INTERNATIONAL ENERGY AGENCY

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

Topical Expert Meeting #82 on

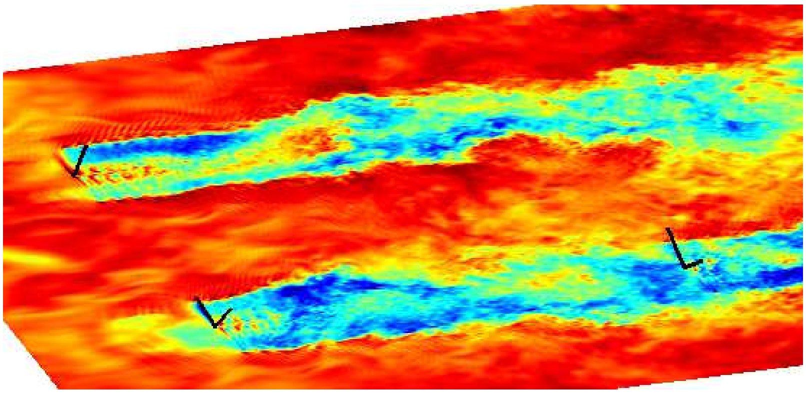
Uncertainty Quantification of Wind Farm Flow Models

Wind Energy Campus

Gotland Department of Earth Sciences

Uppsala University Campus Gotland

June 12th in Visby



Scientific Co-ordination: Félix Avia Aranda

CENER (Centro Nacional de Energías Renovables)

Ciudad de la Innovacion 7, 31621 Sarriguren (Navarra) Spain
Phone: +34 948 25 28 00
E-mail: favia@cener.com

Copies of this document can be obtained from:

CENER
Félix Avia Aranda
Ciudad de la Innovación 7
31621 Sarriguren (Navarra) Spain
Phone: +34 948 25 28 00
E-mail: favia@cener.com

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

International Energy Agency

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

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

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

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

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

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

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

IEA Wind TASK 11: BASE TECHNOLOGY INFORMATION EXCHANGE

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

Carballeira Wind Farm - Spain

Two Subtasks

The task includes two subtasks.

The objective of the first subtask is to develop recommended practices (RP). In 2013 were edited RPs on "Social Acceptance of Wind Energy Projects", "Wind Integration Studies" and. "Ground-Based Vertically Profiling Remote Sensing for Wind Resource Assessment".

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 70 volumes of proceedings have been published. In the series of Recommended Practices 16 documents were published and five of these have revised editions.

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

Operating Agent

CENER
Félix Avia Aranda
Ciudad de la Innovación 7
31621 Sarriguren (Navarra) Spain
Phone: +34 948 25 28 00
E-mail:favia@cener.comE-mail:favia@cener.com

COUNTRIES PRESENTLY PARTICIPATING IN THE TASK 11	
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
Mexico	Instituto de Investigaciones Electricas - IEE
Netherlands	Rijksdient voor Ondernemend Nederland (RVO)
Norway	The Norwegian Water Resources and Energy Directorate - NVE
Spain	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas CIEMAT
Sweden	Energimyndigheten – Swedish Energy Agency
Switzerland	Swiss Federal Office of Energy - SFOE
United Kingdom	CATAPULT Offshore Renewable Energy
United States	The U.S Department of Energy -DOE

CONTENTS

PRESENTATIONS

1. INTRODUCTORY NOTE

Background

As wind energy computational models become more advanced to support engineering practice it also becomes more difficult to determine the confidence levels of their predictions. Uncertainty quantification (UQ) deals with the characterization of the impact of system inaccuracies on the final quality of interest. These inaccuracies come from lack of knowledge associated to the physical processes of the measurement or modeling system. Uncertainty on wind energy systems is also greatly influenced by the inherent variability of the driving boundary conditions.

This Topical Expert Meeting (TEM) on "Uncertainty Quantification of Wind Farm Flow Models" originates from the growing interest that the topic has recently experienced in various wind energy forums.

The IEA-Wind has several research Tasks related to model evaluation at various sub-system levels: rotor aerodynamics (**Task 29 MexNext**), offshore platforms (**Task 30 OC5**) and external wind conditions (**Task 31 Wakebench**). These Tasks have developed methodologies for model verification and validation and conducted a series of model intercomparison benchmarking exercises to compare models against each other and versus observational data. While systematic validation is essential to determine the level of confidence of the simulation tools, the ultimate goal of the evaluation process is to quantify the associated uncertainties, since these determine the impact of model inaccuracies on the wind energy system performance.

New IEA Tasks on wind forecasting and wind energy systems engineering are also being formulated with uncertainty assessment

The **IEC 61400-15** group is developing a standard for wind resource assessment, energy yield and site suitability that includes a large subgroup on the characterization of uncertainties of wind farm design drivers. Uncertainty in wind farm development is related to project risk assessment and financial cost. A survey conducted for the last AWEA Wind Resource Assessment Seminar (Orlando, December 2014), among various top consultants in North America, showed that uncertainty estimates based on current engineering uncertainty assessment methods are not correlated to the actual deviations observed on project performance. A debate is open on whether these traditional methodologies can be used in connection to project risk assessment or if there is a need for a more rigorous uncertainty quantification methodology.

The New European Wind Atlas project (NEWA) project (2015-2020) will develop a probabilistic wind atlas methodology to characterize not only the most probable wind resource over Europe but also the associated uncertainty. New models for downscaling the wind resource from mesoscale to microscale will be thoroughly validated with high-fidelity experimental campaigns across Europe. This new technology shall reduce resource characterization uncertainties below 3% for flat homogeneous terrain and below 10% in complex terrain.

The Atmosphere to Electrons (A2e) research initiative (2015-2021) from the U.S. Department of Energy aims at significant reductions of the cost of energy (up to 20%) by improving the understanding of the complex physics governing the wind flow into and within wind farms. The link between performance uncertainty, financial risk and levelized cost of energy will allow a comprehensive assessment of the impact of research on the wind industry.

This TEM is organized together with the kick-off meeting of the second phase of Task 31 Wakebench in order to map the knowledge that the wind energy sector currently has on UQ applied to wind farm flow models. The definition of a UQ flow modeling framework is a new work package of Task 31. This will be incorporated in the second edition of the Wakebench Model Evaluation Protocol (Sanz Rodrigo and Moriarty, 2015).

A rigorous method for UQ is lacking in general in the wind energy community. Disparate physical scales and modeling communities make this task challenging. Nevertheless, this is an essential step to make wind energy more competitive in terms of project financing compared to conventional energy sources.

Flow Modeling Uncertainties in Wind Resource Assessment

In wind resource assessment practice, UQ is typically quantified in terms of the p_x percentiles (p_{50}, p_{75}, p_{90} are often used) or exceedance probabilities of the wind farm's annual energy production (AEP), as part of the project risk assessment during wind farm planning and financing. Hale (2015) provides a couple of examples on the financial impact of uncertainty: for a 200 MW project, a 3% difference on the AEP P50 means $17MM difference in the net project value; a 1.5% difference on P95 results in $1.5MM difference on the net project value. The flow model can be a large contributor to this uncertainty especially in complex terrain and large wind farm arrays.

Typical sources of flow modeling uncertainty are:

- Natural variability of the flow model inputs: wind speed, wind direction, wind rose, turbulence intensity, stability, seasonal effects, vegetation, waves etc
- Lack of user consistency on model implementation: different interpretation of model inputs, lack of standardized quality-check on measurements, meshing strategy, etc
- Lack of good characterization of input data and their variability: topographic description, limited and uncertain onsite measurements, idealized wind turbine specifications, etc
- Input dependent model "parameters" typically in connection to turbulence models
- Lack of adequacy of the flow model: too drastic assumptions in order to produce simulations in a reasonable time, etc.
- Lack of numerical convergence due to too short simulation time, instability of the turbulence model used etc.
- Too high numerical dissipation due to too coarse grids

These uncertainties are broadly classified as aleatoric (statistical) and epistemic (systematic). Aleatoric uncertainty related to the physical variability of the system cannot be reduced but needs to be characterized in order to be properly quantified. UQ intends to deal with epistemic uncertainties and aleatoric uncertainties using statistical techniques to characterize the probability distributions that govern the uncertainty process.

Objectives

The primary goals of this TEM are:

- To gather experts on UQ working in the wind energy field
- To identify state-of-the-art UQ techniques that can be reasonably applied to wind farm flow models in engineering practice
- To discuss potential challenges in the implementation of UQ methods
- To outline a work plan for IEA Task 31 to develop a UQ framework

Intended Audience

While the TEM is focused on wind farm flow models, since this is the topic of Task 31, the meeting is open to experts on uncertainty quantification in general. Wind industry practitioners of UQ are especially encouraged to participate in order to inform about current practices, limitations and impact on real life projects. Researchers are welcome to propose UQ methodologies and data needs.

References

Hale E (2015) The Uncertainty of Uncertainty. 2015 Wind Energy Systems Engineering Workshop, University of Colorado Boulder, Colorado, January 2015.

Sanz Rodrigo J, Moriarty P (2015) Model Evaluation Protocol for Wind Farm Flow Models. Deliverable of IEA-Task 31

2. AGENDA

Friday 12th June

>08:30 **Registration**. Collection of presentations

>08:45 **Introduction by Host**

Dr. Stefan Ivanell, Associate Professor, Head of Section, Wind Energy Campus Gotland Department of Earth, Sciences Uppsala University Campus Gotland

>09: 05 **Recognition of Participants**

>09:15 **Introduction by Task 11 Operating Agent.**

Felix Avia, Operating Agent Task 11 IEAWind R&D

>09:30 **Introduction to TEM**

Dr. Javier Sanz Rodrigo_ CENER

1st Session Individual Presentations:

>09:45 **Flow model uncertainty - a review from industry perspective**

Mr. Wiebke Langreder, Wind Solutions, Denmark

>10:10 **Multi fidelity of wind farm flow models**

Mr. Pierre-Elouan Réthoré, RISO DTU Wind Energy, Denmark

>10:35 **Uncertainty of Power Production Predictions of Stationary Wind Farm Models using Monte-Carlo Simulation of Horns Rev**

J.P. Murcia, P.-E. Réthoré, A. Natarajan, J. D. Sørensen, K. Hansen

>10:35 **How much do CFD models improve the accuracy of the flow modeling?**

Dr. Barbara Jimenez Douglas, UL International GmbH-DEWI, Germany

***>11:00* Multi-scale Wake Experiment Planning Through a Formal Validation Process**

Dr. David Maniaci, SANDIA; USA

●*11:25* ***Coffee Break***

***>11:45* Uncertainty of data used in Wind Farm Flow Model validation**

Dr. Kurt Schaldemose, Hansen, DTU Windenergy, Denmark

***>12:10* Uncertainties from lidar measurements and how these propagate to modeling**

Ph.D. Rebecca J. Barthelmie, Cornell University, USA, NY

***>12:35* Sensitivity analysis of the atmospheric boundary layer under a wide range of stability and geostrophic wind conditions**

Dr. Javier Sanz Rodrigo, CENER, Spain

●***13:00 Lunch***

2nd Session Individual Presentations:

***>14:00* Ensemble based stochastic wind power penetrated reserve electricity market optimization**

Dr. Bahri Uzunoglu, Centre for Renewable Electric Energy Conversion Uppsala University, Sweden

***>14:25* Uncertainty related standards and R&D initiatives**

Dr. Patrick J. Moriarty, NREL, USA, CO

***>15:15* Discussion**

***>15:45* Summary of Meeting**

***>16:00* End of the meeting**

3. LIST OF PARTICIPANTS

The meeting was attended by 19 participants from 7 countries. Table 1 lists the participants and their affiliations.

	Name	Surname	Job Centre	Country
1	**Li**	**Li**	*North China Electric Power University*	China
2	**Yongqian**	**Liu**	*North China Electric Power University*	China
3	**Xiaodong**	**Wang**	*North China Electric Power University*	China
4	**Kurt Schaldemose**	**Hansen**	*DTU Windenergy*	Denmark
5	**Wiebke**	**Langreder**	*Wind Solutions*	Denmark
6	**Juan Pablo**	**Murcia León**	*RISO DTU Wind Energy*	Denmark
7	**Pierre-Elouan**	**Réthoré**	*RISO DTU Wind Energy*	Denmark
8	**Paul**	**van der Laan**	*DTU Windenergy*	Denmark
9	**Rupert**	**Storey**	*RISO DTU Wind Energy*	Denmark
10	**Soren**	**Andersen**	*DTU Windenergy*	Denmark
11	**Niels**	**Trohlborg**	*DTU Windenergy*	Denmark
12	**Richard J.**	**Foreman**	*UL International GmbH-DEWI*	Germany
13	**Barbara**	**Jimenez Douglas**	*UL International GmbH-DEWI*	Germany
14	**Takeshi**	**Kamio**	*The University of Tokyo*	Japan
15	**Javier**	**Sanz Rodrigo**	*CENER*	Spain
16	**Bahri**	**Uzunoglu**	*Uppsala University*	Sweden
17	**Patrick J.**	**Moriarty**	*NREL*	USA, CO
18	**David Charles**	**Maniaci**	*SANDIA*	USA, NM
19	**Rebecca J.**	**Barthelmie**	*Cornell University*	USA, NY

iea wind

The International Energy Agency Implementing Agreement for
Co-operation in the Research, Development, and Deployment of Wind Energy Systems
www.ieawind.org

4. SUMMARY

A TEM on Uncertainty Quantification of Wind Farm Flow Models was jointly organized between IEA Task 11 and Task 31 "Wakebench" [1]. The TEM coincides with the kick-off meeting of the second phase of Wakebench that now includes a work package, lead by the Technical University of Denmark, dedicated to the introduction of uncertainty quantification (UQ) in the Task's Model Evaluation Protocol. The TEM was used as initial survey of existing practices and initiatives in the wind energy community to deal with UQ.

Besides Task 31, there were presentations about two other initiatives on the topic, notably: the PRUF project under the Atmosphere to Electrons research program of the U.S. Department of Energy and the IEC 61400-15.

PRUF (Performance, Risk, Uncertainty, and Finance) investigates the impact that project uncertainties have on financial structures, capital costs, perceptions of financial risk, and levelized cost of energy (LCOE) for wind [2]. This project includes all the stakeholders involved in the assessment of wind resource uncertainties and their impact on project financial risk. An important asset of this initiative is the collection of representative data from existing projects from the U.S. industry to support the UQ process.

The IEC 61400-15 "Assessment of Wind Resource, Energy Yield and Site Suitability input conditions for wind power plants" is active since February 2014 and gathers stakeholders from 10 countries. The main objective is to create an IEC standard that facilitates the adoption of a unified methodology for energy yield and site suitability assessment. This includes, as any IEC norm, normative as well as informative aspects. Among the normative aspects, initial steps are addressing documentation and reporting requirements to help ensure the traceability of the process. A catalogue of uncertainties will be formulated so everyone categorizes uncertainty sources in the same way. Methods for the assessment of wind conditions will be formulated but not necessarily in the normative part of the standard.

Both PRUF and IEC are ultimately looking at how uncertainties are perceived at the project financing level. Ad-hoc uncertainty quantification methods based on engineering practices in industry are common place here. In contrast, a formal UQ method based on a probabilistic approach is the alternative proposed in the IEA Task 31. This formal approach typically requires a large number of simulations to propagate input and model uncertainties.

Finding the right balance between the more formal and the more engineering approaches towards UQ shall be the main objective in the long term. In this process, it is also important to find methods that can make use of various model fidelity levels to gain accuracy at an affordable computational cost.

Benchmarking exercises like those organized in Task 31 or the CREYAP (Comparison of Resource and Energy Yield Assessment Procedures) exercises organized by the European Wind Energy Association [3] are good instruments to discuss UQ methods as part of wind resource assessment methodologies.

The interested reader shall follow any of these forums to get acquainted with progress in UQ methods applied to wind assessment.

References:

[1] IEA Task 31 Wakebench Phase 2: http://windbench.net/wakebench2
[2] PRUF project: https://a2e.pnnl.gov/about/pruf
[3] Mortensen N, Jørgensen H.E. (2013) Comparative Resource and Energy Yield Assessment Procedures (CREYAP) Pt. II. http://www.ewea.org/events/workshops/wp-content/uploads/2013/06/EWEA-RA2013-Dublin-5-5-Niels-G-Mortensen-DTU-Wind-Energy.pdf

PRESENTATIONS

Flow Model Uncertainty – a review from user perspective

Wind Solutions

Wiebke Langreder

TEM Visby 12.6.2015

What type of user am I?

- Engineer (not meteorologist or similar)
- 20 years in wind resource assessment
- Working for
  - Manufacturer in DK, UK, and Germany
  - (own) consultancy Wind Solutions
- What do I use flow models for?
  - AEP (incl. P90 – of course ☺)
  - Site suitability
- Which models do I use?
  - WAsP
  - WAsP CFD (mainly suitability context)
  - Supervised work with different CFD tools
- Misc. conference publications, book chapters… (all on the practical side ☺)

Why has uncertainty become so popular?

Economic driver:

- Increase confidence of financers
- “Makes money cheaper”
- Reduce CoE!

- TP Wind 3% vision (2008) by 2030

June 2015 Wind Solutions 3

Consequences

1. Initiatives/Standards/Guidelines etc
- Wakebench/TEM
- IEA Best Practice Remote Sensing
- IEC 61400-15
- PCWG (Power Curve Working Group)
- Many more

2. Data Sharing initiatives
- PCWG
- DONG offshore data
- Many more

June 2015 Wind Solutions 4

Uncertainty in Resource assessment

MEASNET Guideline from 2009

- Following uncertainties should be covered
  - Measurement
  - Data Integrity
  - Data Analysis
  - Derived parameter
  - Correlation and LT
  - Flow modelling
  - Wake Modelling
  - Power Curve

Input

Modelling

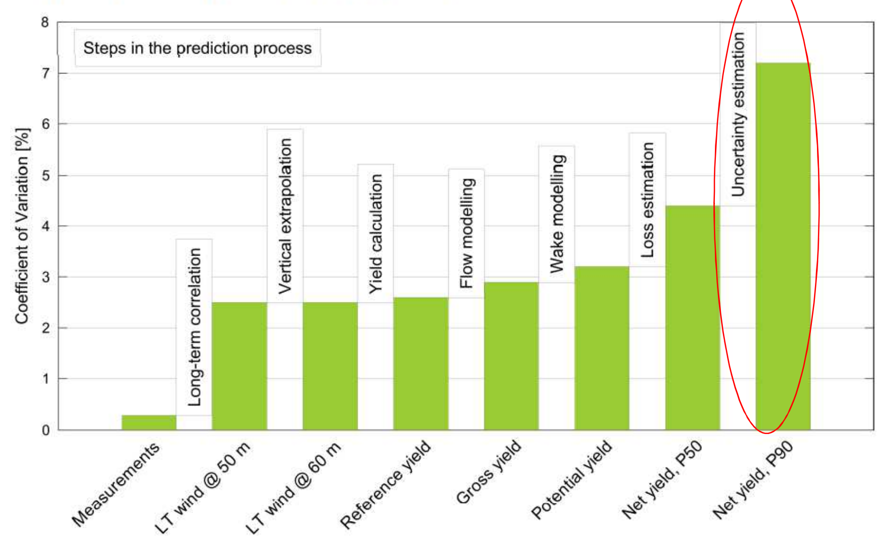
Response

No guideline on how to derive uncertainties – nicely reflected in CREYAP (blind test organized by EWEA)

June 2015 Wind Solutions 5

CREYAP 1 (2011, 36 participants)

Steps in the prediction process



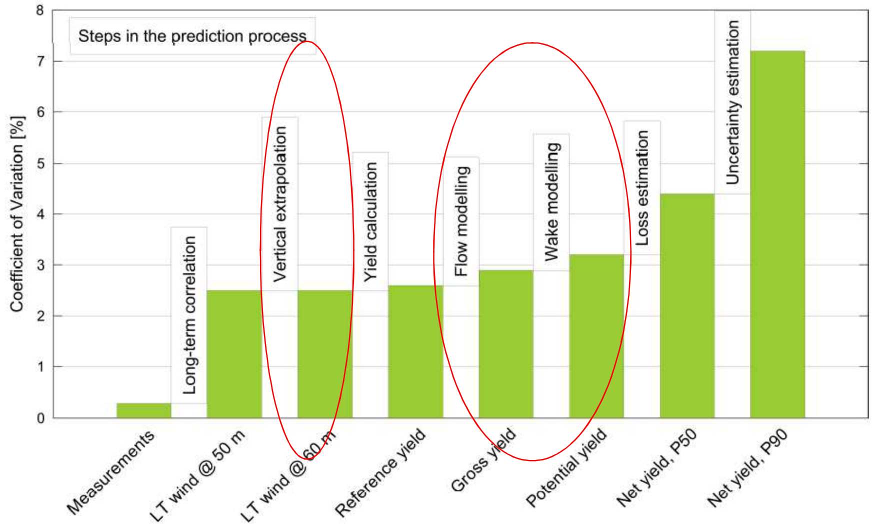
Which are the big ones?

