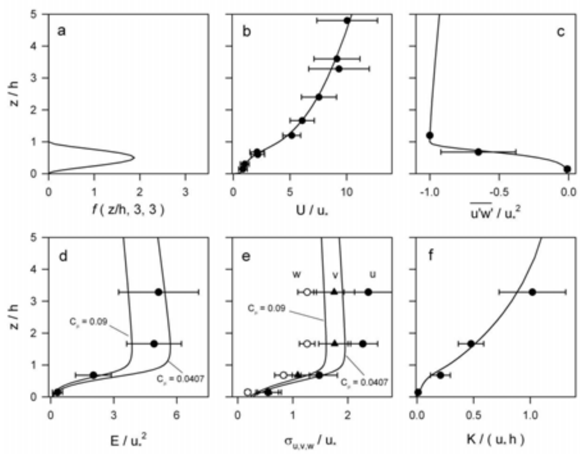
## Implementing plant drag: forest




Turbulence statistic within and above Pine Scots forest at Hyytiälä, Finland under near-neutral conditions (Rannik et al., 2003)

(after Boy et al., 2011)

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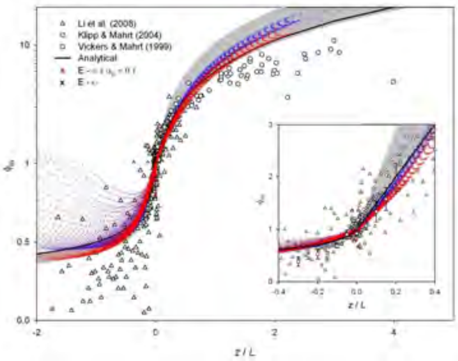
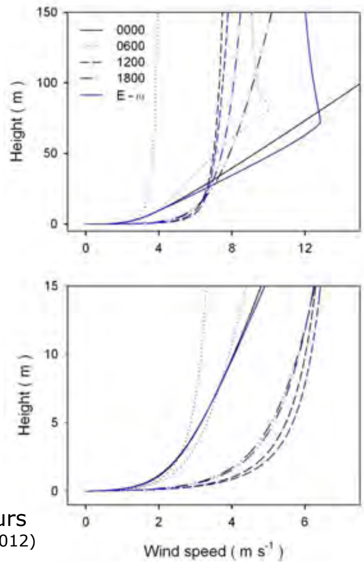
## Implementing buoyancy: bare surface



Non-dimensional shear values $\Psi_m$ as function of stability ($z/L$)
(Monin and Obukhov, 1954; Businger et al., 1971; Dyer, 1974; Sogachev et al., 2012)




Wind profiles for different hours
(Paulson, 1970; Sogachev et al. 2012)

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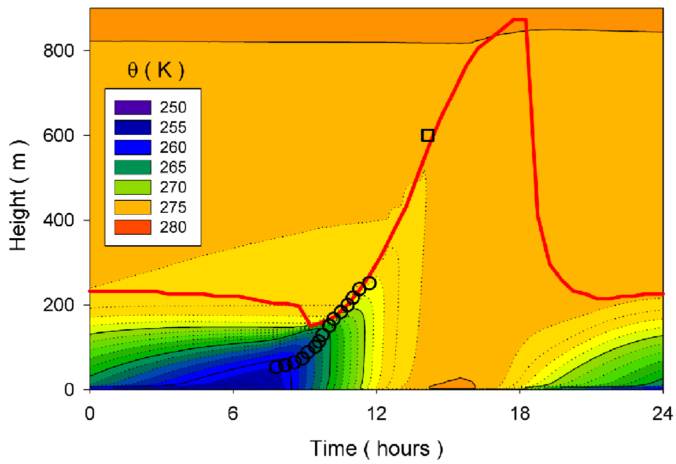
## Implementing buoyancy: forest




ABL dynamics above a forested surface on March 13, 2006, Southern Finland (Laakso et al., 2007)

(after Sogachev 2009)

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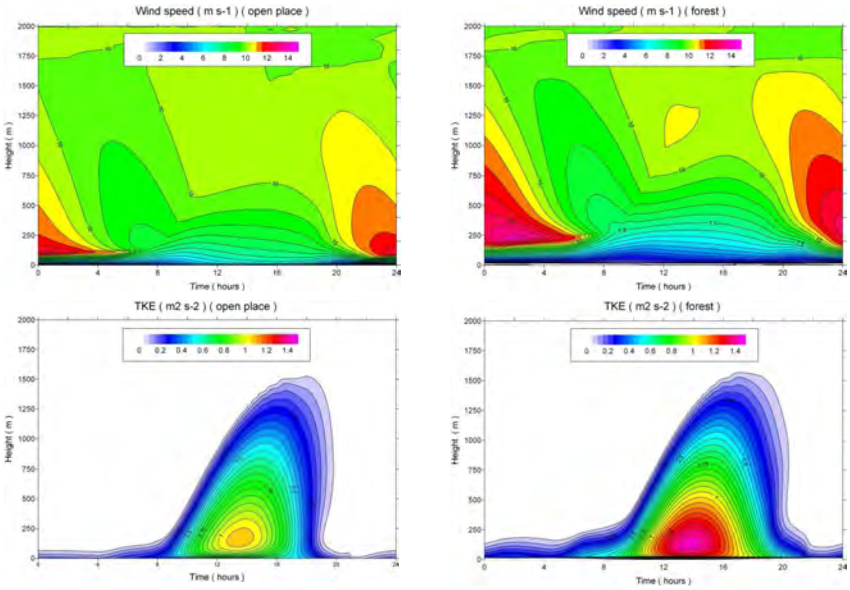
## Applications : ABL parameters evolution

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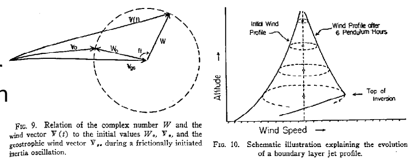
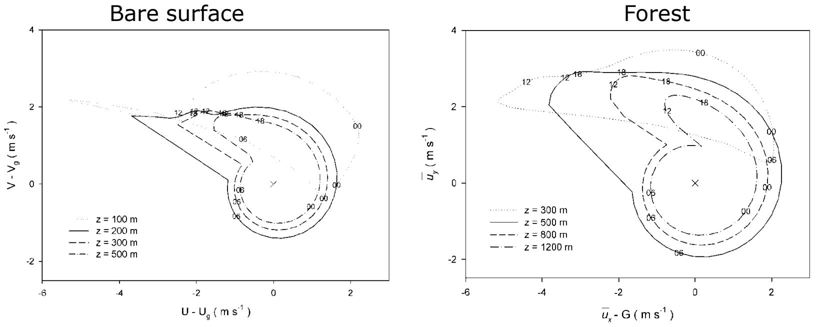
## SCADIS vs Blackadar's theory

Blackadar (1957) assumed that the ageostrophic component of the wind, released of all frictional constraint near sunset, undergoes an inertial oscillation leading to supergeostrophic values of the wind several hours later.




Geostrophic wind deviation hodographs at different heights above bare surface and a forest during fair weather. Numbers on curves indicate the local time.

(after Sogachev and Leclerc, 2011)

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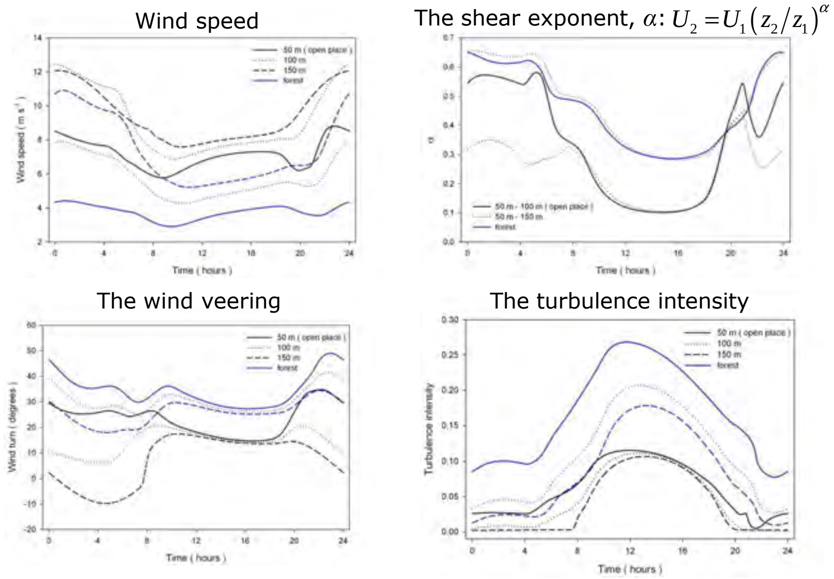
## ABL effects on wind energy related variables

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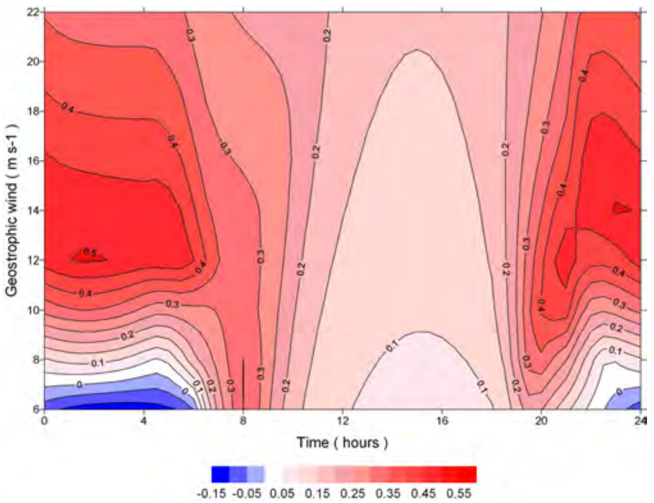
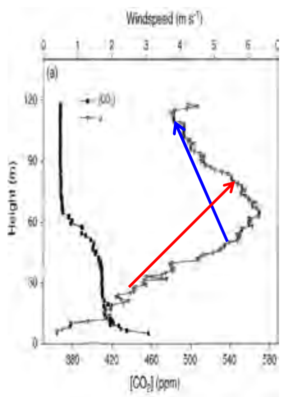
## The shear exponent above a bare surface (50m – 150m) as a function of wind speed




Mathieu et al. 2005 (crop)

DTU Wind Energy, Technical University of Denmark

## Modelling of Askervein flow

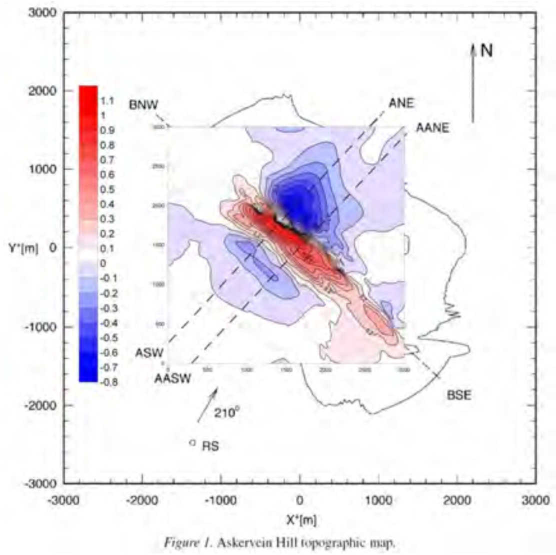
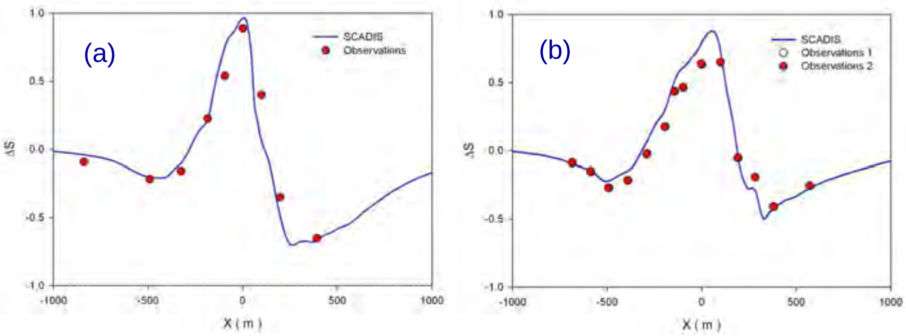



*Figure 1.* Askervein Hill topographic map.

DTU Wind Energy, Technical University of Denmark

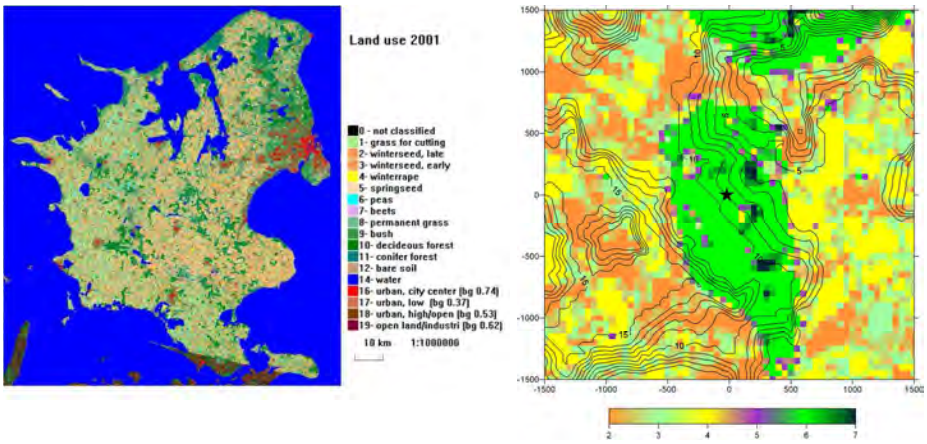
## Modelling of Askervein flow




Dimensionless speed-up, ΔS at z = 10 m above the ground along lines A (a) and AA (b). During measurements along line AA two different sets of instruments were used.

DTU Wind Energy, Technical University of Denmark

Application to Sorø site: topography and landuse

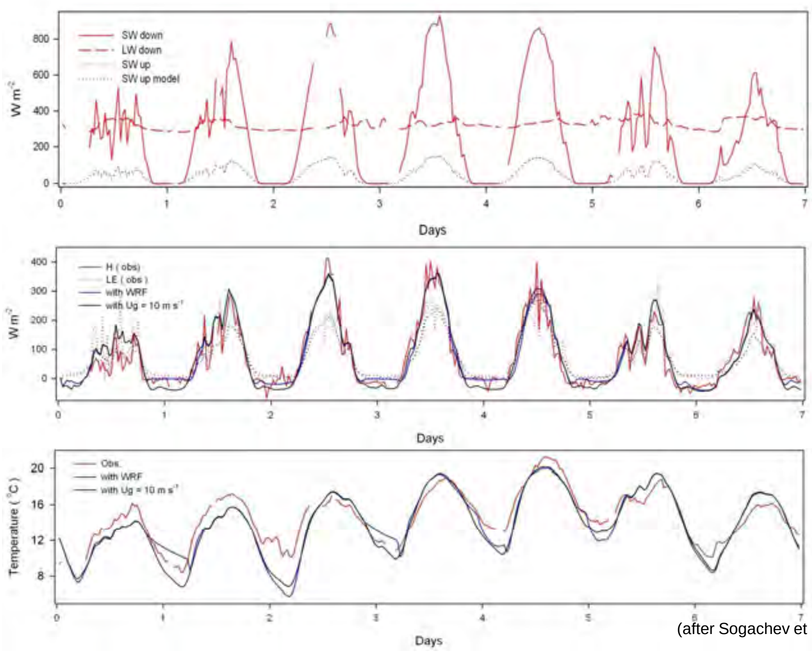



*2 – bare surface; 3 – grass; 4 – crop; 5 – shrubs; 6 – deciduous forest; 7 – coniferous forest*

Risø DTU, Danmarks Tekniske Universitet

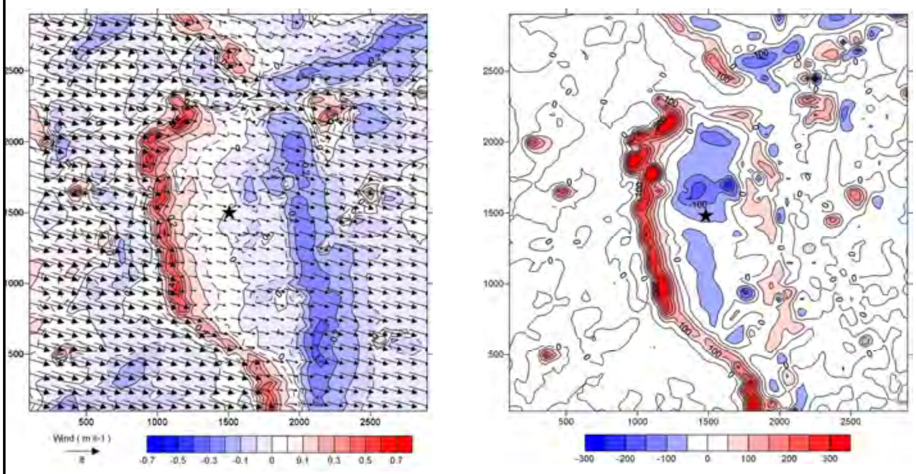
(after Sogachev et al . 2013)

Evaluation of model (20-26 June, 2010)




(after Sogachev et al . 2013)

Wind field (m $s^{-1}$) (@25 m) and Imb = (Rn-G) – (LE+H) (W $m^{-2}$) at 15.00
( clear sky conditions )



Risø DTU, Danmarks Tekniske Universitet

(after Sogachev et al . 2013)

## Summary

Two-equation closure is a pragmatic compromise between simple first-order and more complex higher-order closure schemes for modelling ABL flows using RANS equations.

The problem of poorly-defined 'extra' coefficients appearing in the supplementary equations – inherent in earlier attempts to treat vegetative canopy and/or buoyancy effects - had seriously limited the use of such closures.

A consistent closure based on the well-known coefficients ($C_{\varphi 1}$, $C_{\varphi 2}$) of the production and destruction terms in supplementary (φ) equations, respectively, and suitable for three canonical (asymptotic) flow regimes – grid turbulence, wall-bounded flow and homogeneous shear flow - was developed.

Numerical tests confirmed the adequacy of the closure.

The practical applicability of RANS models based on this closure for estimation of wind energy related variables during ABL evolution was demonstrated by the SCADIS model.

The model will have to be coupled to an aeroelastic model to be able to predict quantitatively the consequences for power production and dynamic loads on wind turbines.

Andrey Sogachev, anso@dtu.dk

**Acknowledgement:** the Center for Computational Wind Turbine Aerodynamics and Atmospheric Turbulence at DTU Wind Energy (formerly Risø DTU) under the Danish Council for Strategic Research, Grant no. 09-067216

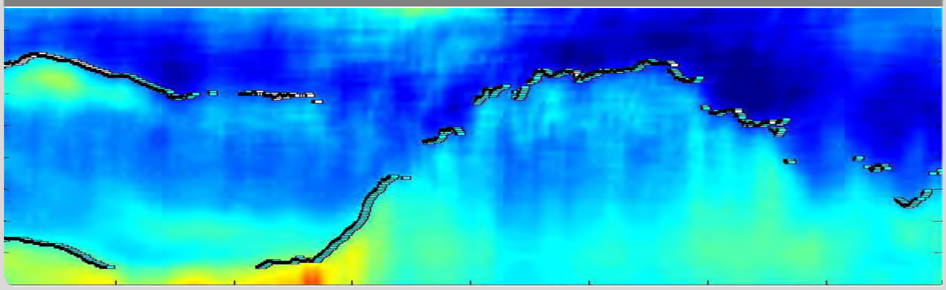
DTU Wind Energy, Technical University of Denmark

Karlsruhe Institute of Technology

# Measured (by SODAR) vertical profiles of Weibull parameters over a hill

**Stefan Emeis**
**stefan.emeis@kit.edu**

INSTITUTE OF METEOROLOGY AND CLIMATE RESEARCH, Atmospheric Environmental Research



KIT – University of the State of Baden-Wuerttemberg and National Research Center of the Helmholtz Association

www.kit.edu

Karlsruhe Institute of Technology

## Flat terrain

2 13.11.2013 Prof. Dr. Stefan Emeis | Weibull parameters over hills

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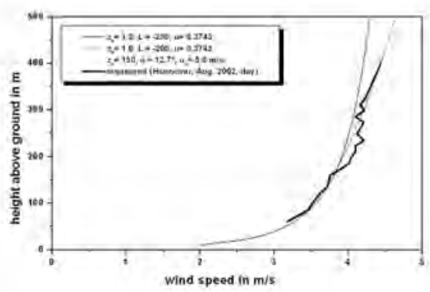
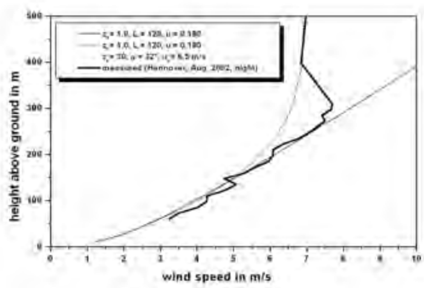
**For comparison:**

**flat homogeneous terrain**

**wind profiles (SODAR data)**




**daytime, convective** | **nocturnal, with low-level jet**

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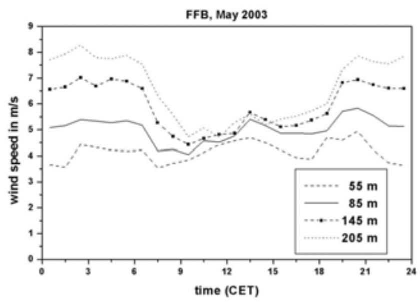
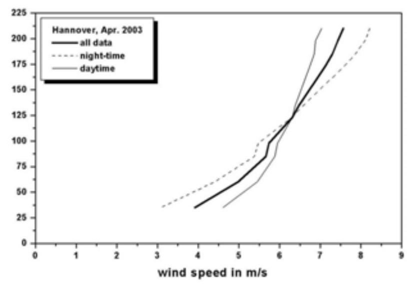
**For comparison:**

**flat homogeneous terrain (SODAR data)**




**diurnal wind variation in four heights** | **cross-over of daytime and nocturnal wind profiles**

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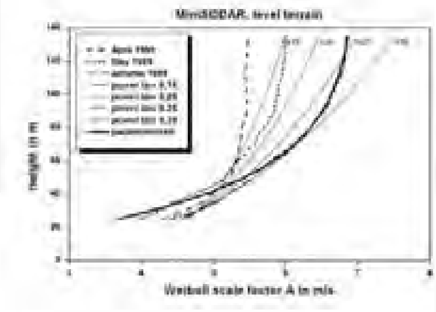
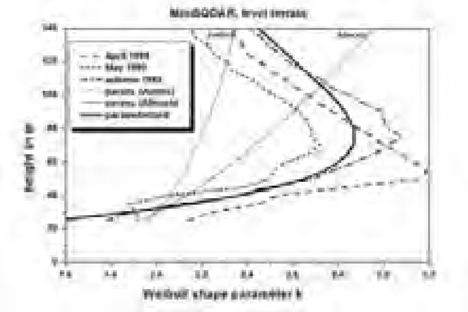
**For comparison:**

**flat homogeneous terrain (SODAR data and empirical relations)**




**Weibull scale parameter**
**($A_0$ = 6.98 m/s, $\gamma$ = 0.03)**

$$A(z) = A_0\left(1 - e^{-\gamma z}\right)$$

**Weibull form parameter**
**($z_A$ = 10 m, $z_m$ = 75 m, $c_2$ = 0.06)**

$$k(z) - k_A = c_2(z - z_A)\exp\left(-\frac{z - z_A}{z_m - z_A}\right)$$

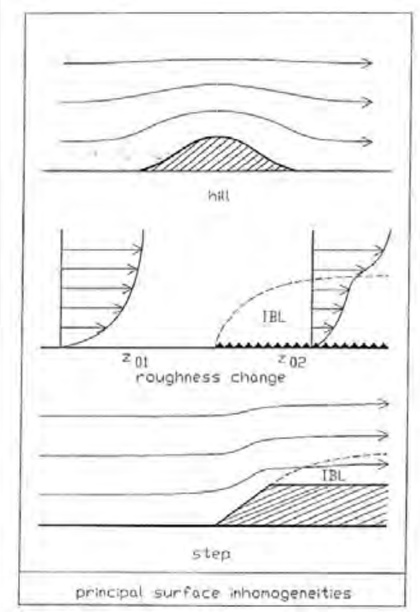
**following Wieringa (1988)**



**Complex terrain**

**Complex terrain**

**different forms of complexity**

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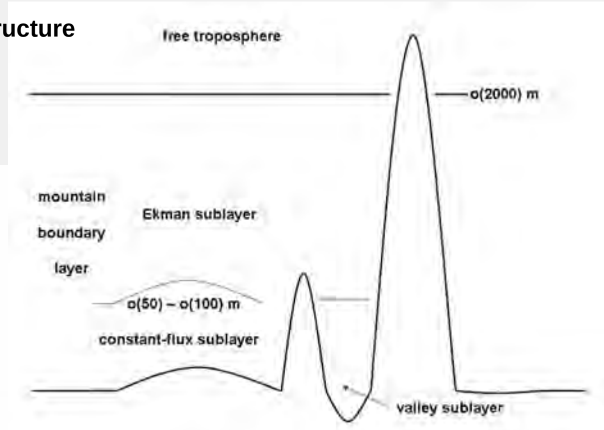
**Complex terrain**

**impact on boundary-layer structure**

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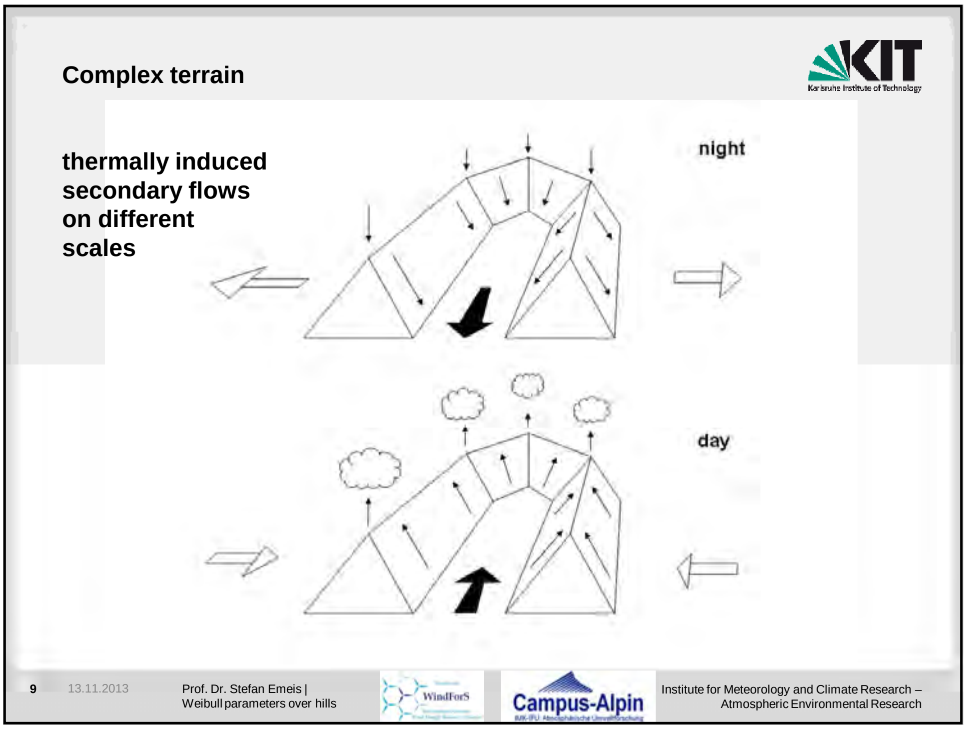
Complex terrain
thermally induced secondary flows on different scales
night
day
9
13.11.2013
Prof. Dr. Stefan Emeis | Weibull parameters over hills
WindForS
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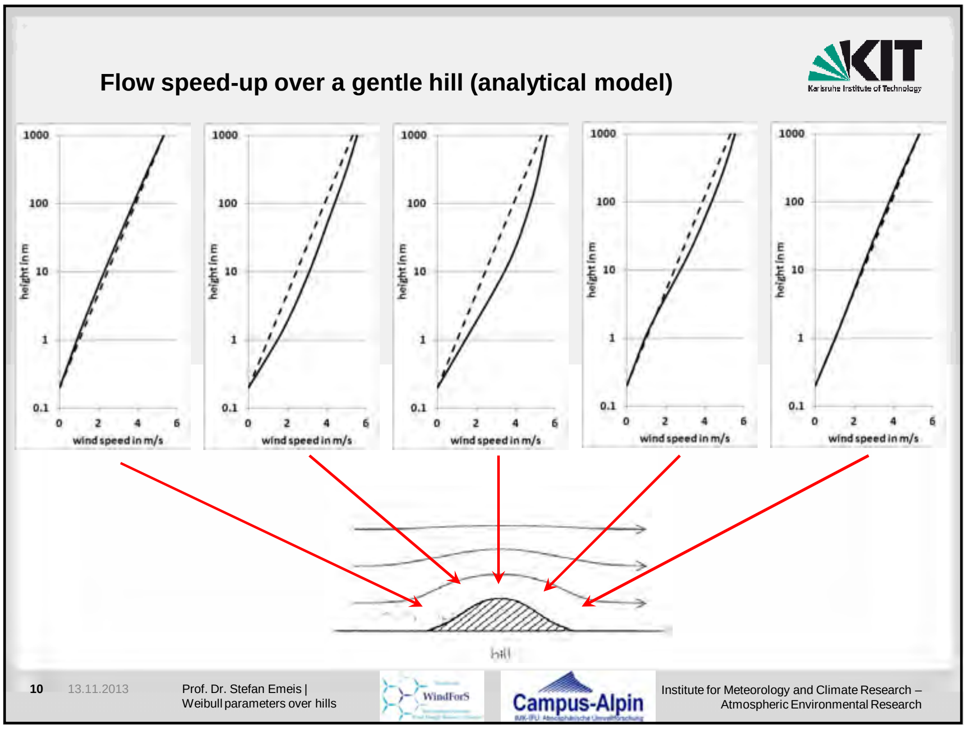
Flow speed-up over a gentle hill (analytical model)
1000
100
10
1
0.1
height in m
wind speed in m/s
0
2
4
6
hill
10
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## Flow speed-up over a gentle hill (analytical model)

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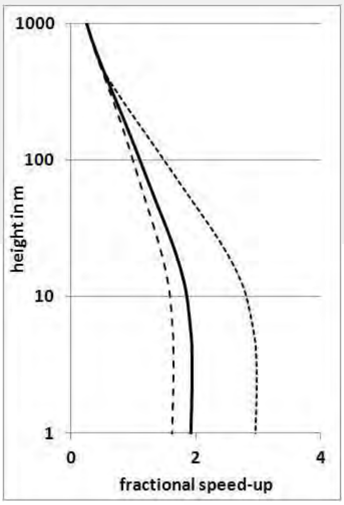
as function of thermal stability

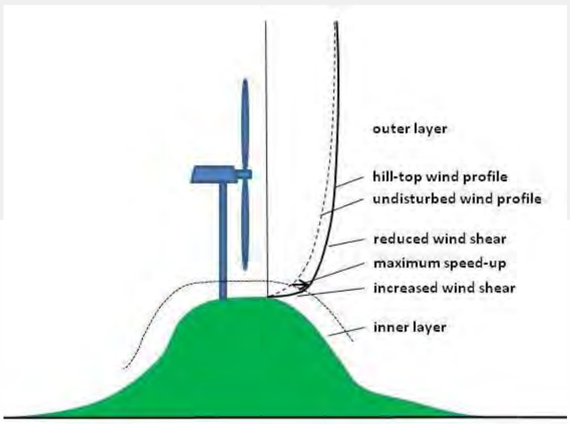
short dash: stable
full: neutral
dash: unstable