“Uncertainty” of Uncertainty ☺

6

CREYAP 1

Steps in the prediction process



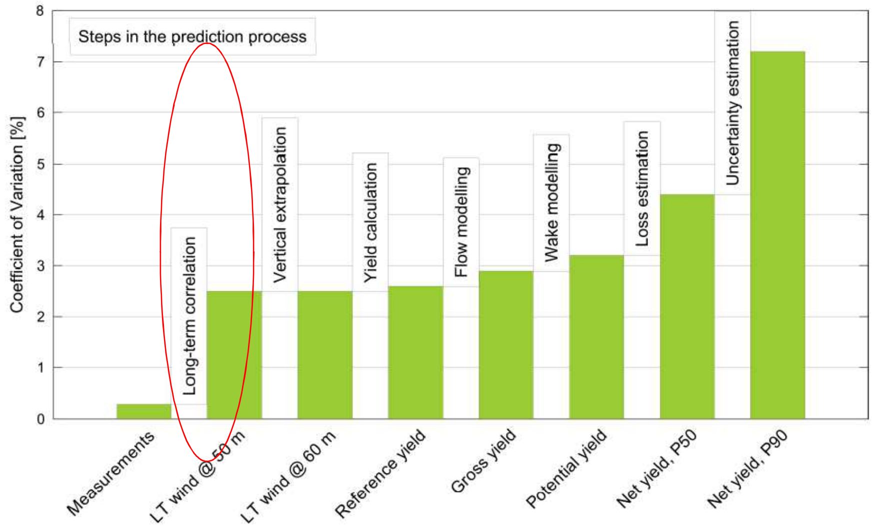
"Uncertainty" of flow models

- Fixed topography
- Fixed roughness
- Relatively benign terrain
- Deviations we see here are due to different models and different users

7

CREYAP 1

Steps in the prediction process



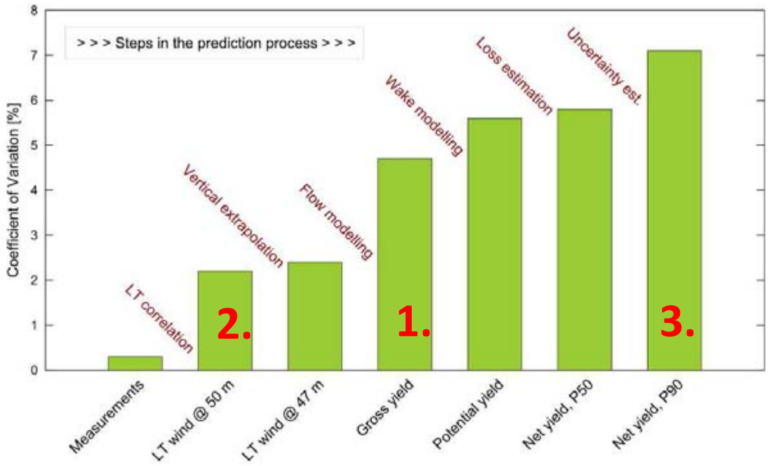
"Uncertainty" of input

- LT correction has far larger "uncertainty" than flow modelling

8

CREYAP II (2013, 60 participants)

Spread for different steps in the prediction process



28 DTU Wind Energy, Technical University of Denmark EWEA CREYAP II 26 Jun 2013

- More complex terrain
- Several masts, several LT sources
- Some roughness had to be done by participants

9

Conclusions: The big ones are:

- LT correction – feeds through into flow modelling (if direction is wrong, your flow modelling will be wrong)
- Flow modelling
- Uncertainty estimate

June 2015 Wind Solutions 10

Hunting information flow modelling uncertainty

- Appr. 1 gazillion conference papers comparing WAsP with CFD
- Vast majority of limited use because
  - Written by somebody who can use WAsP and not CFD
  - Written by somebody who can use CFD and not WAsP
  - Background info is missing (mesh, resolution, stability, RIX ….)
  - Number of test sites too small, no statistical significance
  - The used code is not commercially available
  - …
- Mostly you get ERRORS and not UNCERTAINTIES ☹

June 2015 Wind Solutions 11

Common contributors to flow model uncertainty

- Vertical extrapolation
- Horizontal extrapolation
- Quality of input maps
- Self-prediction
- (wake models)

June 2015 Wind Solutions 12

Vertical extrapolation

- A lot of consultants use 1% uncertainty in wind speed per 10m vertical extrapolation:
- Mast height 80m, HH 100m, thus 2% wind speed uncertainty
- My own little analysis says something different (all using WAsP)
  - 7 sites, 29 masts, 20 to 130m, 155 data points
  - Split into flat and complex

June 2015 Wind Solutions 13

Vertical extrapolation - Flat

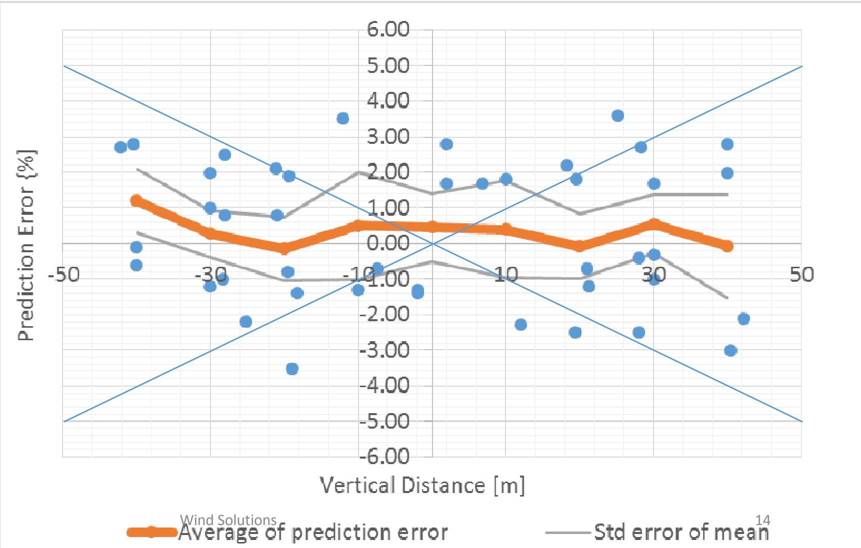
Convention:

- - predicting "down"
- + predicting "up"

No significant difference if …

- I go up or down
- Jump 20 or 40m

1% per 10m might not hold!

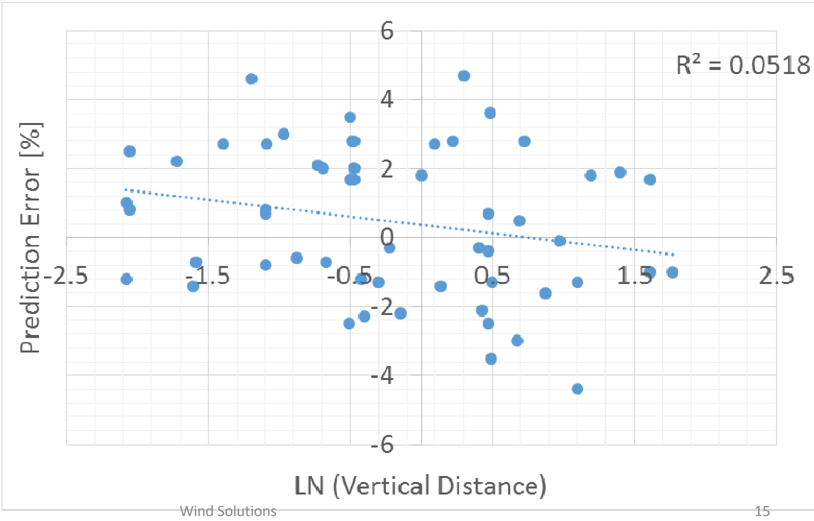


June 2015 Wind Solutions 14

Vertical extrapolation - Flat
Logarithm of vertical distance

No award winning results

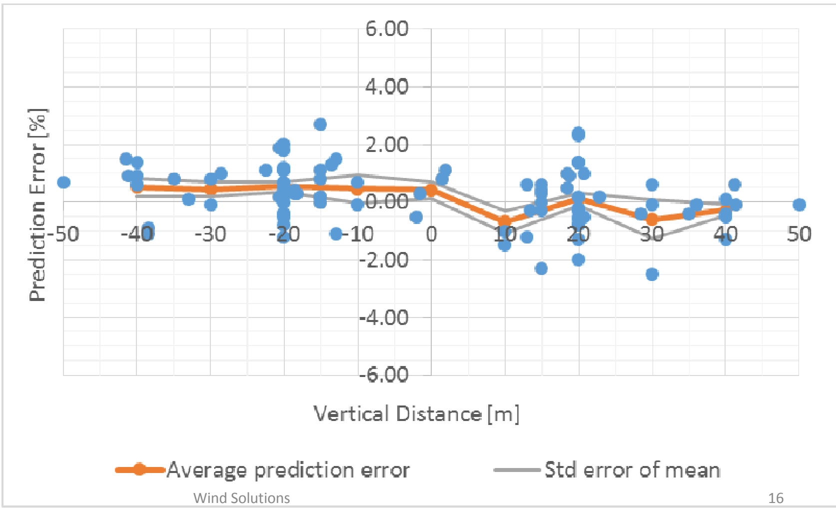
There is no correlation



June 2015 Wind Solutions 15

Vertical extrapolation - complex

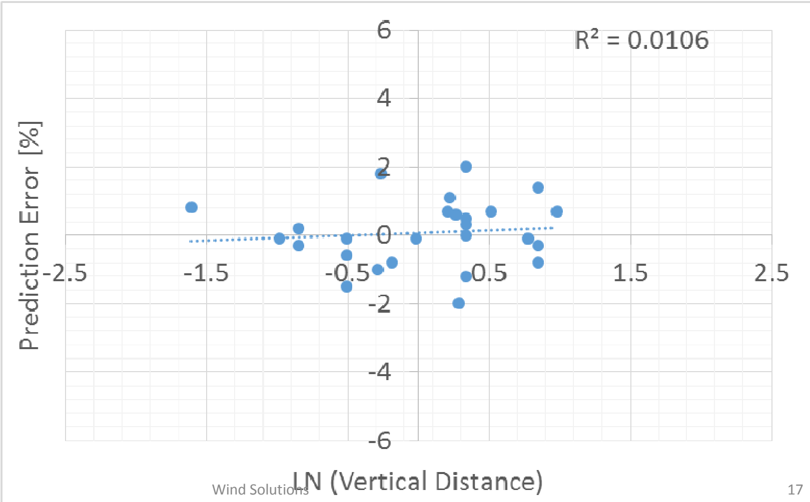
- Less scatter
- Error smaller than in flat terrain!
- 1% per 10m does not hold



June 2015 Wind Solutions 16

Vertical extrapolation – complex logarithm of vertical distance

- Deep sigh



June 2015 Wind Solutions 17

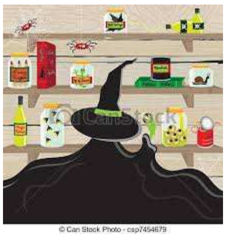
Take-aways vertical extrapolation

- 1% per 10m height difference seems to be too conservative particularly in complex terrain
- Vertical prediction error higher in flat terrain than in complex terrain (but also far more dependent on subjective decisions)

June 2015 Wind Solutions 18

Horizontal extrapolation

- Most difficult



- Nice one:

A systematic method for quantifying flow model uncertainty in wind resource assessment

Alex Clerc [a], Mike Anderson [a], Peter Stuart [a]

[a] Renewable Energy Systems Ltd, Beaufort Court, Egg Farm Lane, Kings Langley WD4 8LR, UK

June 2015 Wind Solutions 19

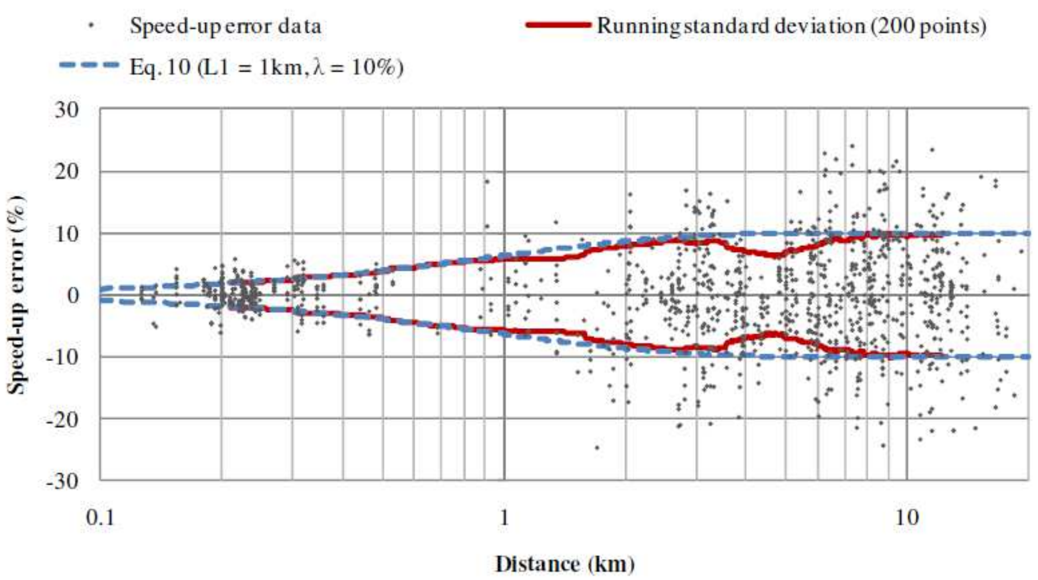


Fig. 2: Speed-up errors, running standard deviation of speed-up errors and u_D vs. distance.

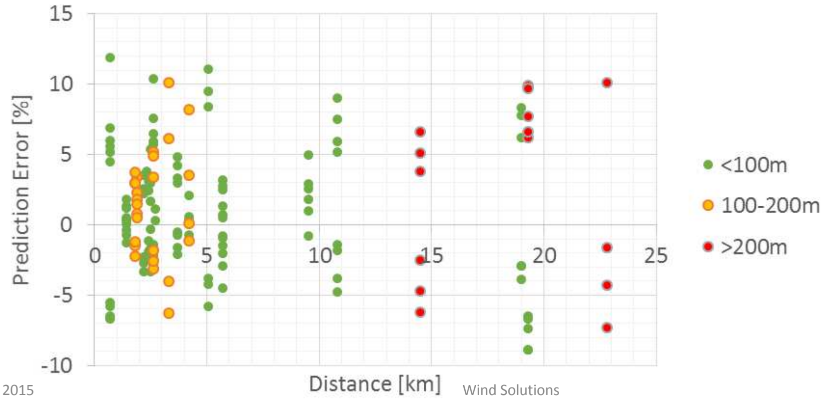
Source: RES

20

And here my results…

How much of the "horizontal" error is really "horizontal"?

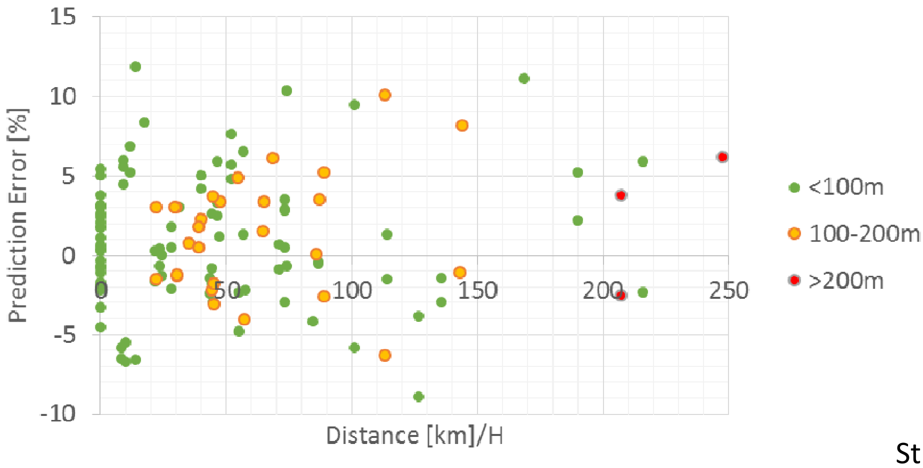
Is there a contribution from elevation difference?



No award-winning results ☹

June 2015 Wind Solutions 21

Plotted differently



Still not award-winning results ☹

June 2015 Wind Solutions 22

Take-aways horizontal extrapolation

- Bad and good news: It does not matter if the distance is 1 or 10 km, error is in the same order.
- So far no indication that horizontal prediction error is correlated with elevation difference…

June 2015 Wind Solutions 23

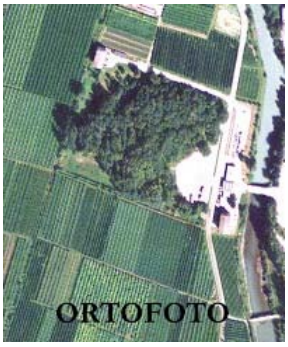
Common contributors to flow model uncertainty

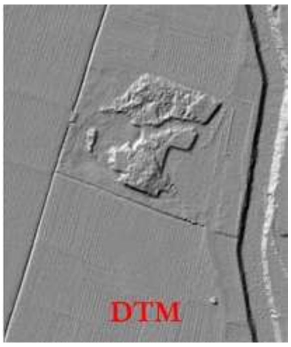
- Vertical extrapolation
- Horizontal extrapolation
- Quality of input maps
- Self-prediction
- (wake models)

June 2015 Wind Solutions 24

Quality maps

- Topography: In real life mostly SRTM
  - Commonly known: flattening in complex terrain
  - But also take care of trees





DTM = digital terrain model

Source: MIR Geospatial technology

June 2015 Wind Solutions 25

Does this matter?

Literature covers mainly differences/errors and not uncertainty:

- GH: Milanesi et al, 2010, Influence of topographic maps on energy production assessment
  - Less than 1% wind speed difference
- Risø 2005
  - Max 1.7% AEP (3 cases)
- I did my own test
  - more like 3% AEP difference between proper cartographic map (5m height contour on site) and SRTM

June 2015 Wind Solutions 26

Quality maps

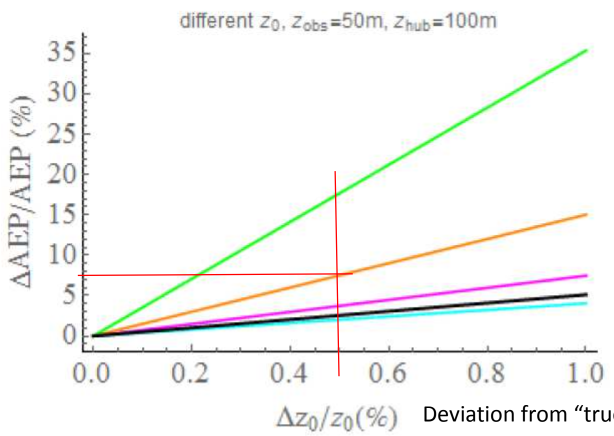
- Topography
- Roughness
  - Not so important in complex terrain though, but very much in flat
  - Sensitivity study done by DTU Risø (H. Jørgensen, 2014)
    http://windpower.org/da/netvaerk_og_projekter/vindkraftnet/vindkraftnet_events.html#796

June 2015 Wind Solutions 27

Errors of AEP (not uncertainty)

- Scenario: 50m Mast, 100m HH

Impact on AEP



Deviation from "true" roughness

Z_0 = 1.0 m

Z_0 = 0.02 m

Z_0 = 0.0002 m

If you get short grass wrong (zo=0.03 instead of zo=0.02) you can get AEP by 7% wrong!

Results coincide nicely with findings from P.Nielsen, Malmø 2014

Source: H. Jørgensen et al 2014

June 2015 Wind Solutions 28

Quality maps

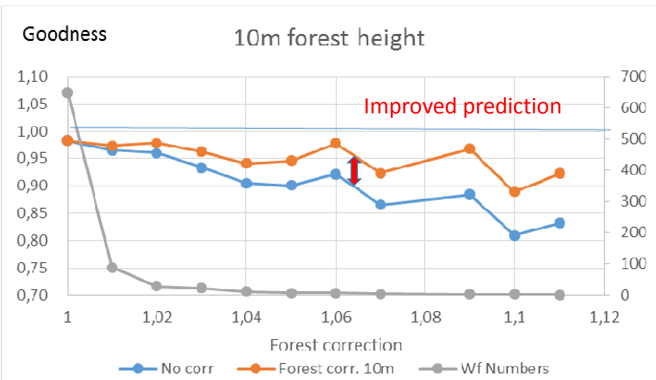
- Topography
- Roughness
  - Not so important in complex terrain though, but very much in flat
  - Sensitivity study done by DTU Risø (H. Jørgensen, 2014)
    http://windpower.org/da/netvaerk_og_projekter/vindkraftnet/vindkraftnet_events.html#796
- Are these values independent from vertical/horizontal extrapolation?
- No….

June 2015 Wind Solutions 29

Effect of forest

- Compare real production with modelled production
- Without forest correction error up to 15% AEP!
- With correction on average less than 5%

Goodness:
How well do we predict compared to real production?



Number of WTG
Grey line

Source: P. Nielsen, Malmø 2014

June 2015 30

Common contributors to flow model uncertainty

- Vertical extrapolation
- Horizontal extrapolation
- Quality of input maps
- Self-prediction
  - How well can we reproduce our measured value?
  - What shall we do with the discrepancy between arithmetic and Weibull mean (WAsP users) ??? And Bi-Weibulls ???