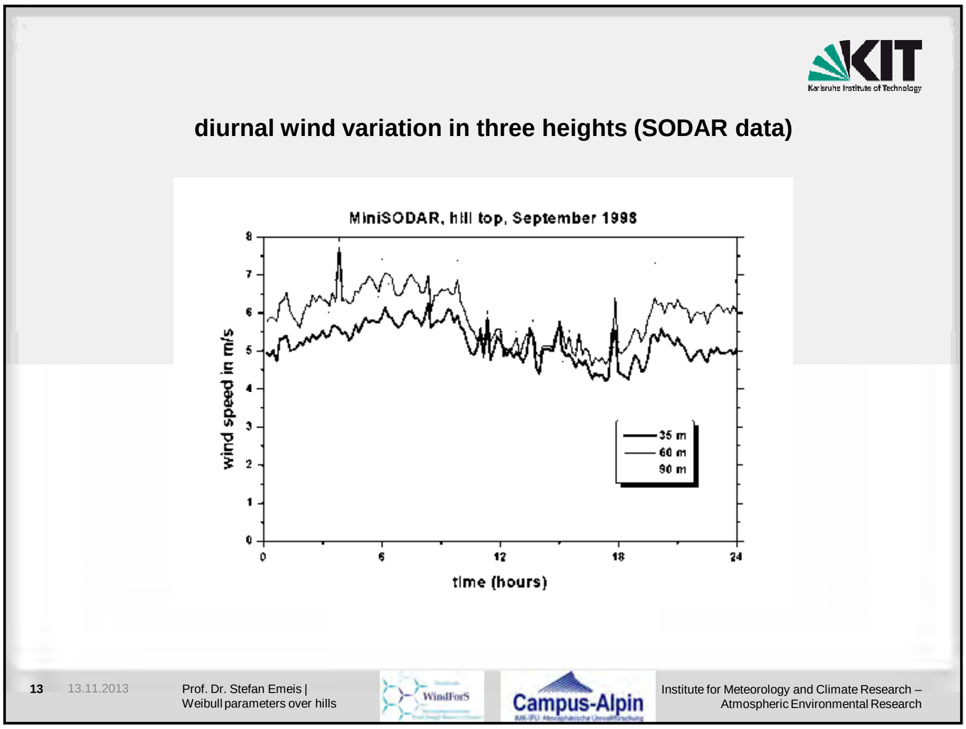

11 13.11.2013 Prof. Dr. Stefan Emeis | Weibull parameters over hills — WindForS — Campus-Alpin — Institute for Meteorology and Climate Research – Atmospheric Environmental Research

## Flow speed-up over a gentle hill

KIT Karlsruhe Institute of Technology




12 13.11.2013 Prof. Dr. Stefan Emeis | Weibull parameters over hills — WindForS — Campus-Alpin — Institute for Meteorology and Climate Research – Atmospheric Environmental Research


diurnal wind variation in three heights (SODAR data)
MiniSODAR, hill top, September 1998
wind speed in m/s
time (hours)
35 m
60 m
90 m
13
13.11.2013
Prof. Dr. Stefan Emeis |
Weibull parameters over hills
Campus-Alpin
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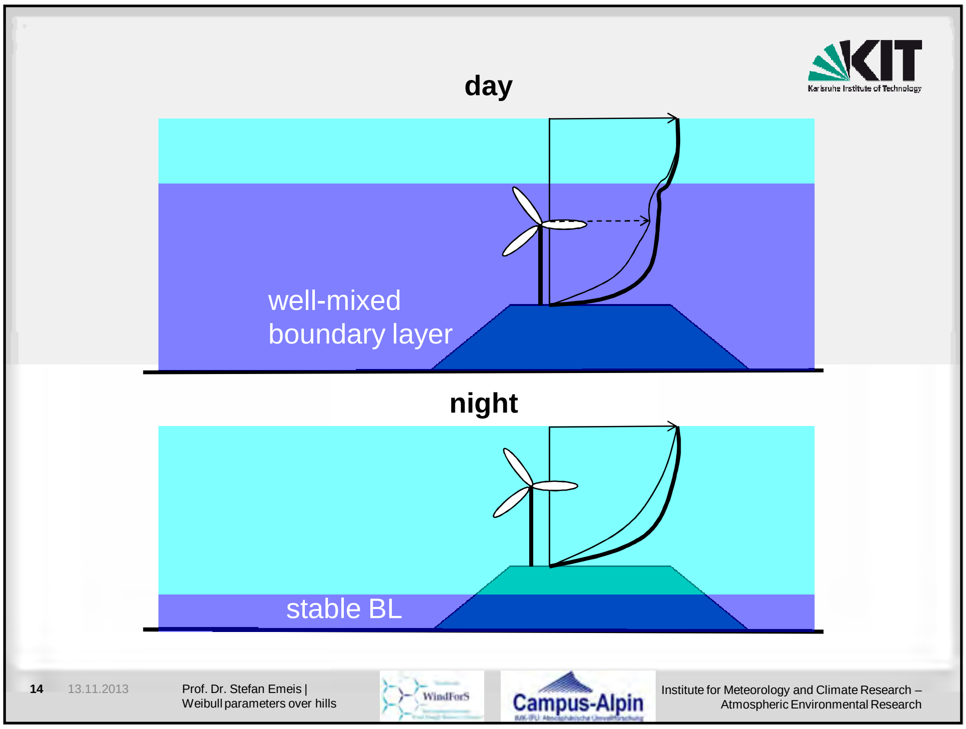
Atmospheric Environmental Research


day
well-mixed
boundary layer
night
stable BL
14
13.11.2013
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Weibull parameters over hills
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## Flow over a gentle hill (SODAR data and empirical relations)

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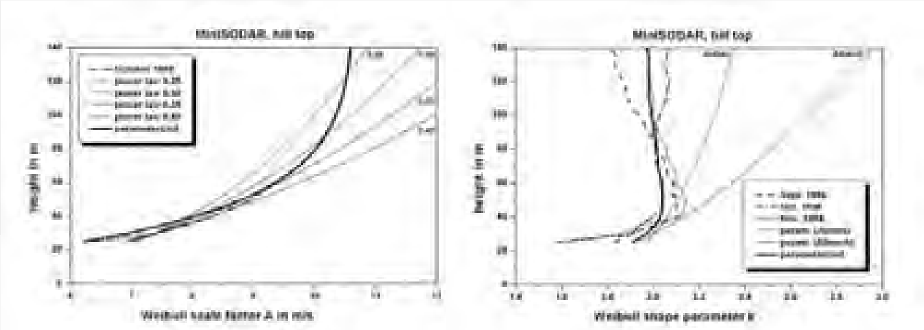


**Weibull scale parameter**
**($A_0$ = 10.67 m/s, $\gamma$ = 0.035)**

$$A(z) = A_0\left(1 - e^{-\gamma z}\right)$$

**Weibull form parameter**
**($z_A$ = 10 m, $z_m$ = 50 m, $c_2$ = 0.01)**

$$k(z) - k_A = c_2\left(z - z_A\right)\exp\left(-\frac{z - z_A}{z_m - z_A}\right)$$

**following Wieringa (1988)**



## Summary

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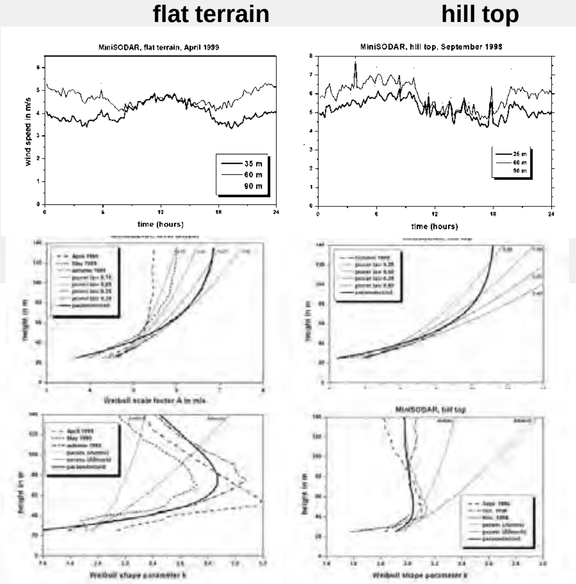
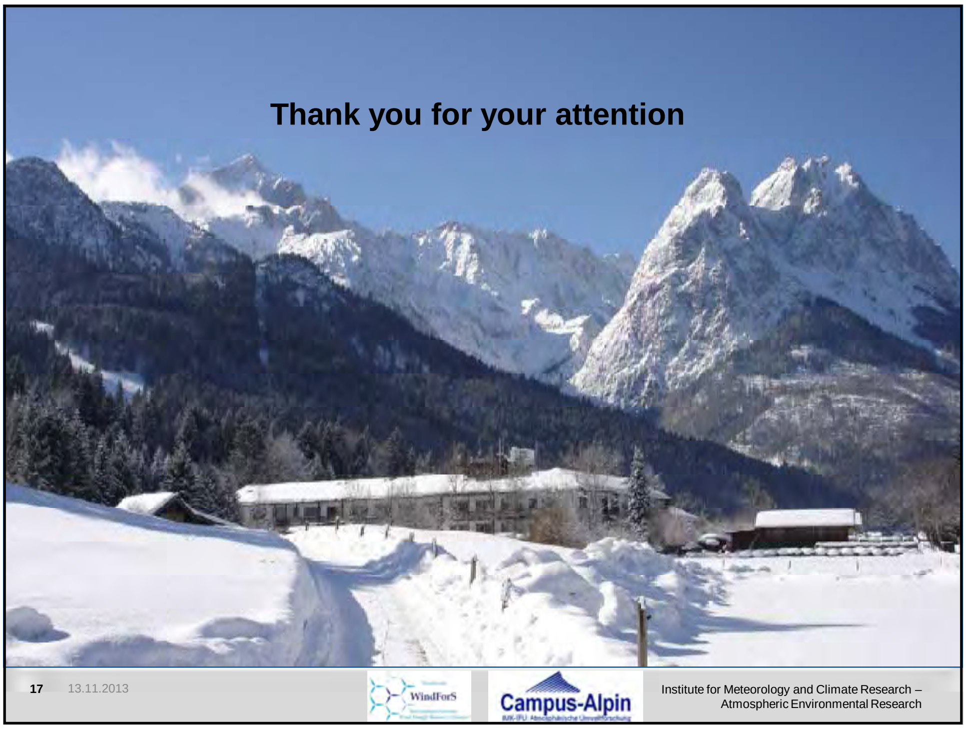
**flat terrain** **hill top**




**diurnal wind variation**

**scale parameter**

**form parameter**


Thank you for your attention
17
13.11.2013
WindForS
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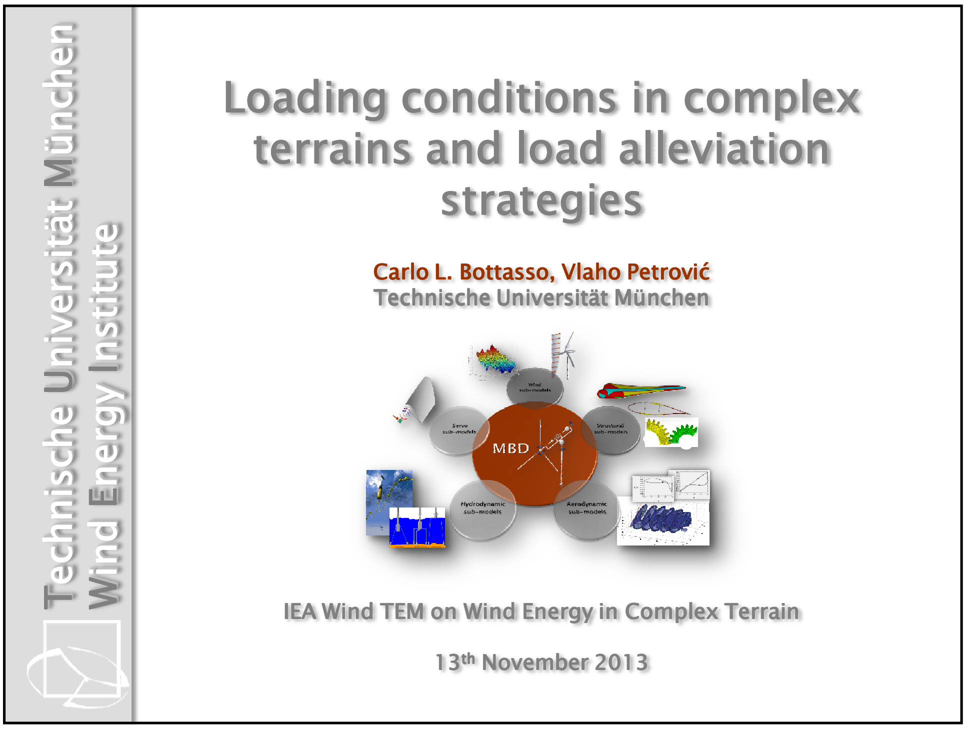
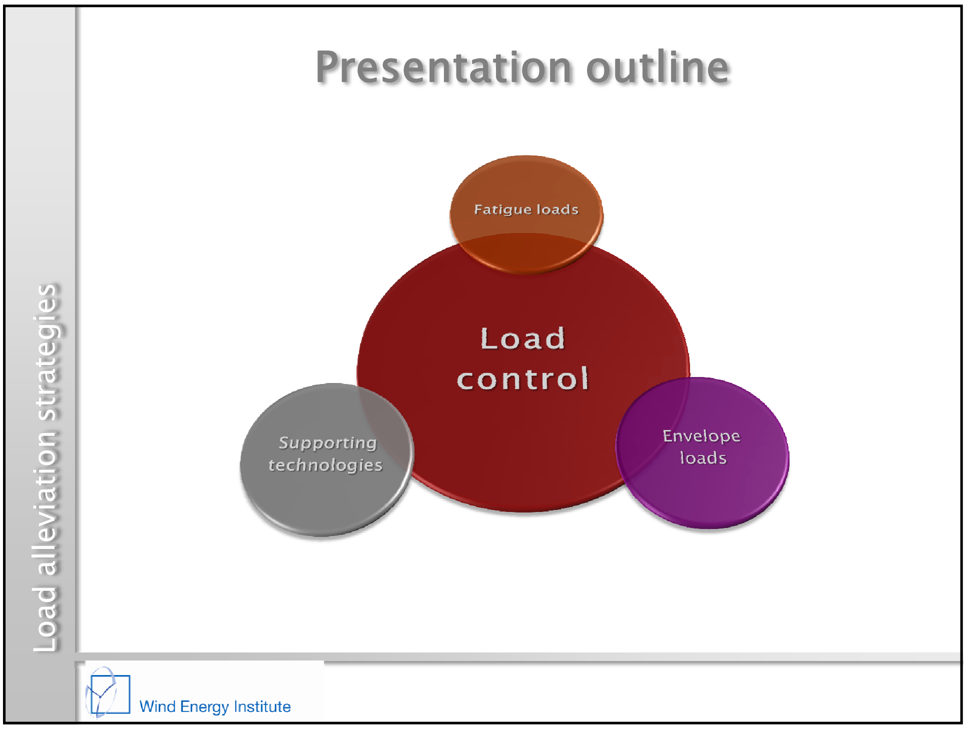
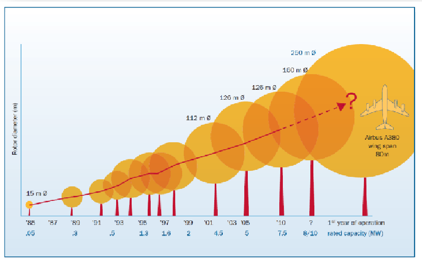

Technische Universität München
Wind Energy Institute
Loading conditions in complex terrains and load alleviation strategies
Carlo L. Bottasso, Vlaho Petrović
Technische Universität München
MBD
IEA Wind TEM on Wind Energy in Complex Terrain
13th November 2013


Load alleviation strategies
Presentation outline
Fatigue loads
Load control
Supporting technologies
Envelope loads
Wind Energy Institute

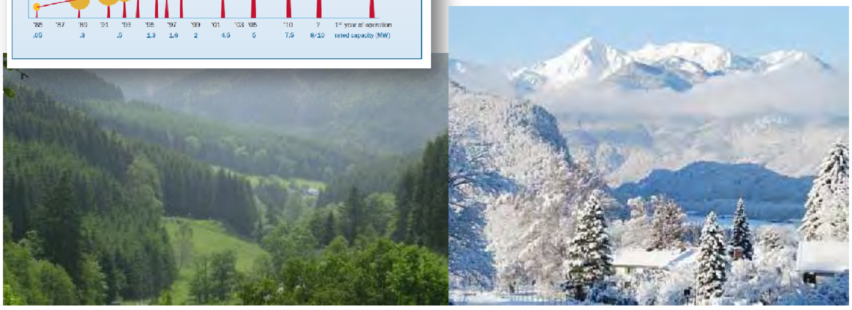
Load alleviation strategies

# Motivation: Need for Load Mitigation



**To decrease cost of energy:**

- Reduce extreme loads
- Reduce fatigue damage
- Limit actuator duty cycle
- Ensure high reliability/availability



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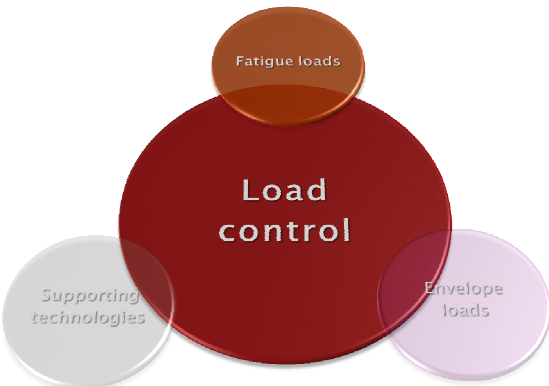
Load alleviation strategies

# Design-Driven Control

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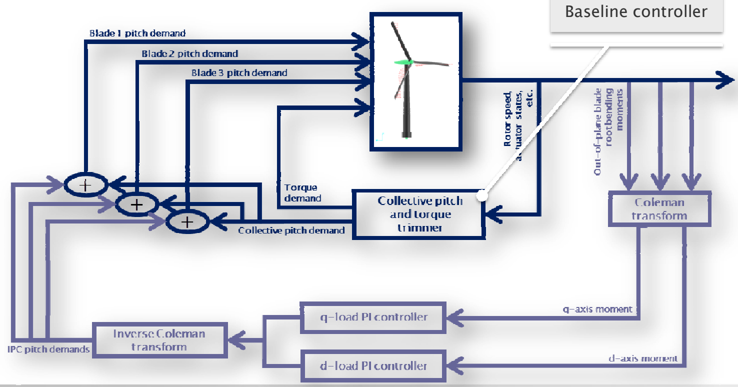
Load alleviation strategies

## Individual pitch control and Higher harmonic control

**Individual blade pitch** controller (Bossanyi 2003):

- Coleman transform blade root loads
- PID control for transformed d-q loads
- Inverse-Coleman-transform to get pitch inputs

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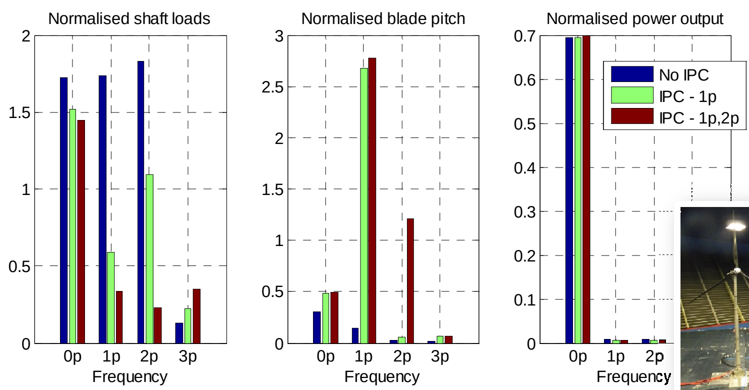
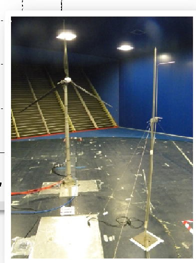
Load alleviation strategies

## Individual pitch control and Higher harmonic control

The same control concept used for alleviation of any load harmonic

Experimental results on model wind turbine



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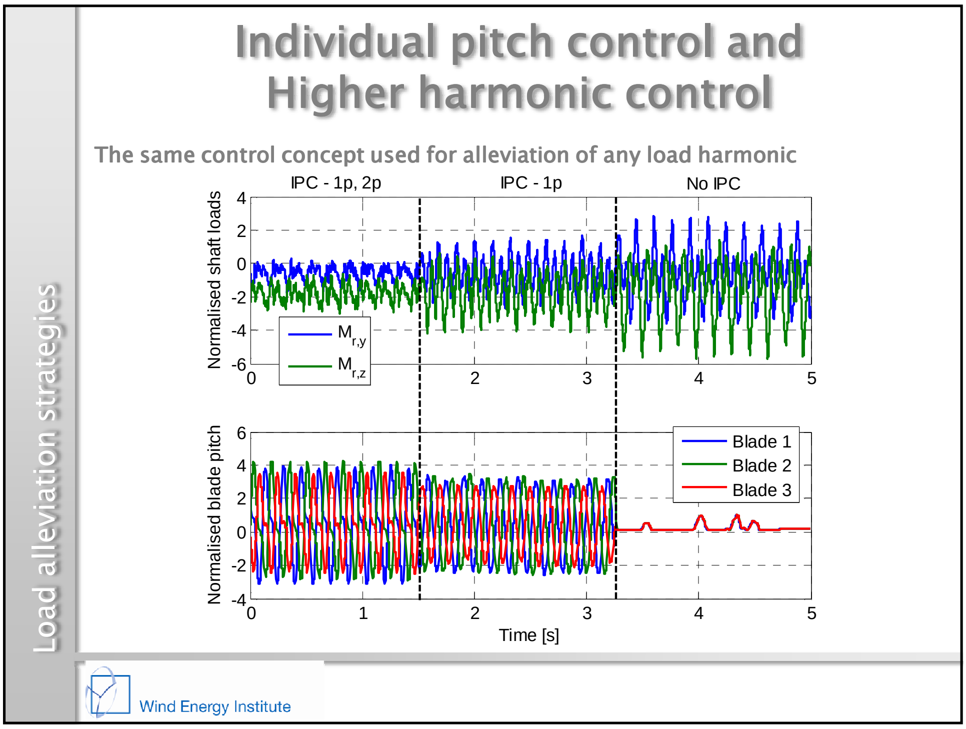
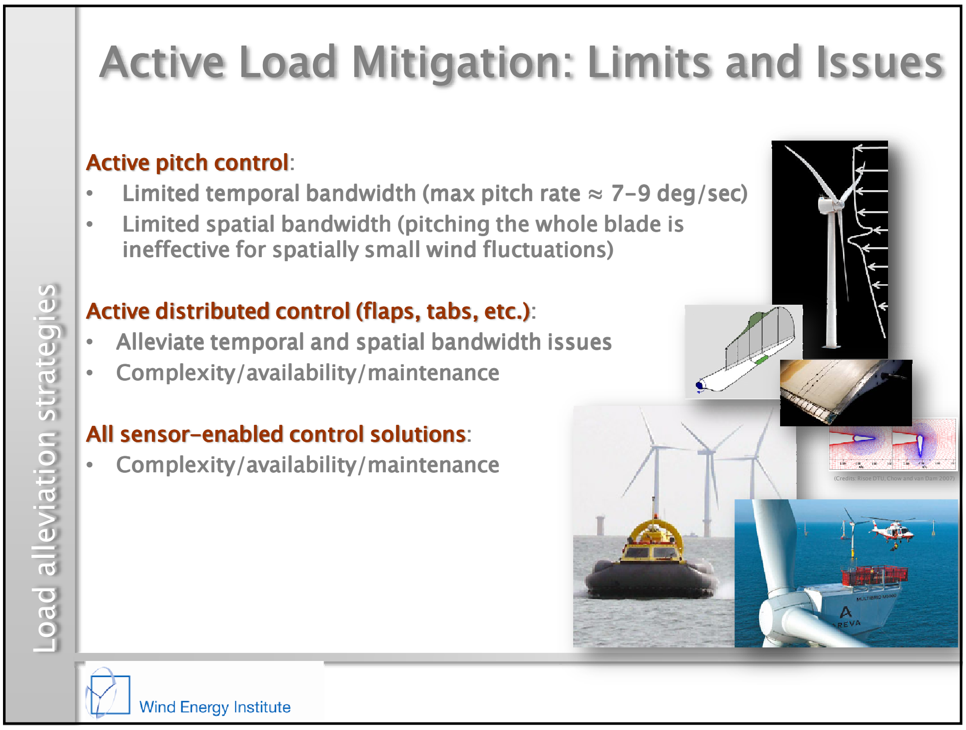

Individual pitch control and
Higher harmonic control
The same control concept used for alleviation of any load harmonic
IPC - 1p, 2p
IPC - 1p
No IPC
Normalised shaft loads
M r,y
M r,z
Normalised blade pitch
Blade 1
Blade 2
Blade 3
Time [s]
Load alleviation strategies
Wind Energy Institute


Active Load Mitigation: Limits and Issues
Active pitch control:
• Limited temporal bandwidth (max pitch rate ≈ 7-9 deg/sec)
• Limited spatial bandwidth (pitching the whole blade is ineffective for spatially small wind fluctuations)
Active distributed control (flaps, tabs, etc.):
• Alleviate temporal and spatial bandwidth issues
• Complexity/availability/maintenance
All sensor-enabled control solutions:
• Complexity/availability/maintenance
Load alleviation strategies
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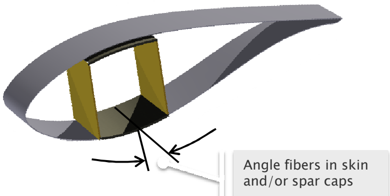
Load alleviation strategies

# Passive Load Mitigation

**Passive control**: loaded structure deforms so as to reduce load

**Two main solutions**:

- **Bend-twist coupling** (BTC): exploit anisotropy of composite materials




- **Swept** (scimitar) **blades**

**Potential advantages**: no actuators, no moving parts, no sensors (if you do not have them, you cannot break them!)

Other passive control technologies (not discussed here):

- Tuned masses (e.g. on off-shore wind turbines to damp nacelle-tower motions)
- Passive flaps/tabs
- …

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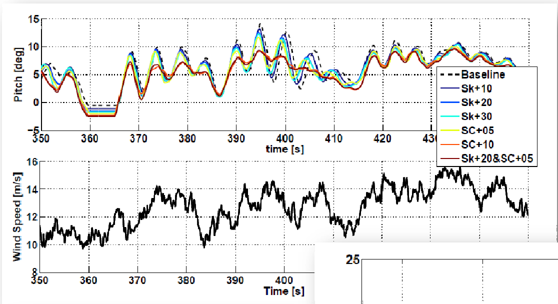
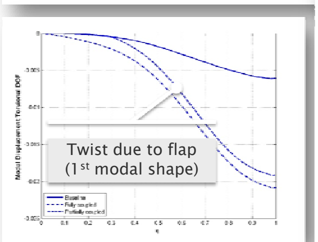
Load alleviation strategies