June 2015 Wind Solutions 31

Wrap up flow uncertainty

- More information about errors rather than uncertainty
- There are some unresolved inter-dependencies between the common contributors
- If we take RES paper serious, then we are in the order of >10ish% wind speed

But if we look at the uncertainty of input...

June 2015 Wind Solutions 32

LT Correction – one example (but not the worst one…)

- 1 year of IEC compliant measurements with Class1 anemometer etc
- 2 industry-accepted meso-scale data sets, 1 re-analysis, all no trend
- 3 industry-accepted processes
- **Resulting energy correction varies by 17%**
- Uncertainty? Depends on how “independent” we see each method and data set….

	Scaling	Artificial time series	
	Wind Index (Energy)	Linear Regression	Matrix
Meso-Product 1	+20%	+15%	+10%
Meso-Product 2	+15%	+11%	**+8%**
Merra 20 y	+22%	+12%	+10%
Merra 30y	**+25%**	+13%	+10%

Source: W.Langreder, EWEA Helsinki 2015

June 2015 Wind Solutions 33

Work ahead…

- GIGO: Garbage in – garbage out!
- Uncertainties of ALL contributors have to be tackled in parallel
- We need “Best Practice Guidance” for each step! Quick win!
- Most people hate statistics, we need to clearer distinguish errors/uncertainties of wind speed/energy
- Inter-dependencies need to addressed

June 2015 Wind Solutions 34

DTU

Multifidelity of Wind Farm Flow Models

Pierre-Elouan Réthoré, Paul van der Laan, Juan Pablo Murcia, Kurt S. Hansen and Florence Marti

Aero-elastic Section, Wind Energy Department, DTU, Risø

IEA Topical Expert Meeting
12 June 2015

DTU Wind Energy
Aero-Elastic Design Section - Risø

DTU

Table of Contents

2 of 19 P.-E. Réthoré et al. DTU Wind Energy Multifidelity

Table of Contents

Motivation

Why Multi-fidelity

- Bridging gap between research and industry
- Optimizations of wind farms using the highest fidelity
- UQ on highest fidelity
- Collaborate instead of compete

DTU

Table of Contents

5 of 19 P.-E. Réthoré et al.
DTU Wind Energy
Multifidelity

DTU

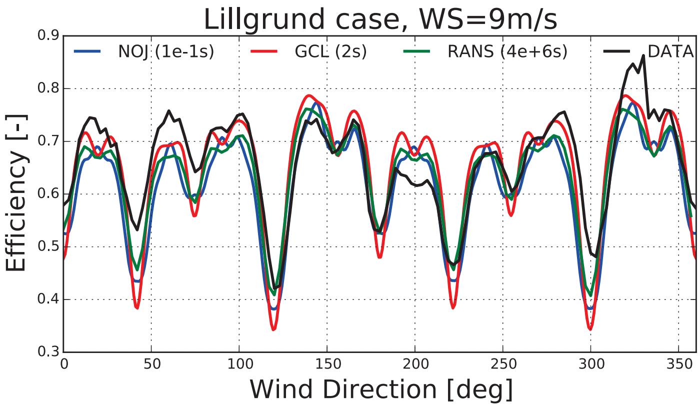
Lillgrund Wind Farm Case

- 48 SWT-2.3-93
- D = 93 m
- P = 2.3 MW
- H = 65 m
- x/D = 3.3, 4.3...
- 2 missing wt

6 of 19 P.-E. Réthoré et al.
DTU Wind Energy
Multifidelity

DTU

Available Models



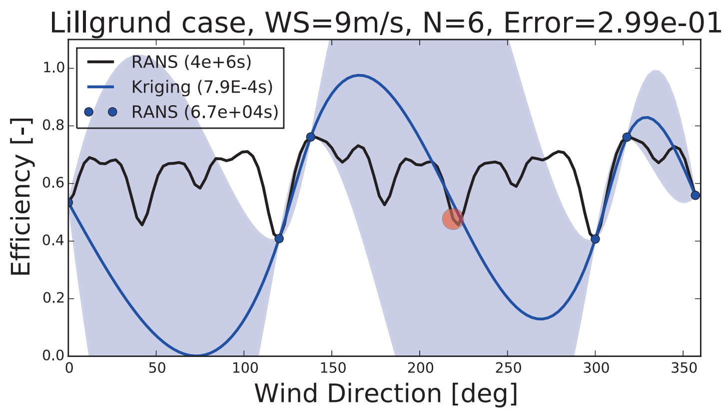
7 of 19 **P.-E. Réthoré et al.** DTU Wind Energy Multifidelity

DTU

Table of Contents

8 of 19 **P.-E. Réthoré et al.** DTU Wind Energy Multifidelity

Kriging



9 of 19 **P.-E. Réthoré et al.** DTU Wind Energy Multifidelity

Table of Contents

10 of 19 **P.-E. Réthoré et al.** DTU Wind Energy Multifidelity

Co-Kriging Concept

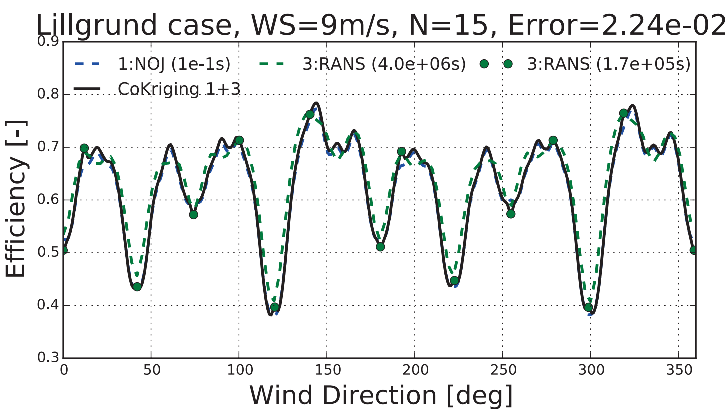
DTU

Using a meta-model from lower order models as prior to build the meta-model of the higher order model

11 of 19 P.-E. Réthoré et al. DTU Wind Energy Multifidelity

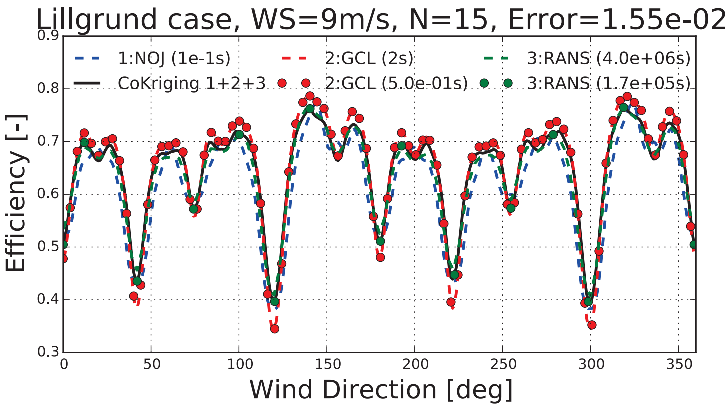
NOJ+RANS

DTU



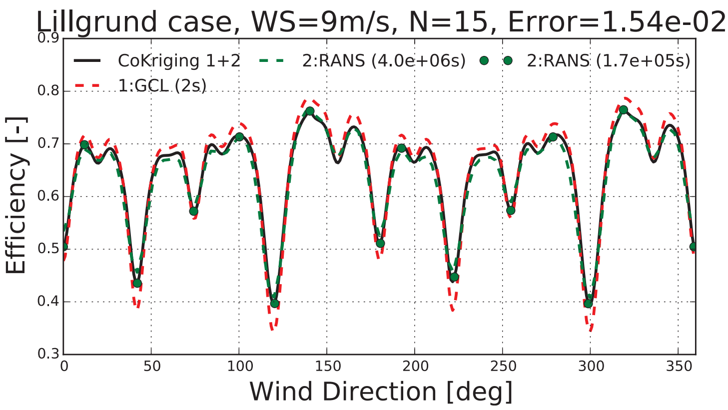
12 of 19 P.-E. Réthoré et al. DTU Wind Energy Multifidelity

NOJ+GCL+RANS



13 of 19 **P.-E. Réthoré et al.** DTU Wind Energy Multifidelity

GCL+RANS



14 of 19 **P.-E. Réthoré et al.** DTU Wind Energy Multifidelity

Table of Contents

15 of 19 P.-E. Réthoré et al. DTU Wind Energy Multifidelity

Connecting All Wind Energy Models in a Worflow

- Collaborative effort between DTU and NREL to create a **F**ramework for **U**nified **S**ystem **E**ngineering and **D**esigned of **Wind** energy plants.
- Based on OpenMDAO, a python based Open source framework for **M**ulti-**D**isciplinary **A**nalysis and **O**ptimization.

16 of 19 P.-E. Réthoré et al. DTU Wind Energy Multifidelity

DTU

Table of Contents

17 of 19 P.-E. Réthoré et al. DTU Wind Energy Multifidelity

DTU

Future Investigation

- Including LES
- Estimating AEP
- Using the model uncertainty to create the meta-model (e.g. Bayesian model averaging)

18 of 19 P.-E. Réthoré et al. DTU Wind Energy Multifidelity

DTU

Meta

Pierre-Elouan Réthoré

pire@dtu.dk
Publications
0000-0002-2300-5440
linkedin.com/in/rethore
github.com/rethore

19 of 19 P.-E. Réthoré et al. DTU Wind Energy Multifidelity

Uncertainty of Power Production Predictions of Stationary Wind Farm Models using Monte-Carlo Simulation of Horns Rev 1

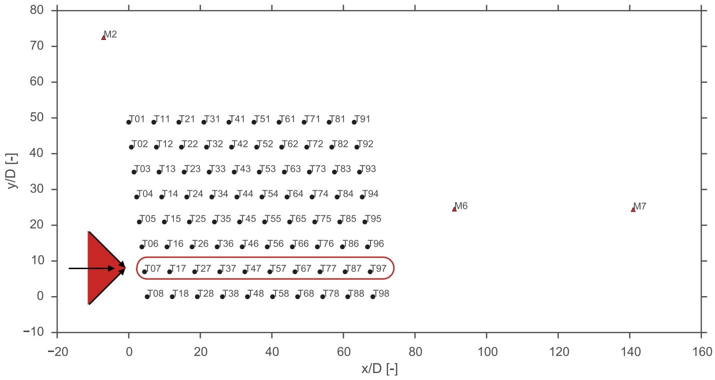
Juan P. Murcia, Pierre-Elouan Réthoré, Anand Natarajan, John D. Sørensen and Kurt Hansen

June 12, 2015

Outline

- Introduction
- Methods
- Results
- Conclusions

Introduction
Horns Rev 1



- Flow Sector: 210-300 degrees.

DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
DTU
3/30

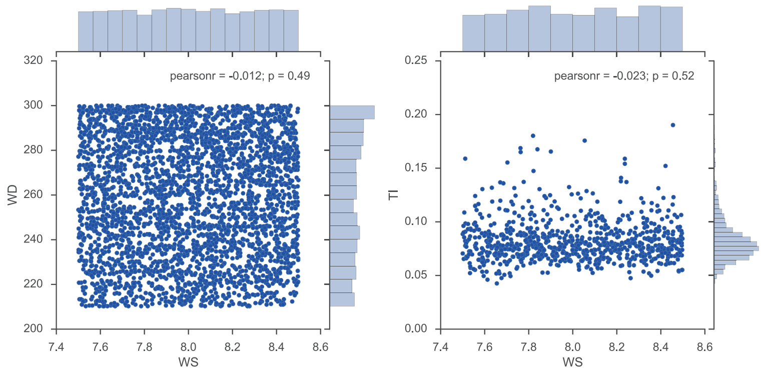
Outline

- Introduction
- **Input Uncertainties**
- Results
- Conclusions

DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
DTU
4/30

Input Uncertainties

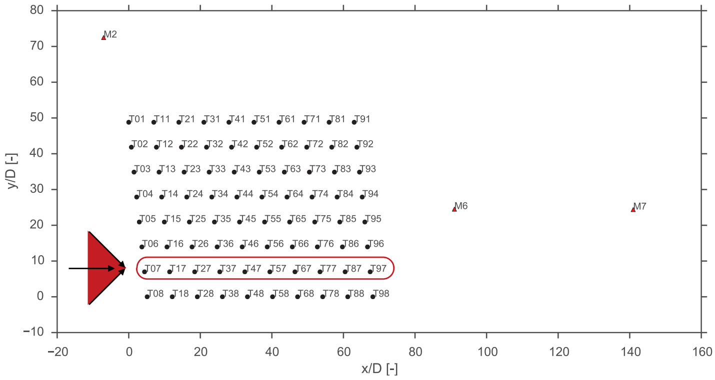
Uniform distribution of WS, WD. Log-Normal TI



Outline

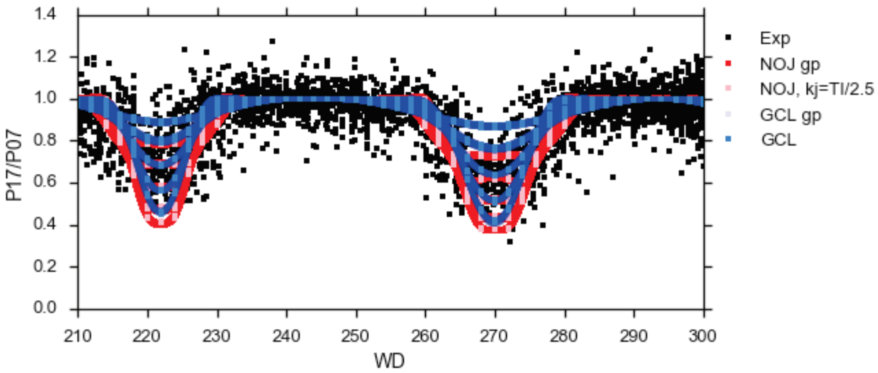
- Introduction
- **Meta-model**
- Results
- Conclusions

Horns Rev 1



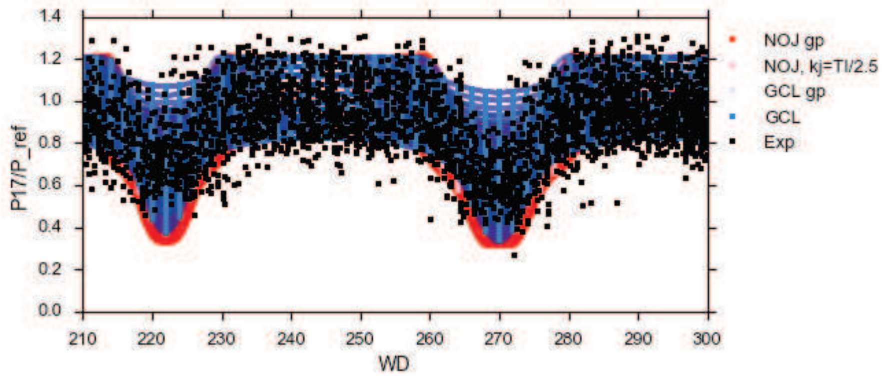
DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
DTU
7/30

Meta-model: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]



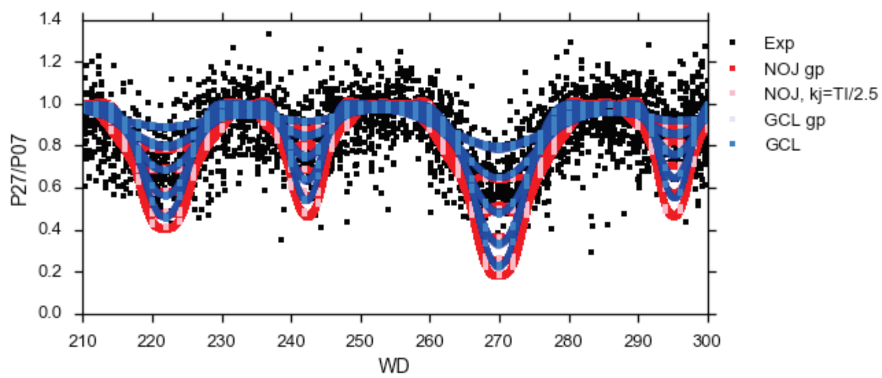
DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
DTU
8/30

Meta-model: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]



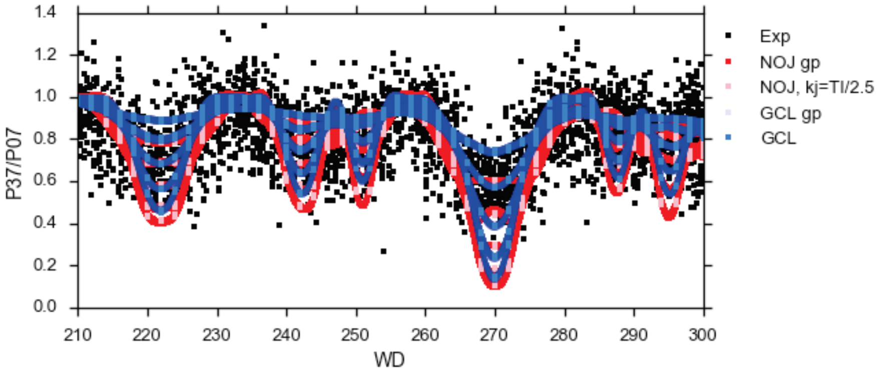
DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
DTU
9/30

Meta-model: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]



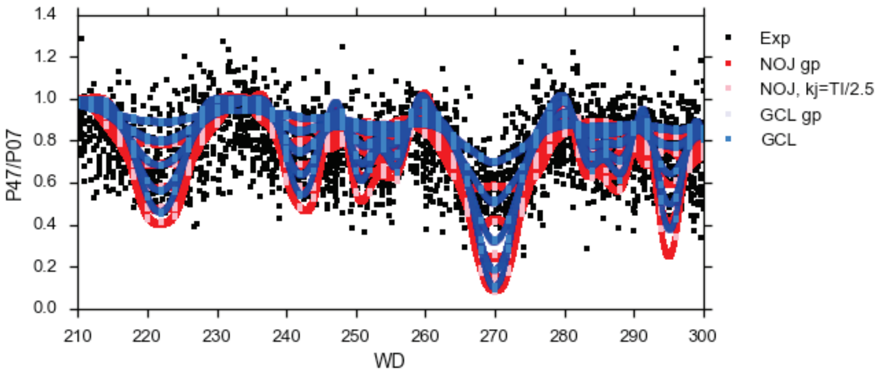
DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
DTU
10/30

Meta-model: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]



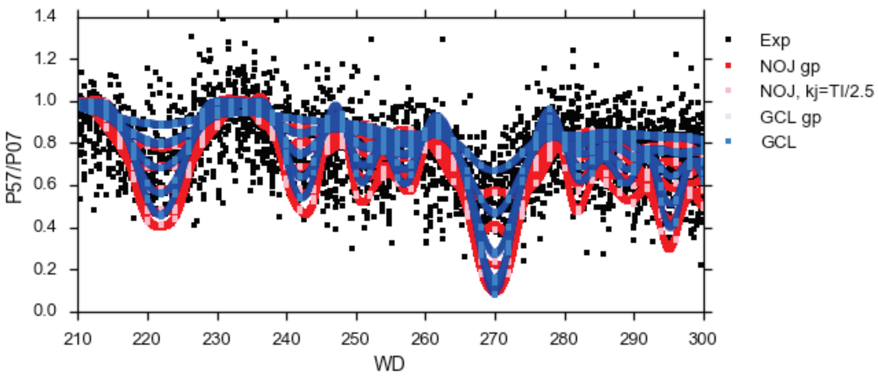
DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
11/30

Meta-model: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]

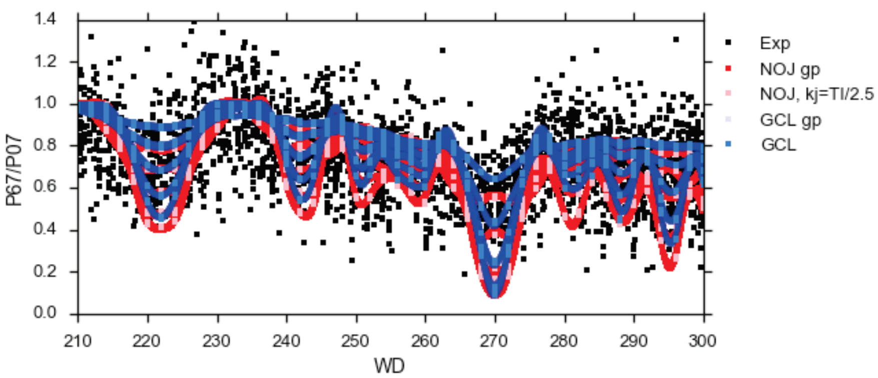


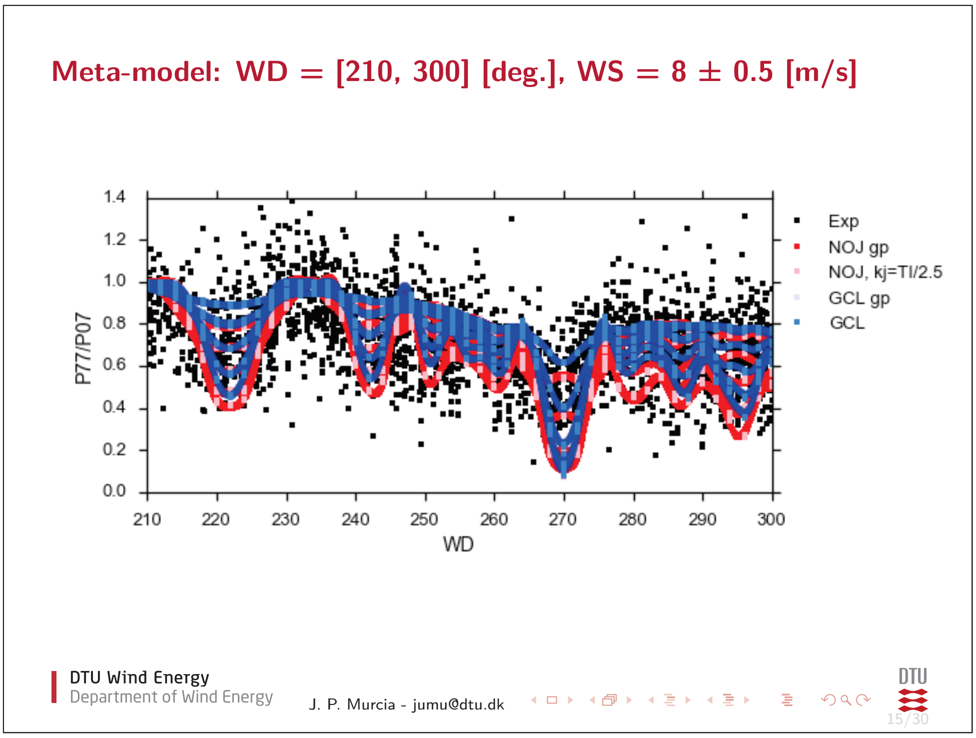
DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
12/30

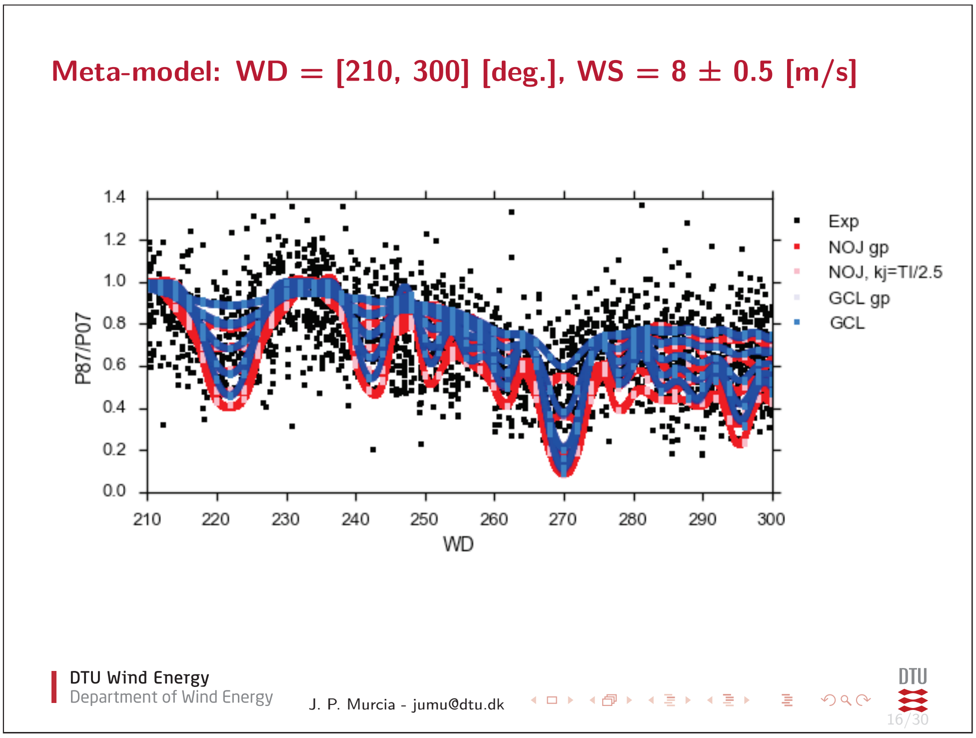
Meta-model: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]



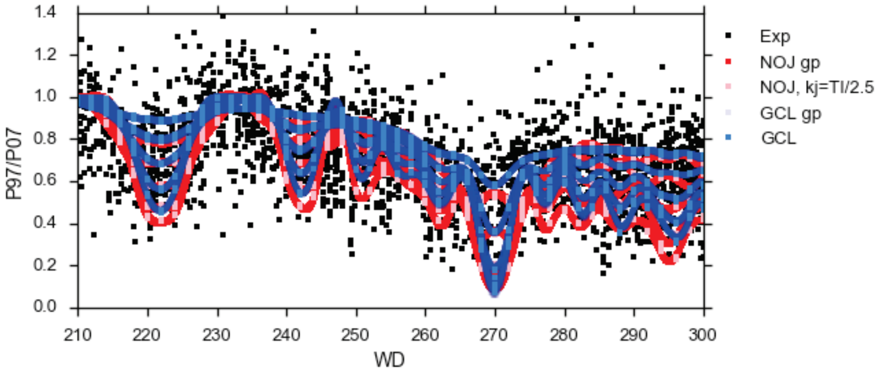
Meta-model: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]




Meta-model: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]
P77/P07
WD
Exp
NOJ gp
NOJ, kj=TI/2.5
GCL gp
GCL
DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
DTU
15/30


Meta-model: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]
P87/P07
WD
Exp
NOJ gp
NOJ, kj=TI/2.5
GCL gp
GCL
DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
DTU
16/30

Meta-model: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]

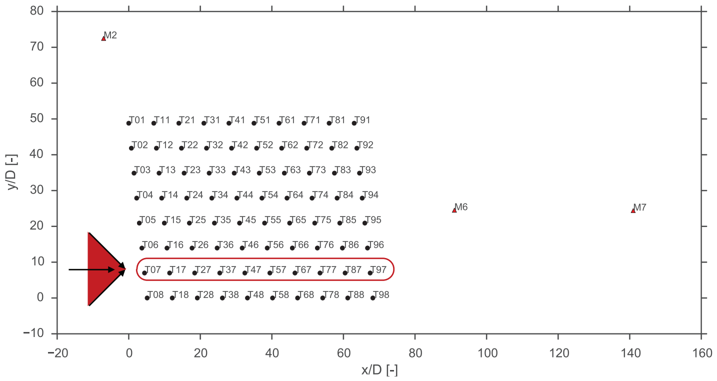


Outline

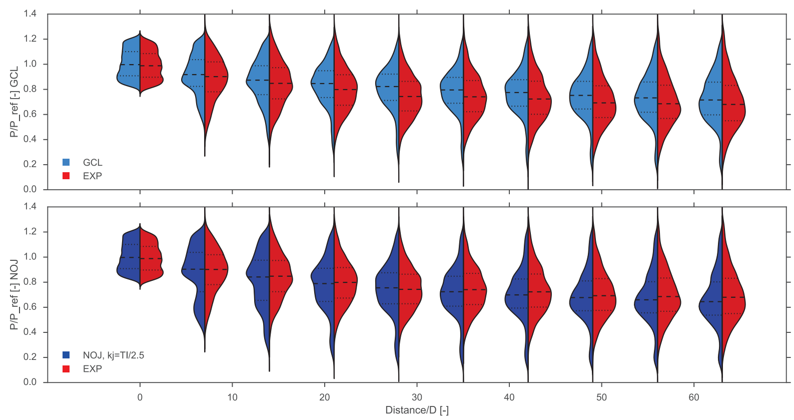
- Introduction
- Methods
- **Results**
- Conclusions

Results

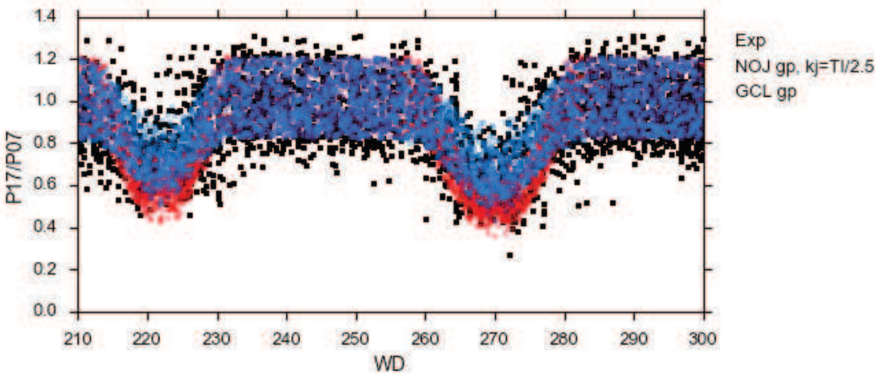
Horns Rev 1



Results: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]

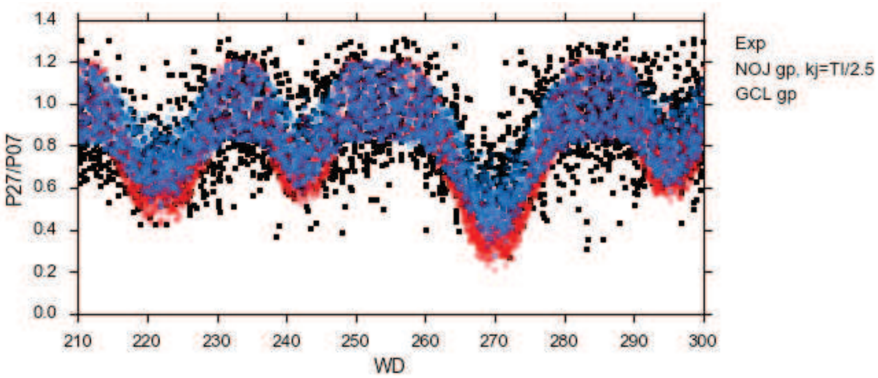


Monte-Carlo Simulations: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]



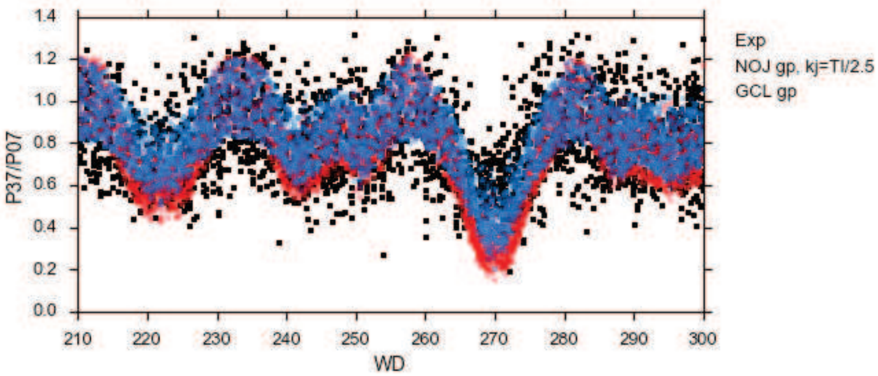
DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
DTU
21/30

Monte-Carlo Simulations: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]



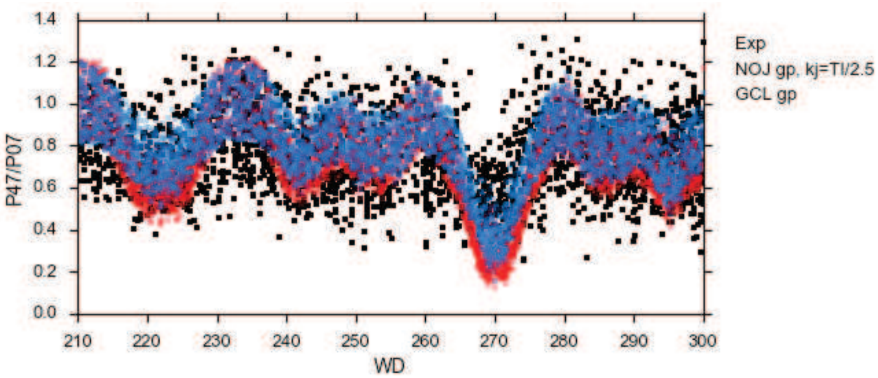
DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
DTU
22/30

Monte-Carlo Simulations: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]



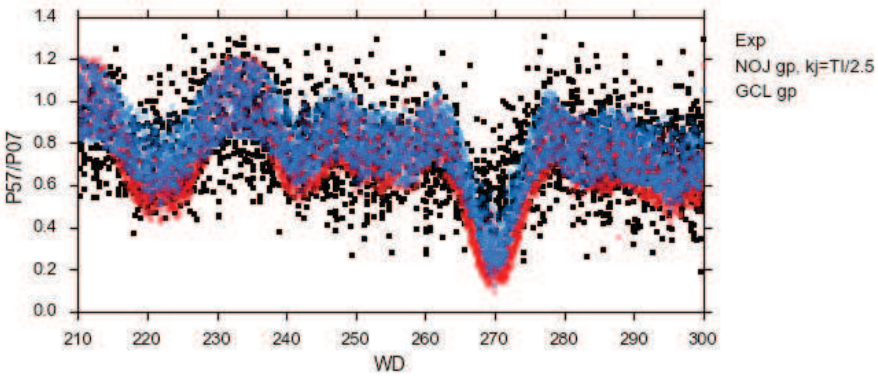
DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
DTU
23/30

Monte-Carlo Simulations: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]

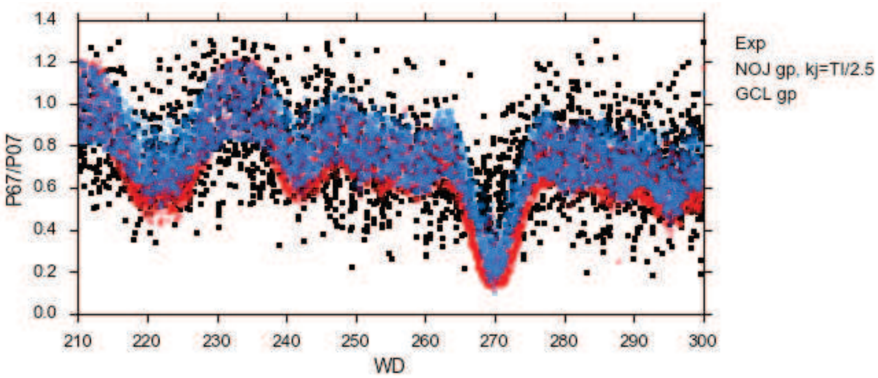


DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
DTU
24/30

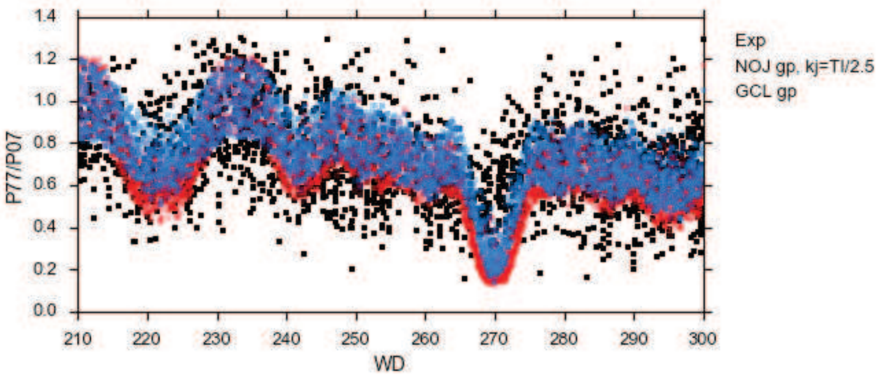
Monte-Carlo Simulations: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]



Monte-Carlo Simulations: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]

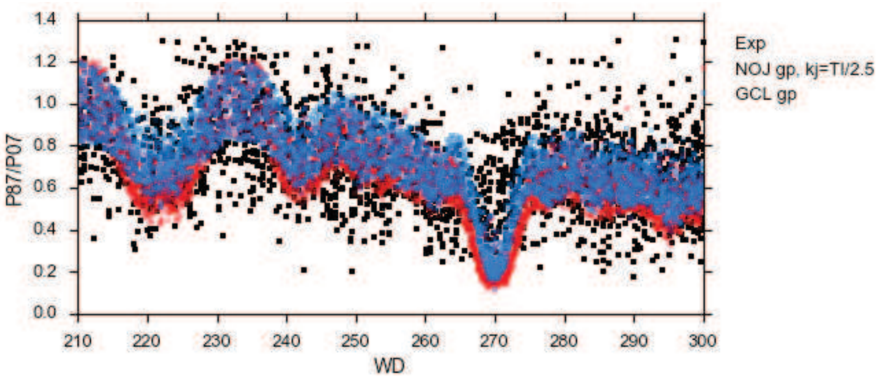


Monte-Carlo Simulations: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]



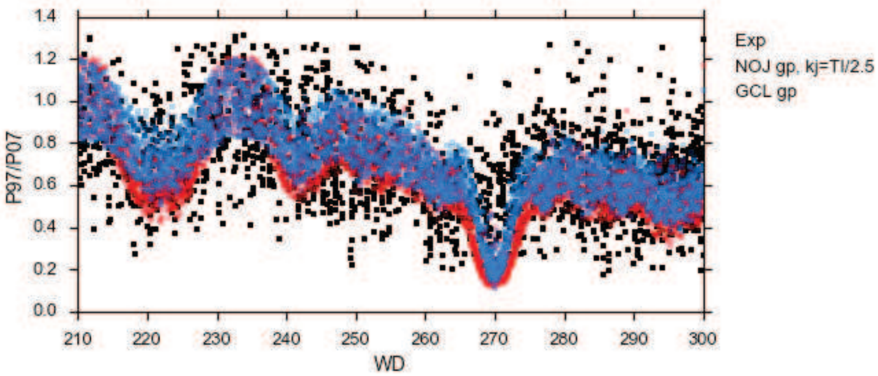
DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
DTU
27/30

Monte-Carlo Simulations: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]



DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
DTU
28/30

Monte-Carlo Simulations: WD = [210, 300] [deg.], WS = 8 ± 0.5 [m/s]



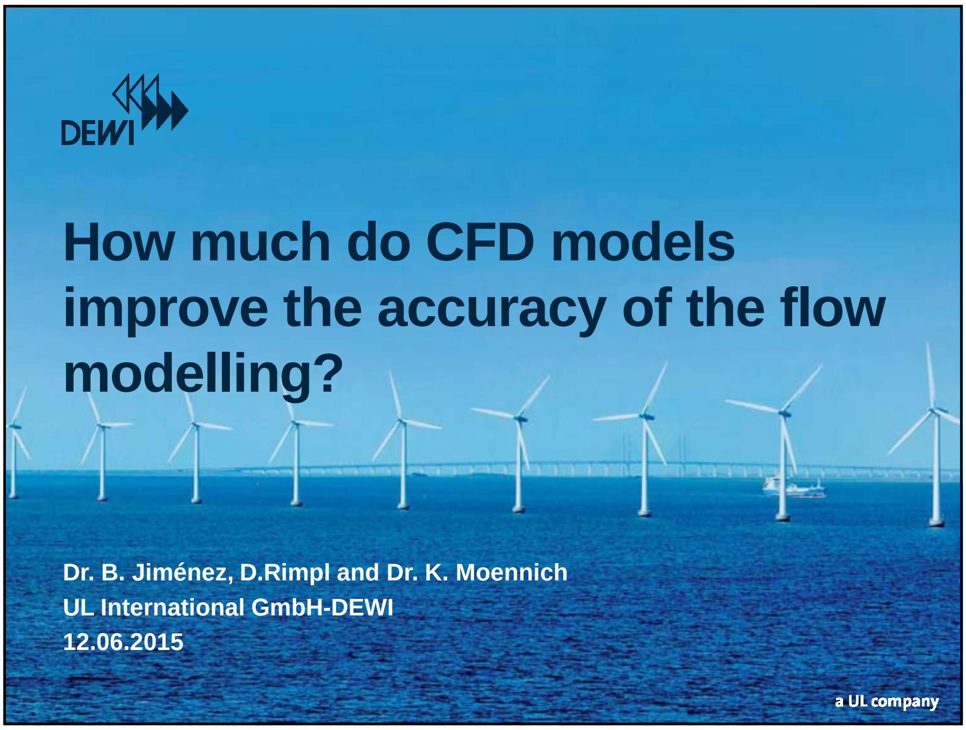
DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
DTU
29/30

Conclusions

Engineering models and linearized CFD

- Using meta-models and Monte-Carlo simulations is possible for individual turbine power production inside a wind farm.

DTU Wind Energy
Department of Wind Energy
J. P. Murcia - jumu@dtu.dk
DTU
30/30



DEWI

CONTENTS

- Compare the cross prediction MM and predicted wind speed at WT position
  - Used CFD models
  - Case studies (8 sites investigated)

  Cross prediction is enough?
  Linear model is sufficient for 2 km distance between MM and WT?