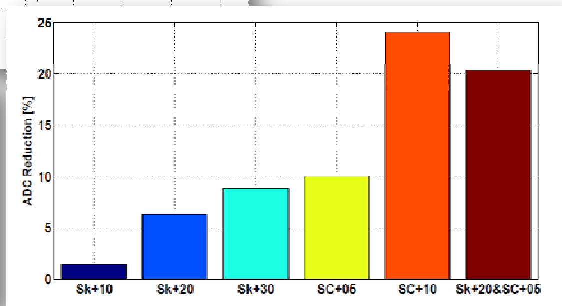
# Effects on Duty Cycle




◄ **Less pitching** from active control because blade passively self-unloads




Much reduced life-time ADC ▼

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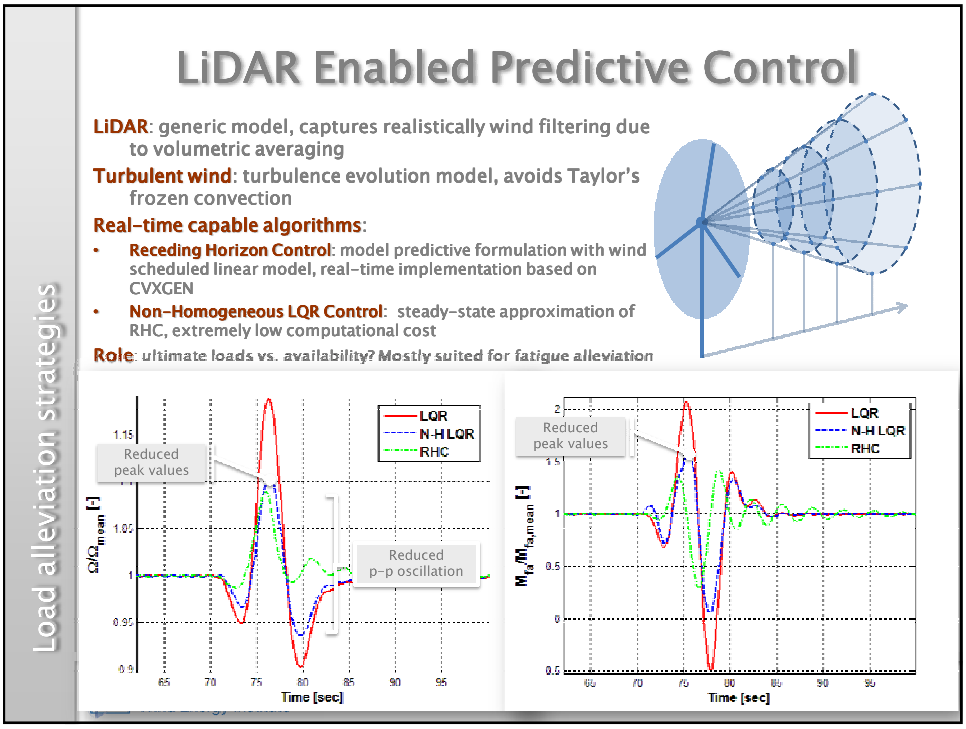
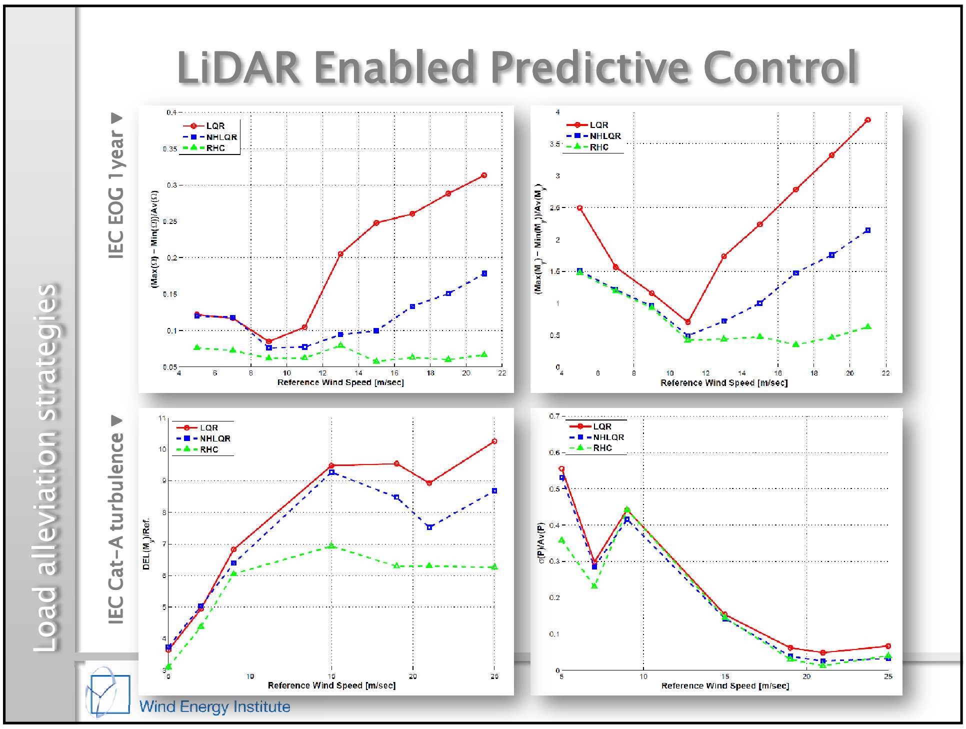
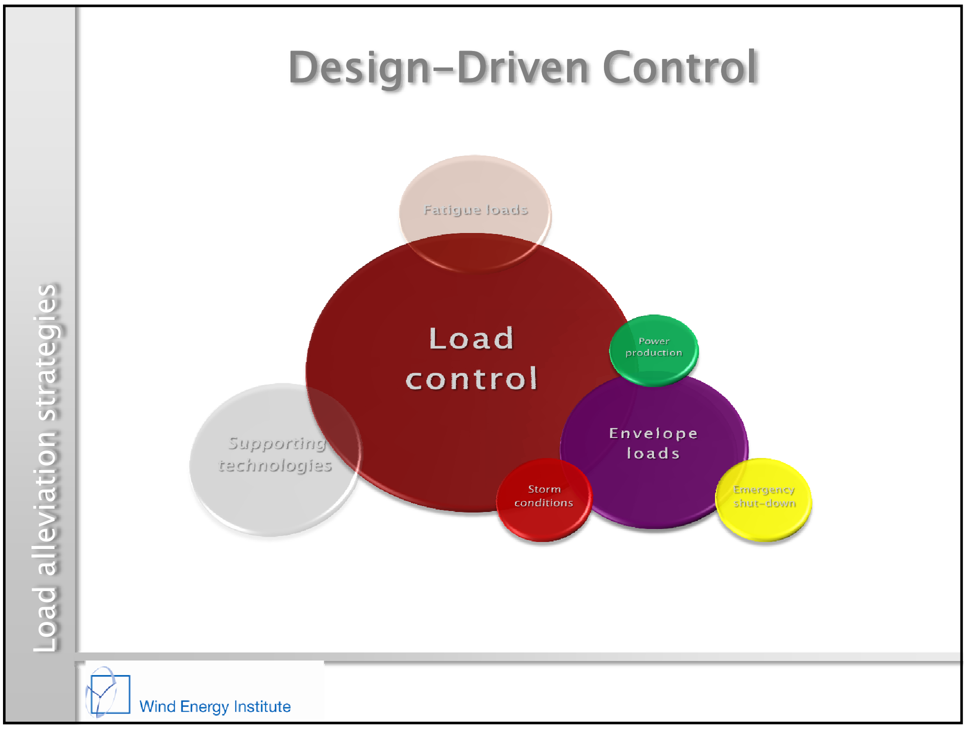
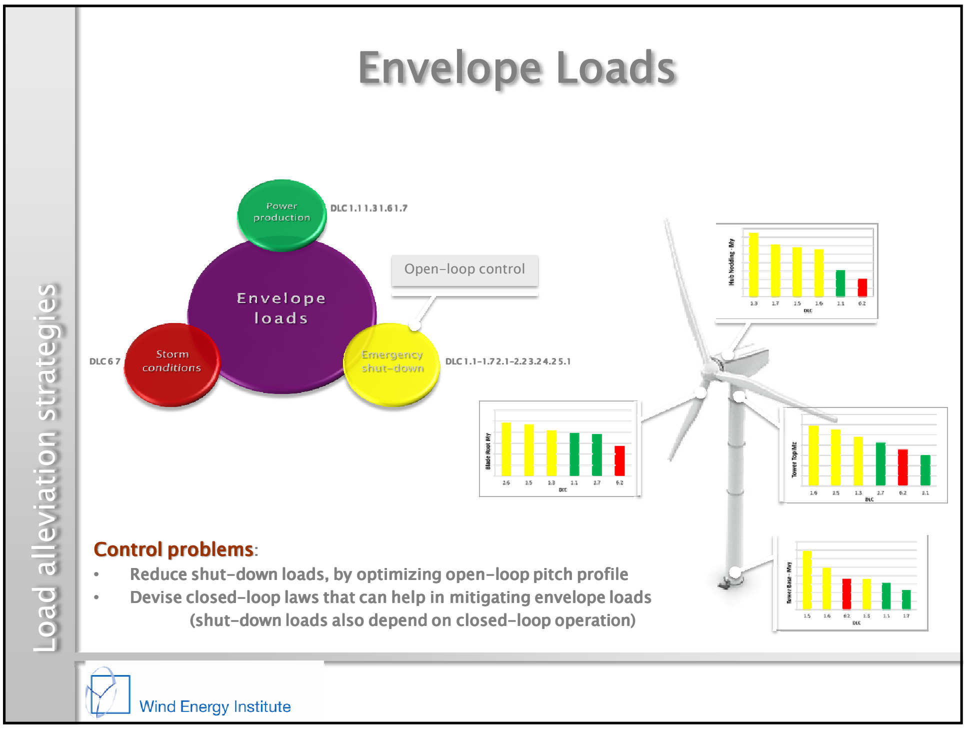

LiDAR Enabled Predictive Control
LiDAR: generic model, captures realistically wind filtering due to volumetric averaging
Turbulent wind: turbulence evolution model, avoids Taylor's frozen convection
Real-time capable algorithms:
• Receding Horizon Control: model predictive formulation with wind scheduled linear model, real-time implementation based on CVXGEN
• Non-Homogeneous LQR Control: steady-state approximation of RHC, extremely low computational cost
Role: ultimate loads vs. availability? Mostly suited for fatigue alleviation
Load alleviation strategies
Reduced peak values
Reduced p-p oscillation
LQR
N-H LQR
RHC
Time [sec]


LiDAR Enabled Predictive Control
Load alleviation strategies
IEC EOG 1 year
IEC Cat-A turbulence
LQR
NHLQR
RHC
Reference Wind Speed [m/sec]
Wind Energy Institute


Design–Driven Control
Fatigue loads
Load control
Power production
Envelope loads
Supporting technologies
Storm conditions
Emergency shut–down
Load alleviation strategies
Wind Energy Institute


Envelope Loads
Power production
DLC 1.1 1.3 1.6 1.7
Open–loop control
Envelope loads
DLC 6 7
Storm conditions
Emergency shut–down
DLC 1.1–1.7 2.1–2.2 3.2 4.2 5.1
Control problems:
• Reduce shut–down loads, by optimizing open–loop pitch profile
• Devise closed–loop laws that can help in mitigating envelope loads (shut–down loads also depend on closed–loop operation)
Load alleviation strategies
Wind Energy Institute

Load alleviation strategies

## Optimization of Open–Loop Pitch Profiles

**Remark**:
Some envelope design–driving loads are generated during emergency shutdowns (example: EOG 1yr, EOG 50 yr, ECD, NTM, DLCs 1.1–1.7 2.1–2.2 3.2 4.2 5.1)

**Need**: find optimal open–loop pitch profile
Considerations:

- Account for both loading and overspeed
- No need to reduce loads passed next dominating load in sorting
- Account for multiple wind speeds and fault times

**Approach**:

- Parameterize open loop pitch profile time history
- Formulate as constrained optimal control problem
- Solve using shooting approach + sequential quadratic programming (SQP) with automatic differentiation (applicable to arbitrarily complex black–box WT simulators)

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Load alleviation strategies

## Optimization of Open–Loop Pitch Profiles

**Optimal control problem**:

Minimize loads and overspeed

$$\min_{\beta(t)} \sum_{i=1}^{N} \left( \left( \max_t M_i(t) \right)^2 + w \left( \max_t \Omega_i(t) \right)^2 \right)$$

$$\max_i \max_t M_i(t) \le M_{\text{lim}}$$ No need to reduce past next envelope load

$$\max_i \max_t \Omega_i(t) \le \Omega_{\max}$$ Limit overspeed to desired value

$$\max_t \dot{\beta} \le \dot{\beta}_{\max}$$ Limit max pitch rate

$$\min_t \dot{\beta} \ge 0$$

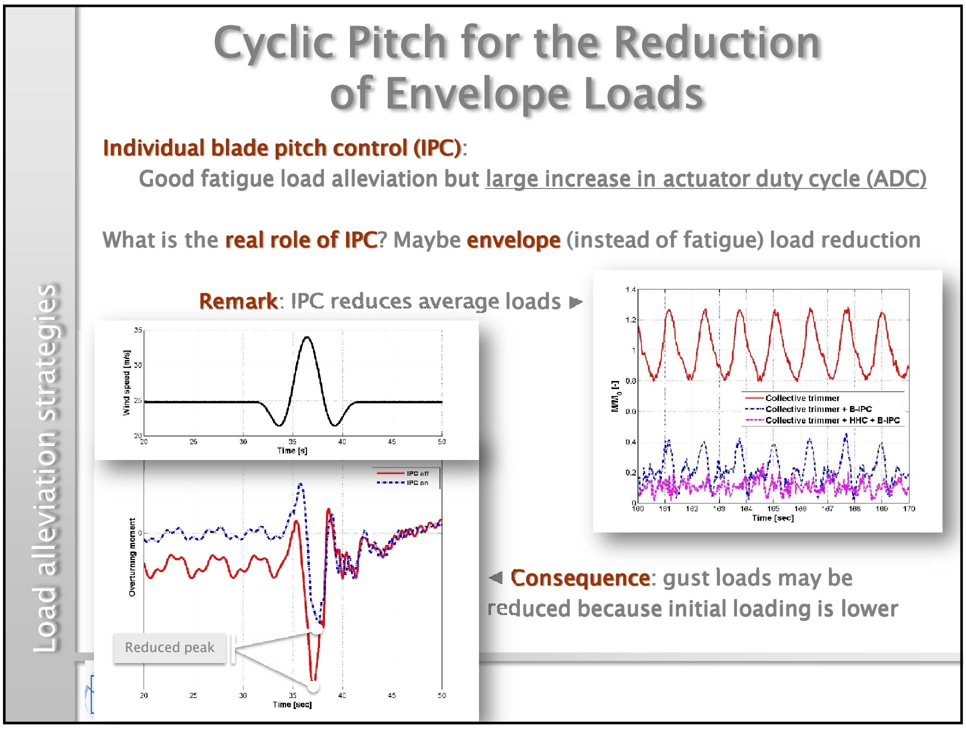
DLCs: **EOG 1yr**, **EOG 50 yr**, **ECD**, **NTM**, …

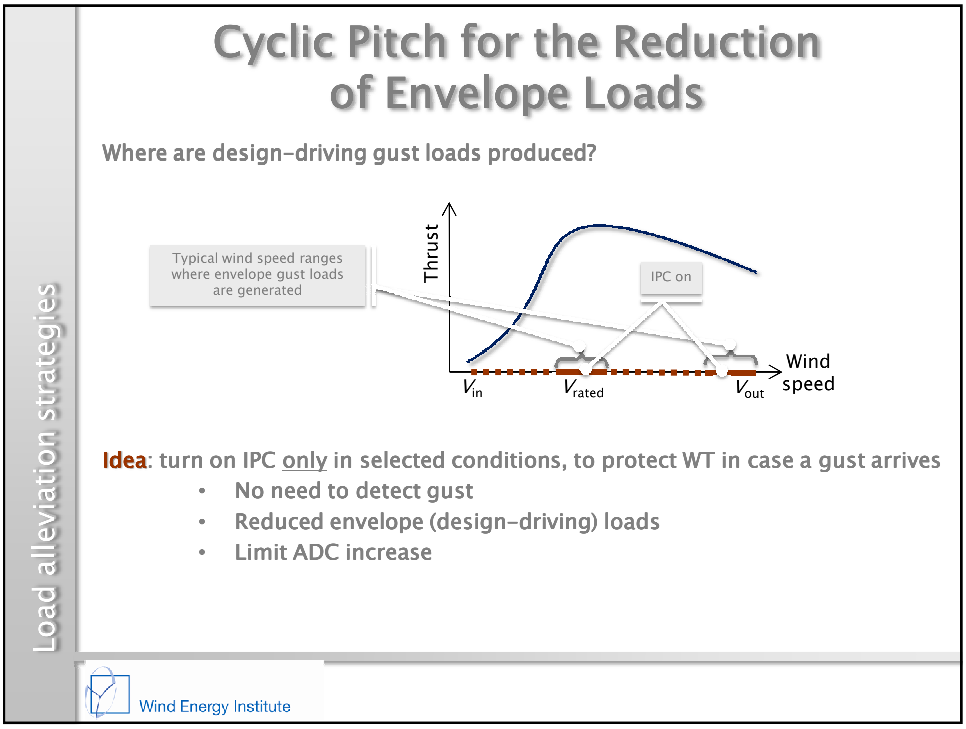
- Multiple reference wind speeds
- Multiple fault times (max wind speed, max wind speed rate, …)
- $N$ = several tens (e.g. 30÷50)

**Parameterized pitch profile** (example):

$$\beta(t) = \beta(0) + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4$$

Wind Energy Institute


Cyclic Pitch for the Reduction of Envelope Loads
Individual blade pitch control (IPC):
Good fatigue load alleviation but large increase in actuator duty cycle (ADC)
What is the real role of IPC? Maybe envelope (instead of fatigue) load reduction
Remark: IPC reduces average loads ►
Collective trimmer
Collective trimmer + B-IPC
Collective trimmer + HHC + B-IPC
Time [sec]
Time [s]
IPC off
IPC on
Overturning moment
Reduced peak
Time [sec]
◄ Consequence: gust loads may be reduced because initial loading is lower
Load alleviation strategies


Cyclic Pitch for the Reduction of Envelope Loads
Where are design-driving gust loads produced?
Typical wind speed ranges where envelope gust loads are generated
Thrust
IPC on
Wind speed
$V_{in}$
$V_{rated}$
$V_{out}$
Idea: turn on IPC only in selected conditions, to protect WT in case a gust arrives
• No need to detect gust
• Reduced envelope (design-driving) loads
• Limit ADC increase
Load alleviation strategies
Wind Energy Institute

Load alleviation strategies

# Cyclic Pitch for the Reduction of Envelope Loads

**Example**: 3MW HAWT

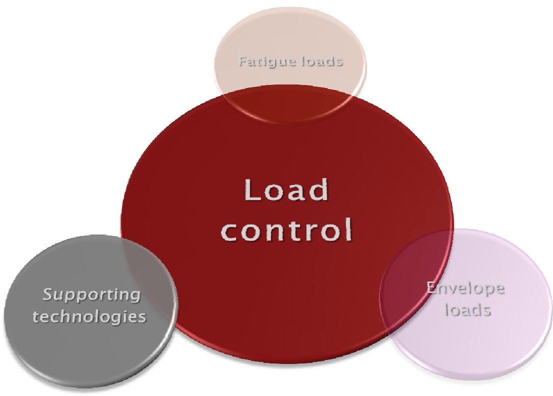
- Significant envelope reductions at hub and tower
- Little ultimate and fatigue load difference between IPC and Selective–IPC
- Noticeable ADC containment

| | LOADS | IPC Always on | Selective-IPC On @ rated & > 18 m/s |
|---|---|---|---|
| ULTIMATE | BLADE Root Moment | | |
| | Mx (Edge) | 2% | 2% |
| | My (Flap) | 4% | 4% |
| | Mz (Torsion) | -3% | -3% |
| | Mxy (Combined) | 2% | 2% |
| | HUB | | |
| | My (Nodding) | -19% | -19% |
| | Mz (Yawing) | -28% | -20% |
| | Myz (Combined) | -21% | -21% |
| | TOWER | | |
| | Mxy @ base (Combined) | 0% | 0% |
| | Mz @ top (Torsion) | -38% | -38% |
| FATIGUE | BLADE Root Moment | | |
| | Mx (Edge) | -0.9% | -0.7% |
| | My (Flap) | -7.4% | -5.0% |
| | Mxy (Combined) | -6.8% | -4.7% |
| | HUB | | |
| | My (Nodding) | -1.8% | -0.2% |
| | Mz (Yawing) | -0.7% | 0.2% |
| | Myz (Combined) | -5.0% | -2.5% |
| | TOWER | | |
| | Mxy @ base (Combined) | -1.5% | -1.7% |
| | Mz @ top (Torsion) | -0.8% | 0.2% |
| | AEP & ADC | | |
| | AEP | -0.4% | -0.4% |
| | ADC | 376% | 241% |

Wind Energy Institute

Load alleviation strategies

# Design–Driven Control

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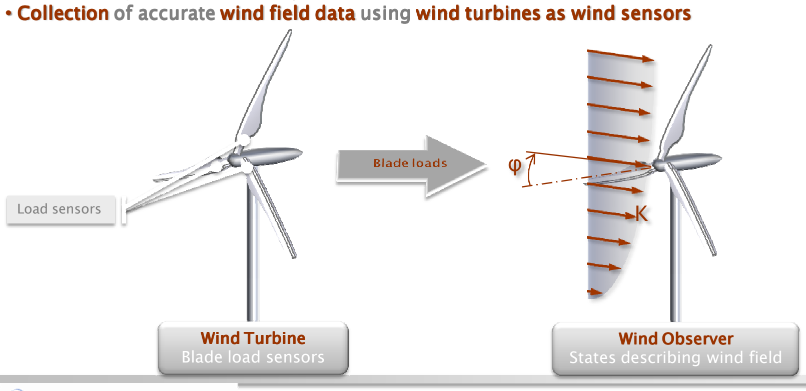
## Wind Observer: the Concept in a Nutshell

The rotor is the **ultimate anemometer**
By interpreting the rotor response, one can infer desired wind states (here: misalignment and vertical shear)

**Advantages**: rotor-effective non-local estimates

**Applications**:
- **Yaw** control, **feed forward** and/or **scheduled control laws**
- **Collection** of accurate **wind field data** using **wind turbines as wind sensors**




Load alleviation strategies

Wind Energy Institute

## Wind Observation from Blade Loads

**Linear input-output wind-scheduled model**: Wind-speed-dependent coefficients

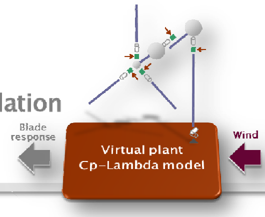
$$w = w_0(V) + A(V)m + B(V)q$$

Observed quantities $w$: cross-flow (wind misalignment) and shear

Driving inputs: – 1P blade root harmonics $m$
– yaw rate $q$ (gyroscopic correction)

**Procedure**:
1. Identify model from observations using Least-Squares
2. Measure loads on-line, demodulate by projection or Coleman-transform to get 1P harmonics
3. Observe cross-flow and shear

Validate concept by high-fidelity aeroelastic simulation

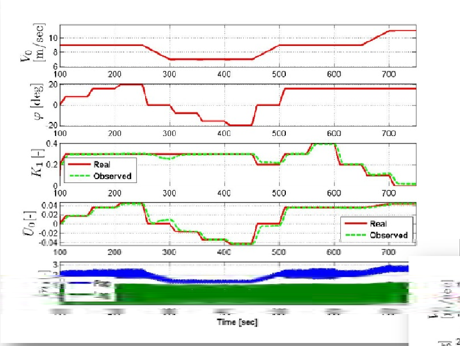



Load alleviation strategies

Wind Energy Institute

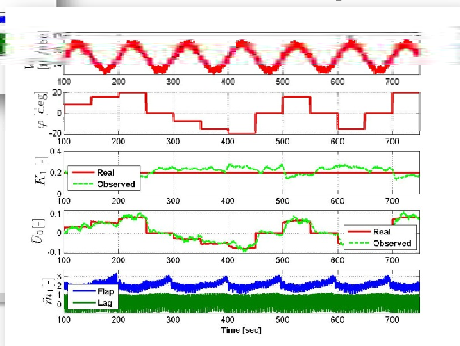
Load alleviation strategies

## Simulation Results




▲ Non-turbulent wind, simultaneous variation of wind speed, misalignment and shear

Turbulent wind, simultaneous variation of wind speed, misalignment and shear ▼




**Simulation**:
verification of simultaneous observability of yaw and shear

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Load alleviation strategies

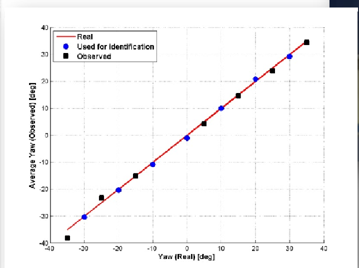
## Wind Tunnel Validation

Field testing is difficult: **ground truth**?

Wind tunnel testing:

- Known wind direction
- Probe-measured vertical shear


Validation:




◄ Real and observed wind misalignment

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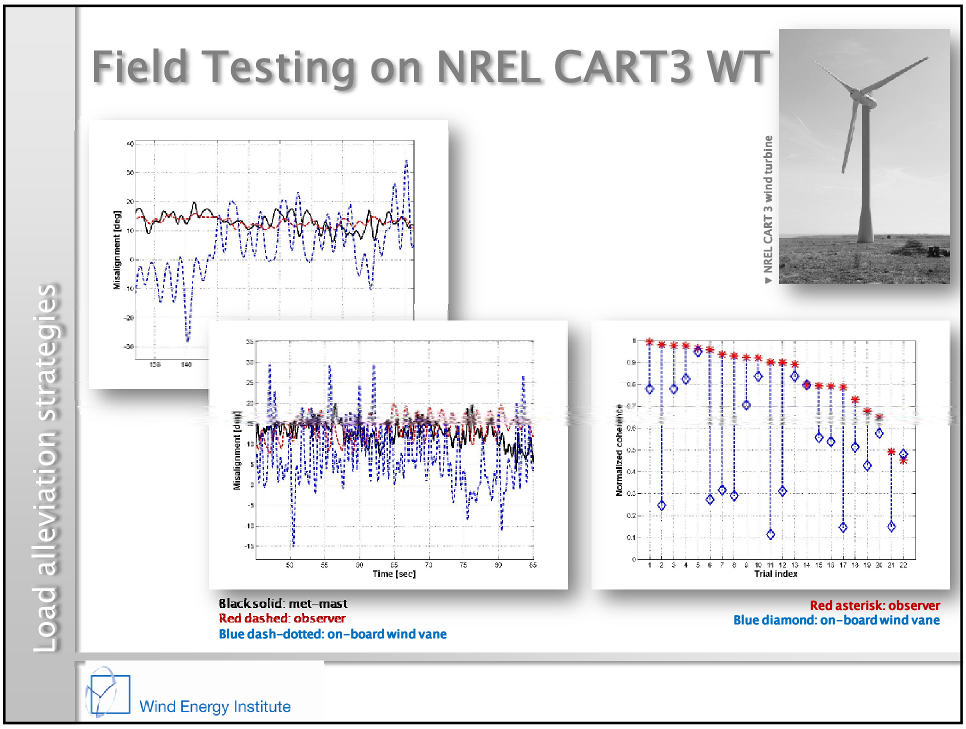

Load alleviation strategies
Field Testing on NREL CART3 WT
NREL CART 3 wind turbine
Misalignment [deg]
Time [sec]
Normalized coherence
Trial index
Black solid: met-mast
Red dashed: observer
Blue dash-dotted: on-board wind vane
Red asterisk: observer
Blue diamond: on-board wind vane
Wind Energy Institute


Load alleviation strategies
Thank you for your attention!
Fatigue loads
Load control
Supporting technologies
Envelope loads
Wind Energy Institute


WINDFORS
Wind Energy
Research Alliance

**IEA Task 11 Topical Expert Meeting: Wind energy in complex terrain**

## Overview of the Research Project „Lidar complex“ - Lidar, UAV and met mast measurements combined with CFD calculations

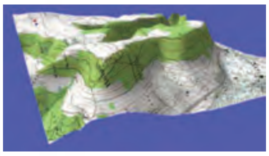
Martin Hofsäß, Dipl.-Ing.
SWE, University Stuttgart
November 12 – 13, 2013

WINDFORS
Wind Energy
Research Alliance

WindForS
Wind Energy
Research Alliance

## Table of contents





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Wind Energy
Research Alliance

## Project overview

A joint **WindForS** research project: „Development of lidar technologies to detect wind field structures in terms of optimizing the use of wind energy in the mountainous, complex terrain " at the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

Research project consists of 7 participants

Start date: Oktober 2012

Duration: 3 years

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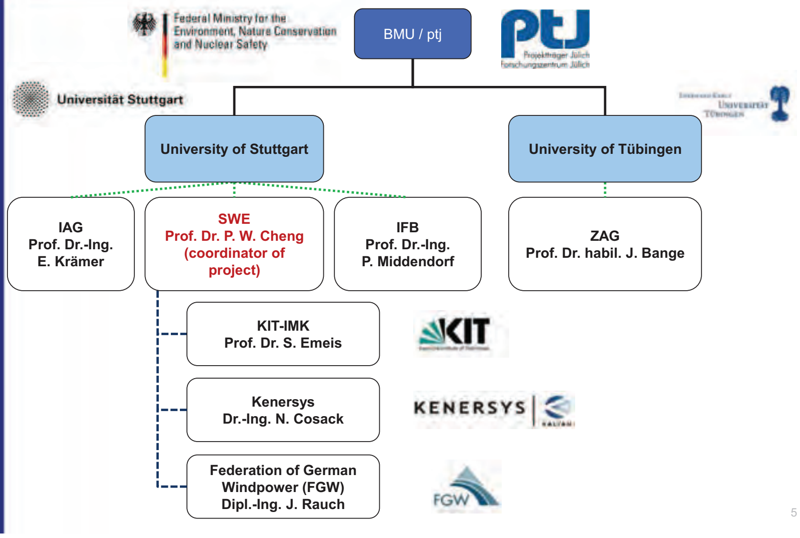
## Organisation of joint research project

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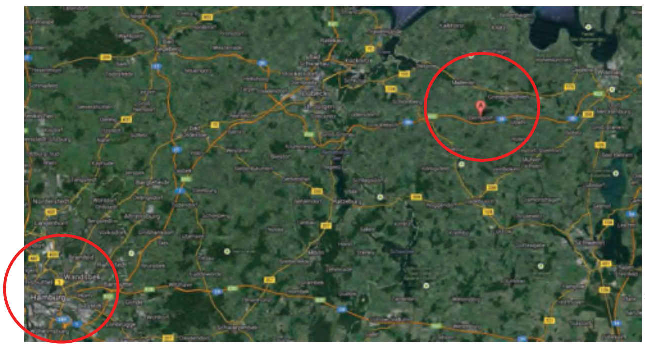
## Location of the “norm” test site

- Grevesmühlen (100km north-east of Hamburg)
- Flat terrain
- IEC 61400 conform site
- 95m high met mast



http://maps.google.de

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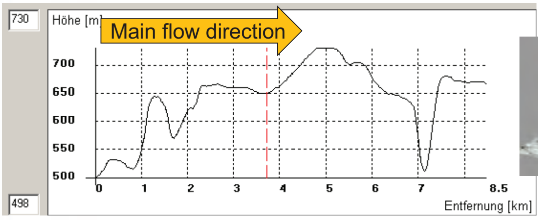
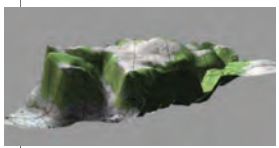
## Location of the "complex" test site

- Schnittlingen (55km east of Stuttgart)
- Location: Swabian Alb

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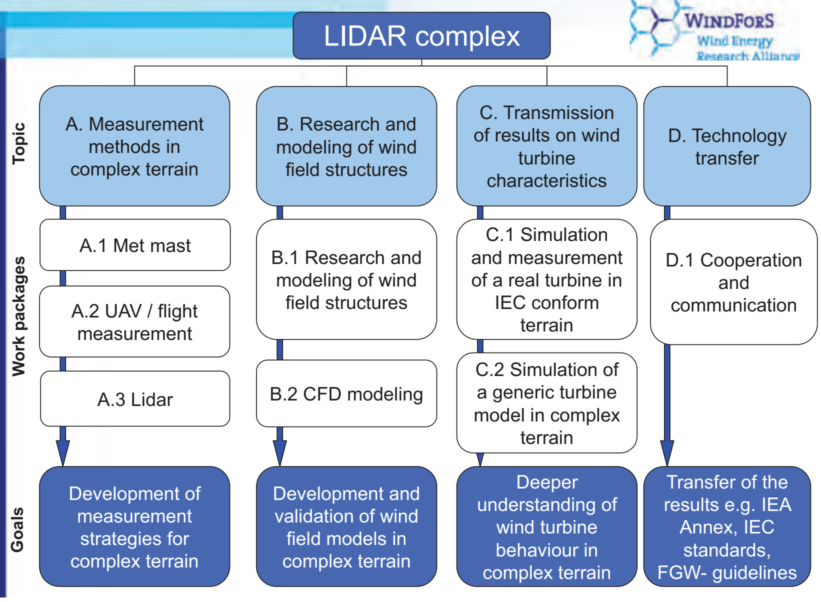

WINDFORS

## A. Measurement methods in complex terrain

- **Standard IEC met mast 100m**
  - equipped with standard sensors (cup anemometers, sonic anemometers, temperature and pressure sensors)
- **Lidar**
  - Nacelle and ground based use of SWE Lidarscanner (short range)
  - 2x Long range Scanner (Galion)
- **UAV - Unmanned Aerial Vehicle**
  - Aircraft
    - Wind speed and direction: 5 hole sensor
    - Metrological Data
    - 100 Hz data acquisition
  - 1x Helicopter
    - Sonic anemometer (e.g. Metek scientific)
    - Metrological Data
    - 50 Hz data acquisition


ZAG

IFB

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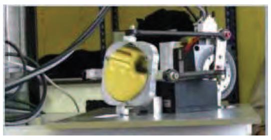
Research Alliance

## Used Lidar-Systeme




[SWE]

[ZAG]

- 2 x Galion long-range Lidars (SWE, KIT)
- 1 x ground base short-range Lidar
- 1 x short-range Lidar-Scanner, installed on the Nacelle of the Kenersys K110 (SWE)

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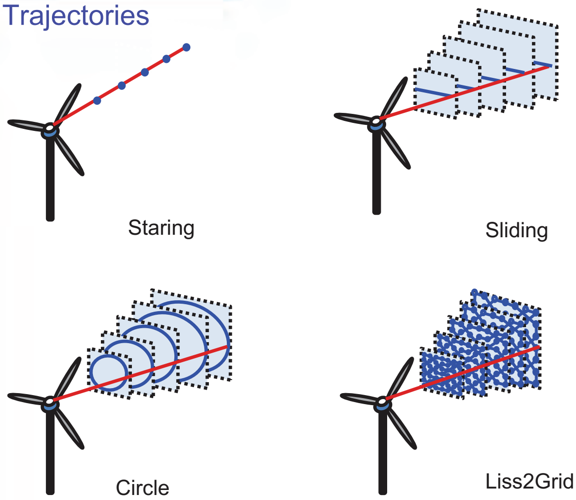
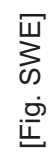
WindForS Wind Energy Research Alliance

## Main Trajectories

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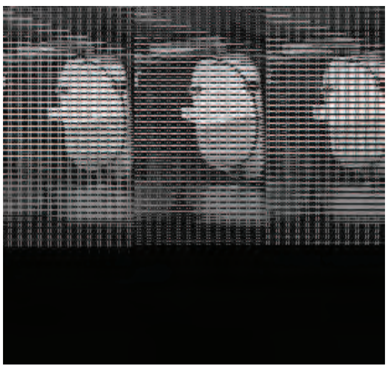
WindForS Wind Energy Research Alliance

## Nacelle-based LiDAR measurements

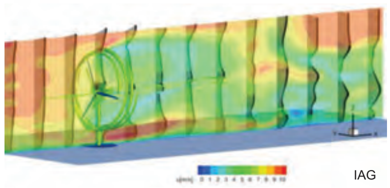


[Fig. SWE]