- Factors which affect performance of the CFD model

2 a UL company

CFD setup overview

	WASP-CFD	OFWIND	Phoenics 3.4
Solver	EllipSys	OpenFOAM	Phoenics
Directional resolution	10 °	5° to 10 ° main WD 15° or 20° side WD	5° to 10 ° main WD 15° or 20° side WD
Cutting radius	≈15 km	≈15 km	≈15 km
Finest mesh resolution Finest mesh radius Finest mesh vertical radius	20m 2 Km ≈300m	≈15m ≈2 Km ≈300m	≈15m ≈2 Km ≈300m
Turbulence model	k-ε	SST k-omega	k-ε
Stability	Neutral		

3

a UL company

Site 1: Cross prediction wind speed analysis

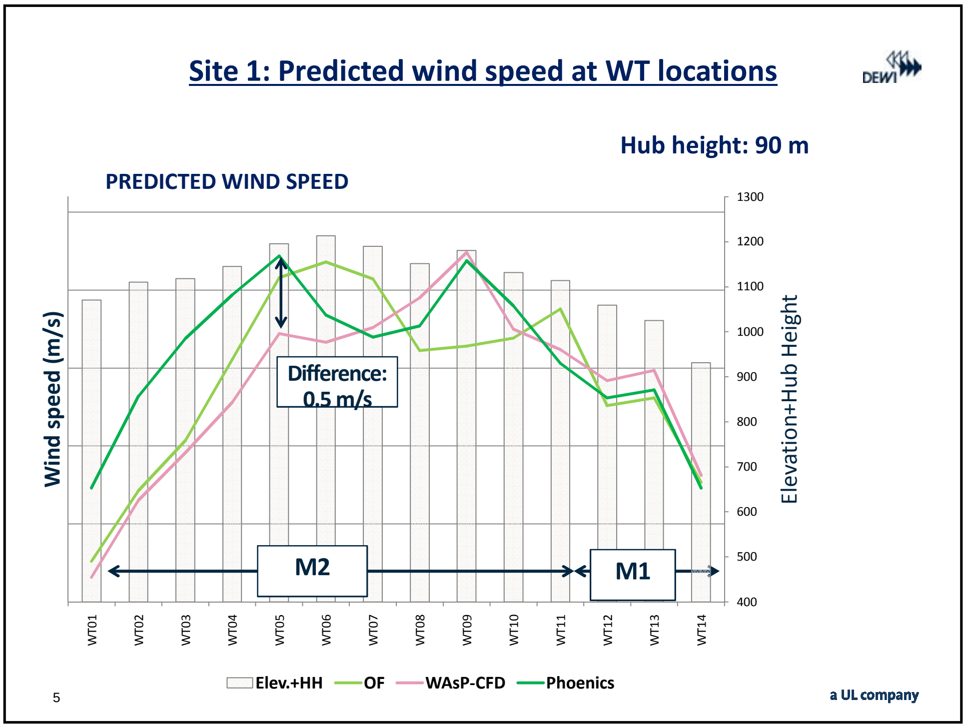
Input two MM:
M1 86m, M2 51m

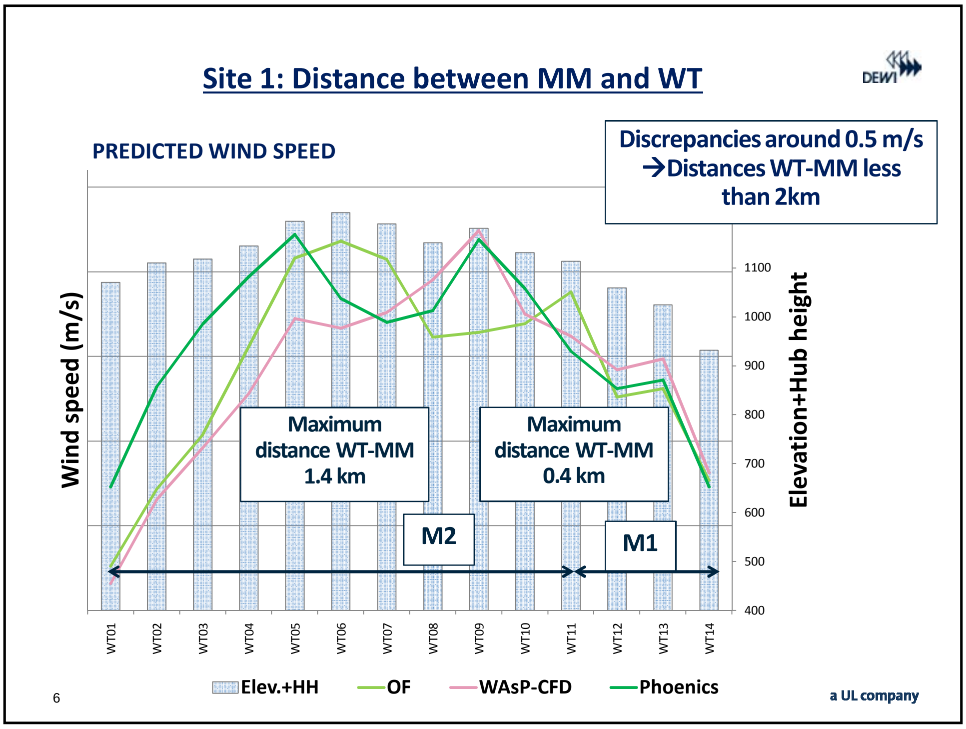
Wind Speed Relation

	Height	OF	WASP-CFD	Phoenics
input: only mast1	86m	(Predicted/Measured)		
measM1 predicted			-	
measM2 predicted		~4%	~7%	~6%
input: only mast2	51m	(Predicted/Measured)		
measM1 predicted		~12%	~9%	~13%
measM2 predicted			-	

4

a UL company


Site 1: Predicted wind speed at WT locations
DEWI
Hub height: 90 m
PREDICTED WIND SPEED
Wind speed (m/s)
Elevation+Hub Height
Difference:
0.5 m/s
M2
M1
WT01 WT02 WT03 WT04 WT05 WT06 WT07 WT08 WT09 WT10 WT11 WT12 WT13 WT14
400 500 600 700 800 900 1000 1100 1200 1300
Elev.+HH OF WAsP-CFD Phoenics
5
a UL company


Site 1: Distance between MM and WT
DEWI
PREDICTED WIND SPEED
Discrepancies around 0.5 m/s
→Distances WT-MM less than 2km
Wind speed (m/s)
Elevation+Hub height
Maximum distance WT-MM 1.4 km
Maximum distance WT-MM 0.4 km
M2
M1
WT01 WT02 WT03 WT04 WT05 WT06 WT07 WT08 WT09 WT10 WT11 WT12 WT13 WT14
400 500 600 700 800 900 1000 1100
Elev.+HH OF WAsP-CFD Phoenics
6
a UL company

Site 2: Cross prediction wind speed analysis

DEWI

Input two MM:
M1 and M2, 80m

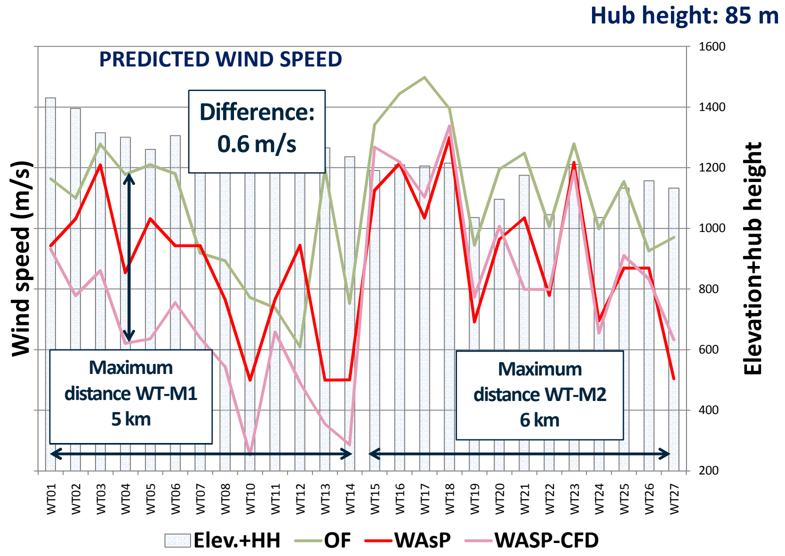
Wind Speed Relation

	Height	OF	WASP-CFD
input: only mast1	80m	(Predicted/Measured)	
measM1 predicted		-	
measM2 predicted		~12%	~10%
input: only mast2	80m	(Predicted/Measured)	
measM1 predicted		~9%	~12%
measM2 predicted		-	

7 a UL company

Site 2: Predicted wind speed at WT locations

DEWI

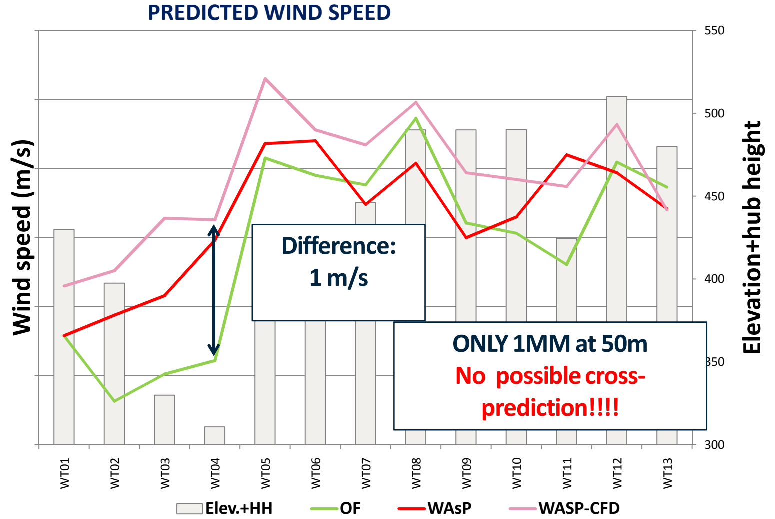


8 a UL company

Site 3: Predicted wind speed at WT locations

Input one MM:
M1 50 m

Hub height: 80 m



9 a UL company

Cross prediction is enough? No

✓Similar cross-predictions results→ Discrepancies between models at predicted turbine locations

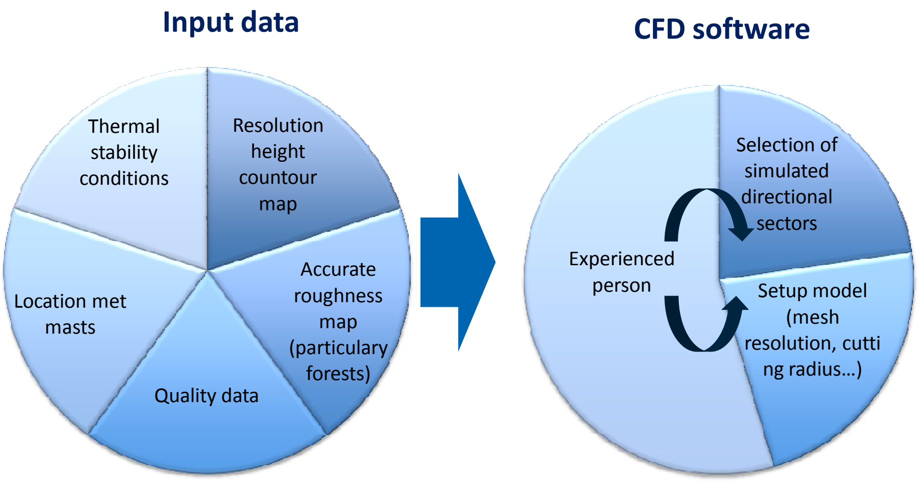
✓Increasing with the complexity of the site

Linear model is sufficient for 2 km distance between MM and WT? No

✓Depends on your site!!!

10 a UL company

Factors which do affect the performance of the CFD model??



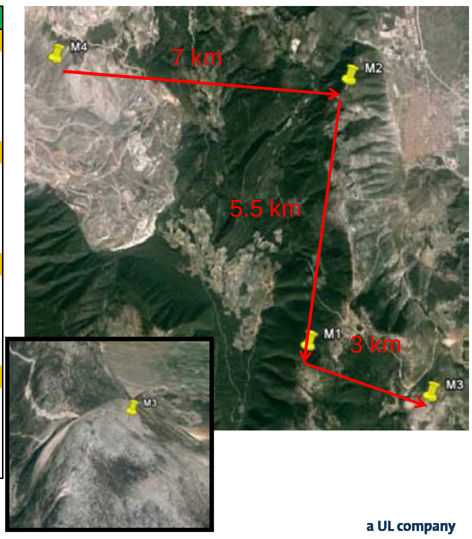
11 a UL company

Location of the met mast

Wind Speed Relation

	Height	OF-WIND / WASP-CFD / Phoenics
input: only mast1	61m	(Predicted/Measured)
measM1 predicted		-
measM2 predicted		~5%
measM3 predicted		**>40%**
measM4 predicted		~12%
input: only mast2	86m	(Predicted/Measured)
measM1 predicted		~8%
measM2 predicted		-
measM3 predicted		**>50%**
measM4 predicted		~15%
input: only mast3	86m	(Predicted/Measured)
measM1 predicted		~25%
measM2 predicted		~25%
measM3 predicted		-
measM4 predicted		~15%
input: only mast4	80m	(Predicted/Measured)
measM1 predicted		~10%
measM2 predicted		~6%
measM3 predicted		**~28%**
measM4 predicted		-

Met masts located in area with high turbulence and flow inclination!!!!



12 a UL company

Quality of the measurements

DEWI

1st period 2008-2012: Around 50% data availability
2nd period 2013-2015: Around 70% data availability

→ Similar long-term average wind speed

← Input: Long-term data

	Height	1st Period	2nd Period
input: only mast1	72m	(Predicted/Measured)	
measM1 predicted		-	
measM2 predicted		~15%	~10%
input: only mast2	62m	(Predicted/Measured)	
measM1 predicted		~25%	~9%
measM2 predicted		-	

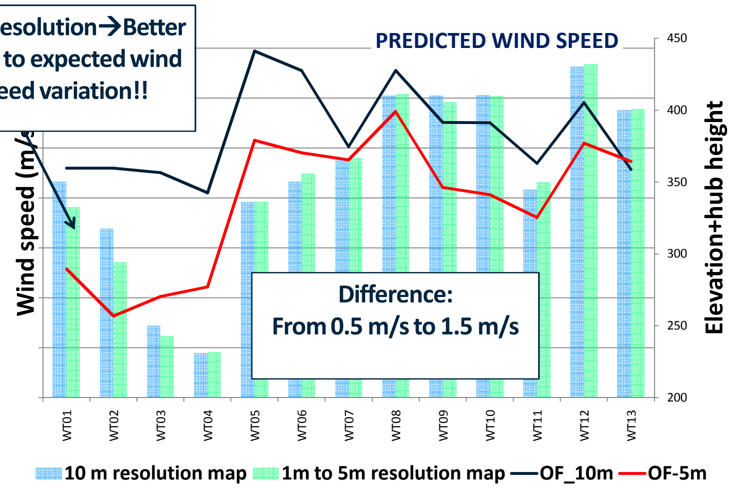
M2 located in area with high flow inclination

13 a UL company

Resolution of the height contour map

DEWI

Finer resolution→Better fitting to expected wind speed variation!!



~3 km around met mast and turbine locations

14 a UL company

SUMMARY

CFD modeling help us to better know the flow over complex terrain
But

✓Similar cross-predictions results→ Discrepancies between models at predicted turbine locations
- ✓Increasing with the complexity of the site

✓How to quantify the uncertainties related to the CFD?
- ✓No common procedures
- ✓Looking for upcoming IEC 61400-15 and IEA TASK 31!!!

✓Linear models could not be necessarily capable to capture the effects in distance less than 2 km WT-MM in complex terrain

15 a UL company

SUMMARY

➢Choose careful the location of the met mast—High turbulence area sometimes are not easy to identify.

➢Good quality of the input data (maps, measurements...)

➢Analyze thermal stability of your site could help to give a better prediction

16 a UL company

Future work

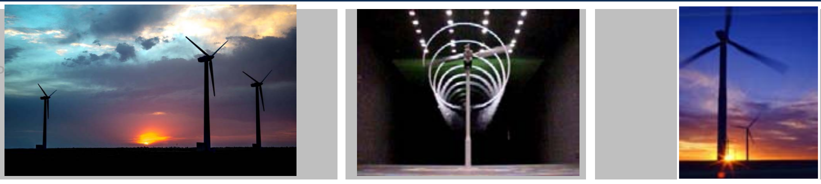
- ✓IEA TASK 31 "WAKEBENCH": Practical methodology and procedures for verification, validation and uncertainty quantification in mesoscale and CFD models.
- ✓CFD and mesoscale coupling

17

a UL company

Exceptional service in the national interest

Sandia National Laboratories



Overview of Planned Wake Validation Experiments

David Maniaci

TEM#82 on Uncertainty Quantification of Wind Farm Flow Models

June 12, 2015

U.S. DEPARTMENT OF ENERGY NNSA

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

What is a Validation Focused Program?

Sandia National Laboratories

Goal

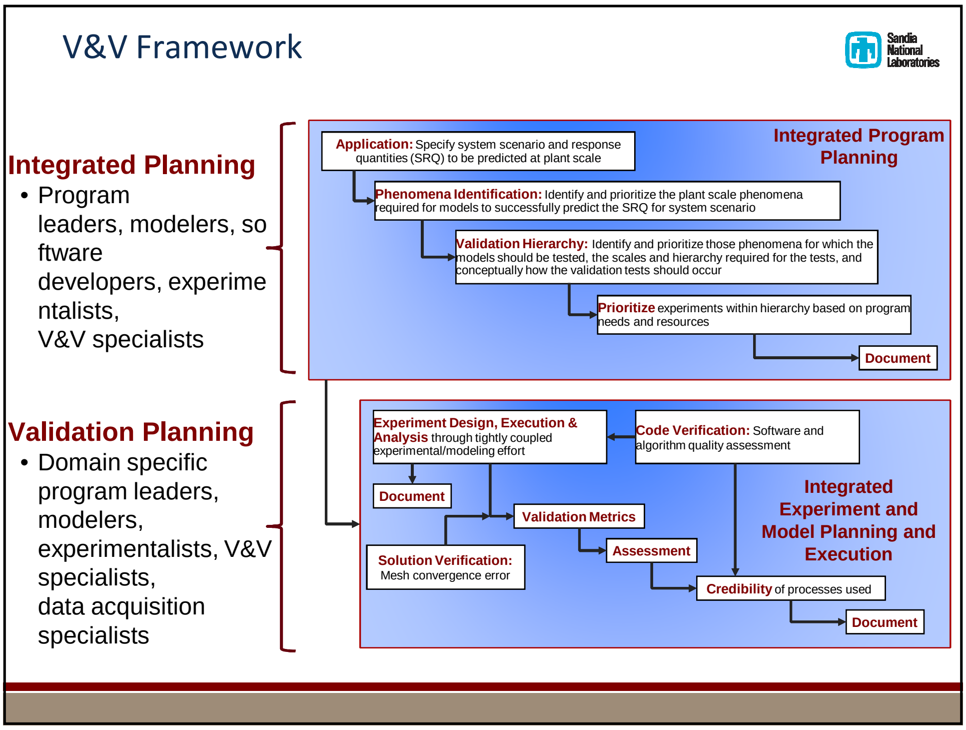
- Formalized highly collaborative approach to planning and executing joint experimental/modeling programs for the purpose of characterizing model accuracy for an intended application

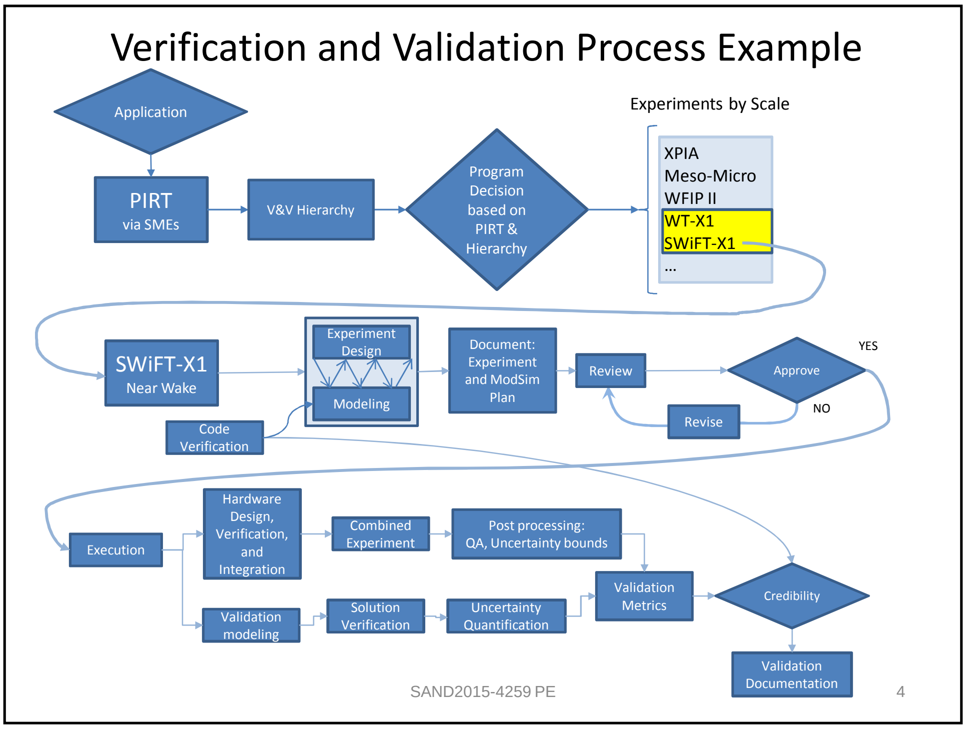
Why?