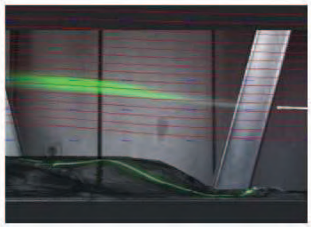
## B. Research and modeling of wind field structures

- CFD modeling of a complex location
- Modeling and measurement of the terrain in a wind tunnel

- Turbulence structure
- Daily and season-dependent differences in the complex location
- Horizontal and vertical wind field shear



IAG



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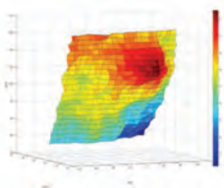
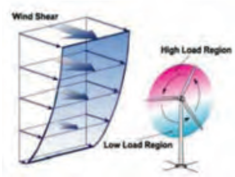
## C. Transmission of results on WT characteristics

- Development of a wind field generator, which use as **input real wind field** measurements (met mast, Lidar data (ground and nacelle based))
- Simulation of real turbine model with wind field generator and comparison with measured turbine loads and electrical power
  → proof of wind field generator
- Simulation of generic wind turbine models (1.5MW, 2.XMW, 5 MW) in a complex site using proved wind field generator and using measured Lidar, UAV and met mast data






HASEGAWA

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## D. Technology transfer (examples)

WindForS Wind Energy Research Alliance

**National**

FGW

- IG LIDAR
- FALK

HUSUM WindEnergy The Leading Wind Energy Trade Fair

HANNOVER MESSE

RAVE RESEARCH AT ALPHA VENTUS

DEWEK

**International**

iea wind

SARS

ewec Europe's premier wind energy event

EUROPEAN MECHANICS SOCIETY

Risø DTU National Laboratory for Sustainable Energy

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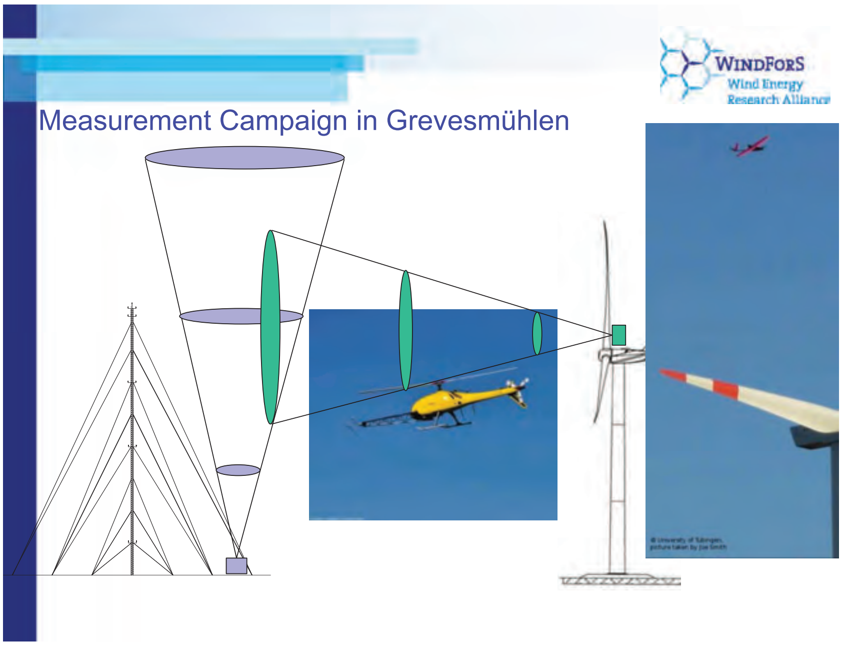
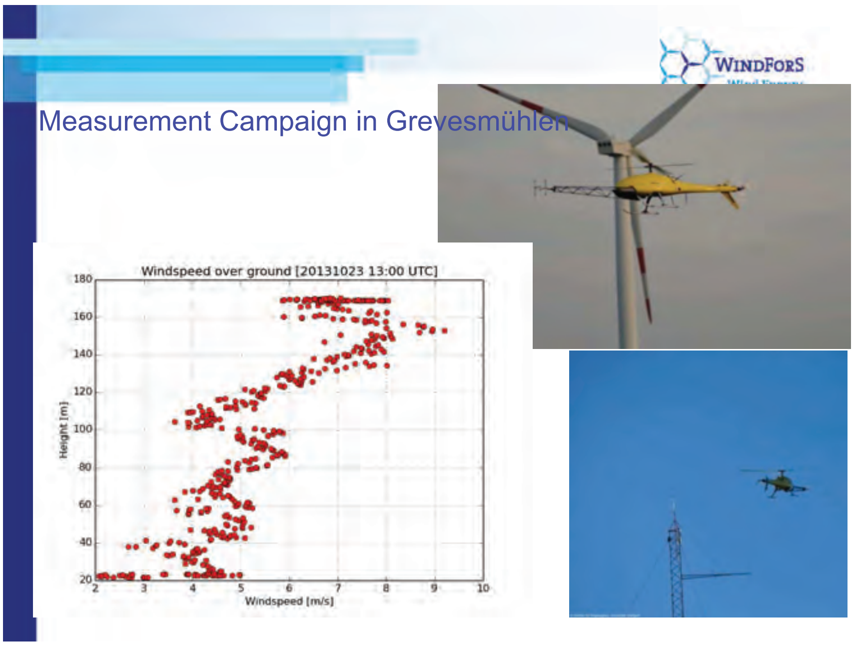
## Measurement Campaign in Grevesmühlen

WindForS Wind Energy Research Alliance


- 21. – 25. October 2013
- Vertical profiles with helicopter and airplane
- Correlation measurements helicopter and met mast
- Inflow and wake measurements with airplane


WINDFORS
Wind Energy
Research Alliance
Measurement Campaign in Grevesmühlen


WINDFORS
Measurement Campaign in Grevesmühlen
Windspeed over ground [20131023 13:00 UTC]
Height [m]
Windspeed [m/s]
180
160
140
120
100
80
60
40
20
2
3
4
5
6
7
8
9
10


## Thank you

Stuttgart Wind Energy (SWE)
Head of department: Prof. Dr. Po Wen Cheng

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Stuttgart Wind Energy at Institute of Aircraft Design
Stuttgart University - Allmandring 5B - D-70569 Stuttgart, Germany
Phone: +49 (0)711 / 6856 - 8308
Fax: +49 (0)711 / 6856 - 8293
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www.uni-stuttgart.de/windenergie

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## Wind field analysis and characterization of sound immission in the vicinity of wind turbines in topologically structured terrain

Jan Tessmer, Thomas Gerz

IEA R&D Wind Task 11 – TEM 75 on
"WIND ENERGY IN COMPLEX TERRAIN"

Stuttgart, 12./13.11.2013


DLR

## Topics

- DLR at short glance
- Research Alliance Windenergy
- DLR major activities in wind energy
- Focus on Wind in complex terrain

DLR

## German Aerospace Center (DLR)

- Research Institution
- Space Agency
- Project Management Agency

7400 employees across
32 institutes and facilities at

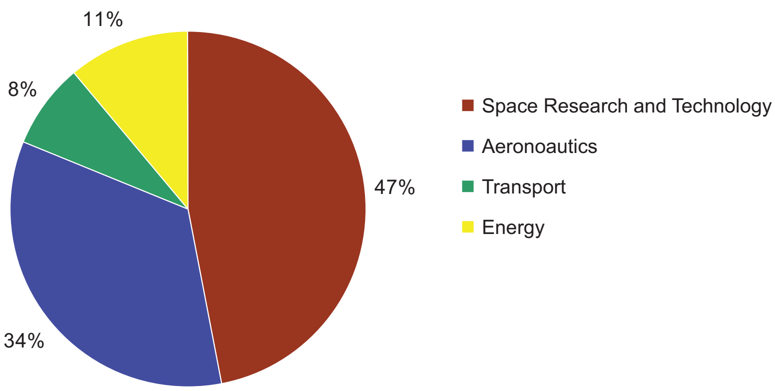
- 16 sites.


Offices in Brussels, Paris
Tokyo and Washington.

DLR

Slide 3

## Percentage of Overall Income from Research and Operations 2011




DLR

Slide 4

## Research Alliance Wind Energy

Research Alliance
Wind Energy

DLR Deutsches Zentrum für Luft- und Raumfahrt

ForWind

Fraunhofer IWES

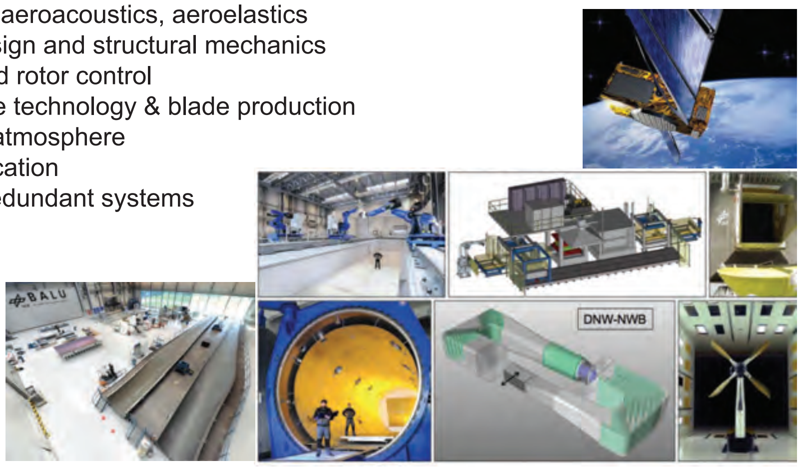
## Research Alliance Wind Energy

Research Alliance
Wind Energy

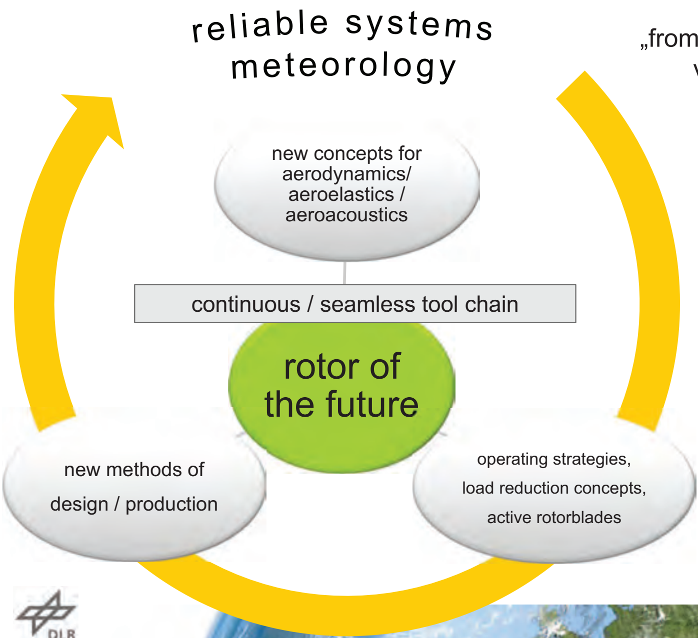
- 7 of 16 federal states
- 14 locations
- approx. 600 staff
- DLR (6 institutes)
- ForWind (26 institutes)
- IWES (10 departments)


## Wind Energy Research at DLR
Infrastructure & Know-how for Tomorrow's Energy Supply

**Transfer of Know-how from Aerospace:**
- Aerodynamics, aeroacoustics, aeroelastics
- Lightweight design and structural mechanics
- Adaptronics and rotor control
- Fiber composite technology & blade production
- Physics of the atmosphere
- System identification
- Reliabile and redundant systems



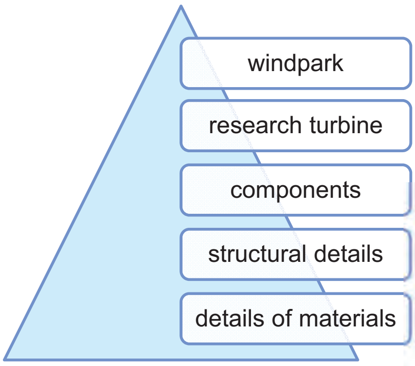

## DLR's Focus Within Wind Energy Research



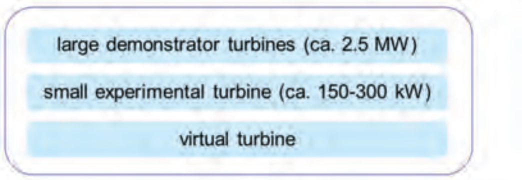

„from wind as a resource via rotor blades to the system"

## DLR Research Platform Wind Energy

In all topics, validation and confidence can only result from real, well-known and fully instrumented turbines of relevant size:

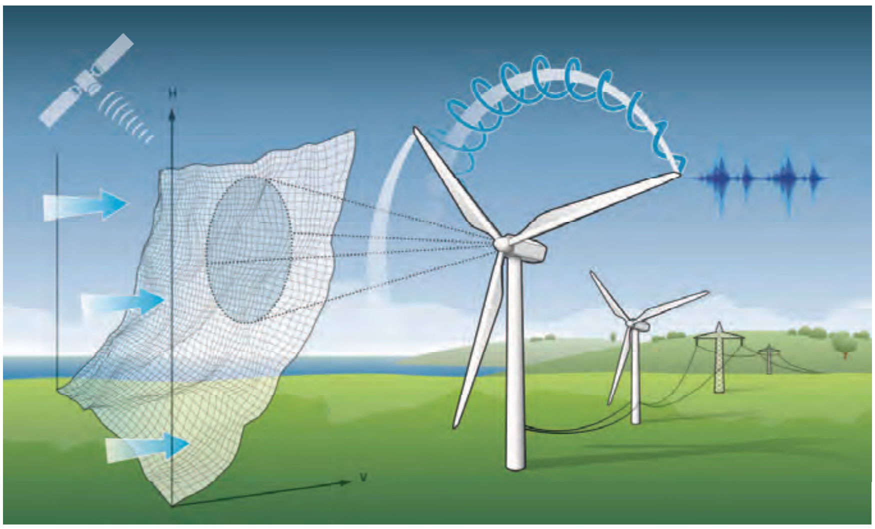



- Measurement and validation of measures and design changes
- Validation of measurement techniques for the wind field
- Holistic and exact modeling & calculation
- Concepts for reliability and redundancy




DLR

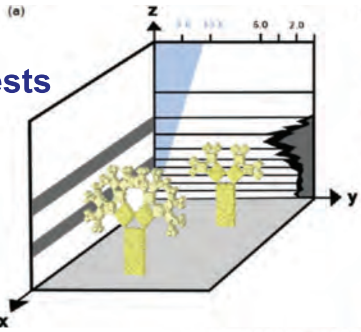
## Focus on Windenergy in complex terrain

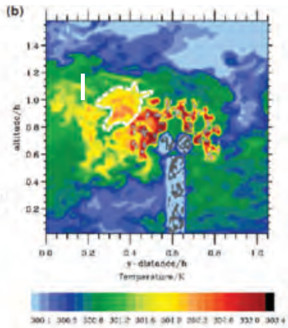


DLR

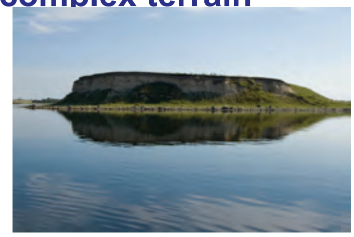
## Expertise: Simulation of boundary layer flows in complex terrain

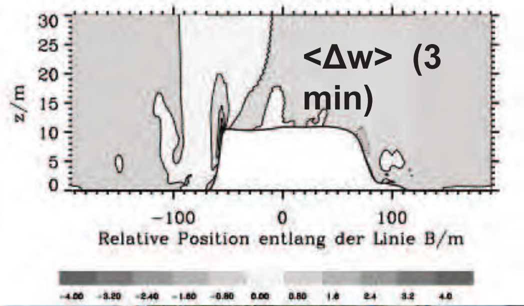
### LES of flows in forests



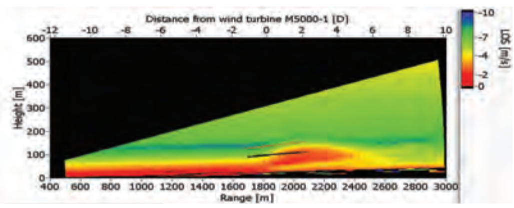

### LES of flows over complex terrain

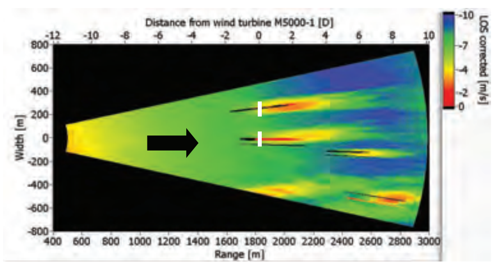




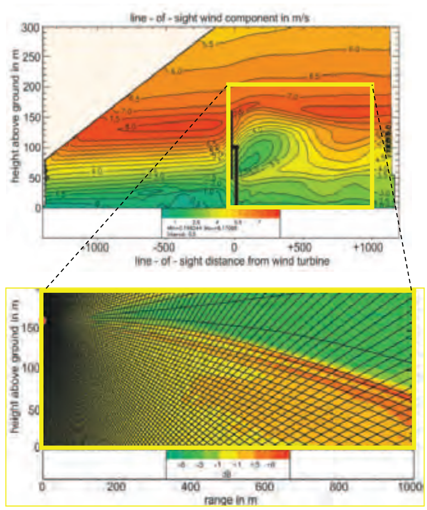

## Expertise:
## Measuring the wind und computation of sound transport

**Wind around a turbine with LIDAR**




**Quantifying the noise immission**



## Methods & Tools

### Simulation of boundary layer flow regimes in complex terrain

Large-eddy simulation code EULAG

### Remote-sensing and in-situ measurement techniques

multiple LIDAR (own development of assessment methods)
microwave radiometers,
ultrasonic anemometers

### Computation of sound propagation

3d Lagrangian sound particle model for high-frequency sound
3d Eulerian finite difference time-domain model for low-frequency sound

## Objectives

### Computation of the 3-dim. non-stationary flow

around the turbine in complex terrain

Source: http://klimawandel-bekaempfen.dgvn.de/meldung/atomausstieg-und-klimaschutz-ergaenzen-einander/

### Measuring the 3-dim. wind field

in the range of several kilometres around a turbine

### Quantification of sound immission

around wind turbines depending on operational mode, meteorological conditions and topography

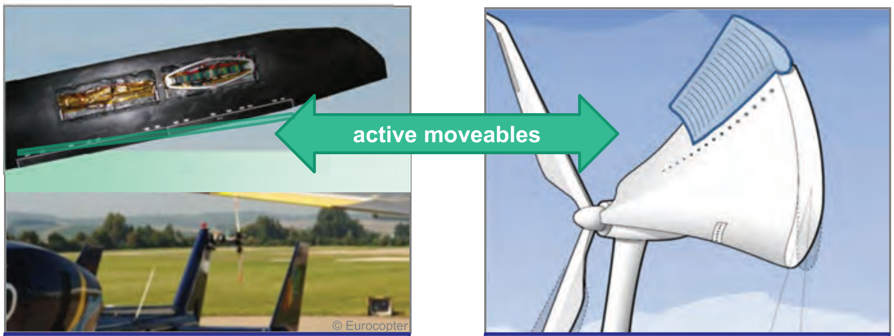
Source: http://www.wind-energie.de/politik/europa

### Application of the coupled model system for flow and sound

Determination of noise dispersion classes
Derivation of parameters for simplified procedures of noise prognosis
Assessment of simulations and measurements

Institute of Flight Systems | Rotorcraft

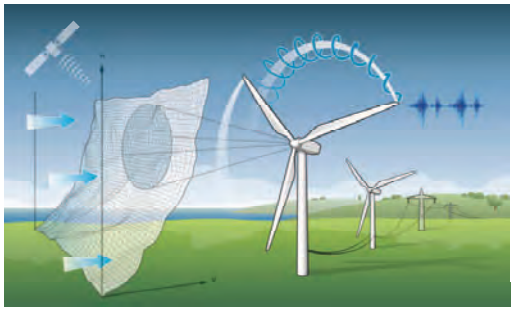
## Knowledge transfer to wind energy systems
## → Project SmartBlades




| Active flaps on rotorcraft | wind turbine |
|---|---|
| - reduction of noise<br>- reduction of vibration<br>- reduction of power required<br>- reduction of loads<br>- stall reduction | - reduction of loads<br>- … |

DLR

## Thank you for your attention!



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## Challenges on Wind Energy Deployment in Complex Terrain

iea wind

**Topical Expert Meeting #75**
**November 2013**

**Nicolás E. Veneranda**

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## Presentation of the expositor

Name: Nicolás E. Veneranda
Job title: Civil Engineer, MSc. Renewable Energies
Project Manager Wind Energy Department at Lahmeyer International GmbH
Office: Bad Vilbel, Germany
- Working as consultant for Lahmeyer since October 2004, mainly focus on Italian wind farm projects.
- 9 years experience in measuring campaigns, wind resource assessment , TDD, construction and O&M monitoring

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## Company Data

| | |
|---|---|
| Lahmeyer Group: | 12 Affiliated Consolidated Companies |
| Foundation: | 1966 (47 years) |
| Headquarter: | Bad Vilbel, Germany |
| Employees (2012): | 1560 (Group) |
| Turnover (2012): | 157 million Euro (Group) |
| Sites: | Company Sites and Subsidiaries in 21 Countries |
| Projects: | In 165 Countries (distribution: 10 % Germany, 90 % abroad) |
| Activity: | Technical and economic planning and consulting services |
| Fields (Group): | Energy; Hydropower & Water Resources; Water Supply & Sanitation; Building & Transportation |

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## Group Organisation

November 2013

**Board of Managing Directors**

**Corporate Management**

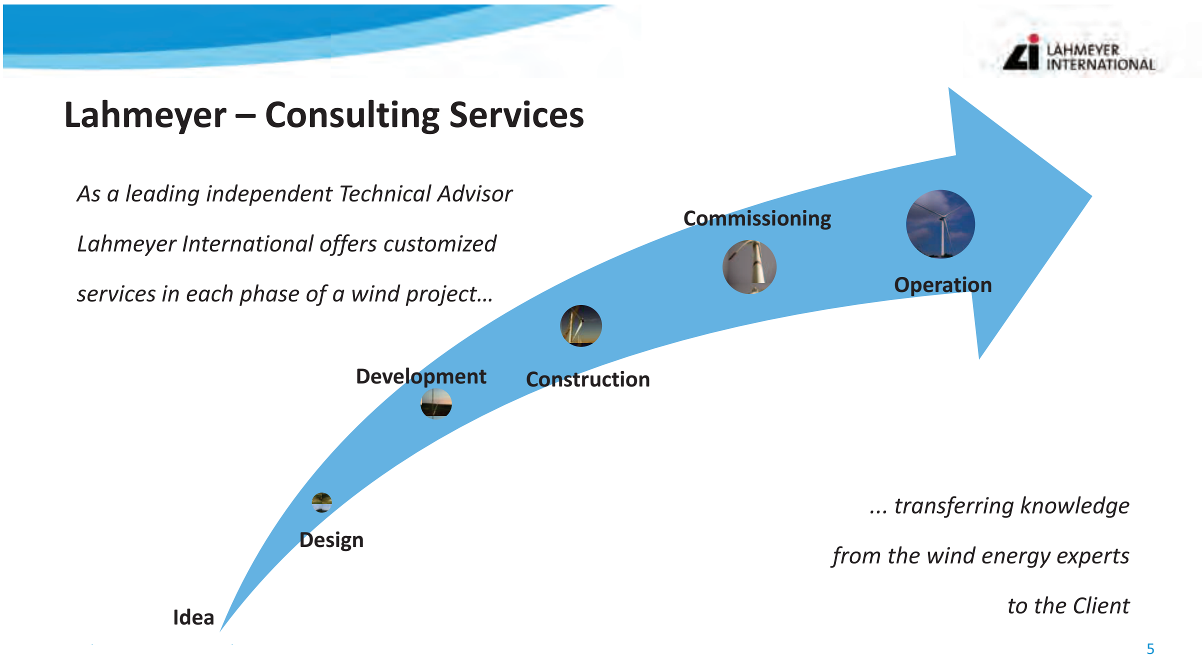
**Staff Units**
- Compliance
- Quality Management
- Occupational Safety
- Data Protection

| Corporate Departments | Energy Division | Hydropower & Water Resources Division | Water Supply & Sanitation Division | Building & Transportation Division | Lahmeyer International (INDIA) Pvt. Ltd. |
|---|---|---|---|---|---|
| Personnel | LI Business Unit Power Plants & Electrical Grids | LI Business Unit Hydropower & Water Resources | Lahmeyer GKW Consult GmbH Mannheim, Germany | Lahmeyer München Ingenieurgesellschaft mbH | Energy |
| Tax | LI Business Unit Renewables & Economics | Hydroprojekt Ingenieurgesellschaft mbH Weimar, Deutschland | | Lahmeyer Berlin GmbH | Hydropower & Water Resources |
| Accounting and Controlling | Lahmeyer International Qatar L.L.C. | Hidro Dizayn Group Ankara, Turkey | | Lahmeyer Rhein-Main GmbH | Transportation |
| Treasury | 000 Lahmeyer International Rus | Lahmeyer Agua y Energía Lima, Peru | | | |
| Information Technology | Consulting Engineers Lahmeyer Nigeria Ltd. | | | | |
| Legal | Lahmeyer IDP Consult | | | | |
| Internal Audit | | | | | |
| Marketing & Business Development Coord. | | | | | |
| Internal Services | | | | | |

Units of Lahmeyer International GmbH

Subsidiaries

4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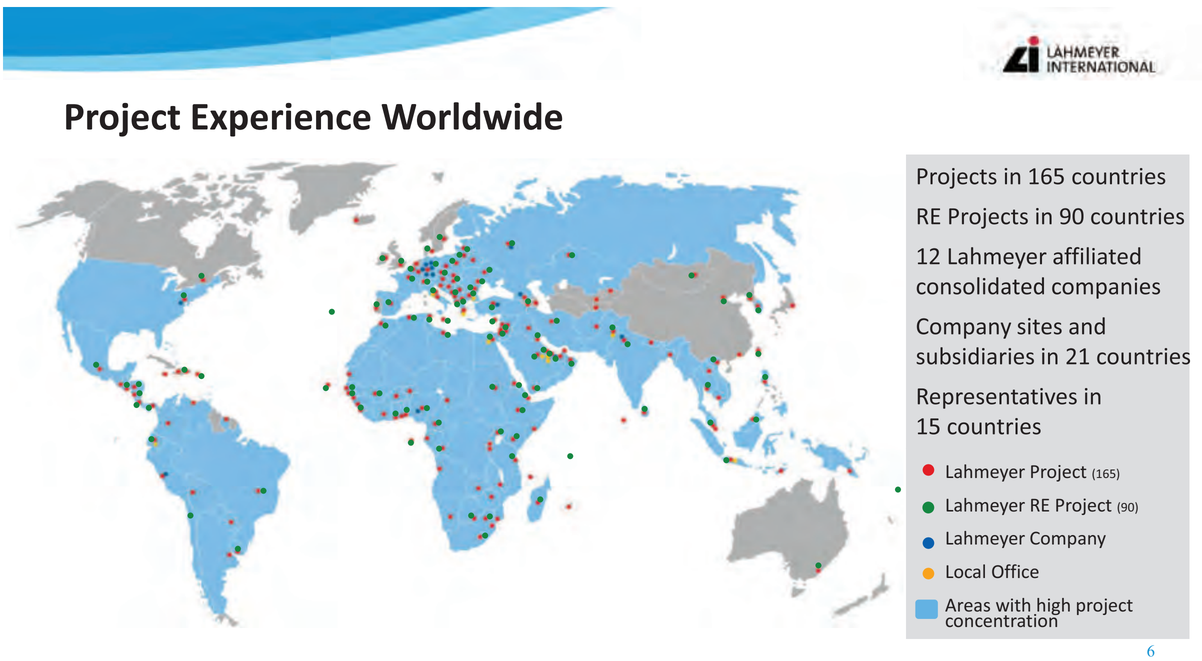
Lahmeyer – Consulting Services
As a leading independent Technical Advisor
Lahmeyer International offers customized
services in each phase of a wind project…
Idea
Design
Development
Construction
Commissioning
Operation
… transferring knowledge
from the wind energy experts
to the Client
5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Project Experience Worldwide
Projects in 165 countries
RE Projects in 90 countries
12 Lahmeyer affiliated consolidated companies
Company sites and subsidiaries in 21 countries
Representatives in 15 countries
Lahmeyer Project (165)
Lahmeyer RE Project (90)
Lahmeyer Company
Local Office
Areas with high project concentration
6

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## Lahmeyer - Key Wind References

| | | | |
|---|---|---|---|
| • Wind measurements masts installed | **> 247** | | |
| • Country wide wind mappings | **13** | | |
| • Wind potential evaluations | **> 405** | wind farms | |
| • Feasibility studies | **> 150** | wind farms | (> **5,540 MW**) |
| • Due diligence studies | **> 745** | wind farms | (>**18,800 MW**) |
| • Construction supervision | **> 75** | wind farms | (> **1,920 MW**) |
| • Operation and maintenance supervision | **> 90** | wind farms | (> **2,500 MW**) |

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## Wind Resource and Energy Yield Estimations

- Development of Wind Measurement Campaigns
- Site Visit and Investigation
- Bankable Wind Studies
  (Accredited to DIN EN ISO/IEC 17025:2005)
  - Analysis of Wind Measurement Data
  - Long-term Correlation
  - Wind Farm Micro-sitting
  - Wind Flow Modeling
  - Loss Estimation
  - Uncertainty Analysis
- IEC Class Assessment
  - Extreme Wind Speeds Analysis
  - Turbulence Assessment
- Wind Forecasting

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## Due Diligence Services

- Investors and Lender's Engineering Services
- Bankable Due Diligence
- Energy Yield Assessments
  - Wind Study Review
  - Production Data Analysis
- Review of Technical Project Concept
  - Turbine Selection
  - Wind Farm Design
- Review of Licenses and Permits
- Contract Assessment
  - Turbine Supply
  - Balance of Plant
  - Interface Control
  - Power Purchase Agreements
  - Operation & Maintenance Contracts
- Maintenance and Repair Cost Forecasts
- Financial Model Review

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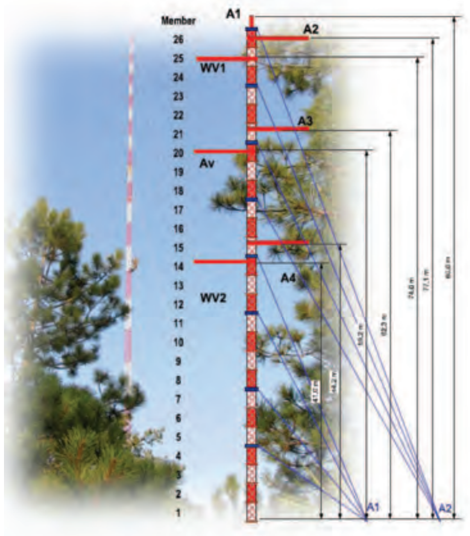
## Planning and Design Services

- Technical and Economic Feasibility Studies
- FEED Studies
- Turbine Technology Assessment & Selection
- Development of Soil Investigation Concepts
- Foundation Structures
  - Evaluation of Options
  - Design and Dimensioning
- Electrical System and Grid Connection Planning
  - Array and Export Cables & Sub-Station
  - Loss Estimations
  - Grid Integration Studies
- Planning of Logistics & Installation Concept
  - Harbors, Vessels, etc.
  - Marine Operations and Installation Concepts
  - Analysis of Meteorological Conditions
- O&M Strategy Development

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## Project Management Services

- Interface Control
- Budget Planning & Monitoring
- Preparation of Project Documentation
- Progress Reporting
- Preparation of Information for Decision Making
- Verification of Invoices and Claim Management
- Establishment of Health and Safety Plan
- Factory Inspections and Acceptance Tests
- Site Management & Construction Supervision
- Time Scheduling and Monitoring
  - Overall Project Planning
  - Weather Risk Evaluation
  - Critical Path Analysis
  - Environmental Monitoring

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## Contractual Services

- Support/Evaluation of Procurement Strategy
- Tendering
  - Drafting of General and Specific Conditions
  - Bid Evaluation & Clarifications
- Contract Review and Negotiation Support
- Evaluation of Contract Interfaces
- Evaluation of Term's and Conditions
  - Comparison to Market Standard
  - Liquidated Damages & Bonus Methods
  - Availability Guarantee
  - Power Curve Warranty
  - Weather Downtime Clauses
  - Warranty and Serial Defect Clauses

Experienced with All Contract Types:

- Turnkey EPC
- Turbine Supply
- Foundation Supply
- Electrical Supply
- Transport and Installation
- O&M Contracts
- Technical and Commercial Management

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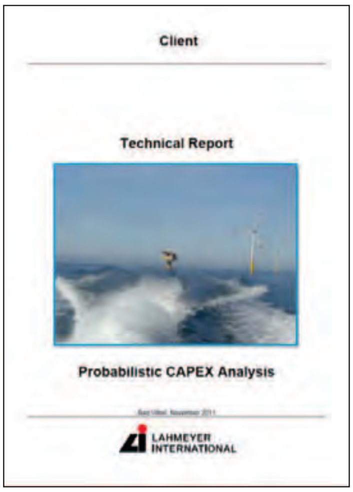
## Financial and Economic Assessment Services

- Design and Review of Financial Models
- Sensitivity Analysis
- Comparison of Off-take Options
- Elaboration Tariff Systems
- Cost Estimates (CAPEX & OPEX)
- Analysis of the Costs of Energy Production
- Cost-benefit Analysis
- Monte-Carlo Analysis
  - CAPEX
  - Delay during Construction
- Risk Analysis and Mitigation Measures

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## Services during Construction

- Construction Supervision and Monitoring
- Supervision of Health and Safety and Harbor Security Plan
- Inspection and Quality Control
- Commissioning Management
- Witnessing and Certification of Acceptance Testing
- Preparation of Punch-Lists
- Factory Acceptance Tests

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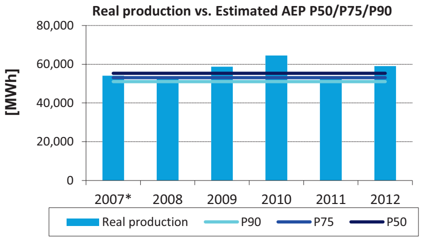
## Services during Operation

- Production Data Analysis
- Wind Farm and Turbine Performance Evaluation
- Short Term Wind and Power Forecasting
- Regular Turbine and Substation Inspections
- Operation and Maintenance Monitoring
- Environmental Monitoring

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## Challenges on Wind Energy Deployment in Complex Terrain

- Wind resource assessment in complex terrain
- Approach of Lahmeyer
- Challenges and on-going tasks
- Power curve measurement in complex terrain
- Challenges on logistics in complex terrain

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## Challenges associated with the wind resource assessment in complex terrain

- Evaluate the complexity of the site;
- Calculate accurately the AEP of individual WTGs;
- Estimate uncertainties associated to the AEP of the individual WTGs;
- Calculate wind speed on hub height with low met masts;
- Estimate the effects of forests;
- Evaluate realistic turbulence intensities at WTG positions;
- Evaluate realistic extreme wind speeds at WTG positions;
- Estimate the flow inclination at individual WTGs at Hh;
- Assessment of energy losses due to turbine load control (sector management parameters);
- Snow and icing affecting measurements and site access.