- Provides a transparent, structured, documented approach for integrate program planning across scales
- Applicable to models of all fidelity, including reduced order models
- High quality data sets well suited for collaborative model validation efforts
- Quantifies prediction uncertainty for use by designers

Foundation of framework used

- Framework developed for nuclear energy, SNL NW, and other programs
- Framework consistent with various ASME and AIAA V&V Guides, Codes and Standards


V&V Framework
Sandia National Laboratories
Integrated Planning
• Program leaders, modelers, software developers, experimentalists, V&V specialists
Validation Planning
• Domain specific program leaders, modelers, experimentalists, V&V specialists, data acquisition specialists
Integrated Program Planning
Application: Specify system scenario and response quantities (SRQ) to be predicted at plant scale
Phenomena Identification: Identify and prioritize the plant scale phenomena required for models to successfully predict the SRQ for system scenario
Validation Hierarchy: Identify and prioritize those phenomena for which the models should be tested, the scales and hierarchy required for the tests, and conceptually how the validation tests should occur
Prioritize experiments within hierarchy based on program needs and resources
Document
Experiment Design, Execution & Analysis through tightly coupled experimental/modeling effort
Code Verification: Software and algorithm quality assessment
Document
Validation Metrics
Solution Verification: Mesh convergence error
Assessment
Credibility of processes used
Document
Integrated Experiment and Model Planning and Execution


Verification and Validation Process Example
Application
Experiments by Scale
PIRT
via SMEs
V&V Hierarchy
Program Decision based on PIRT & Hierarchy
XPIA
Meso-Micro
WFIP II
WT-X1
SWiFT-X1
...
SWiFT-X1
Near Wake
Experiment Design
Modeling
Code Verification
Document: Experiment and ModSim Plan
Review
Approve
YES
NO
Revise
Execution
Hardware Design, Verification, and Integration
Combined Experiment
Post processing: QA, Uncertainty bounds
Validation modeling
Solution Verification
Uncertainty Quantification
Validation Metrics
Credibility
Validation Documentation
SAND2015-4259 PE
4

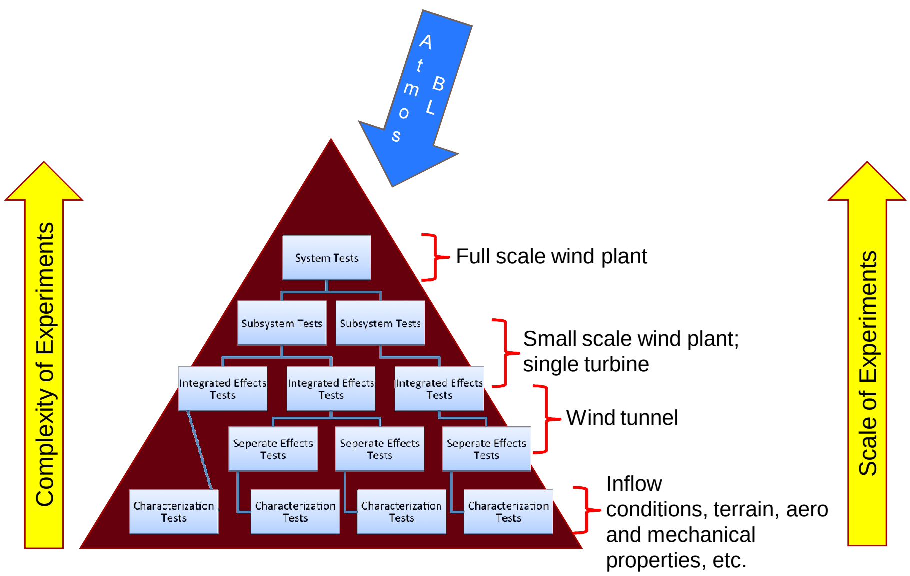
Backbone of Prioritization Process: PIRT

PIRT: Phenomenon Importance Ranking Table

- Consensus based
- Provides gap analysis of ability to model phenomena
  - Physics gaps
  - Numerical gaps
  - Data gaps
  - Validation gaps
- Gap analysis used to prioritize planning, including experimental planning

Phenomenon	Importance at Application Level	Model Adequacy		
		Physics	Code	Val
Turbine scale flow phenomena				
Blade Aero / Wake Generation				
Blade load distribution effects and rotor thrust	H	M	L	L
Tip and root vortex development, and evolution and merging	H	M	L	L
Vortex sheet and rollup (in addition to tip/root vortex)	M	M	M	L
Blade generated turbulence characteristics (energetic scales)	H	L	L	L
Root flow acceleration effect ('hub jet')	Unknown	M	L	L
Boundary layer state on turbine performance (roughness, soiling, bugs, erosion)	H	L	L	L
Boundary layer state (Re)	L	M	L	L
BL details near TE and LE	H	M	L	L
Rotational augmentation	H	L	L	L
Dynamic stall	H	L	L	L
Unsteady inflow effect (turb. intensity, spectra, coherence; veer, shear)	H	L	L	L
Blade flow control	M	L	L	L
Tower/rotor/nacelle wake interactions	H	M	L	L
Icing	L	L	L	L

PIRT Leads to the Validation Hierarchy



Validation Hierarchy Leads to Validation Experiments

Validation is a process of characterizing model error, not a binary statement of model validity

Characteristics of a successful validation programs

- Highly collaborative – team includes experimentalist, modelers, V&V specialist
- Models are used during the design phase to
  - Assure that the experiments are sensitivity to the phenomena of interest
  - Help optimize the experiments, i.e. define sensor location, density, sampling rates, …
  - Assure that the experiments can be unambiguously modeled (failure to do this is the most common reason for the failure of a validation exercise)
- Estimates of data uncertainty and model prediction uncertainty play a key role model validation process
- Model credibility is established by following a formal verification and validation process

Definition of a Modeling Campaign:

1.) What is to be predicted?
2.) Under what scenario?
3.) Impact of the model results on final design decisions?

Definition of an Experimental Campaign:

1.) **Objective**: What will be validated and what are the test conditions?

2.) **Method**: How will this data be gathered? What is the setup and instrumentation?

3.) **Environment/Requirements**: What are the requirements and constraints on the test campaigns? What is the required resolution/accuracy/time-scale?

4.) **Desired Outcome**: What will success mean? How will it be quantified? How will this increase credibility at full scale?

8

Validation data request

- An example Validation Data requirement:
  - Objective: quantify distribution of blade spanwise load
  - Method: surface pressure measurements and/or spanwise strain measurements
  - Environment: clean uniform inflow, turbulent inflow with quantified turbulence character and shear character
  - Success criteria: measurement data available with quantified inflow including uncertainty bounds.

9

SAND2015-4259 PE

Wake Generation, Propagation, Dispersion

PIRT Issues related to wake propagation, dispersion:

- Skew and meander of aggregate wake, wake vorticity diffusion, dissipation,
  - All heavily influenced by ABL
- Best tested in ABL wind tunnel for which BL inflow state (including turbulence) is well characterized and controlled with sufficient instrumentation resolution in the wake region using a smaller rotor (D ~ 1 m)

Wake Generation, Propagation, Dispersion

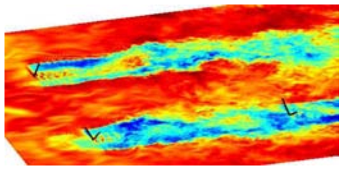
Sandia National Laboratories

Scale up to natural ABL at Reynolds number closer to utility scale

- ABL wind tunnel does not include the large scale unsteady inflow effects observed in nature – SWiFT does

Why SWiFT?

- Provide ABL that includes the unsteady effects at more relevant scales and larger Reynold's numbers
- Provides a test bed to develop/test field instrumentation at a scale that will be used for eventual tests at full sized facilities



Future Steps: Turbine-turbine interaction:

- Near future SWiFT testing
- Possible Milan wind tunnel tests
- Follow-on testing in operating wind plant

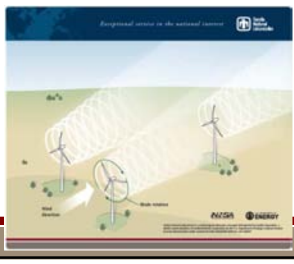
SWiFT site layout and capabilities

Sandia National Laboratories

DOE/SNL Scaled Wind Farm Technology (SWiFT) facility
hosted by Texas Tech University (TTU)

SWiFT exists to:

- Reduce turbine-turbine interaction and wind plant underperformance
- Public, open-source validation data
- Advance wind turbine technology



Facilities:

- Three variable-speed variable-pitch modified wind turbines with full power conversion and extensive sensor suite
- Two heavily instrumented inflow anemometer towers
- Site-wide time-synchronized data collection

12

SAND2015-4259 PE

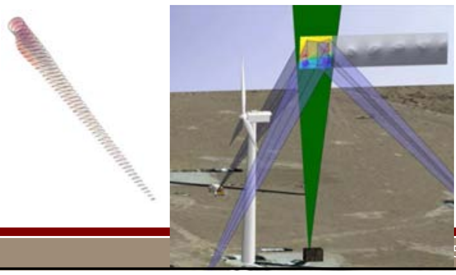
Sandia National Laboratories

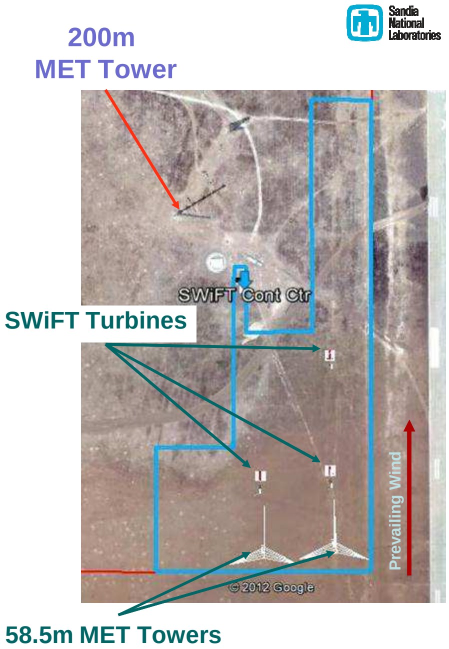
SWiFT-X1: Near Wake Validation

Goal: Validate HFM ability to predict blade loading and near wake structure given MET tower inflow measurements.

Measurements:

- ABL Condtions:
  200m MET, Sodar, and Radar Profiler
- Inflow: Dual 58.5m MET towers
- Rotor and Tower Strains and Accels.
- Rotor spanwise loading: Pressure taps and/or distributed strain measurements
- New rotors functionally scaled from utility turbine
- Near Wake Flow Diagnostic: SWIS





5-4259 PE

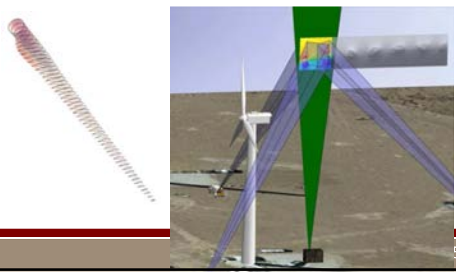
Sandia National Laboratories

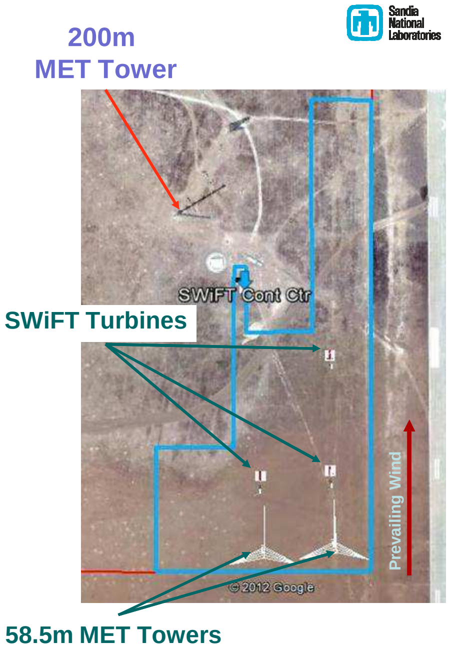
SWiFT-X2+: Wake Meandering and Turbine-Turbine Interaction

Goal: Validate HFM ability to predict blade loading and near wake structure given MET tower inflow measurements.

Measurements:

- Far Wake:
  - Re-deployable MET tower
  - Scanning Lidar
  - TTU Ka-band mobile Doppler radars
  - Flow-angle sensors on downstream turbine
- Downstream turbine loads
- Correlation with ABL observations

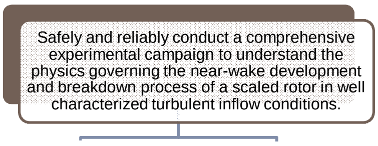




5-4259 PE

SWiFT test requirements schema

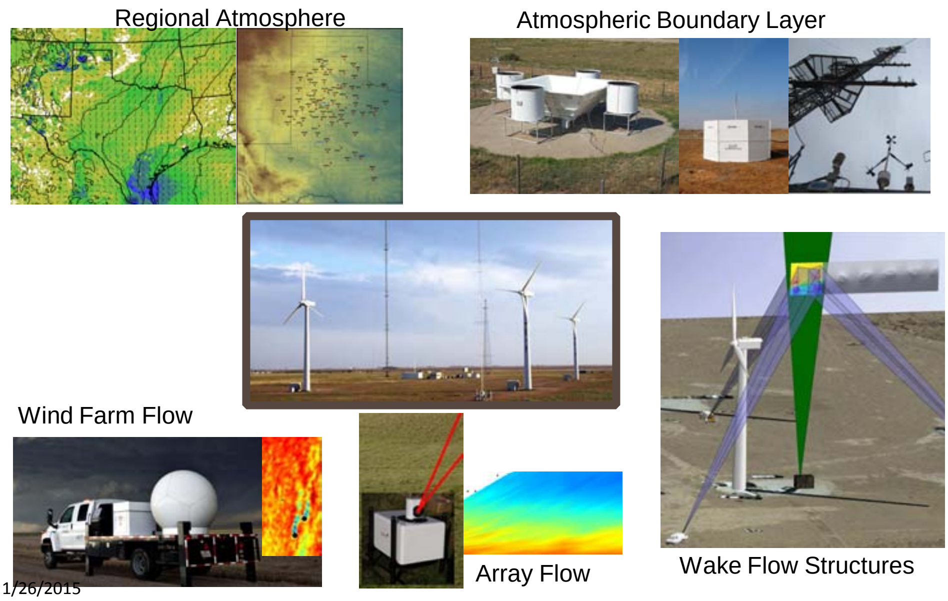
- Design of new test hardware for SWiFT could be done based on known operational envelopes and using standard rotor design practices and standard farm flow measurements.
- At the same time, design of a V&V test campaign begins with the PIRT process, which determines a test campaign specification, which leads to a test procedure.
- Interdependency 1: The test campaign specification drives aspects of test hardware and test instrumentation.
- Interdependency 2: The hardware operational requirements drives aspects of the V&V test procedure.



15

SAND2015-4259 PE

SWiFT Integrated Experiment Planning



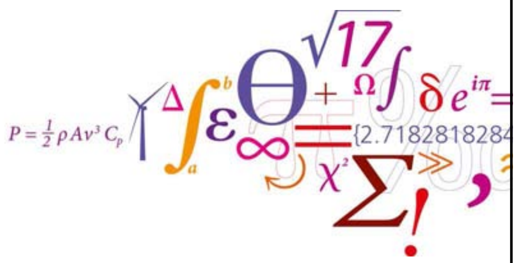
1/26/2015


Sandia National Laboratories
Thank you!

Uncertainty of data used in Wind Farm Flow Model validation

Kurt S. Hansen
DTU Wind Energy

E-mail:kuhan@dtu.dk



DTU Wind Energy
Department of Wind Energy

Outline

1) Introduction;
2) State-of-art flow analysis in wind farms;
3) Problems when using SCADA data;
4) Preparations before flow analysis;
5) Improving the data quality - today;
6) Uncertainty of wind turbine power values;
7) Uncertainty of inflow conditions;
8) Conclusion;

Introduction

Measuring high quality wind farm data is a huge and costly task.

- Requires a long measuring period;
- Requires many measuring postitions, high instrument quality and regular calibration;
- Individual wind turbine operational values e.g. power, pitch, rotor speed, nacelle wind speed, yaw position,..

- Undisturbed inflow conditions (wind and wind direction @ hub height)

- No standards or procedures coverering such measurements;
- Requirement given in IEC 61400-12-1; *Wind turbine power performance testing* may be used as a guideline;

3 **DTU Wind Energy, Technical University of Denmark** IEA WIND TEM#82, Visby, June 12th 2015

State-of-art: flow analysis in wind farms

Inflow conditions:

1) Use (undisturbed) mast recordings or
2) derive inflow conditions from undisturbed wind turbines.

Wind turbine operational parameters are recorded as 10-minute SCADA data (=supervisory control and data acquisition);

SCADA data is recorded by each individual wind turbine controller and stored in a central database.

4 **DTU Wind Energy, Technical University of Denmark** IEA WIND TEM#82, Visby, June 12th 2015

Problems when using SCADA data

1) Each wind turbine behave individually;
2) Each wind turbine logger has been set-up with individual parameters;
3) The instruments do not have accisble documentation for calibration or maintenance;
4) Wind turbine power performance has not validated;
5) Yaw (nacelle) position has not calibrated;
6) The met mast lacks instrument calibration or maintenance records - often;
7) The met mast covers a limited inflow sector eg. ±60°;
8) Derived inflow conditions are based on undisturbed power and yaw measurements.

Preparations before flow analysis

a) Identification of wind farm layout;
b) Organization and synchronization of the data sources;
c) Qualification of data;
d) Characterization of inflow conditions;
e) Identification of filter criteria.

DTU

How are we improving the data quality?

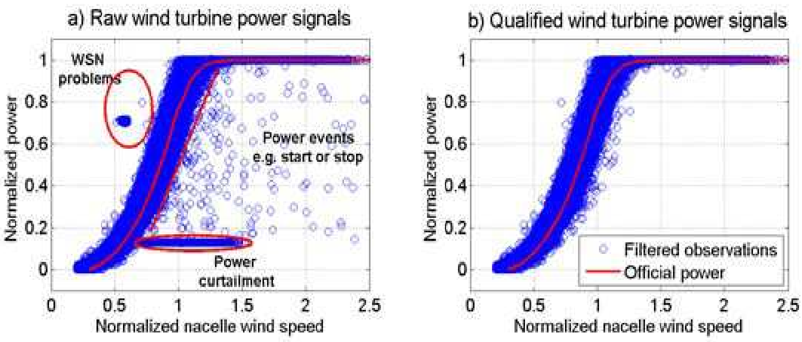
Mast measurements
- Signal control (test for stationarity and outliers);
- Wind speed inter-comparison (between different level or sources);
- Wind direction inter-comparison (between different level or sources);
- Seasonal variations of temperature;

Qualifying wind turbine operational parameters
- Exclude periods, which includes parking, idling or start/stop events;
- Exclude periods, which includes power outliers (power vs nacelle wind speed);
- Exclude periods with power curtailment;

7 DTU Wind Energy, Technical University of Denmark IEA WIND TEM#82, Visby, June 12th 2015

DTU

Example of power signal qualification



8 DTU Wind Energy, Technical University of Denmark IEA WIND TEM#82, Visby, June 12th 2015

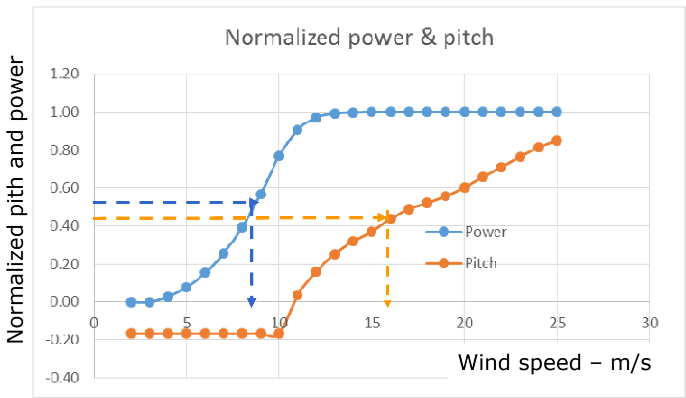
Uncertainty of wind turbine power values

- Uncertainty on AEP_{wt} for a stand-alone wind turbine for U>10 m/s ~ 4%, assuming:
  - Flat, undisturbed inflow;
  - High quality wind measurements;
  - Calibrated power transducers;
- Uncertainity on AEP_{park} for a group of wind turbines for U>10 m/s => >20%, assuming:
  - Offshore conditions;
  - No inflow measurements;
  - Internal wakes;
  - Lack of calibrated instruments;

9 DTU Wind Energy, Technical University of Denmark IEA WIND TEM#82, Visby, June 12th 2015

Inflow conditions: wind speed

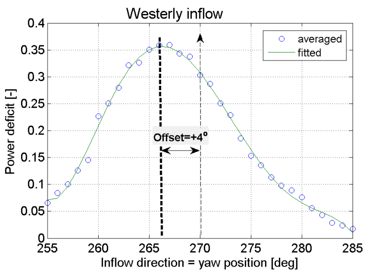
The wind speed is derived from the combined power & pitch curves.