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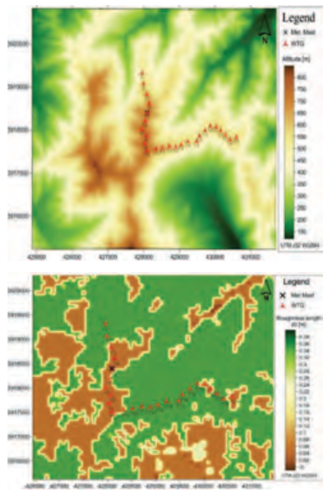
## Challenges associated with the wind resource assessment in complex terrain

### Estimate of complexity

- Boundaries of the terrain. Extension of the site to model?
- RIX and Δ RIX (terrain feature)
  - Complexity of the terrain at WTG and met mast (Δ RIX)
- Site characterization is important
  - Flow distortion
  - Wind veer

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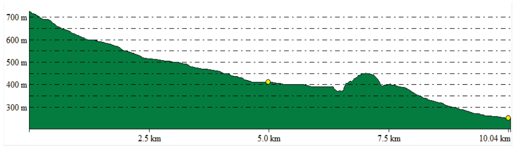
## Challenges associated with the wind resource assessment in complex terrain

### Estimate complexity of the site

### e.g. South-Korea wind farm site




- Slope is gradually lower from west to east in the map
  - Not that complex
- Many small mountains (450m – 500m a.s.l.) are distorting wind flow toward wind farm

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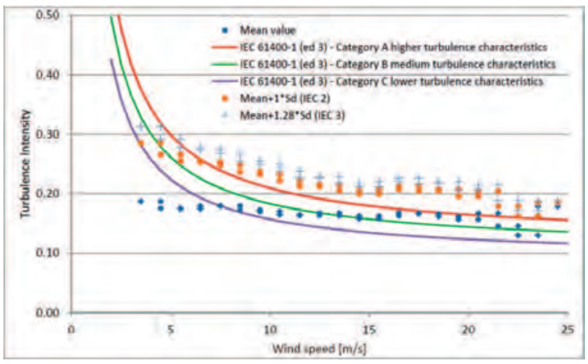
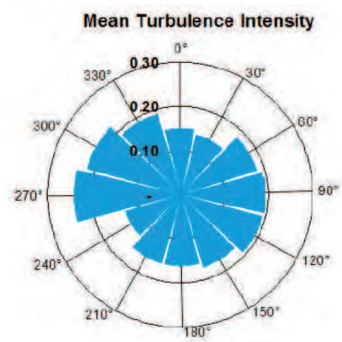
## Challenges associated with the wind resource assessment in complex terrain

### Turbulence intensities at mast position (mast 86m h)

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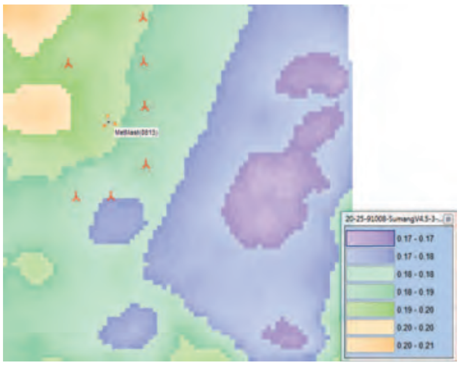
## Challenges associated with the wind resource assessment in complex terrain

### Turbulence intensities at WTG positions by CFD



- WTGs are optimized in order to maximize AEP
  - distance from mast $\leq$ 450 m due to land permit
- Height : 406 – 420m
- Ambient Turbulence Intensity
  - Mast position = 0.17
  - WTG positions = 0.19 ~ 0.20

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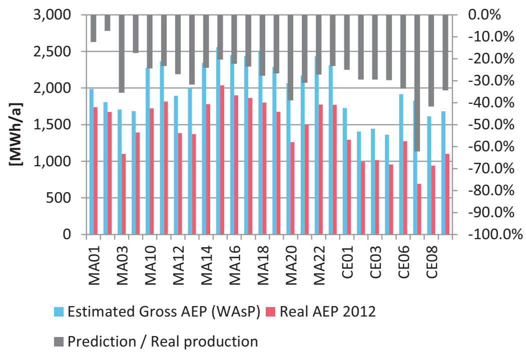
## Challenges associated with the wind resource assessment in complex terrain

- Estimate accurately the AEP of individual WTGs Example deviations estimations WRA to real production (example Sicily, Italy )

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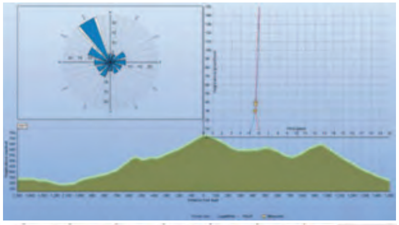
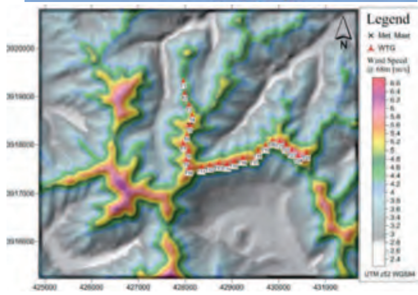
## Challenges associated with the wind resource assessment in complex terrain





### Lahmeyer approach for WRA in complex terrain

- Sitting met masts with „zero“ wind maps
- Modeling:
  - Meteodyn WT;
  - WAsP-CFD in WindPRO (evaluating using this tool)

### Possible trends in modeling in complex terrain

- Scanning wind Doppler LIDARs (might replace a flow model by measured wind distribution) - very complex terrain



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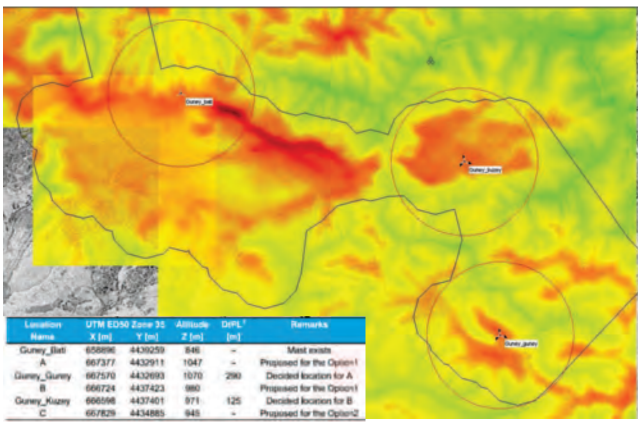
## Challenges associated with the wind resource assessment in complex terrain

### Sitting met masts with „zero“ wind maps in order to optimize representativeness of measurement (e.g. Turkey)

- Güney_Bati existing mast located at 846 m asl. With the zero wind map, Lahmeyer estimated points A and B (with elevation 950m and 1070m) had lower wind regime.
- The Client installed the masts and Lahmeyer proved the prediction from the zero wind map, new masts had lower mean wind speeds. Client stopped projects A and B.



| Location Name | UTM ED50 Zone 35 X [m] | Y [m] | Altitude Z [m] | D(PL)[1] [m] | Remarks |
|---|---|---|---|---|---|
| Guney_Bati | 658896 | 4439259 | 846 | - | Mast exists |
| A | 667377 | 4432911 | 1047 | - | Proposed for the Option1 |
| Guney_Guney | 667570 | 4432693 | 1070 | 290 | Decided location for A |
| B | 666724 | 4437423 | 980 | | Proposed for the Option1 |
| Guney_Kuzey | 666598 | 4437401 | 971 | 125 | Decided location for B |
| C | 667829 | 4434885 | 945 | - | Proposed for the Option2 |

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## Challenges associated with the wind resource assessment in complex terrain

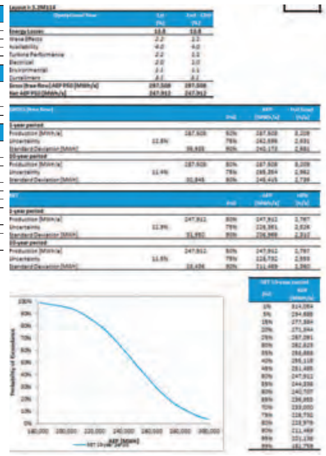
### Estimate uncertainties associated to the AEP of the individual WTGs

- Distance to met masts (horizontal and vertical) (Representativeness radius MEASNET Evaluation of Site-Specific Wind Conditions)
- Homogeneous roughness conditions?
- Complexity terrain WTG and met mast (Δ RIX)
- Sensitivity of the Model on wind direction deviations
- Estimate degree single uncertainties correlate (correlation matrix)

| Measurement - wind speed related | P10-1 [%] | P10-2 |
|---|---|---|
| Wind Speed (cup anemometer) | 1.4 | 1.4 |
| Remote Sensing (Sodar/Lidar ) | 0.0 | 0.0 |
| Mounting | 1.2 | 1.2 |
| **Subtotal (measurement)** | **2.0** | **2.0** |

| Data processing - wind speed related | P10-1 [%] | P10-2 [%] |
|---|---|---|
| Data Integrity | 1.0 | 1.5 |
| Data Analysis | 1.3 | 4.8 |
| Long-term correlation | 3.5 | 3.5 |
| **Subtotal (data processing)** | **3.9** | **6.1** |

| Annual Enery Production | energy related → ↓ wind speed related [%] | 3.2M114 [%] |
|---|---|---|
| **Total Uncertainy of Measurement and Data Processing** | ***4.5*** | ***7.1*** |
| **Prediction horizon [years]** | | |
| *1-year wind deviation* | ***3.9*** | ***6.2*** |
| *10-year wind deviation* | ***1.2*** | ***1.9*** |
| **Modelling** | | **6.3** |
| **Power curve** | | **6.0** |
| **Reference WEC** | | **0.0** |
| ***Total Uncertainty on Gross (free flow) Production (1-year)*** | | **12.8** |
| ***Total Uncertainty on Gross (free flow) Production (10-year)*** | | **11.4** |
| **Losses (uncertainy of loss estimations)** | | **1.0** |
| ***Total Uncertainty on NET Production (1-year)*** | | **12.9** |
| ***Total Uncertainty on NET Production (10-year)*** | | **11.5** |





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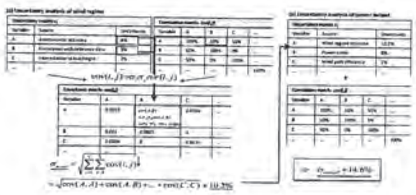
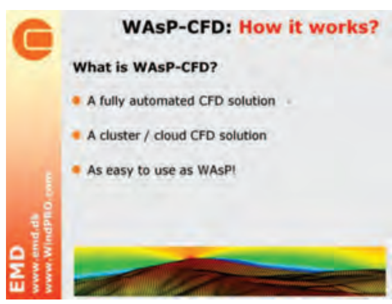
## Challenges associated with the wind resource assessment in complex terrain



### On going tasks

- Evaluation of dependence of flow modeling uncertainty factors;
- Integration of uncertainty results into PoE tools (Gross free-flow, net, uncertainty at individual WTG level);
- Interest in using of WAsP-CFD tool (internal discussion).



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## Challenges in power curve measurement in complex terrain

- Power curve measurement with LIDAR
- Power curve measurement with nacelle mounted anemometers (IEC 61400-12-2 instead of IEC 61400-12-1) motivation is applicability (i.e. penalties for case of underperformance).
- Calibration of wind turbine wind vanes in complex terrain

Picture from DTU Wind Energy, Technical University of Denmark – presentation on Nacelle mounted LIDAR - Danish Wind Power Research 2013 27/05/2013 Fredericia

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## Challenges on logistics in complex terrain

- Obtaining permits is real obstacle for many projects (e.g. South Korea)
  - Enormous impact of civil works on landscape
- Transportation to the site
  - Wind affecting site transportation (e.g. South Korea);
  - High slopes (35% e.g. Costa Rica);
  - R of curves, clearance area (e.g. South Korea)
    - 1 week for 100km from harbor to site;
    - Possible solution: foldable blades or blades in pieces.


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## Contact

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**Lahmeyer International GmbH,** Friedberger Str. 173, 61118 Bad Vilbel, Germany

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IEA Task 11 Topical Expert Meeting 75 “Wind Energy in complex terrain” 12th ant 13th Nov. 2013, Stuttgart

# Benchmarks of CFD simulation in complex terrain

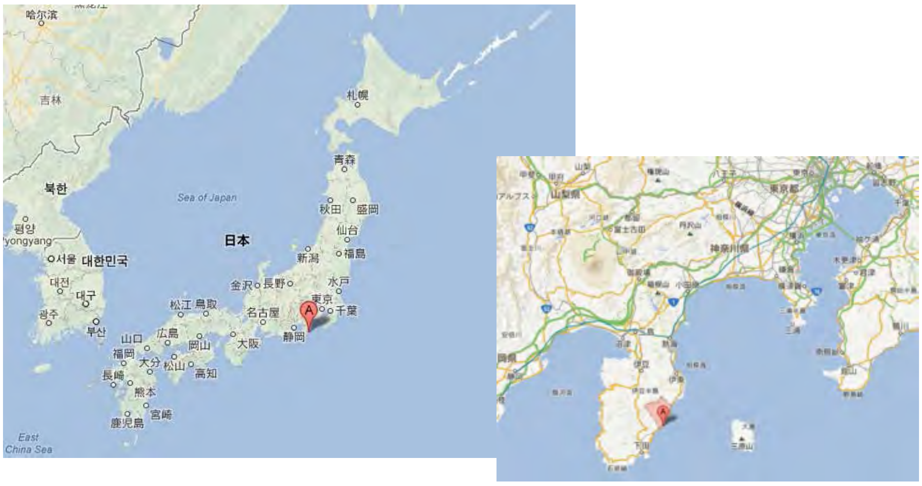
Nov. 13, 2013

Yuko Ueda
Wind Energy Institute of Tokyo



## Proposal of Higashiizu for Wakebench Test Case

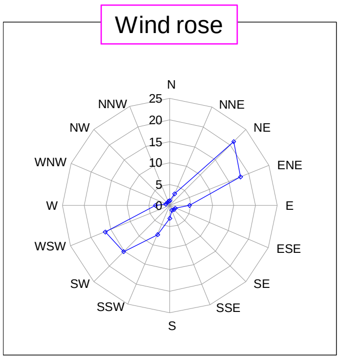
- Higashiizu is complex terrain
- Field measurement data
- Wind tunnel measurement data

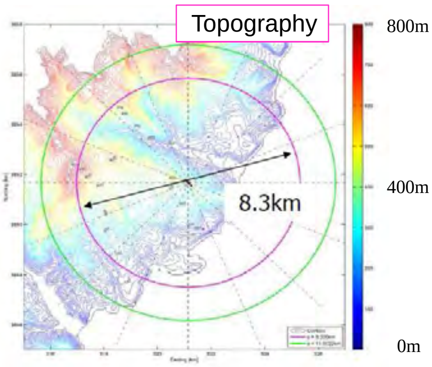


## Field measurement campaign at Higashiizu site

### A site of complex terrain in Japan

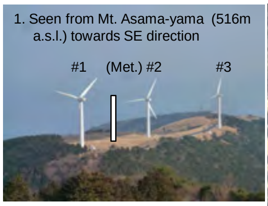
- ✓ Field measurement campaign was performed in the NEDO wind power guideline project (2006-2008).
- ✓ In the field measurement campaign, high-speed sampling data of wind speed using the ultrasonic anemometer at the 30m a.g.l. were obtained.

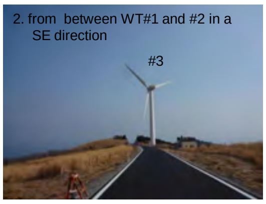


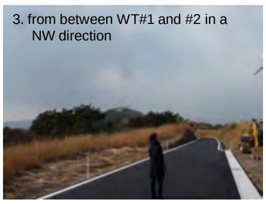



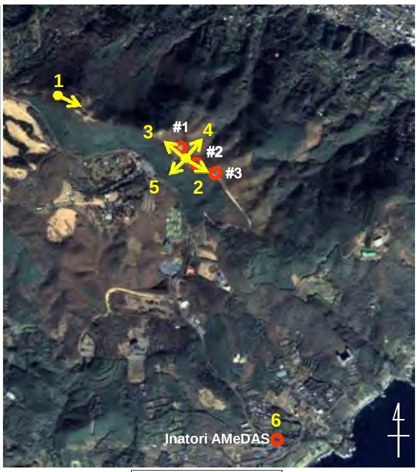


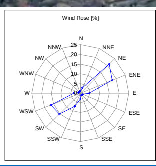

## Higashiizu site



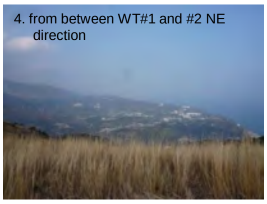



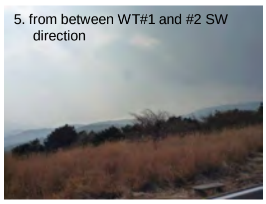



MAP: Yahoo Japan




## Measurement results of sector-wise wind speed profiles

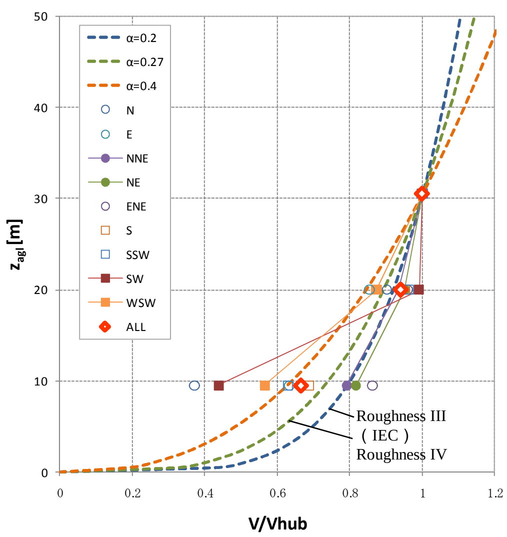



Fig. Sector-wise wind speed profiles

- **Field measurement data**
  - ✓Date: June, 2006 – Dec., 2007
  - ✓Ultrasonic anemometers（3 components）
  - ✓4Hz sampling
- **Data processing**
  - ✓Sectorwise averaging in 16 direction bins
  - ✓Exclusion of sectors in the wake of the neighboring turbines（ESE, SE, SSE, W, WNW, NW）

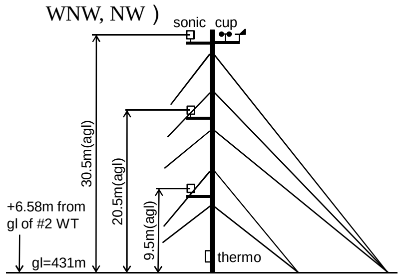


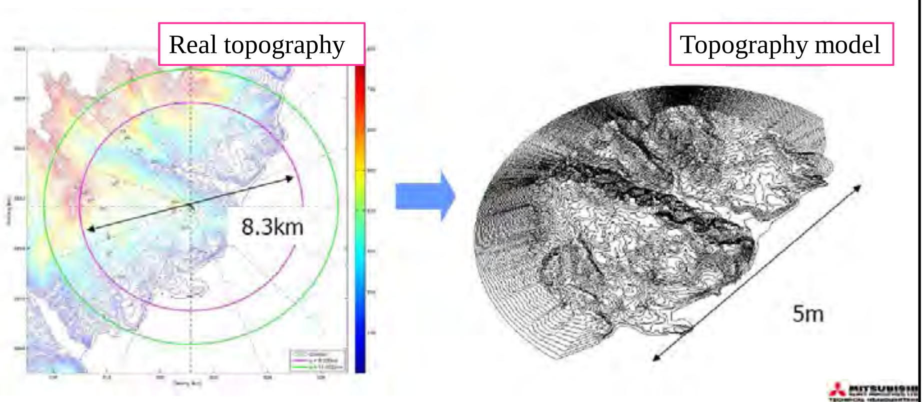

Fig. Met-mast and configuration of anemometers

Ref.) NEDO guideline project measurement data（June, 2006 – Dec, 2007, Higashiizu site).



## Wind tunnel measurement [1/3]

- Higashiizu is one of the most difficult sites for evaluation of the wind speed by CFD.
- Wind tunnel measurement was performed for evaluation of CFD.
- Topography model
  - ✓ Scale: 1/1,667 (real topography diameter : 8.3km → model : 5m)
  - ✓ Slope area: for the prevention of flow separation at the edge of the model



## Wind tunnel measurement [2/3]

### Large scale boundary layer wind tunnel

| | | |
|---|---|---|
| Test section | 6m(W) x 5m(H) x 30m(L) | |
| Inlet wind speed | 6 m/s | |
| Reynolds number | 1 x $10^5$ (based on the center height of the model) | |
| Model topography | $D$= 5 m (without slope), $z_{center}$=270mm, Max. slope angle is 30degrees | |
| Inlet wind profile at the slope edge | Power law exponent | 0.2 |
| | Turbulence intensity | 0.17(z=30mm), 0.15(z=60mm), 0.12(z=120mm) |
| Hot-wire anemometer | ➢ wind speed and turbulence intensity profile at 6 positions<br>➢ 2 different wind directions | |
| Roughness | smooth surface / rough surface ($z_0$=0.18) | |

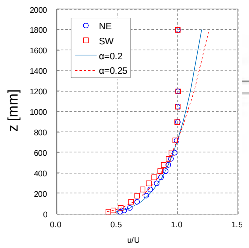



Fig. Wind profile at inlet position of terrain slope

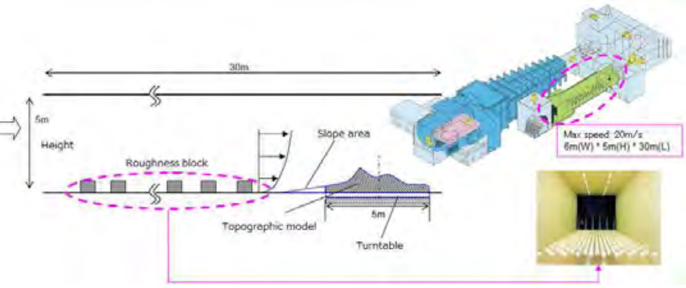



Fig. Schematic description of the wind tunnel configuration



## Wind tunnel measurement [3/3]


Smooth surface, NE

Rough surface, SW

## Comparison of wind speed profiles between field and wind tunnel measurements

- **Evaluation of the effect of surface roughness**
  - ✓ Wind tunnel measurement by terrain model with roughness showed good agreement with field data.

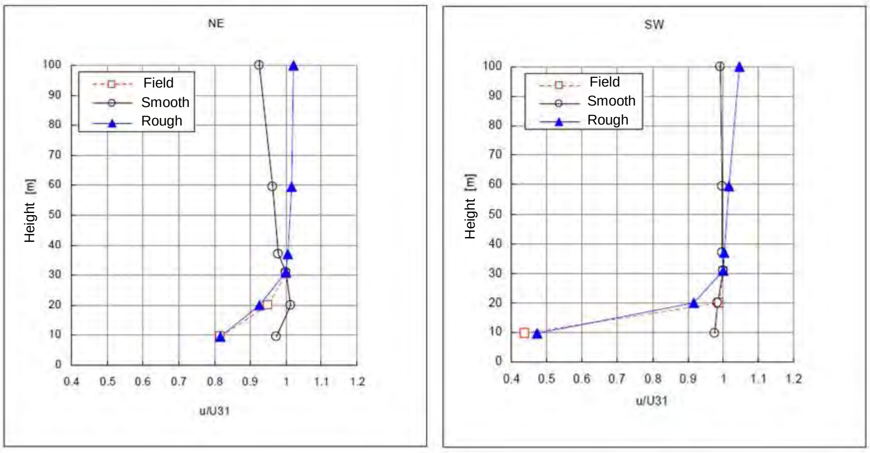



Fig. Wind profiles at the reference mast position

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## Proposal for blind test of neutral flow at Higashiizu site

- **Conditions for CFD**
  - ✓ Wind speed and direction
    - ➢ alpha=0.2 at the slope edge
    - ➢ NE and SW
  - ✓ Roughness effect:
    - ➢ Smooth surface
    - ➢ Rough surface($z_0$=0.18)
  - ✓ Measurement points
    - ➢ 6 (5 on the site, 1 at the sea side)
  - ✓ Validation data:
    - ➢ Wind profile at each point
    - ➢ Turbulence intensity (or turbulence kinetic energy) at each point

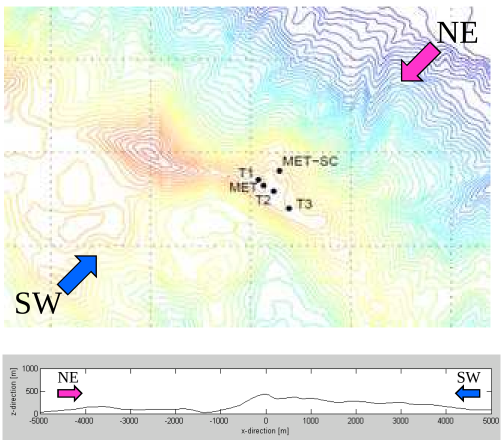


Fig. Topography of Higashiizu site and the positions of the evaluation points

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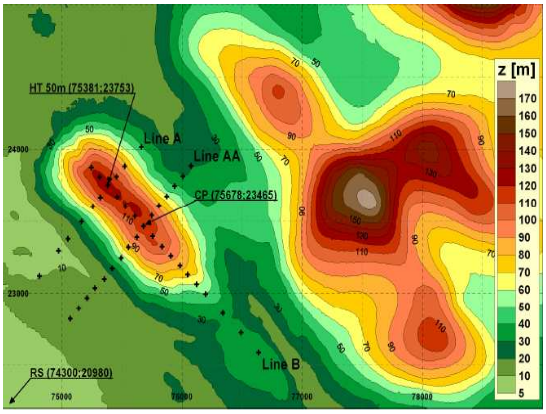
## Test Case: Askervein Hill



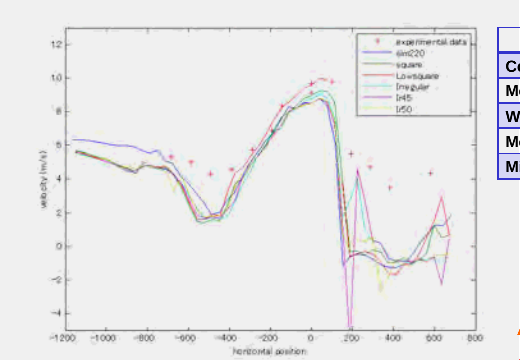

- Situated in Scotland
- Regular shape, 116m height
- 1983-1985 : measurement campaigns (Taylor and Teunissen , York University)
- 10m masts across 3 lines (AA, A, B)
- Non dimensional speed up :
  - $\Delta S = \frac{V - V_{ref}}{V_{ref}}$ with $V = \sqrt{u^2 + v^2}$
- Normalized TKE : $\tau^* = \frac{TKE}{{V_{ref}}^2}$



## Overview of used software

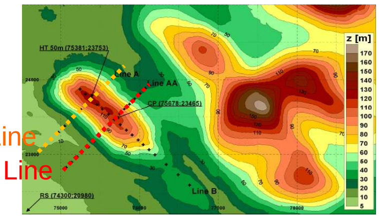
| | Software A | Software B |
|---|---|---|
| Turbulence Model | LES (standard Smagorinsky) | RANS (standard k-ε) |
| Discretization method | FDM(Finite Difference Method) | FVM(Finite Volume Method) |
| Coordinate system | Generalized curvilinear coordinate | Generalized curvilinear coordinate |
| Inlet flow condition | Power Low<br>$u(z) = U_{BL}(\frac{z}{H_{BL}})^{\alpha}$<br>With $U_{BL}$ the speed above the BL, $H_{BL}$ the boundary layer height, $\alpha$ the power exposant | Logarithmic Law<br>$u(z) = \frac{u_\tau}{\kappa}\ln(\frac{z}{z_0})$<br>With $\kappa$ the Von Karman constant, $u_\tau$ the friction velocity and $z_0$ the roughness height |

## Results of Software A : Speed-up of AA Line [1/2]




Speed-up on AA line

| | Calculation conditions |
|---|---|
| **Computational domain** | 4km×4km×1km |
| **Mesh number** | 200×200×40 |
| **Wind direction** | 210° |
| **Mesh type** | Regular mesh |
| **Minimum mesh size $\Delta x_{min}$** | 20m |

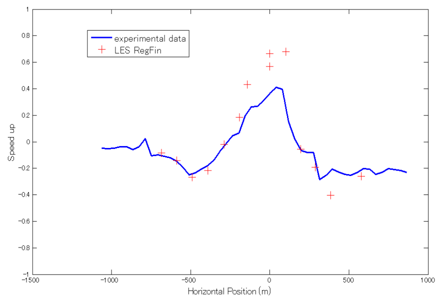



| No. | Legend in figure | Calculation conditions |
|---|---|---|
| 1 | Square | Basic |
| 2 | Sim220 | Wind direction 220° |
| 3 | Lowsquare | Vertical domain size 500m |
| 4 | Irregular | Irregular mesh （$\Delta x_{min}$=7.1m） |
| 5 | Irre45 | Irregular mesh,<br>Number of mesh in vertical direction 45 |
| 6 | Irre50 | Irregular mesh,<br>Number of mesh in vertical direction 50 |

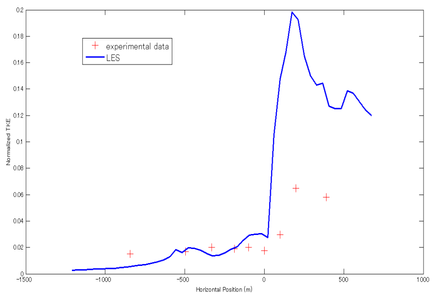
➔ No great results



## Results of Software A : Speed-up of AA Line [2/2]




Speed-up AA line

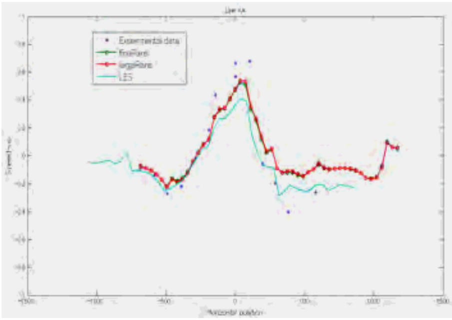



Normalized TKE AA line

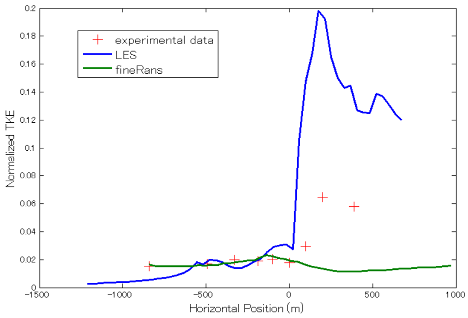
| | Calculation conditions |
|---|---|
| **Computational Domain** | 3km×4km×1km |
| **Mesh Number** | 280×300×40 |
| **Wind Direction** | 210° |
| **Mesh type** | Regular Mesh |
| **Minimum mesh size $\Delta x_{min}$** | 10.7m |

- Overall great improvement
- Underestimation of speed up at hill top
- Overestimation of TKE at hill top
- Limitation of maximum number of cells of commercial software

## Results of Software B: Speed-up of AA Line



Speed-up on AA line




Normalized TKE on AA line

| fineRans | Values |
|---|---|
| **Mesh number** | 223*224*60 |
| **Number of cells** | 2,997,120 |

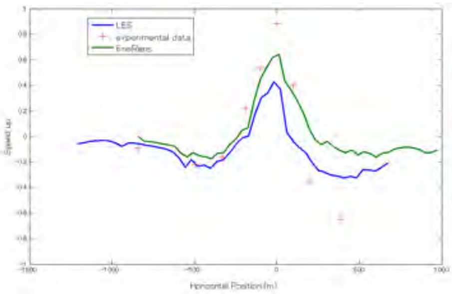
| largeRans | Values |
|---|---|
| **Mesh number** | 195*205*40 |
| **Number of cells** | 1,599,000 |

| Parameters | Values |
|---|---|
| **Physical domain size** | 5km×5km×0.87km |
| **Mesh type** | Refined toward center |
| **Wind direction** | 210° |
| **Turbulence Model** | Standard k-epsilon |

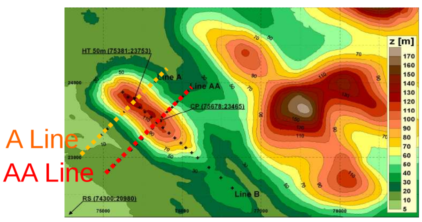
- No grid sensitivity
- Sleep side of the hill issues
- Big TKE underestimation at the top of the hill



## A Line speed up issues



Speed-up on A line




- Important transient effects :
  - ✓ Well known weakness of RANS models
  - ✓ LES supposed to perform better.
- Transient effect:
  - ✓ Region poorly adapted to put wind turbines.
    - ➔ Impact further downstream ?
    - ➔ Difficulty with the lee side of the hill

## Computational cost

- RANS
  - ✓ Very low computational cost
    - ➢ Multi directional simulation can be performed on a laptop.
- LES
  - ✓ Heavy computational cost
    - ➢ Not yet grid at convergence.
    - ➢ However quite affordable today.

| Software | Software A | Software B |
|---|---|---|
| **Turbulence model** | **LES** | **RANS** |
| **Device name** | NVIDIA TESLA C2075 | Intel Core i7-2860QM |
| **Type of device** | GPU | CPU |
| **Number cores** | 448 | 4 (1 used) |
| **Power frequency** | 1.15GHz | 2.5 GHz |
| **Memory** | 6 GB GDDR5 | 8GB RAM |
| **Computational time** | ~ 3hours | ~ 1 hour |

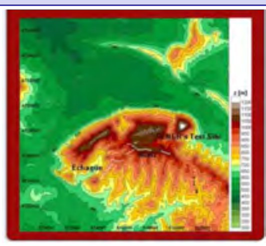


## Conclusion

| Software | Software A | Software B |
|---|---|---|
| **Turbulence model** | **LES** | **RANS** |
| **Computational cost** | High | Low |
| **Mesh sensitivity** | High | Low |
| **Speed-up** | Correct (Underestimation at the top) | Correct (Issues with the lee side) |
| **TKE** | Overestimation at the hill top. Potentially good? | Good on flat place, bad for the hill |
| **Transient effect** | Poor. Potentially good? | Bad |
| **Potential** | Great :<br>- TKE, transient effect.<br>- Coupling with wind turbine simulation (NREL : SOWFA)<br>Long term. | Already quite effective<br>Room for improvement, with URANS (cf F. A. Castro) |

- Limitations of the study
  - ✓ Different inlet conditions.
  - ✓ No variable roughness.
  - ✓ Only 10 meters masts
  - ✓ Simple geometry.

Alaiz case. →



Sketch of the building-block approach for the Alaiz case study

## Future Work

- To build a evaluation procedure of $I_{ref}$ using CFD results and validate it for many cases using various CFD software.

**Estimation procedure for reference turbulence intensity at turbine position**

Calculate the turbulence standard deviation at 15m/s using measured data

$$\sigma_m = \sigma_m\big|_{U_m=15}$$

$\sigma$: turbulence standard deviation
[subscript] $h$: hub height, $m$: met mast, $w$: wtg

Assume the turbulence standard deviation at hub height equal to that of measured height
Estimate $I_{ref}$ at hub height met mast position

$$I_{ref,hm} = \frac{\sigma_m}{U_{hm}} \quad , \quad U_{hm} = U_m \left(\frac{z_{hm}}{z_m}\right)^{\alpha} \quad , \quad \sigma_{hm} = \sigma_m$$

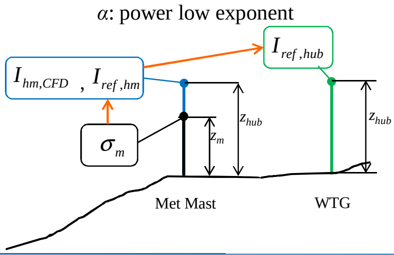
$I_{ref}$ : turbulence intensity at 15m/s
$U$: 10 min. averaged wind speed
$Z$: height(a.g.l)
$\alpha$: power low exponent

Calculate the correction factor for turbulence intensity

$$C_I = \frac{I_{ref,hm}}{I_{hm,CFD}} \quad , \quad I_{hm,CFD} = \sum_{i=1}^{n} I_{hm,CFD}(\theta_i) \cdot f_m(\theta_i)$$

Estimate $I_{ref}$ at WTG position

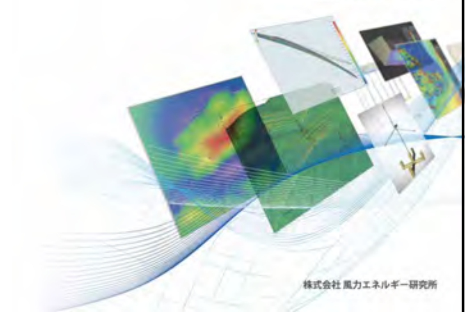
$$I_{ref,hw} = C_I I_{hw,CFD}$$






Thank you for your attention.

Yuko Ueda
ueda@windenergy.co.jp

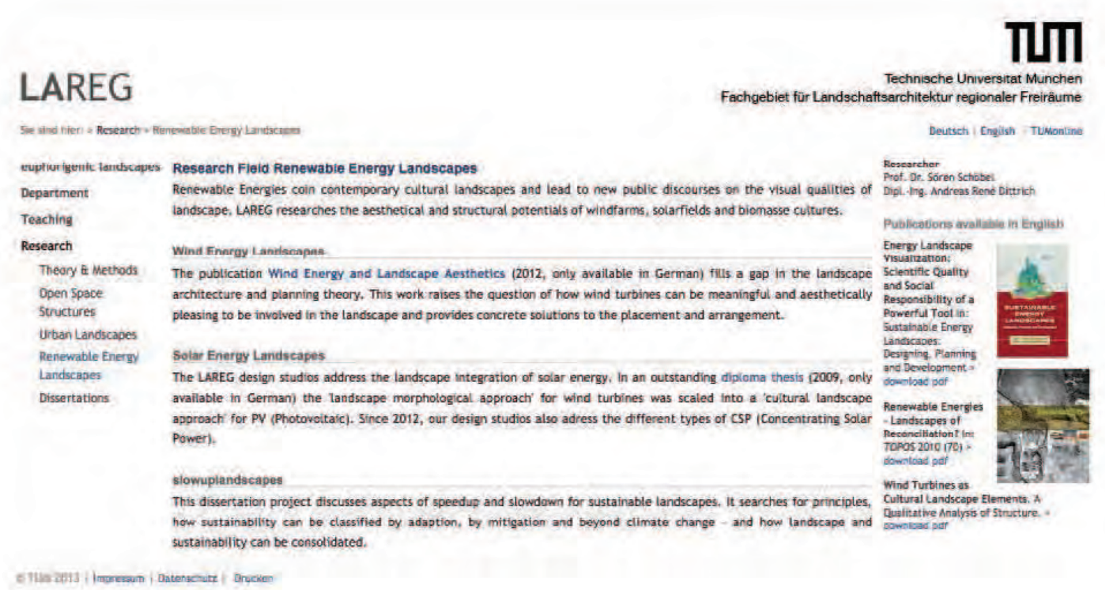


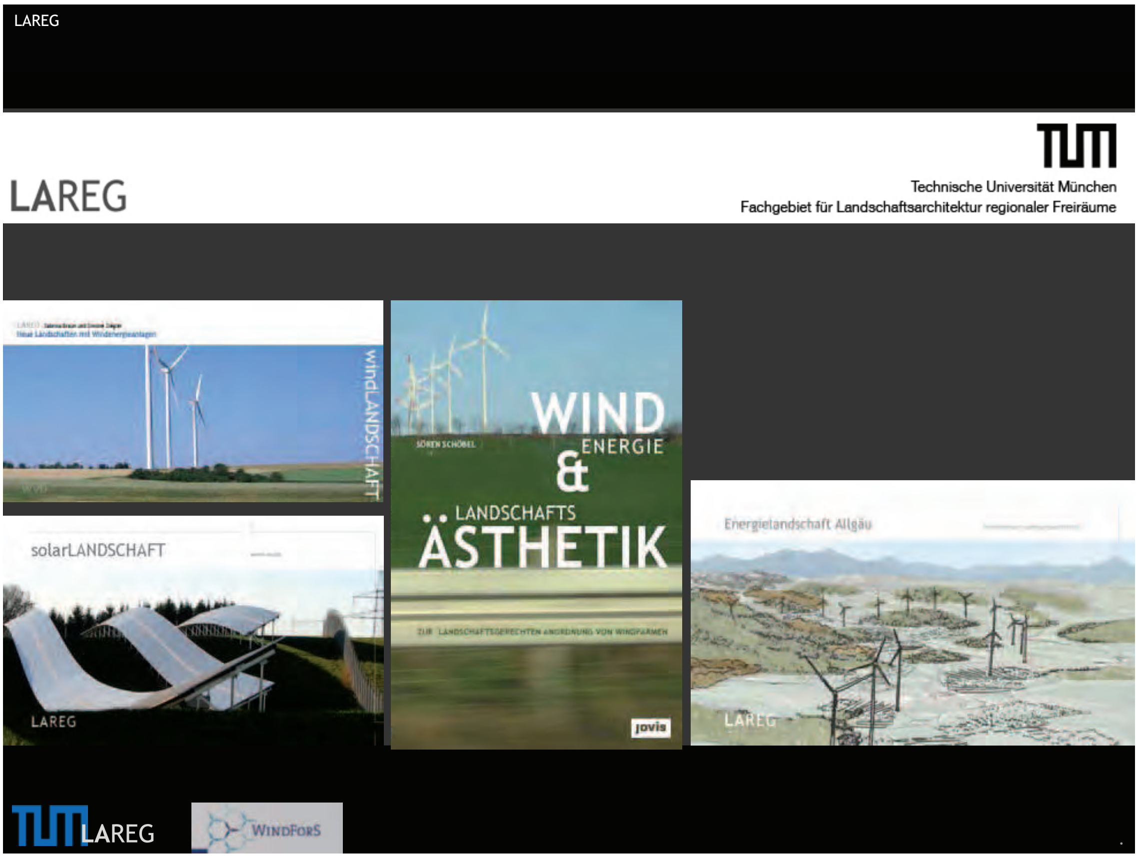
IEA Task 11 Topical Expert Meeting #75 on
**Challenges on Wind Energy Deployment in Complex Terrain**

## Landscape Character Assessments on Windfarms in Populated Complex Landscapes on the Example of Southern Germany

Landscape Architecture and Regional Open Space (TUM LAREG)
www.lareg.wzw.tum.de
Prof. Dr. Sören Schöbel-Rutschmann

Landscape Character Assessments on Windfarms in Populated Complex Landscapes




LAREG
LAREG
Technische Universität München
Fachgebiet für Landschaftsarchitektur regionaler Freiräume
windLANDSCHAFT
solarLANDSCHAFT
LAREG
SÖREN SCHÖBEL
WIND
ENERGIE
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ÄSTHETIK
jovis
Energielandschaft Allgäu
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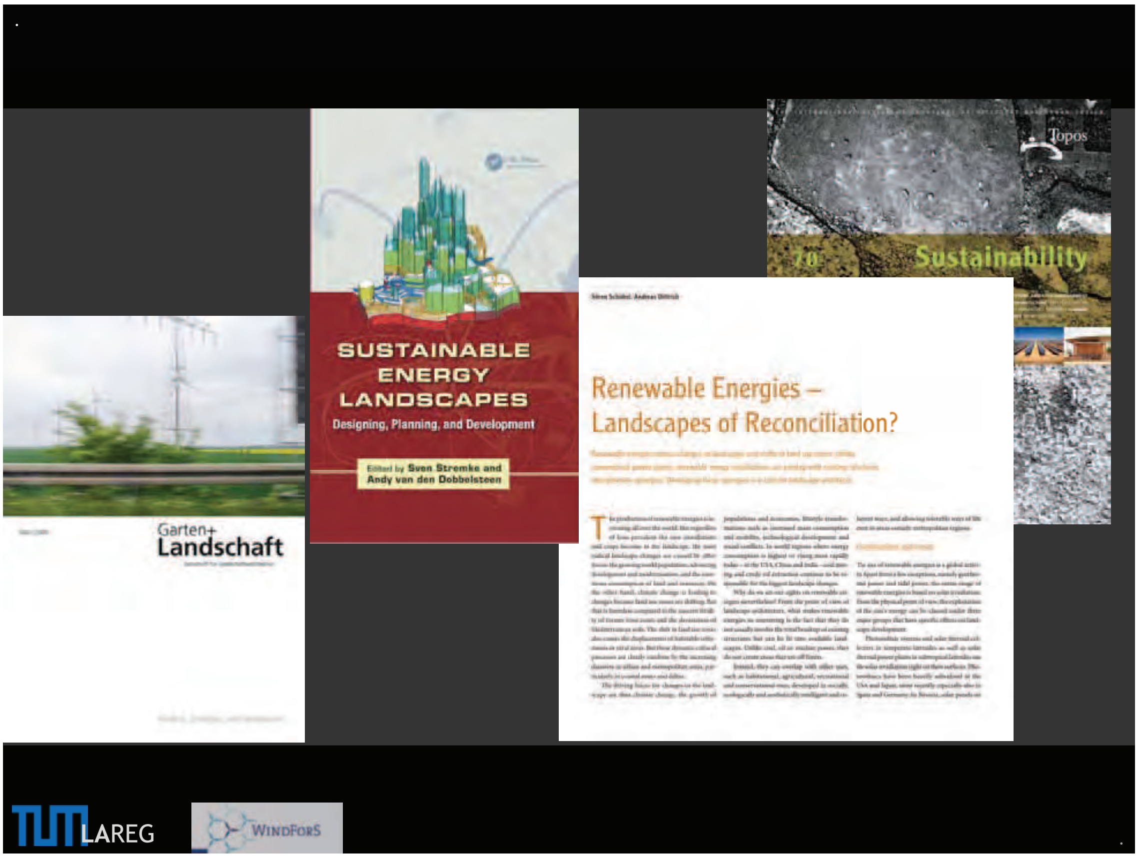
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Sustainability
SUSTAINABLE ENERGY LANDSCAPES
Designing, Planning, and Development
Edited by Sven Stremke and Andy van den Dobbelsteen
Renewable Energies – Landscapes of Reconciliation?
Garten+ Landschaft
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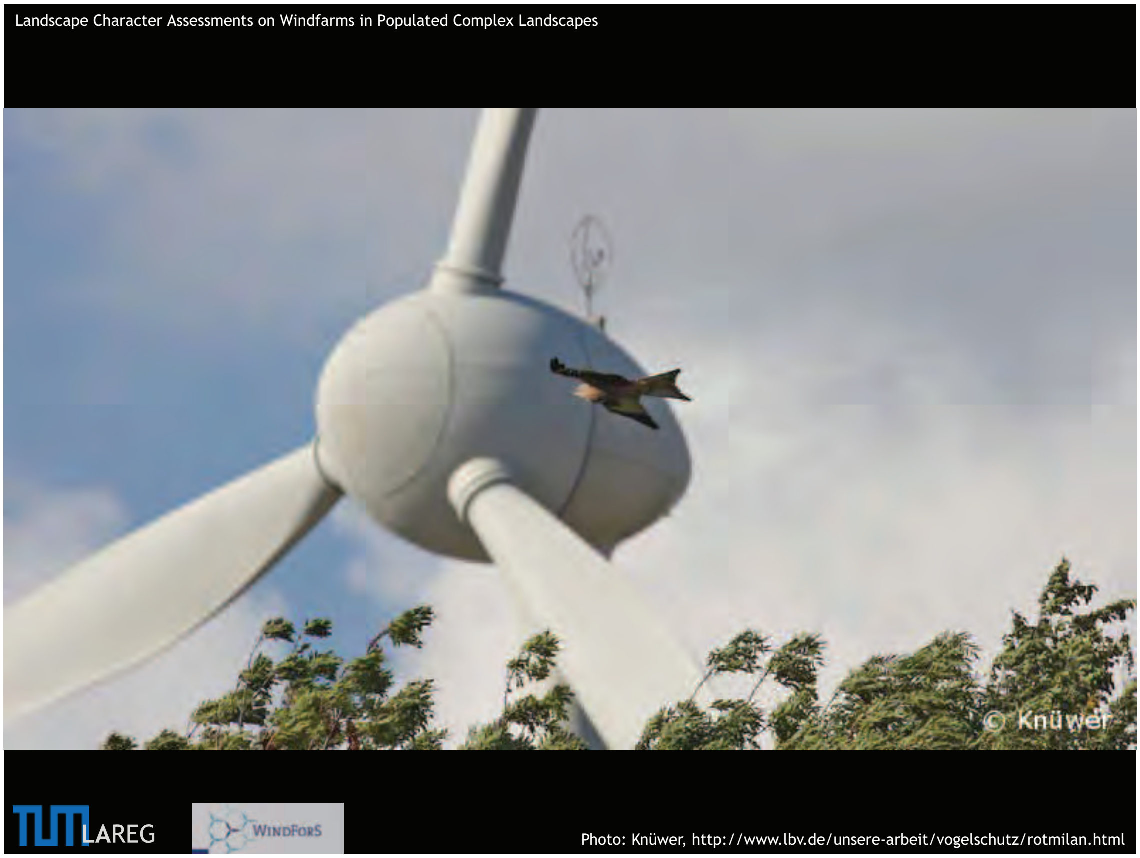
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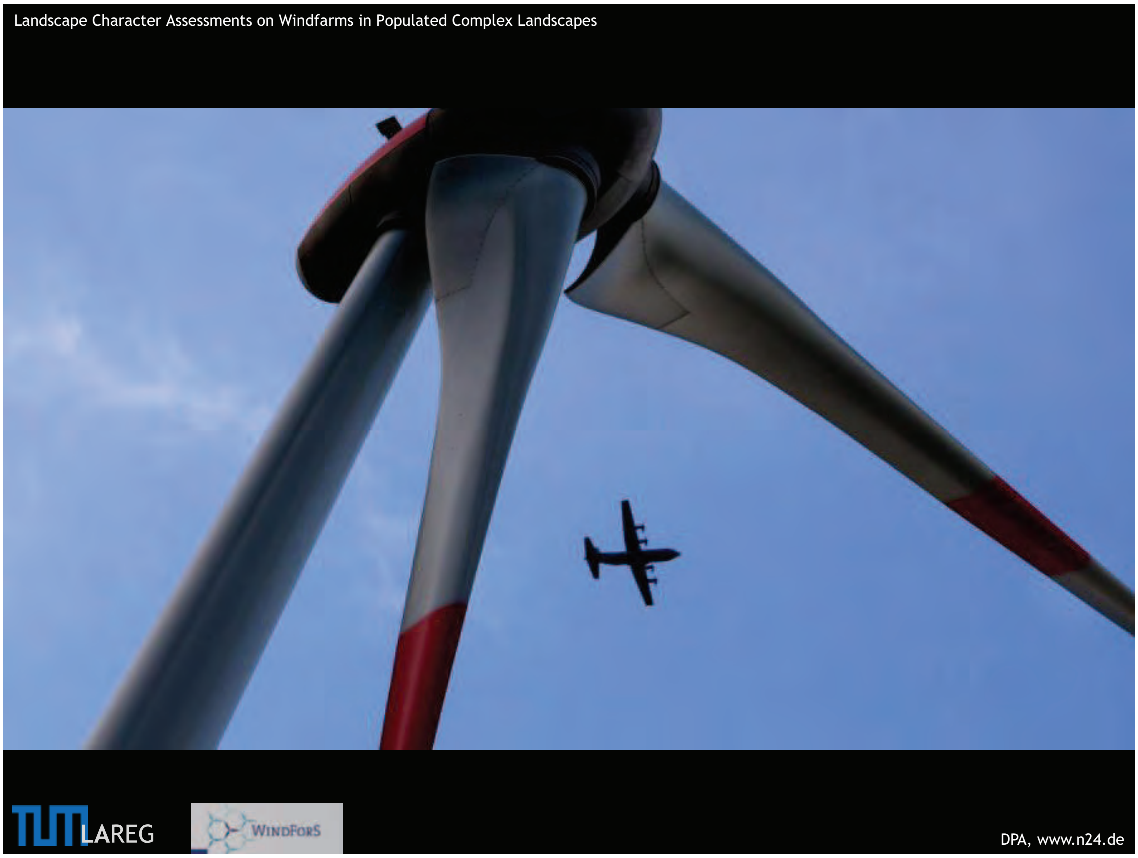
Landscape Character Assessments on Windfarms in Populated Complex Landscapes
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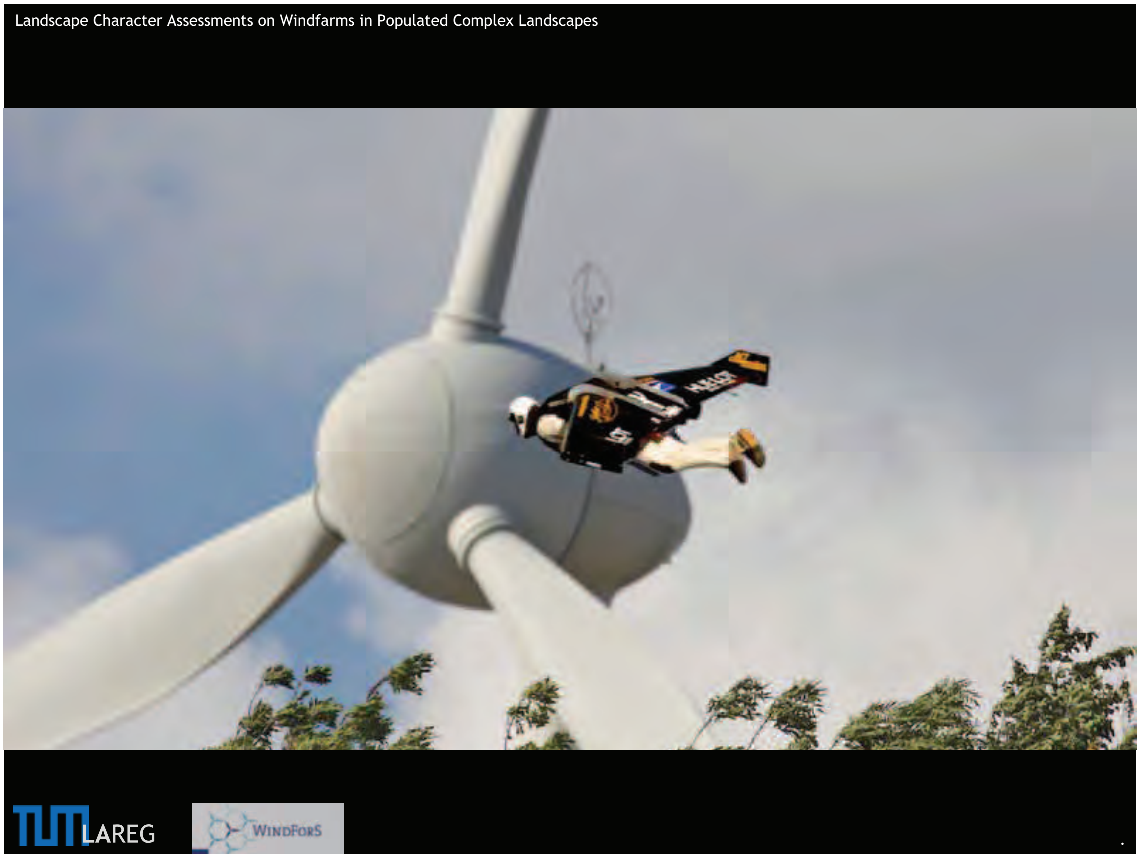
Landscape Character Assessments on Windfarms in Populated Complex Landscapes
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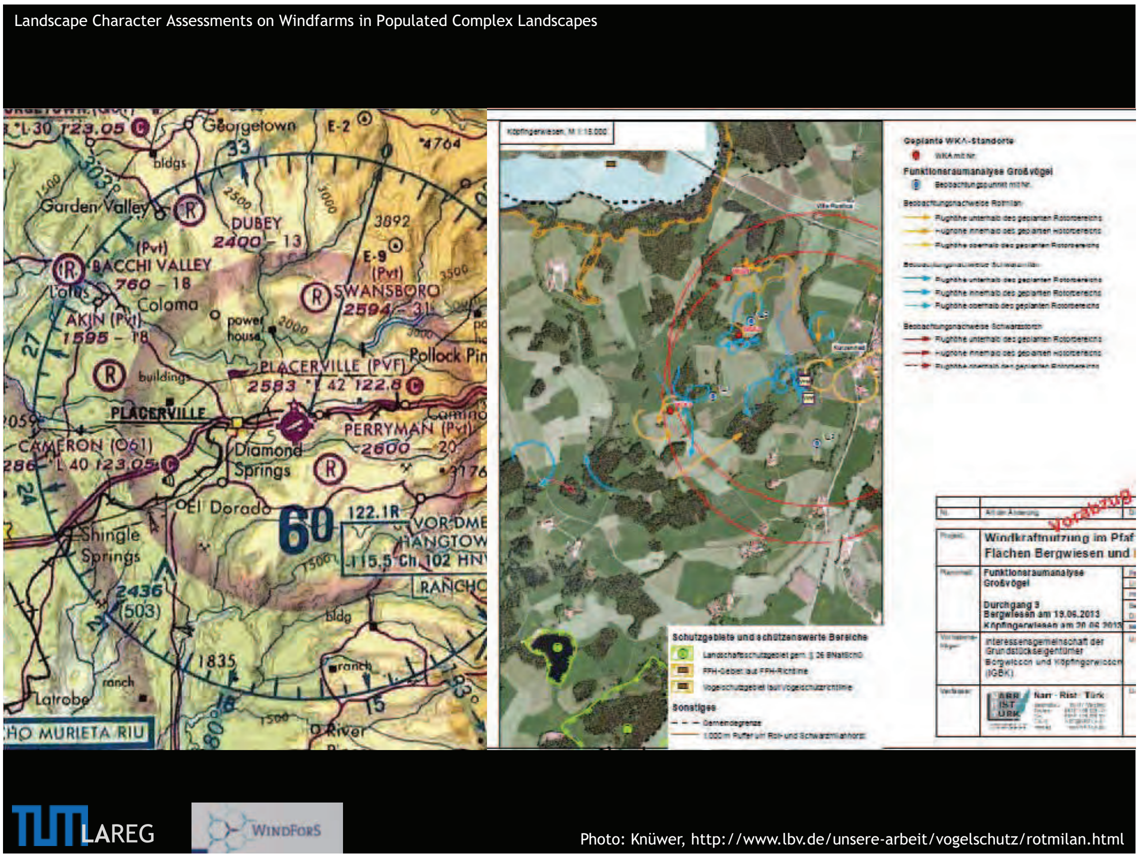
Landscape Character Assessments on Windfarms in Populated Complex Landscapes
Georgetown
Garden Valley
BACCHI VALLEY
Coloma
DUBEY
SWANSBORO
PLACERVILLE (PVF)
PLACERVILLE
CAMERON (O61)
Diamond Springs
PERRYMAN (Pvt)
El Dorado
Shingle Springs
Latrobe
60
Windkraftnutzung im Pfaf
Flächen Bergwiesen und
Funktionsraumanalyse Großvögel
Vorabzug
Schutzgebiete und schützenswerte Bereiche
Sonstiges
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Photo: Knüwer, http://www.lbv.de/unsere-arbeit/vogelschutz/rotmilan.html

Landscape Character Assessments on Windfarms in Populated Complex Landscapes

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Fotos: Alois Wohlfahrt, Eckhard Heise. Mainpost