10 DTU Wind Energy, Technical University of Denmark IEA WIND TEM#82, Visby, June 12th 2015

Inflow conditions: wind direction

- Lack of wind direction measurements;
- Calibration of yaw (=nacelle) position *YPos* is needed;



Problem: we vant to use wt *YPos* as an inflow reference,
How can we calibrate the *YPos*?

Solution: calculate the power deficit = 1-P_{wake}/P_{free} - as function of *Ypos.*

11 **DTU Wind Energy, Technical University of Denmark** IEA WIND TEM#82, Visby, June 12th 2015

Uncertainty on the inflow conditions to wind farms

1) Wind speed - measured;
   - The uncertainty can be calculated from the instrument classification, setup, terrain effects and database.

2) Wind speed – derived from power values;
   - The uncertainity is expected to be (rather) high and cannot be calculated;

3) Wind direction – measured;
   - The uncertainty should be less than 5°to fullfill the IEC power standards;

4) Wind direction – derived from the yaw position;
   - The uncertainty is expected to be high and cannot be calculated.

12 **DTU Wind Energy, Technical University of Denmark** IEA WIND TEM#82, Visby, June 12th 2015

Conclusion

- Presently the uncertainty of wind farm verification dataset are very high.
- The reason is that it is extremely costly to establish a full-scale, reference dataset.

References

[1] WAKEBENCH best practise Guidelines for Wind Farm Flow Models, edited by J. S. Rodrigo and P. Moriaty, IEA-Wind Task 31, First Edition, April 2015

Cornell University

Uncertainty in lidar arc scan measurement

H. Wang[1], R. J. Barthelmie[1], S. C. Pryor[2], G. Brown[3]
1. Sibley School of Mechanical and Aerospace Engineering, Cornell University
2. Department of Earth and Atmospheric Science, Cornell University
3. SgurrEnergy Ltd.

TEM#82,June 12, 2015

CornellEngineering

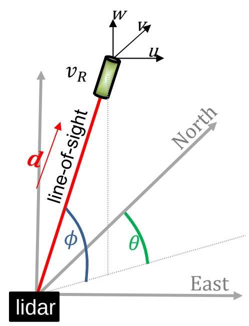
Cornell University

Content

- Introduction
- Lidar radial velocity uncertainty
- Predicted arc scan uncertainty
- Observed arc scan uncertainty
- Annual energy prediction uncertainty
- Conclusions

Cornell University

1. Intro: Lidar wind estimate



$\boldsymbol{d}$: unit directional vector
$\boldsymbol{v}$: wind velocity vector [*u*,*v*,*w*]
ϕ: elevation angle
θ: azimuth angle

- ❑ A lidar measures the radial velocity

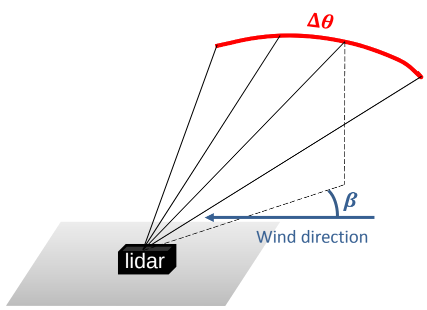
$$v_R = \boldsymbol{d}^T\boldsymbol{v}$$

$$\boldsymbol{d}^T = [cos\phi sin\theta, cos\phi cos\theta, sin\phi]$$

- ❑ Estimate wind velocity by solving a system of equations
  - Non-linear: $\boldsymbol{v_R} = G(\boldsymbol{v})$
  - Linear: $\boldsymbol{v_R} = \mathbf{G}\boldsymbol{v}$
- ❑ $\mathbf{G}$ is related to a scan geometry
  - Velocity-Azimuth-Display (VAD) scans
  - Arc scans

Cornell University

1. Intro: Arc scans



a sector scan that samples at *N* azimuth angles with an arc span $\Delta\theta$, and the line-of-sight and wind direction form an angle $\boldsymbol{\beta}$.

- ❑ Assumptions:
  - Horizontally homogeneous
  - Zero vertical wind speed
- ❑ Wind estimate is a linear inverse problem

$$\hat{\boldsymbol{v}} = [\hat{u}, \hat{v}]^T = \mathbf{G}\boldsymbol{v_R}$$

$$\mathbf{G} = \left(\mathbf{D}^{\mathrm{T}}\mathbf{D}\right)^{-1}\mathbf{D}^{\mathrm{T}}$$

$$\mathbf{D} = \cos\phi \begin{bmatrix} \sin\theta_1 & \cos\theta_1 \\ \sin\theta_2 & \cos\theta_2 \\ \vdots & \vdots \\ \sin\theta_N & \cos\theta_N \end{bmatrix}$$

Cornell University

1. Intro: Arc scan uncertainty

- Arc scans provide the horizontal wind speed:

$$\hat{V} = \sqrt{\hat{u}^2 + \hat{v}^2}$$

- The uncertainty of $\hat{V}$ is approximated by

$$\sigma_{\hat{V}} = \sqrt{c_{11}\hat{u}^2 + c_{22}\hat{v}^2 + 2c_{12}\hat{u}\hat{v}}/\hat{V}$$

where c_{ij} is from the covariance matrix of $\hat{\boldsymbol{v}}$

$$\mathbf{C} = \mathrm{var}(\hat{\boldsymbol{v}}) = \mathbf{G}(\mathbf{A} + \sigma_e^2\mathbf{I})\mathbf{G}^T$$

- σ_e^2: variance of v_R measurement
- $\mathbf{A}$: covariance of matrix of $\boldsymbol{v}_R$
- $\mathbf{G}$: scan geometry

- **QUESTION: How to design a scan geometry to minimize uncertainty?**

Cornell University

2. Radial velocity uncertainty

- σ_e & SNR [1],[2]

σ_e^2 < 0.01 m^2 s^{-2}, if SNR > -20 dB

- Bias & pitch/roll (80 m)

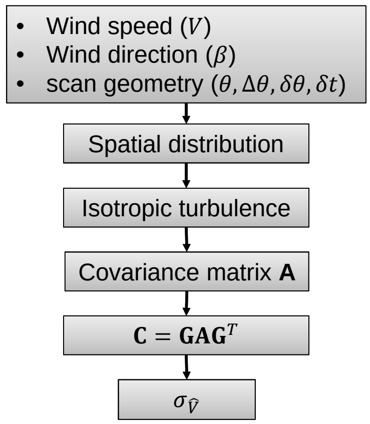
Small error if pitch/roll angle <±1°
Power law (a = 0.2) for wind shear

When SNR is reasonably high, pitch and roll are close to zero, turbulence intensity is not too high, σ_e^2 can be ignored

[1] Pearson, G. N., & Collier, C. G. (1999). A pulsed coherent CO2 lidar for boundary-layer meteorology. *Quarterly Journal of the Royal Meteorological Society, 125*(559), 2703-2721.
[2] Frehlich, R. (2001). Estimation of velocity error for Doppler lidar measurements. *Journal of Atmospheric and Oceanic Technology, 18*(10), 1628-1639.

Cornell University

3. Predicted uncertainty



- $\delta\theta$: azimuth increment
- δt: sampling interval

Cornell University

3. Predicted uncertainty

❑ The covariance matrix A

$$\alpha_{ij}(\boldsymbol{p}_{ij}) = \iint_0^{\infty} [W(s_i - r_i)W(s_j - r_j)K_r(\boldsymbol{q}_{ij})]ds_i ds_j$$

- $\boldsymbol{p}_{ij} = \boldsymbol{r}_i - \boldsymbol{r}_j - \Delta\boldsymbol{p}_{ij}$ is the relative position between two v_R
- $\Delta\boldsymbol{p}_{ij}= [(i-j)\delta t]\boldsymbol{u}_0$ is the wind-induced separation
- $\boldsymbol{q}_{ij} = \boldsymbol{s}_i - \boldsymbol{s}_j - \Delta\boldsymbol{p}_{ij}$ and $\boldsymbol{s}_i = s_i\boldsymbol{d}_i$
- W is the weight function
- $K_r(\boldsymbol{p}) = \boldsymbol{d}_i^T\boldsymbol{C}(\boldsymbol{p})\boldsymbol{d}_j$ is the point radial velocity covariance

  where $\boldsymbol{C}(\boldsymbol{p}_{ij})$ is the wind velocity covariance matrix at two points separated by $\boldsymbol{p}$

Cornell University

3. Predicted uncertainty

- Isotropic turbulence covariance matrix[3]

$$c_{lk}(\boldsymbol{p}) = c_u(p)\delta_{lk} + \frac{1}{2}p\frac{dc_u}{dp}\left(\delta_{lk} - \frac{p_l p_k}{p^2}\right)$$

  - $p = |\boldsymbol{p}|$, and p_1, p_2 and p_3 are the separation distances in the streamwise, transverse and vertical directions, respectively.
  - $c_u(p)$ is the auto-covariance of streamwise velocity

- Exponential decay function

$$c_u(p) = \sigma_u^2 e^{-\frac{p}{L_u}}$$

  - σ_u^2 is the variance of streamwise velocity
  - L_u is the turbulence integral length scale

[3] Wyngaard, J. C.: Turbulence in the Atmosphere, Cambridge University Press, 2010.

Cornell University

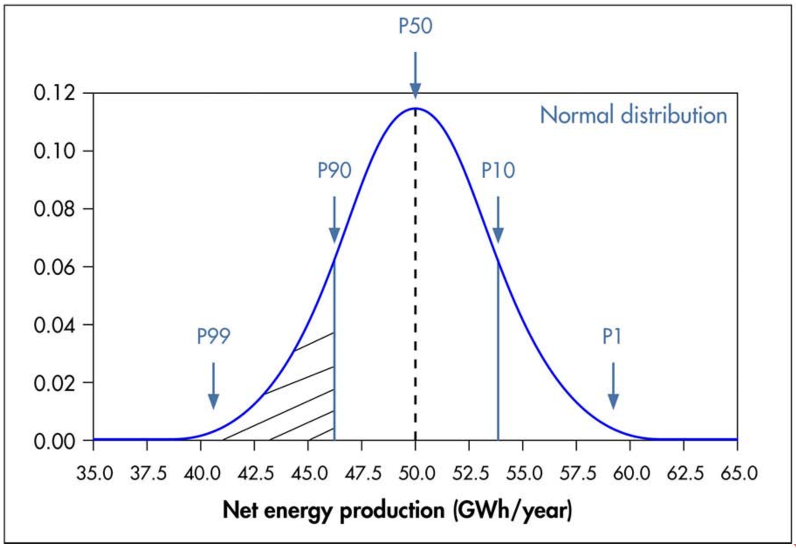
4. Conclusions

- Arc scan uncertainty is proportional to TI.
- The lowest uncertainty can be obtained by aligning lidar beams to the wind direction.
- Placing lidar beams 45° relative to wind direction can cause high uncertainty.
- Uncertainty can be reduced by increasing the arc span and lowering the beam number per arc scan
- A small arc span is NOT recommended for sites with high surface roughness and high wind direction variability.

Cornell University

Resources

Figure 1: Distribution For Energy Exceedance Probabilities



From Bailey and Kunkel, North American Windpower April 2015

Cornell University

Uncertainty costs

- Areas identified for reduced uncertainty can be improved by lidar measurements

Figure 2: Typical Energy Production Uncertainty Values

Uncertainty Sources	Mean	Max.	Min.
Wind Flow Modeling	4.0%	8.0%	2.4%
Long-Term Average	3.2%	4.8%	2.1%
Total Plant Losses	3.5%	4.8%	3.2%
Wind Shear	2.6%	6.4%	0.0%
Measurement Quality	2.4%	4.8%	1.6%
Evaluation Period Wind Resource	1.9%	6.0%	1.5%
Wind Speed Frequency Distribution	1.0%	1.5%	0.6%
Field Verification	0.5%	1.0%	0.2%
Total Energy Uncertainty	**7.5%**	**13.5%**	**5.2%**

Bailey and Kunkel, 2015

Cornell University

Acknowledgement

- U.S. National Science Foundation (#1464383)
- U.S. Department of Energy (DEEE0005379)

Questions?

Thank you for your attention

Hui (John) Wang
hw425@cornell.edu

CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES

Sensitivity analysis of the atmospheric boundary layer under a wide range of stability and geostrophic wind conditions

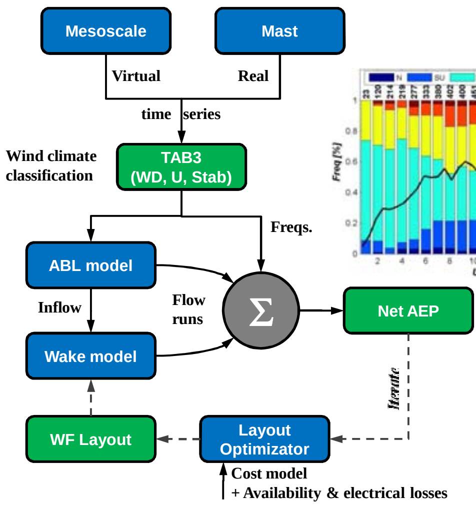
Javier Sanz Rodrigo

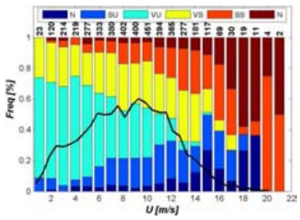
IEA Wind Topical Expert Meeting #82, Visby, 12 June 2015

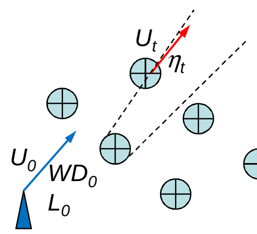
Acknowledgements: This work has been carried out with the support from the "MesoWake" Marie Curie International Outgoing Fellowship (PIOF-GA-2013-624562).

Gobierno de Navarra

Background: Approach for offshore wind farm design







$$AEP_t = \sum_1^{N_d}\sum_1^{N_u}\sum_1^{N_s} TAB3(i,j,k)P(U_t)8760$$

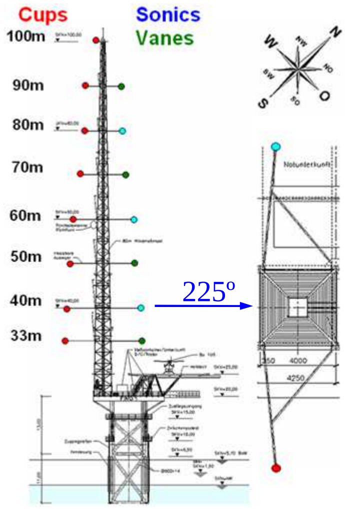
$U_t = A_t U_0$ $A_t(i,j,k)$ Mast to turbine speed-up factor

$$AEP_{net} = \sum_1^{N_t} AEP_t \eta_t$$

CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES Gobierno de Navarra

The Fino1 Test Case

- Profile measurements
  - o Cup anemo. {33,40,50,60,70,80,90,100}
  - o Wind direction {33,50,70,90}
  - o T, RH {33,40,50,70,100}
- Flux measurements
  - o Sonic anemometers {40,60,80}
- Quality control:
  - o Mast distortion / open-sea: WD = 225±45º
  - o Remove tilt angles with planar fit method
  - o Remove data with very low fluxes and velocity gradients prompt to large errors
- Period: Jan-Dec 2006, 2635 hourly samples



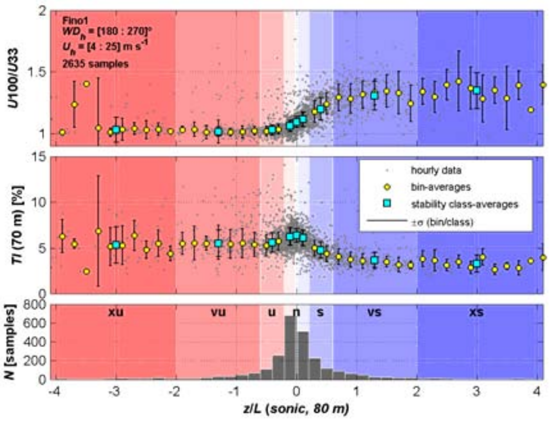
CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES
Ciemat
Gobierno de Navarra

Classification of atmospheric stability

- For convenience we shall assume a symmetric classification on the unstable range
- Focus on hub-height stability → wider range of *z/L*
- $4 < U_{hub} < 25$
- |z/L| > 2 : large scatter (extreme stability)

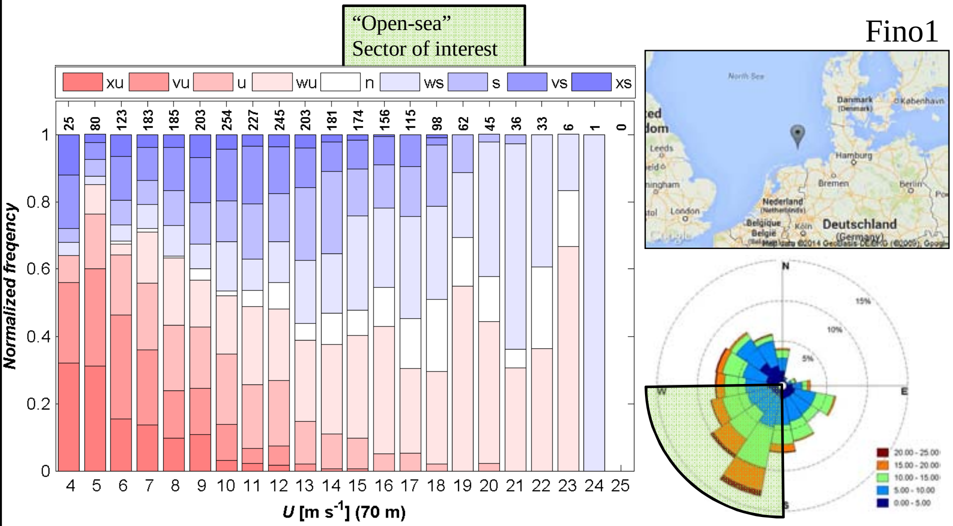
9 classes

- ❑ near-neutral (n) $0 < \zeta < 0.02$
- ❑ weakly stable (ws) $0.02 < \zeta < 0.2$
- ❑ stable (s) $0.2 < \zeta < 0.6$
- ❑ very stable (vs) $0.6 < \zeta < 2$
- ❑ extremely stable (xs) $\zeta > 2$



CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES
Ciemat
Gobierno de Navarra

Stability distributions: Stability vs Wind Direction



CENER | Gobierno de Navarra

CFDWind1D Single-Column-Model

- 1D ABL modeling assumptions:
  - ❑ Horizontally homogeneous conditions: d/dx→0, d/dy→0
  - ❑ No radiation and phase-change heat transfer

Geostrophic Wind: $$\left(U_g, V_g\right) = \frac{1}{\rho f_c}\left(-\frac{\partial P}{\partial y}, \frac{\partial P}{\partial x}\right)$$

Coriolis parameter: $$f_c = 2\Omega \sin\phi$$

- 1D Momentum and Energy equations:

$$\frac{\partial U}{\partial t} = f_c(V - V_g) - \frac{\partial \overline{uw}}{\partial z}$$

$$\frac{\partial V}{\partial t} = -f_c(U - U_g) - \frac{\partial \overline{vw}}{\partial z}$$

$$\frac{\partial \Theta}{\partial t} = -\frac{\partial \overline{w\theta}}{\partial z}$$

Kinematic momentum and heat fluxes

$$\left(\overline{uw}, \overline{vw}\right) = -K_m\left(\frac{\partial U}{\partial z}, \frac{\partial V}{\partial z}\right)$$

$$\overline{w\theta} = -K_h\frac{\partial \Theta}{\partial z} = -\frac{K_m}{\Pr}\frac{\partial \Theta}{\partial z}$$

- Closure problem: Determine eddy viscosity $K_m \sim u\, l_m$ [m²/s]

CENER | Gobierno de Navarra

CFDWind1D: 0th-order strain-rate closure (*l-S*)

- Eddy-viscosity from strain-rate: $K_m = l_m^2 S = l_m^2 \left[\left(\frac{\partial U}{\partial z} \right)^2 + \left(\frac{\partial V}{\partial z} \right)^2 \right]^{1/2}$
- Diagnostic equation for l_m: $l_m = \dfrac{\kappa z}{\phi_m \left(\frac{z}{L} \right) + \frac{\kappa z}{\lambda}}$
- Local stability parameter: $\zeta = z/L$