Landscape Character Assessments on Windfarms in Populated Complex Landscapes

| Visual citeria |
|---|
| *„harmful effects on the environment“ > paradigm of prevention*<br>(FEDERAL IMMISSION CONTROL ACT) |
| A. shaddow effects, ‚disco effect‘ etc. |
| B. vertical visual impact (proportions): distances from dwellings<br>2-3 H (HIGHER ADMINISTRATIVE COURT FOR THE LAND OF NORDRHEIN-WESTFALEN)<br>2,5-4 H (BAVARIAN WIND ENERGY DECREE 2011)<br>-10 H (BAVARIAN MINISTERIAL DIRECTIVE 2013, COALITION AGREEMENT OF THE FEDERAL GOVERNMENT 2013) |
| C. horizontal visual impact (panoramas): encirclement of dwellings<br>60° in every field of view (180°) must be kept free = max. encirclement of 2 x 120° (BAVARIAN MINISTERIAL DIRECTIVE 2013) |

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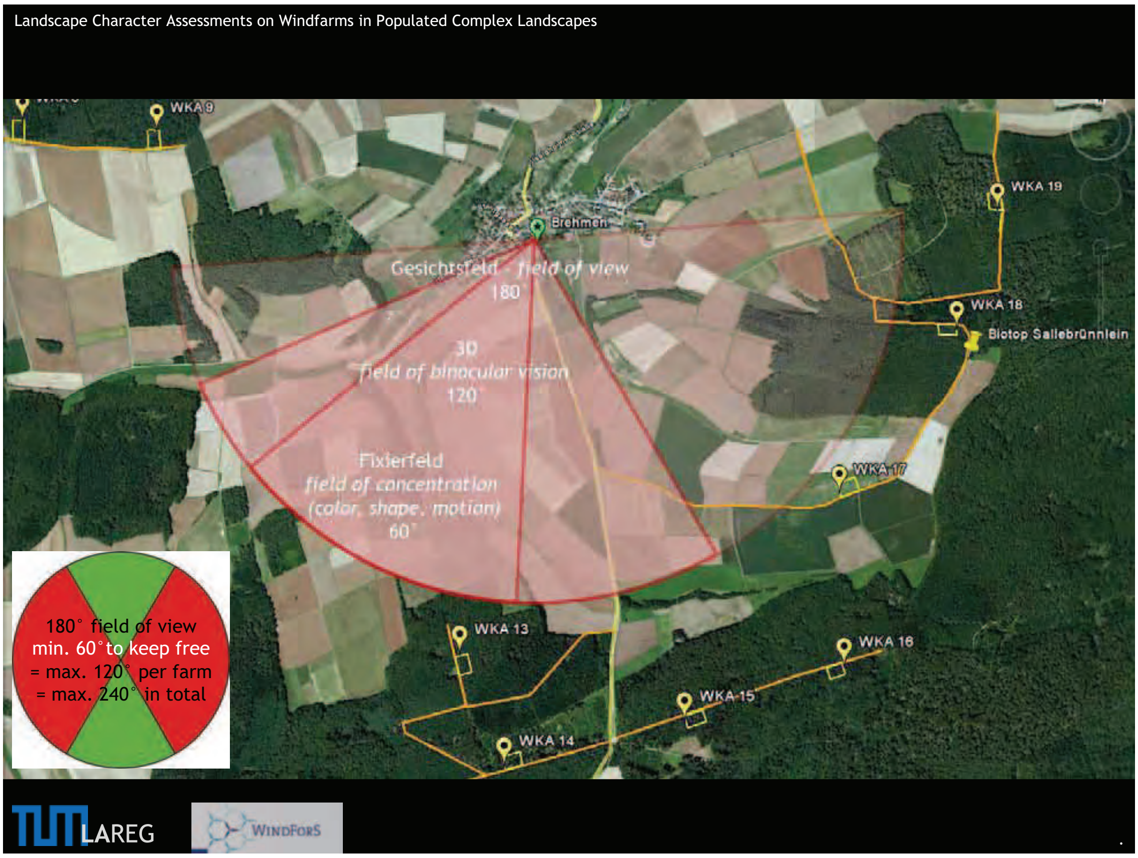
Landscape Character Assessments on Windfarms in Populated Complex Landscapes
2-H
3-H
Unterfranken ist nicht d
ROTHHAUSEN: WINDKRAFT JA - WENN DER STANDORT STIMMT KANN MAN 84 % IGNORIEREN ??
JA zu 10-H !
LAREG
WINDFORS
ökoplan, Gutachten zur Beurteilung der „optisch bedrängenden Wirkung" von Windenergieanlagen in Marl
Fotos: Alois Wohlfahrt, Eckhard Heise. Mainpost
Logo: Bürgerinitiative Zukunft Mönchberg


Landscape Character Assessments on Windfarms in Populated Complex Landscapes
WKA 9
WKA 19
Brehmen
Gesichtsfeld - field of view
180°
WKA 18
Biotop Sallebrünnlein
30°
field of binocular vision
120°
Fixierfeld
field of concentration
(color, shape, motion)
60°
WKA 17
180° field of view
min. 60° to keep free
= max. 120° per farm
= max. 240° in total
WKA 13
WKA 16
WKA 15
WKA 14
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Landscape Character Assessments on Windfarms in Populated Complex Landscapes

| Visual criteria |
|---|
| *„harmful effects on the environment“ > paradigm of prevention*<br>(FEDERAL IMMISSION CONTROL ACT) |
| A. shaddow effects, ‚disco effect‘ etc. |
| B. vertical visual impact (proportions): distances from dwellings<br>2-3 H (HIGHER ADMINISTRATIVE COURT FOR THE LAND OF NORDRHEIN-WESTFALEN)<br>2,5-4 H (BAVARIAN WIND ENERGY DECREE 2011)<br>-10 H (BAVARIAN MINISTERIAL DIRECTIVE 2013, COALITION AGREEMENT OF THE FEDERAL GOVERNMENT 2013) |
| C. horizontal visual impact (panoramas): encirclement of dwellings<br>60° in every field of view (180°) must be kept free = max. encirclement of 2 x 120° (BAVARIAN MINISTERIAL DIRECTIVE 2013) |

| Aesthetical criteria | |
|---|---|
| *„intrinsic value of nature“ > paradigm of protection*<br>(FEDERAL NATURE CONSERVATION ACT) | *„anthropocentric value of landscape“ > paradigm of planning*<br>(EUROPEAN LANDSCAPE CONVENTION) |

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Landscape Character Assessments on Windfarms in Populated Complex Landscapes

| Visual criteria |
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| Aesthetical criteria | |
|---|---|
| *„intrinsic value of nature“ > paradigm of protection*<br>(FEDERAL NATURE CONSERVATION ACT) | *„anthropocentric value of landscape“ > paradigm of planning*<br>(EUROPEAN LANDSCAPE CONVENTION) |
| A. Soft Selection Criterion<br>“… wind turbines … should in particular not be built in protected … landscape-shaping ridges.” (BAVARIAN STATE DEVELOPMENT PROGRAM) | |
| B. Visual Impact Mitigation Regulation<br>value gradations - pre-existing impacts = compensatory payment (BAVARIAN WIND ENERGY DECREE 2011) | |

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Landscape Character Assessments on Windfarms in Populated Complex Landscapes

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Landscape Character Assessments on Windfarms in Populated Complex Landscapes

| Wertstufe Landschafts-Bild[b] | Ausprägung der Landschaftsbildeinheit | Ersatzzahlung bei Einzelanlagen<br>Kosten pro laufenden Meter Gesamtanlagenhöhe pro Anlage | Ersatzzahlung bei Windfarmen (3-7 Anlagen)<br>Kosten pro laufenden Meter Gesamtanlagenhöhe pro Anlage | Ersatzzahlung bei Windfarmen (ab 8 Anlagen)<br>Kosten pro laufenden Meter Gesamtanlagenhöhe pro Anlage |
|---|---|---|---|---|
| Wertstufe 1<br>*Value Level 1* | Landschaften mit geringer Bedeutung für das Landschaftsbild und die naturbezogene Erholung; intensive, großflächige Landnutzung do … ze … be … ba … kehrsanlagen, Deponien, Abbauflächen, Industriegebiete);<br>*Landscape with low importance for the scenic beauty, nature based recreation … disturbing pre-loads …* | 180 € | 135 € | 90 €<br>*90 € x 200 m = 18.000 €* |
| Wertstufe 2 | Landschaften mit mittlerer Bedeutung für das Landschaftsbild und die naturbezogene Erholung; naturraumtypische und kulturhistorische Landschaftselemente sowie landschaftstypische Vielfalt vermindert und stellenweise überformt aber noch erkennbar; Vorbelastungen zu erkennen; | 360 € | 315 € | 270 € |
| Wertstufe 3 | Landschaften mit hoher Bedeutung für das Landschaftsbild und die naturbezogene Erholung; naturräumliche Eigenart und kulturhistorische Landschaftselemente im Wesentlichen noch gut zu erkennen; beeinträchtigende Vorbelastungen gering; hierunter fallen u. a. weniger sensible Bereiche von Landschaftsschutzgebieten bzw. von Schutzzonen von Naturparken, Alpengebiet im Sinn der Verordnung über das Landesentwicklungsprogramm Bayern (Zonen A und B); | 600 € | 555 € | 510 € |
| Wertstufe 4 | Landschaften mit sehr hoher Bedeutung für das Landschaftsbild und die naturbezogene Erholung; Natur weitgehend frei von visuell störenden Objekten; extensive kleinteilige Nutzung dominiert; hoher Anteil naturraumtypischer Landschaftselemente; hoher Anteil natürlicher landschaftsprägender Oberflächenformen; hoher Anteil kulturhistorischer bedeutsamer Landschaftselemente bzw. historischer Landnutzungsformen;<br>hierunter fallen u. a. auch folgende Gebiete:<br>Nationalparke, Kernzonen der Biosphärenreservate, besonders sensible Bereiche von Landschaftsschutzgebieten bzw. von Schutzzonen von Naturparken, Alpengebiet im Sinn der Verordnung über das Landesentwicklungsprogramm Bayern (Zone C); | 1200 € | 1155 € | *1.110 € x 200 m = 222.000 €* |

[b] Die Ermittlung der Wertstufen erfolgt in einem Umkreis des Fünfzehnfachen der Anlagenhöhe (Anlagenhöhe = Nabenhöhe inklusive Rotorblätter) um die Anlage.

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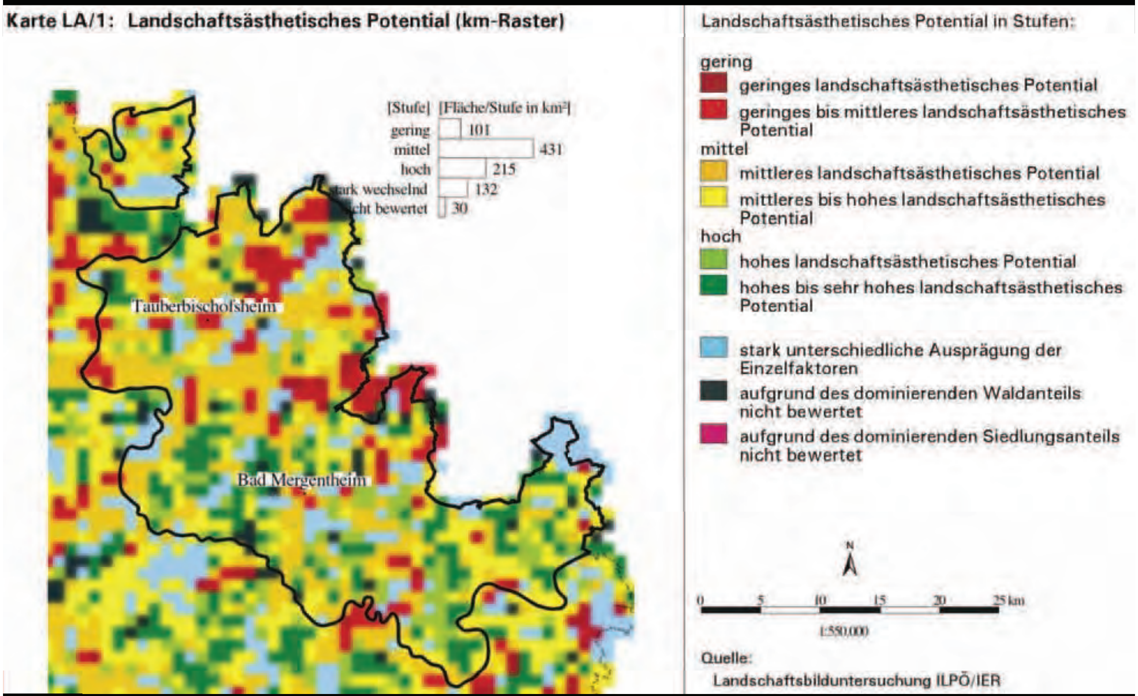
Bayerischer Windenergieerlass 2011

Landscape Character Assessments on Windfarms in Populated Complex Landscapes




LAREG WINDFORS

Bayerischer Windenergieerlass 2011

Landscape Character Assessments on Windfarms in Populated Complex Landscapes

| Visual citeria | |
|---|---|
| *„harmful effects on the environment" > paradigm of prevention* (FEDERAL IMMISSION CONTROL ACT) | |
| A. shaddow effects, ‚disco effect' etc. | |
| B. vertical visual impact (proportions): distances from dwellings<br>2-3 H (HIGHER ADMINISTRATIVE COURT FOR THE LAND OF NORDRHEIN-WESTFALEN)<br>2,5-4 H (BAVARIAN WIND ENERGY DECREE 2011)<br>-10 H (BAVARIAN MINISTERIAL DIRECTIVE 2013, COALITION AGREEMENT OF THE FEDERAL GOVERNMENT 2013) | |
| C. horizontal visual impact (panoramas): encirclement of dwellings<br>60° in every field of view (180°) must be kept free = max. encirclement of 2 x 120° (BAVARIAN MINISTERIAL DIRECTIVE 2013) | |
| **Aesthetical criteria** | |
| *„intrinsic value of nature" > paradigm of protection* (FEDERAL NATURE CONSERVATION ACT) | *„anthropocentric value of landscape" > paradigm of planning* (EUROPEAN LANDSCAPE CONVENTION) |
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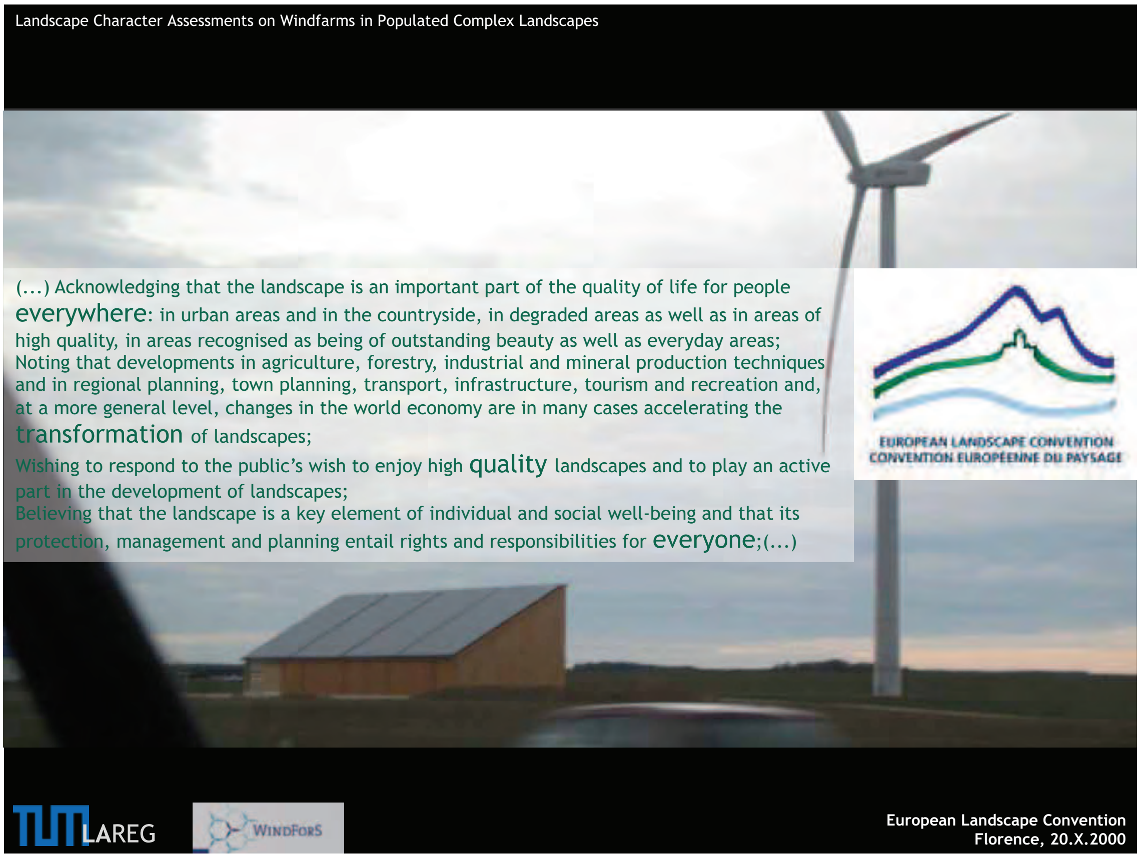
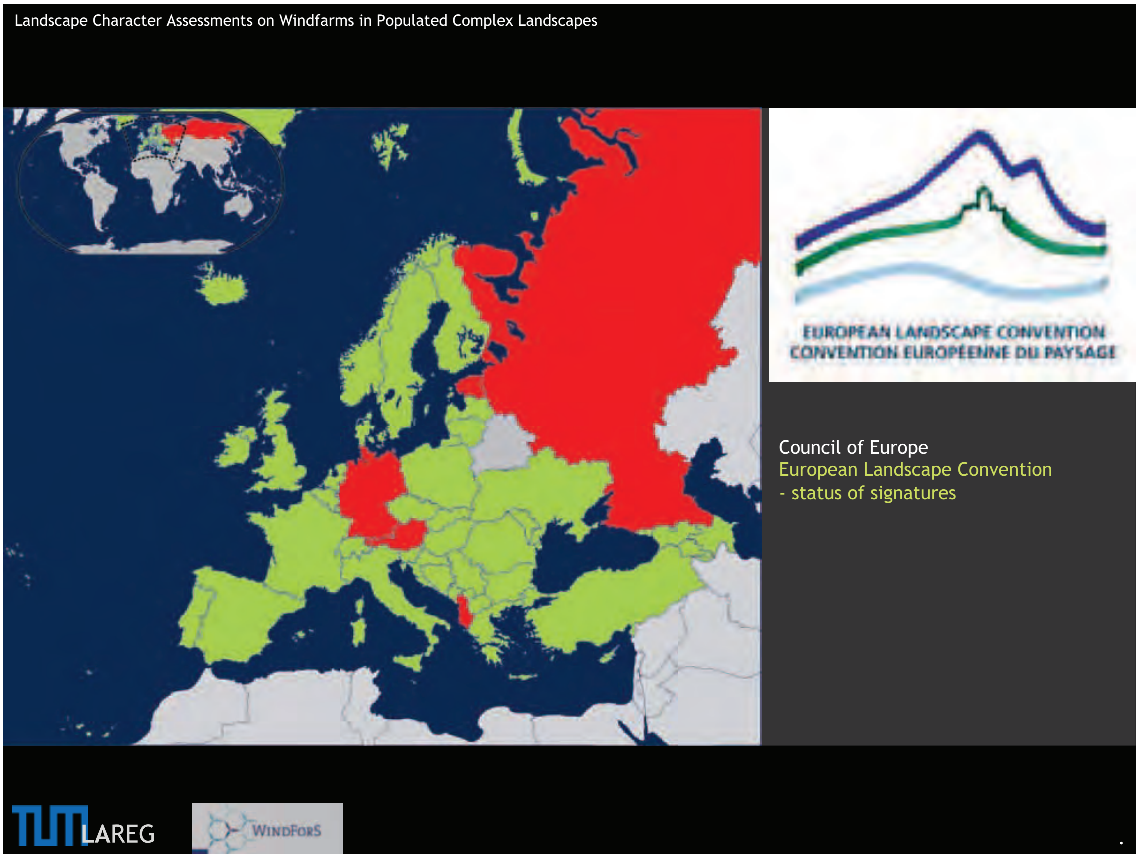

Landscape Character Assessments on Windfarms in Populated Complex Landscapes
(...) Acknowledging that the landscape is an important part of the quality of life for people everywhere: in urban areas and in the countryside, in degraded areas as well as in areas of high quality, in areas recognised as being of outstanding beauty as well as everyday areas;
Noting that developments in agriculture, forestry, industrial and mineral production techniques and in regional planning, town planning, transport, infrastructure, tourism and recreation and, at a more general level, changes in the world economy are in many cases accelerating the transformation of landscapes;
Wishing to respond to the public's wish to enjoy high quality landscapes and to play an active part in the development of landscapes;
Believing that the landscape is a key element of individual and social well-being and that its protection, management and planning entail rights and responsibilities for everyone;(...)
EUROPEAN LANDSCAPE CONVENTION
CONVENTION EUROPÉENNE DU PAYSAGE
LAREG
WINDFORS
European Landscape Convention
Florence, 20.X.2000


Landscape Character Assessments on Windfarms in Populated Complex Landscapes
EUROPEAN LANDSCAPE CONVENTION
CONVENTION EUROPÉENNE DU PAYSAGE
Council of Europe
European Landscape Convention
- status of signatures
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Landscape Character Assessments on Windfarms in Populated Complex Landscapes




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Guides for siting and designing (France, Scotland) based on ELC

Landscape Character Assessments on Windfarms in Populated Complex Landscapes

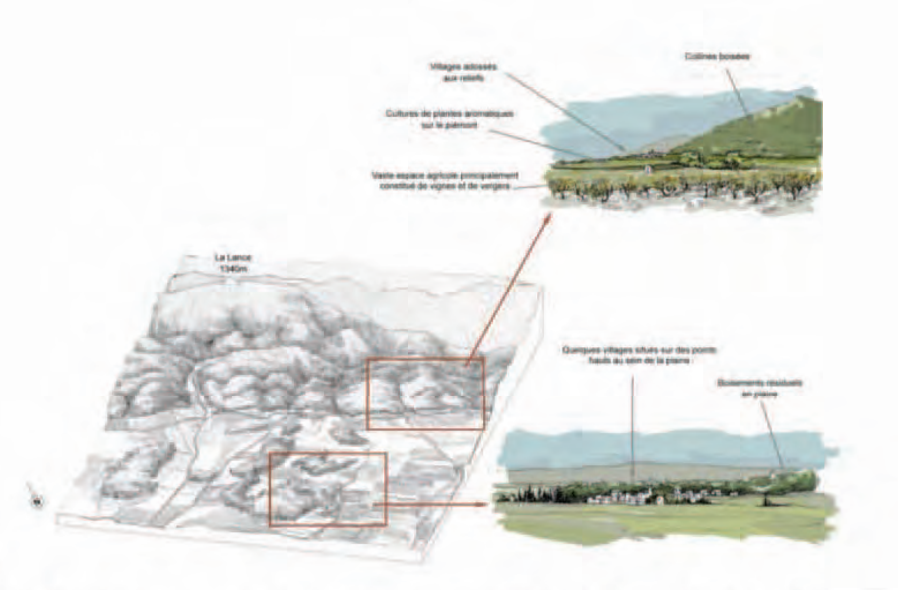

Abb. 32 - Landschaftsmodell und parallel dargestellte Interpretationsskizzen (Quelle: Atelier des Paysages, Arbre&Sens und Carto-graphic)


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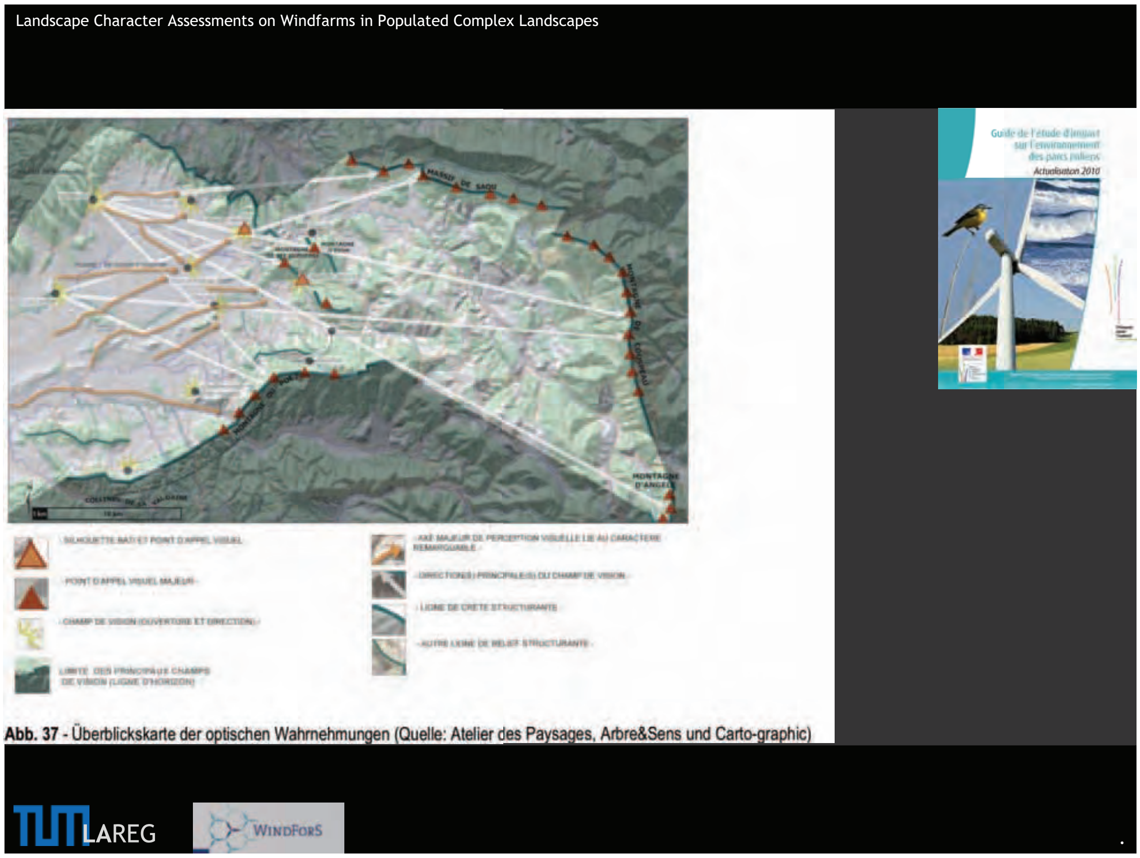
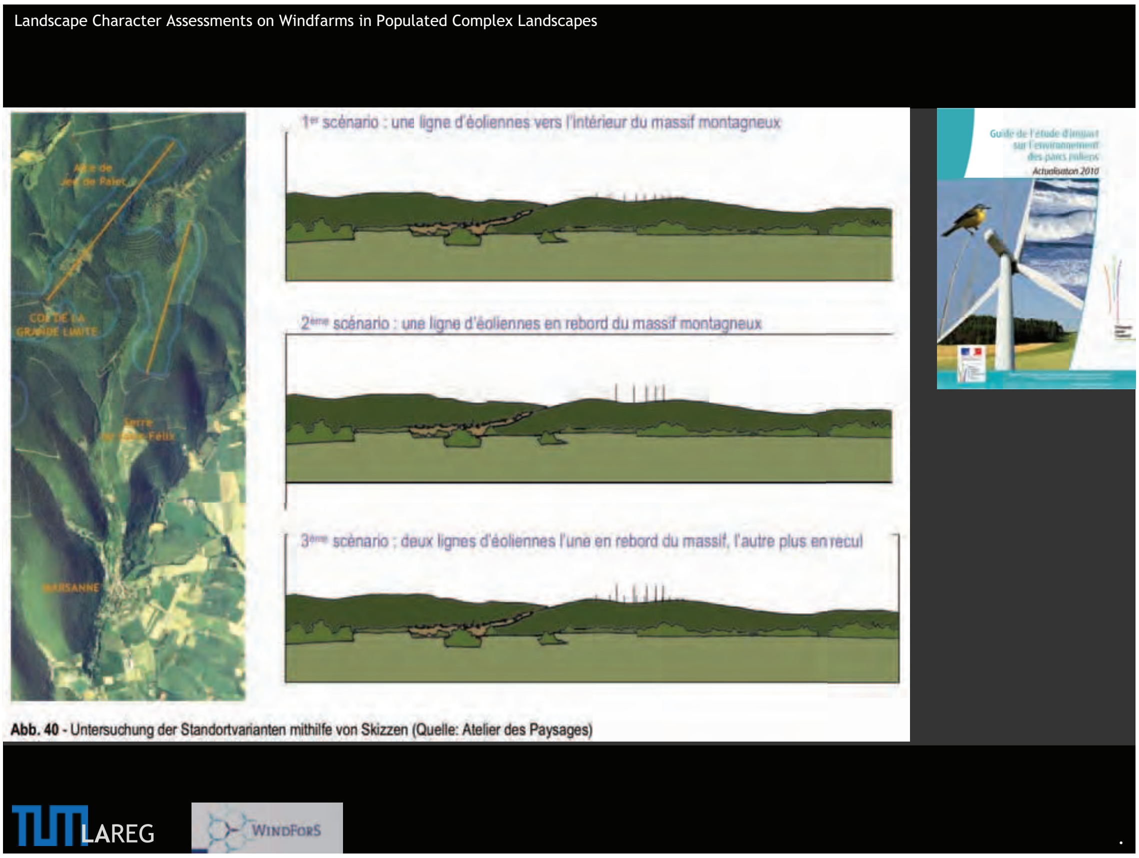

Landscape Character Assessments on Windfarms in Populated Complex Landscapes
Guide de l'étude d'impact sur l'environnement des parcs éoliens
Actualisation 2010
Abb. 37 - Überblickskarte der optischen Wahrnehmungen (Quelle: Atelier des Paysages, Arbre&Sens und Carto-graphic)
LAREG
WINDFORS


Landscape Character Assessments on Windfarms in Populated Complex Landscapes
1er scénario : une ligne d'éoliennes vers l'intérieur du massif montagneux
2ème scénario : une ligne d'éoliennes en rebord du massif montagneux
3ème scénario : deux lignes d'éoliennes l'une en rebord du massif, l'autre plus en recul
Guide de l'étude d'impact sur l'environnement des parcs éoliens
Actualisation 2010
Abb. 40 - Untersuchung der Standortvarianten mithilfe von Skizzen (Quelle: Atelier des Paysages)
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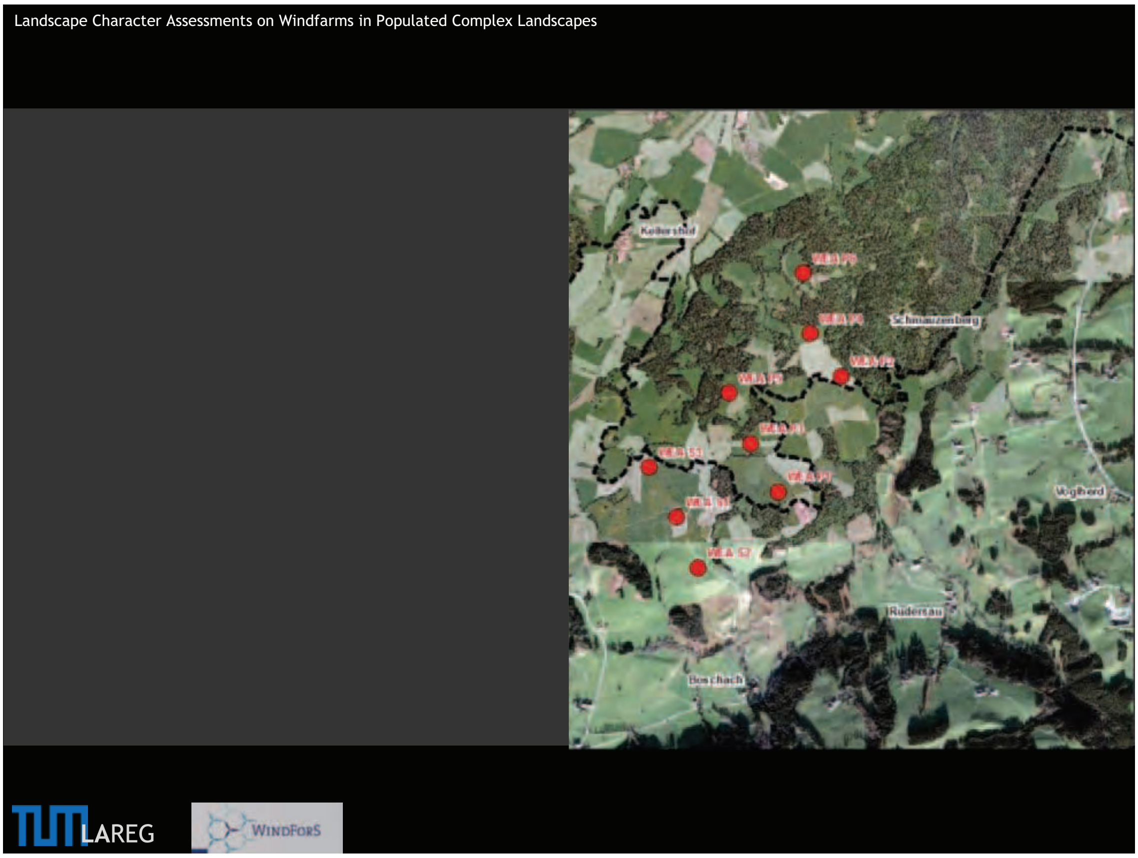
Landscape Character Assessments on Windfarms in Populated Complex Landscapes
"… wind turbines close to UNESCO World Heritage Sites is frequently problematic." (BAVARIAN MINISTERIAL DIRECTIVE 2011)
Sonderband 3
Regenerative Energien und Welterbestätten
LAREG



Landscape Character Assessments on Windfarms in Populated Complex Landscapes
Schmalzenberg
Vogelherd
Rudersau
Boschach
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Landscape Character Assessments on Windfarms in Populated Complex Landscapes


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Landscape Character Assessments on Windfarms in Populated Complex Landscapes

LAREG WINDFORS

Geologische Karte von Bayern 1:500.000

Landscape Character Assessments on Windfarms in Populated Complex Landscapes


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Landscape Character Assessments on Windfarms in Populated Complex Landscapes


LAREG WINDFORS

Geologische Karte von Bayern 1:500.000
Ausschnitte Köpfinger Wiesen / Bergwiesen

Landscape Character Assessments on Windfarms in Populated Complex Land


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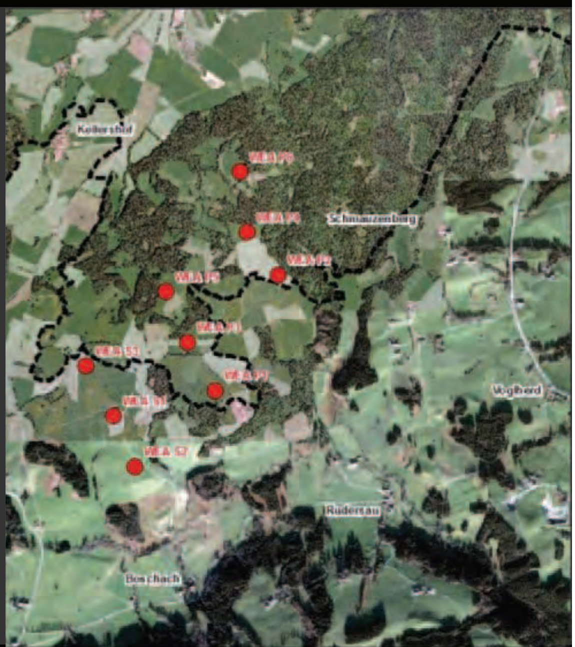
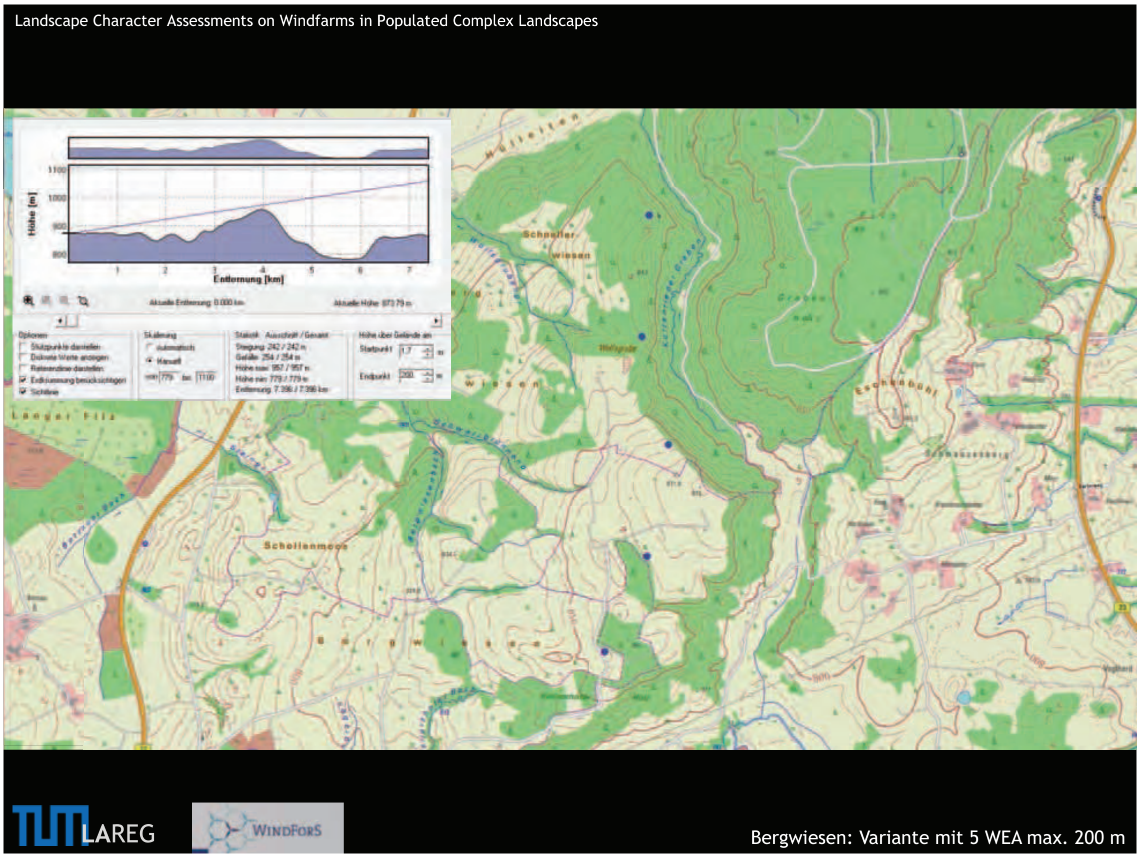
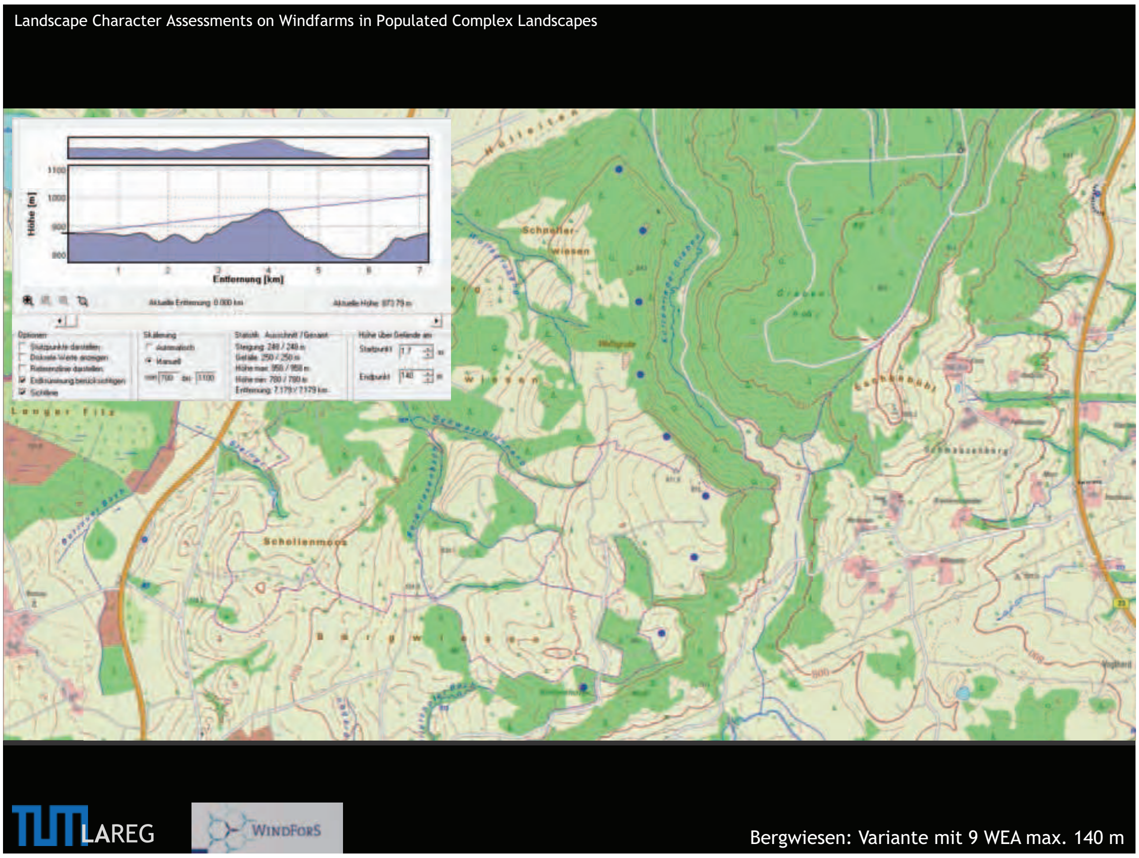
Landscape Character Assessments on Windfarms in Populated Complex Landscapes



LAREG WindForS


Landscape Character Assessments on Windfarms in Populated Complex Landscapes
LAREG
WINDFORS
Bergwiesen: Variante mit 5 WEA max. 200 m


Landscape Character Assessments on Windfarms in Populated Complex Landscapes
LAREG
WINDFORS
Bergwiesen: Variante mit 9 WEA max. 140 m


Landscape Character Assessments on Windfarms in Populated Complex Landscapes
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Bergwiesen - Visualisierung 200 m Anlagen


Landscape Character Assessments on Windfarms in Populated Complex Landscapes
LAREG
WINDFORS
Bergwiesen - Visualisierung 200 m Anlagen

Landscape Character Assessments on Windfarms in Populated Complex Landscapes

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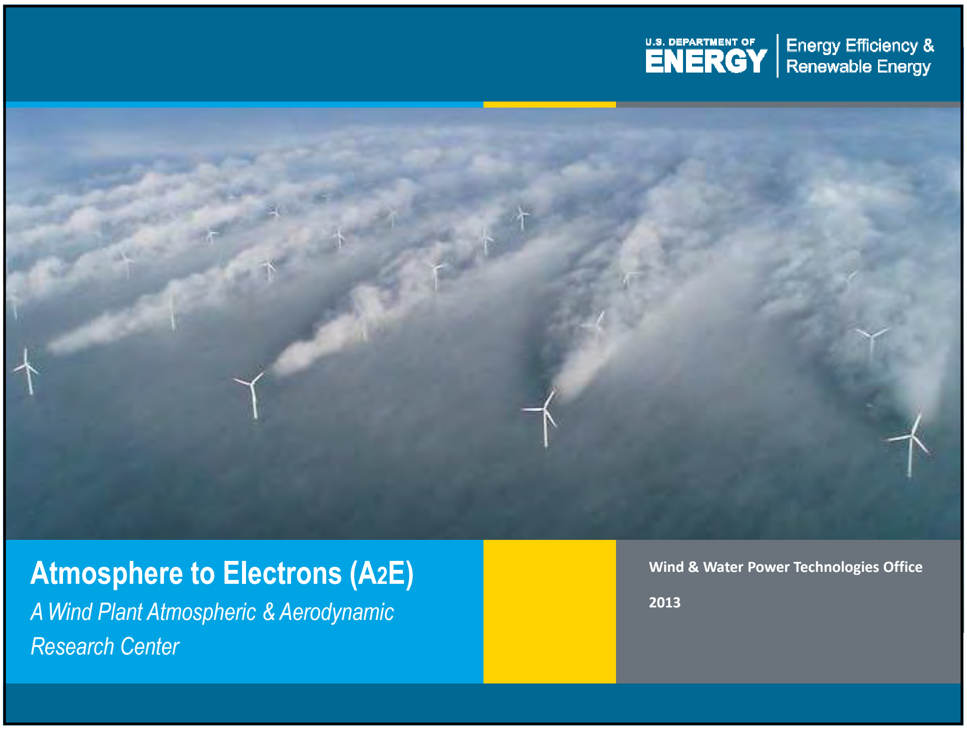
IEA Task 11 Topical Expert Meeting #75 on
Challenges on Wind Energy Deployment in Complex Terrain

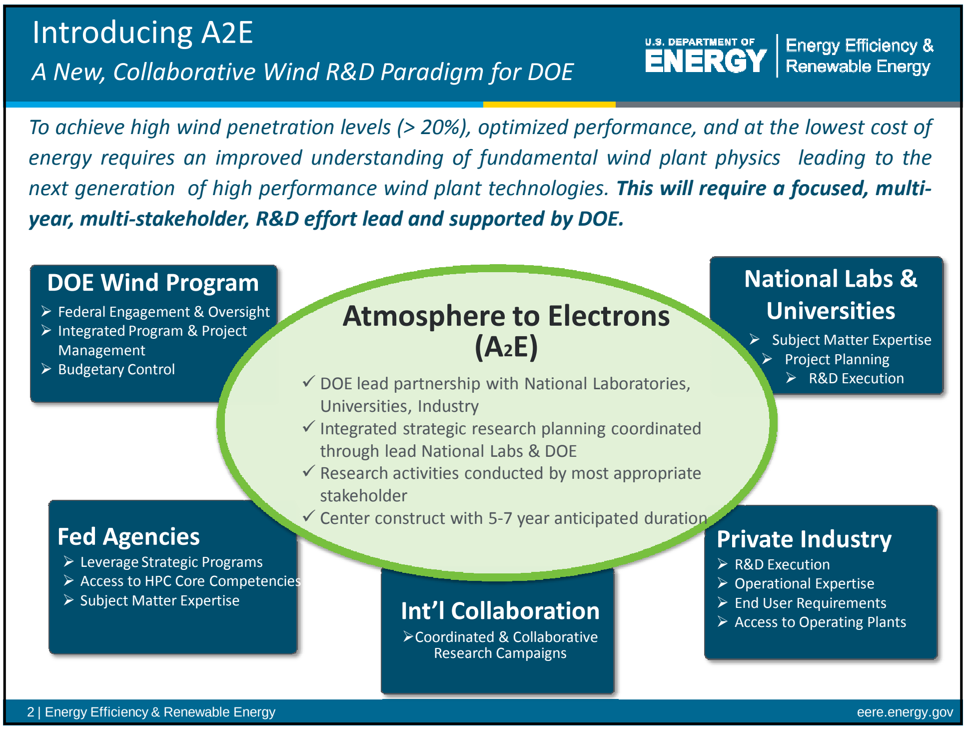
Landscape Character Assessments on Windfarms in Populated Complex Landscapes
on the Example of Southern Germany

Thank you for your attention.

Landscape Architecture and Regional Open Space (TUM LAREG)
www.lareg.wzw.tum.de
Prof. Dr. Sören Schöbel-Rutschmann

LAREG WINDFORS


U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy
Atmosphere to Electrons (A2E)
A Wind Plant Atmospheric & Aerodynamic Research Center
Wind & Water Power Technologies Office
2013


Introducing A2E
A New, Collaborative Wind R&D Paradigm for DOE
U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy
To achieve high wind penetration levels (> 20%), optimized performance, and at the lowest cost of energy requires an improved understanding of fundamental wind plant physics leading to the next generation of high performance wind plant technologies. This will require a focused, multi-year, multi-stakeholder, R&D effort lead and supported by DOE.
DOE Wind Program
Federal Engagement & Oversight
Integrated Program & Project Management
Budgetary Control
Atmosphere to Electrons (A2E)
DOE lead partnership with National Laboratories, Universities, Industry
Integrated strategic research planning coordinated through lead National Labs & DOE
Research activities conducted by most appropriate stakeholder
Center construct with 5-7 year anticipated duration
National Labs & Universities
Subject Matter Expertise
Project Planning
R&D Execution
Fed Agencies
Leverage Strategic Programs
Access to HPC Core Competencies
Subject Matter Expertise
Int'l Collaboration
Coordinated & Collaborative Research Campaigns
Private Industry
R&D Execution
Operational Expertise
End User Requirements
Access to Operating Plants
2 | Energy Efficiency & Renewable Energy
eere.energy.gov

## The Need for a New Collaborative R&D Framework

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

**Goals and Objectives for a new, low cost wind power paradigm…**

1. **Optimized Performance of Existing Wind Plants**
   - Increase Power Production 8%
   - LCOE Reduction 10%
   - Predicted Power Performance Probability (P50/P99) 98%
2. **Seamless Grid Integration at High Penetration (>20%)**
   - Improve 24 Hour Ahead Forecasted Power Production Accuracy 20%
   - Reduce Annual Curtailment 5%
3. **Next Generation Wind Plant Technology Development**
   - CapEx Reduction 15%
   - Increase Capacity Factory ($C_F$) 20%
   - O&M Reduction 15%
   - Reduced Acoustic Emissions by 5%

**…Require the following types of R&D….**

1.
   a. Quantify contributing factors to underperformance
   b. Minimize array loss effect
   c. Improve performance prediction confidence
   d. Improve reliability and reduce major component failure rates
2.
   a. Quantify gaps in boundary layer physics models
   b. Characterize physical atmospheric phenomena
   c. Improve high fidelity atmospheric models
   d. Assess inter- and intra-array effects on macro and micro climatology
   e. Integrate real-time forecast models into dispatch & operational control strategies
3.
   a. Explore optimal wind plant configurations
   b. Optimize turbine systems for next generation wind plant designs
   c. Develop scaled prototypes of new tech
   d. Develop pre-commercial prototypes at full scale

**….Which require the following activities and capabilities:**

- **Focused science & technology initiatives**
  - HPC, small- & large-scale experiments, field tests, design tools, etc.
- **Long-term integrated planning and execution**
  - Requires central planning group consisting of technical experts
  - Requires flexible, multi-year funding decisions
- **Multi-stakeholder engagement**
  - Must engage national labs, industry, international experts, & universities
- **Public dissemination of results**
  - Results must benefit the entire U.S. wind industry

**Atmosphere to Electrons (A2E)**
- ✓ DOE lead partnership with National Laboratories, Universities, Industry
- ✓ Integrated strategic research planning coordinated through lead National Labs & DOE
- ✓ Research activities conducted by most appropriate stakeholder
- ✓ Center construct with 5-7 year anticipated duration

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## A2E Operating Principles

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

*The A2E program goals represent a "Grand Challenge" opportunity[1] requiring a fundamentally different operating paradigm. The Wind Program will address this opportunity utilizing the following operating principles:*

**I. Ensure research priorities reflect multi-stakeholder input**

**II. Formulate research challenges and identify gaps in the public domain**

**III. Leverage all available resources and synergistic research activities**

**IV. Identify an appropriate implementation strategy for execution**

**V. Develop a common, open platform for R&D and tech transfer**

[1] Office of Science "Grand Challenges of Advanced Computing for Energy Innovation," 2012

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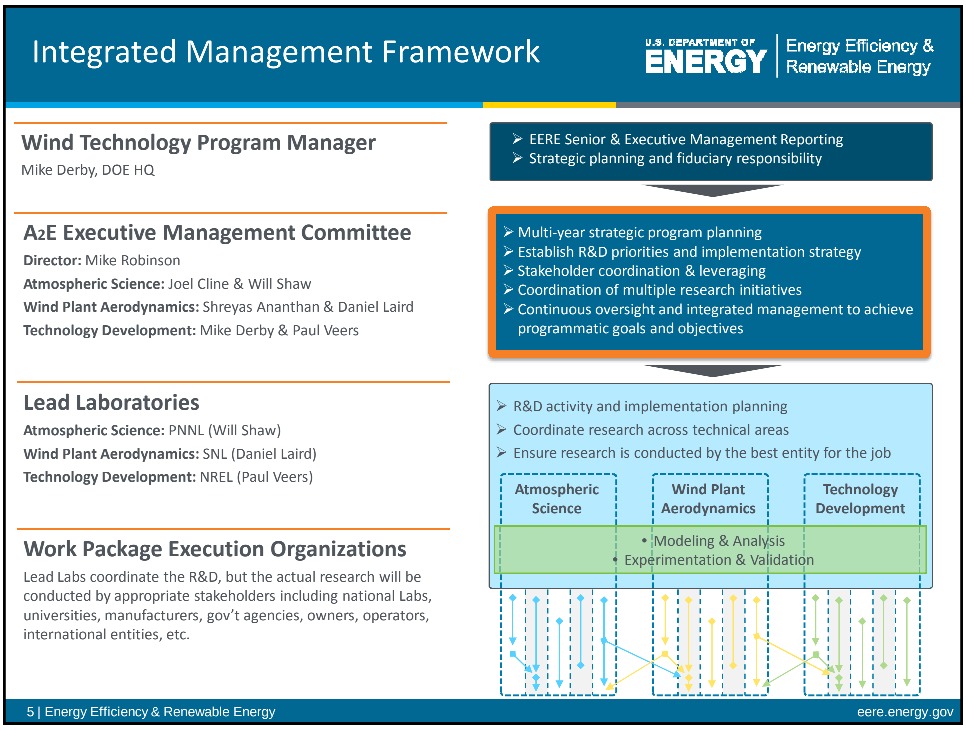
Integrated Management Framework
U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy
Wind Technology Program Manager
Mike Derby, DOE HQ
A2E Executive Management Committee
Director: Mike Robinson
Atmospheric Science: Joel Cline & Will Shaw
Wind Plant Aerodynamics: Shreyas Ananthan & Daniel Laird
Technology Development: Mike Derby & Paul Veers
Lead Laboratories
Atmospheric Science: PNNL (Will Shaw)
Wind Plant Aerodynamics: SNL (Daniel Laird)
Technology Development: NREL (Paul Veers)
Work Package Execution Organizations
Lead Labs coordinate the R&D, but the actual research will be conducted by appropriate stakeholders including national Labs, universities, manufacturers, gov't agencies, owners, operators, international entities, etc.
➢ EERE Senior & Executive Management Reporting
➢ Strategic planning and fiduciary responsibility
➢ Multi-year strategic program planning
➢ Establish R&D priorities and implementation strategy
➢ Stakeholder coordination & leveraging
➢ Coordination of multiple research initiatives
➢ Continuous oversight and integrated management to achieve programmatic goals and objectives
➢ R&D activity and implementation planning
➢ Coordinate research across technical areas
➢ Ensure research is conducted by the best entity for the job
Atmospheric Science
Wind Plant Aerodynamics
Technology Development
• Modeling & Analysis
• Experimentation & Validation
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eere.energy.gov


External Merit Review
U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy
Wind Technology Program Manager
Mike Derby, DOE HQ
A2E Executive Management Committee
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Atmospheric Science: Joel Cline & Will Shaw
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External Merit Review Board
• Chaired by Sandy Butterfield, CTO Boulder Wind Power, AWEA Board Liaison with R&D committee, Former Chief Engineer of National Wind Technology Center.
• Board constituency reflecting sector representation from industry, national laboratories, academia, government agencies, and international stakeholders
• Provide program review and strategic guidance input in the formulation of A2E goals and implementation approaches.
• Participate in Annual Merit Review meetings
• External assessment of program performance and future initiatives
• Assessment of program impact on industry needs and challenges
• Help coordinate and leverage external research initiatives and resources
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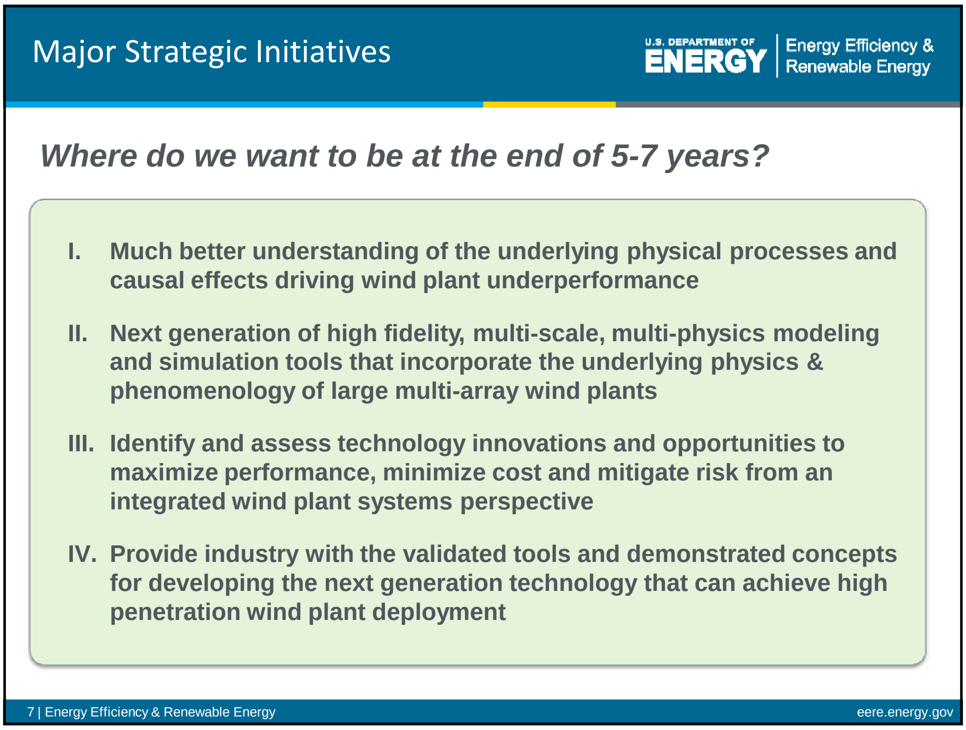
Major Strategic Initiatives
U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy
Where do we want to be at the end of 5-7 years?
I. Much better understanding of the underlying physical processes and causal effects driving wind plant underperformance
II. Next generation of high fidelity, multi-scale, multi-physics modeling and simulation tools that incorporate the underlying physics & phenomenology of large multi-array wind plants
III. Identify and assess technology innovations and opportunities to maximize performance, minimize cost and mitigate risk from an integrated wind plant systems perspective
IV. Provide industry with the validated tools and demonstrated concepts for developing the next generation technology that can achieve high penetration wind plant deployment
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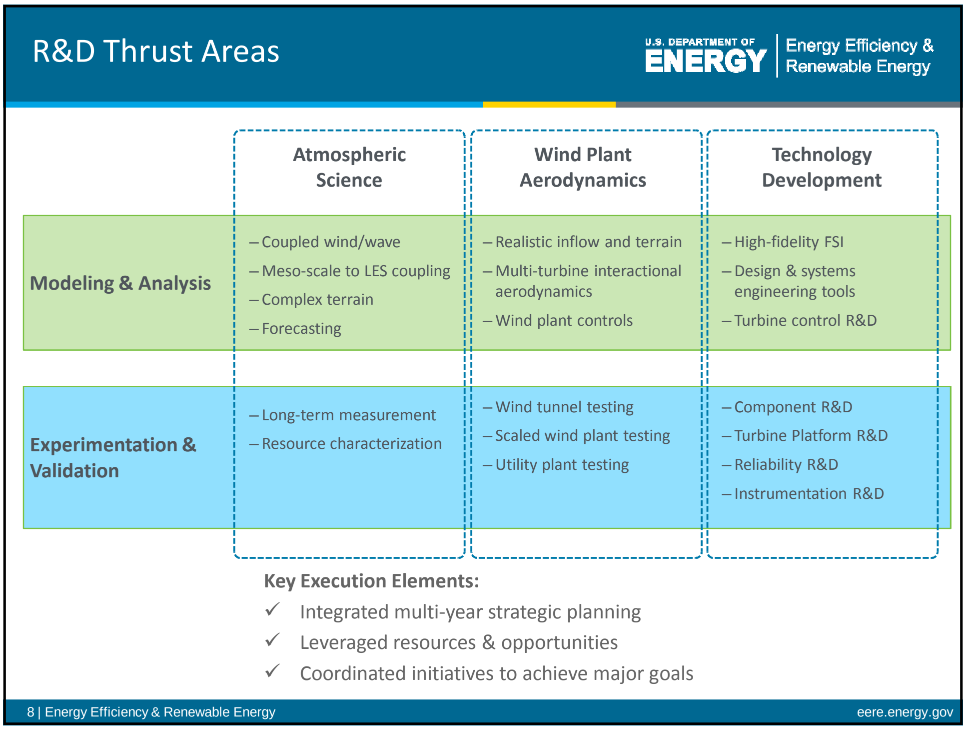
R&D Thrust Areas
U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy
Atmospheric Science
Wind Plant Aerodynamics
Technology Development
Modeling & Analysis
– Coupled wind/wave
– Meso-scale to LES coupling
– Complex terrain
– Forecasting
– Realistic inflow and terrain
– Multi-turbine interactional aerodynamics
– Wind plant controls
– High-fidelity FSI
– Design & systems engineering tools
– Turbine control R&D
Experimentation & Validation
– Long-term measurement
– Resource characterization
– Wind tunnel testing
– Scaled wind plant testing
– Utility plant testing
– Component R&D
– Turbine Platform R&D
– Reliability R&D
– Instrumentation R&D
Key Execution Elements:
✓ Integrated multi-year strategic planning
✓ Leveraged resources & opportunities
✓ Coordinated initiatives to achieve major goals
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## A2e and HPC Initiatives: Key Questions (1)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- What simulation capability do we want by 2020? 2030? 2050?
  - *Resulting capability must allow DOE and industry to reach cost and performance goals*
  - *Must fundamentally rethink DOE's approach to using HPC for solving wind energy problems to reach a step-change*
- Ensure simulation results impact design codes and operational tools
  - *Plant siting and layout analysis*
  - *Improved operational strategies*
  - *Plant-level system engineering and optimization*
  - *Mid- to low-fidelity (design tools) model development*

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## A2e and HPC Initiatives: Key Questions (2)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- What are the fundamental gaps and barriers for an integrated multi scale modeling approach?
  - —*Common need*
    - *Multi-scale, multi-physics, high-fidelity models*
    - *Improved model accuracy and rigorous V&V*
    - *Sources of error must be identified and uncertainties must be modeled*
  - —*Wind Plant Control Volume*
    - *Mesoscale <-> Wind plant scale <-> Turbine scale*
    - *Wind/wave coupling and complex terrain*
    - *Atmospheric stability and inflow turbulence*
    - *Deep-array effects*
  - —*Wind Turbine Control Volume*
    - *Aero-structural coupling*
    - *Aero-acoustics capability*
    - *Turbine-wake interaction*

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## A2e and HPC Initiatives: Key Questions (3)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- What experiments are required to get at the necessary physics? Resources include:
  - *WFIPs atmospheric measurement campaigns (long-term)*
  - *NASA Ames Wind-tunnel testing*
  - *Scaled Wind Farm Test (SWiFT) Facility*
  - *Full-scale field tests at operating wind farms*

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