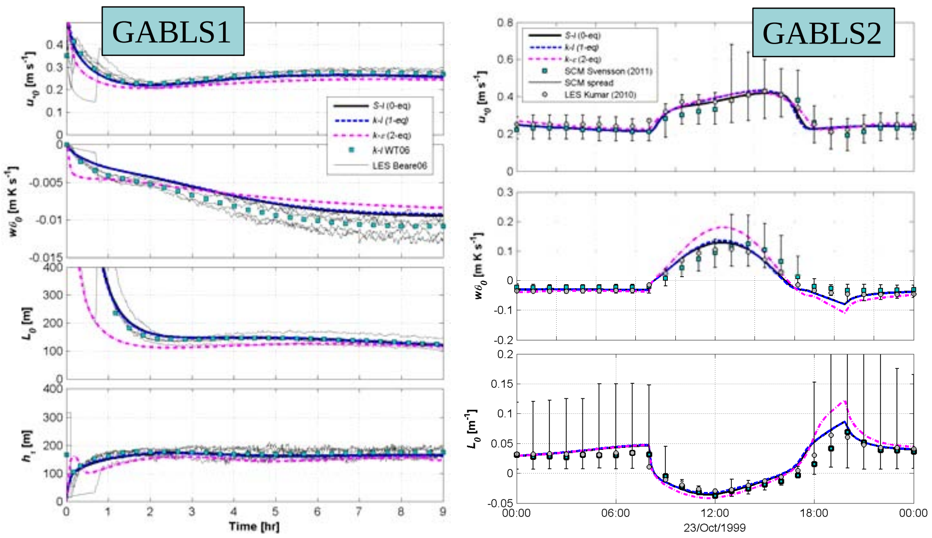
$\lambda = 2.7 \cdot 10^{-4} \dfrac{S_g}{|f_c|}$ (Blackadar, 1962) — Length-scale limiter in neutral conditions (empirical)

$\phi_m(\zeta) = \begin{cases} (1-5\zeta)^{-1/4} & \zeta < 0 \\ 1+5\zeta & \zeta \geq 0 \end{cases}$ (Dyer, 1974) — Stability function (empirical)

- Offshore: $z_0 = C_{ch} \dfrac{u_*^2}{g}$; $C_{ch} \approx 0.008 : 0.06$ (Charnock, 1955)
- Site calibration on: $\phi_m(z/L)$ and C_{ch}

CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES — Ciemat — Gobierno de Navarra

CFDWind1D: Verification on GABLS cases



CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES — Ciemat — Gobierno de Navarra

Non-dimensional velocity gradient

- Poor fit of Dyer's stability function at low heights
- Local-scaling based only on z/L not sufficient in offshore conditions?

$$\frac{\kappa z}{u_*}\frac{\partial U}{\partial z} = \phi_m\left(\frac{z}{L}\right)$$

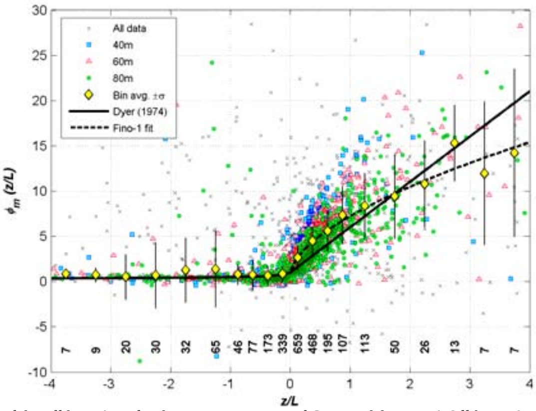
Dyer (1974)

$$\phi_m(\zeta) = \begin{cases} (1-5\zeta)^{-1/4} & \zeta < 0 \\ 1+5\zeta & \zeta \geq 0 \end{cases}$$

Fino-1 fit

$$\phi_m(z/L) = 1 + b_m\zeta\left(1+\frac{b_m}{a_m}\frac{z}{L}\right)^{a_m-1}$$

$$a_m = 0.6; \quad b_m = 30$$



Sanz Rodrigo J (2011) Flux-profile characterization of the offshore ABL for the parameterization of CFD models. *EWEA Offshore 2012 proceedings*, Amsterdam, The Netherlands, November 2011

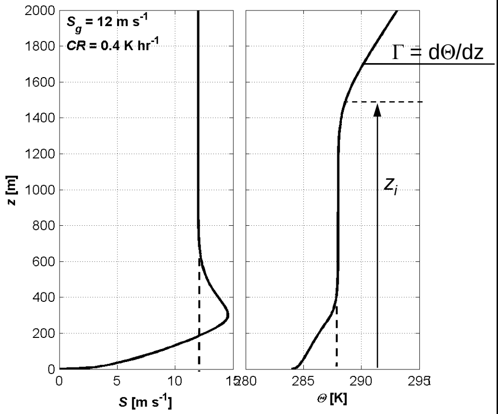
CENER Gobierno de Navarra

CFDWind1D Set-up

- Inputs:
  - ❑ f_c = 1.18e-4 1/s
  - ❑ S_g = [4:2:44] m/s
  - ❑ CR = [-4:0.2:4] K/hr
  - ❑ z_0 = $C_h u_*^2/g$ (Charnock)
  - ❑ Γ = [0.1:10] K/km
  - ❑ z_{top} = 4000 m

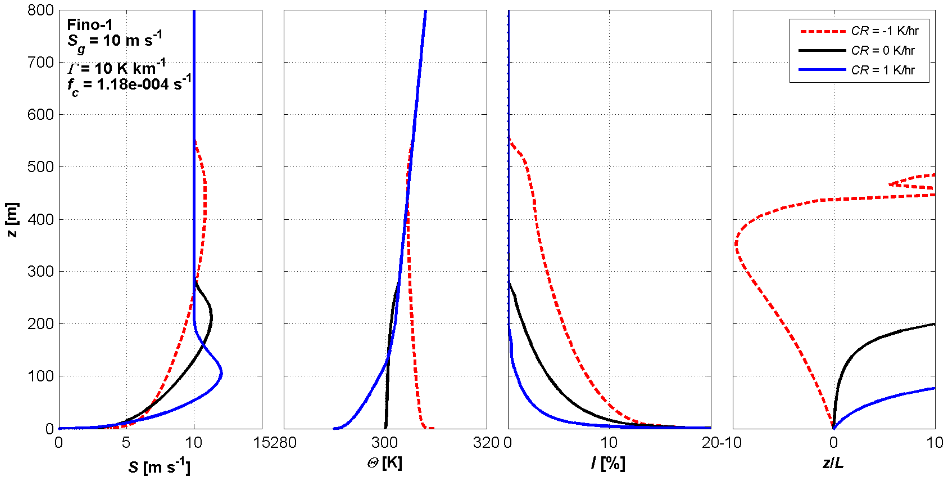
- z_i =0 initially to remove this parameter which is difficult to assess a priori

GABLS1 approach to reach quasi-steady profiles:
- Simulation until quasy-steady state is reached (4.5 inertial cycles)
- Profiles are averaged during the last hour



CENER Gobierno de Navarra

CFDWind1D Sample profiles



CENER · Gobierno de Navarra

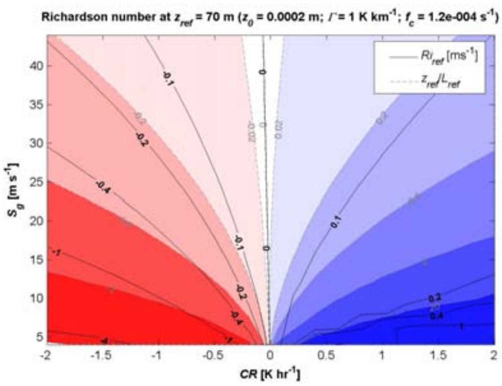
Sensitivity Analysis on Variables of Interest

- Reference height: z_{ref} = 70 m (hub-height)
- Area of interest: $z_{ref} \pm R$ = 33:90 m (rotor diameter)

Variables of interest: $\delta = f(S_g, CR, \Gamma) \rightarrow$ 3D look-up tables (+ z for profiles)

- Hub-height velocity S_{ref}
- Stability: $\zeta_{ref} = z_{ref} / L_{ref}$
- Turbulence Intensity $I_{ref} = \sigma_s / S_{ref}$
- Wind shear exponent $\alpha_{ref} = \alpha_{33/90}$
- Wind veer: $WD_{90} - WD_{33}$
- Boundary layer height h_τ (z where $\tau = 0.05\tau_0$)

Stability classes (symmetric unstable)
- ❑ near-neutral (n) $0 < \zeta < 0.02$
- ❑ weakly stable (ws) $0.02 < \zeta < 0.2$
- ❑ stable (s) $0.2 < \zeta < 0.6$
- ❑ very stable (vs) $0.6 < \zeta < 2$
- ❑ extremely stable (xs) $\zeta > 2$

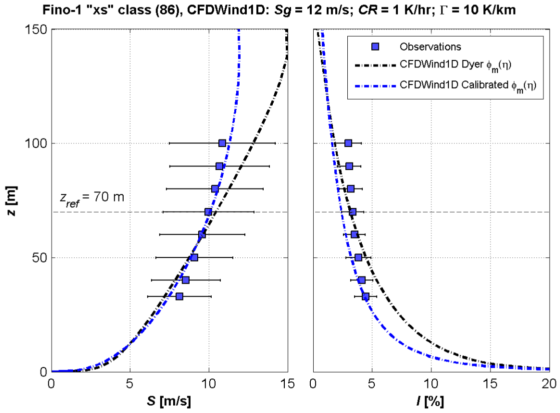


CENER · Gobierno de Navarra

Fit to class-averaged profiles

Preliminary Results

- Given {S_{ref}, α_{ref}, ζ_{ref}}, for each stability class, find the nearest neighbour in look-up tables → (S_g, CR, Γ)
- **Uncalibrated** model: Dyer (onshore) stability function and C_{Ch} = 0.01 (default)
- **Calibrated** model: Fino-1 stability function and C_{Ch} = 0.01



CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES · Ciemat · Gobierno de Navarra

Conclusions

- Using ABL instead of SL models imply new variables of difficult assessment from measurements
- The “GABLS1” approach to obtaining quasy-steady conditions allows to find mean profiles with similar characteristics to stability class-averaged observations
- A profile-fit methodology based on look-up tables allows defining boundary conditions for each class based on reference measured values of velocity, wind shear and stability
- The model can then be used to simulate wake effects using realistic mean profiles calibrated to onsite measurements
- Default onshore stability functions (Dyer) provide reasonably good velocity profiles
- Flux-profile measurements can be used to introduce better calibration of the wind profile in stable conditions
- Turbulent intensity using default (uncalibrated) configuration leads to overprediction in the *xu* to *ws* range
- The Charnock constant may be used to calibrate turbulence.

CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES · Ciemat · Gobierno de Navarra

UQ Outlook

- Explore how best select profile classes to characterize design parameters in an efficient way (meta models).
- Make use of look-up tables to infer the impact of input uncertainties on target variables
- Explore more realistic ways of populating profile classes and averaging following the observed *pdf* profiles
- Introduce wakes

CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES   Gobierno de Navarra

Outline
Introduction
Generation of quantiles through ensemble of forecasts for wind power output
Simultaneous optimal bidding in two energy markets
Revenue and market design for wind producers
Optimized bidding method
Conclusion
References

UPPSALA UNIVERSITET

Ensemble based stochastic wind power penetrated reserve electricity market optimization

Bahri Uzunoğlu

Department of Engineering Sciences, Division of Electricity
Centre for Renewable Electric Energy Conversion
Angstrom Laboratory, Uppsala University
Postal address: Box 534 51 21 UPPSALA, Sweden
Email: bahri.uzunoglu@angstrom.uu.se

Bahri Uzunoğlu IEA Wind Topical Expert Meeting 82

Outline
Introduction
Generation of quantiles through ensemble of forecasts for wind power output
Simultaneous optimal bidding in two energy markets
Revenue and market design for wind producers
Optimized bidding method
Conclusion
References

UPPSALA UNIVERSITET

Bahri Uzunoğlu IEA Wind Topical Expert Meeting 82

Introduction

- Trading optimal wind power in energy and regulation market offers possibilities for increasing revenues as well as impacting security of the system in a positive way Menin and Uzunoglu (2015) Liang et al. (2011). The bidding in both energy and regulation markets can be computed through stochastic optimization using ensembles wind flow models.
- Based on this optimization, the impact of price ratios between energy and reserve market can be investigated to analyse the impact of price ratios.
- Our parametric study revealed that as long as up-regulation prices are below day-ahead energy, the algorithm will bid in both markets to optimize revenue. When regulation prices are higher than day-ahead then it only bids energy in the regulation market with the current objective function which introduces several possibilities of customization.

Generation of quantiles through ensemble of forecasts for wind power output

- The majority of tools provide point forecasts which are given as only one measurement of the predicted power output. A more useful result is a probability forecast which quantifies the uncertainties of the predictions of the regional context. Probabilistic wind forecasts are often based on ensemble prediction systems that can use different scale flow models Zupanski et al. (2006) Uzunoglu et al. (2007) Uzunoglu (2007) Xiong et al. (2007) with data assimilation.
- Numerical flow prediction models are run with different initial conditions or different physical models to generate the uncertainty in the forecast to improve predictions. Their potential for efficient use on parallel computers with large-scale models is another advantage.

Generation of quantiles through single deterministic forecast

- In this study, single deterministic or point forecast variance margin of the employed time series will be used to generate the time series Menin and Uzunoglu (2015).
- Several post processing techniques through definition of parametric distributions or quantile regression exist for ensembles based on quantiles that are generated through this approach. Ensembles may be jointly described with a probability distribution function.

Outline
Introduction
Generation of quantiles through ensemble of forecasts for wind power output
Simultaneous optimal bidding in two energy markets
Revenue and market design for wind producers
Optimized bidding method
Conclusion
References
Generation of quantiles through single deterministic forecast

Generation of quantiles through single deterministic forecast

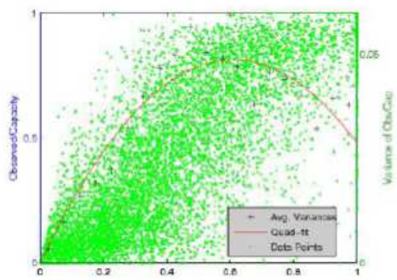


Figure: VARIANCE - Observed production and its variance plotted to the forecasted power. All the variables are normalized to installed capacity. Perfect prediction would render a 1:1 ratio and therefore a perfectly diagonal line.

Bahri Uzunoğlu IEA Wind Topical Expert Meeting 82

Simultaneous optimal bidding in two energy markets

- This portion of the investigation focuses on the tertiary reserve service, which may also be known as balance service.
- It is used to correct energy imbalances during each operating hour of contracted power exchanges. Deviations from planned production result in penalized energy prices rendering less-than-expected revenues.
- Errors in forecast are reflected directly in revenues due to these deviations of contractual energy delivery. A larger error in forecast does not necessarily mean a larger revenue penalty because it depends on whether the error is favorable for the system or not.

Revenue and market design for wind producers

The total revenue constitutes the sum from both markets at each hour, represented by equation 1. Using the same notation as Menin and Uzunoglu (2015) Liang et al. (2011), R_E is revenue from the regular energy market and R_{UR} is the revenue from up regulation. π is the price, P_c is committed power, and T is the additional revenue (positive or negative) from deviation, each for the respective market. These relationships are summarized below:

$$R = R_E + R_{UR} \quad (1)$$

$$R_E = \pi_E P_{cE} + T_E \quad (2)$$

$$R_{UR} = \pi_{UR} P_{cUR} + T_{UR} \quad (3)$$

$$R = \underbrace{\pi_E P_{cE} + T_E}_{R_E} + \underbrace{\pi_{UR} P_{cUR} + T_{UR}}_{R_{UR}} \quad (4)$$

Revenue and market design for wind producers

$$T_E = \begin{cases} \pi_{E+}(P_t - P_{cE}), & P_E \geq P_{cE} \\ \pi_{E-}(P_t - P_{cE}), & P_E < P_{cE} \end{cases} \tag{5}$$

This optimization assumes that up regulation prices are lower than energy prices, and the price of under provision of either is higher than the respective base price. Additionally, it is assumed that for wind energy, the electricity market is designed in such a way that it fulfills the third price relationship. These assumptions are shown below:

$$0 \leq \pi_{UR+} \leq \pi_{UR} \leq \pi_{UR-} \tag{6}$$

$$0 \leq \pi_{E+} \leq \pi_E \leq \pi_{E-} \tag{7}$$

$$0 \leq \pi_{UR+} \leq \pi_{E+} \leq \pi_{UR-} \leq \pi_{E-} \tag{8}$$

Optimized bidding method

The optimization of revenue is a maximization problem of the expected revenue by bidding in both markets. Certain restrictions, or contingencies, must apply in order to represent real conditions. Committed power may not exceed total installed capacity. P_{tmax} is the installed capacity of the wind farm. The expected revenue objective function derivations is given by Liang et al. (2011), the closed form of this objective function is as below.

$$\begin{aligned} \max \quad & E[R(P_{cE}, P_{cUR})] \\ \text{s.t.} \quad & P_{t\,\max} - P_{cE} - P_{cUR} \geq 0 \\ & P_{cE} \geq 0, \quad P_{cUR} \geq 0 \end{aligned} \tag{9}$$

For a solution in nonlinear programming to be optimal, the expected revenues partial derivatives with respect to P_{cUR} and P_{cE} defines the optimal bidding strategy necessary conditions via inequality constraints of the Karush Kuhn Tucker conditions.

Optimized bidding method

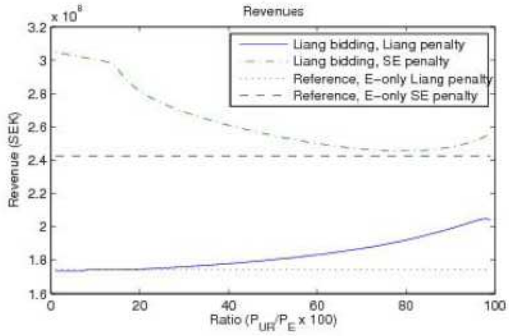


Figure: Revenue vs price ratio:Revenue curves for total revenue vs up regulation to spot price ratio

Outline
Introduction
Generation of quantiles through ensemble of forecasts for wind power output
Simultaneous optimal bidding in two energy markets
Revenue and market design for wind producers
Optimized bidding method
Conclusion
References

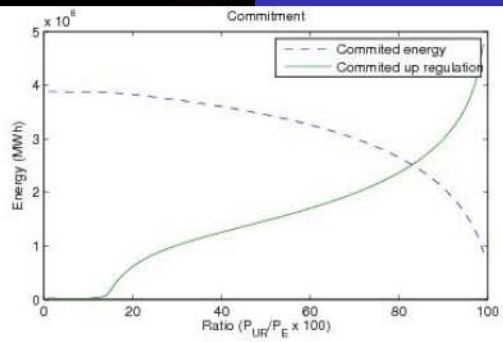


Figure: Energy commitment vs price ratio:Revenue curves for total revenue vs up regulation to spot price ratio

Bahri Uzunoğlu IEA Wind Topical Expert Meeting 82

Optimized bidding method

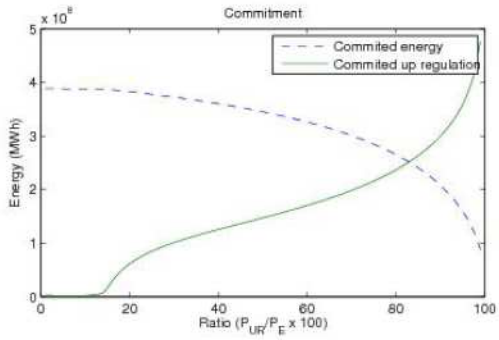


Figure: Commitment curves.

Conclusion

- This algorithm was initially designed for a market where up-regulation prices are lower than regular energy and penalties are high, especially for over-production which are null in the Swedish observed scenario.
- Nonetheless, in this scenario where the penalty for not delivering up-regulation is minimal and the price is higher than the regular day-ahead market, it is profitable to participate in up-regulation market and not in the energy market.
- However, this investigation only observes how a small wind farm behaves in up-regulation hours due to the lack of prices for down-regulation or zero imbalance hours.
- The assumption that the wind power producer is small enough not to change market price results in no penalty for under-generation. This may be applied as a differentiated penalty and serve as an incentive for larger scale participation in the up-regulation market.

Conclusion

- Ensemble methods create a probabilistic forecast in time that can be used power system optimization in reserve and energy market.
- The parametric study reveals that as long as up-regulation prices are below day-ahead energy, the algorithm will bid in both markets to optimize revenue.
- In order to use a joint bidding algorithm in markets similar to Swedish market, it must be optimized for these specific market conditions, or a broader algorithm may be designed with inputs that describe the market behaviors to tweak its performance according to these

Bahri Uzunoğlu IEA Wind Topical Expert Meeting 82

UPPSALA UNIVERSITET

Liang, J., Grijalva, S., and Harley, R. (2011). Increased wind revenue and system security by trading wind power in energy and regulation reserve markets. *Sustainable Energy, IEEE Transactions on*, 2(3):340–347.

Menin and Uzunoglu (2015). Parametric sensitivity study for wind power trading through stochastic reserve and energy market optimization. IEEE Greentech.

Uzunoglu, B. (2007). Adaptive observations in ensemble data assimilation. *Computer Methods in Applied Mechanics and Engineering*, 196(41-44):4207 – 4221.

Uzunoglu, B., Fletcher, S. J., Zupanski, M., and Navon, I. M. (2007). Adaptive ensemble reduction and inflation. *Quarterly Journal of the Royal Meteorological Society*, 133(626):1281–1294.

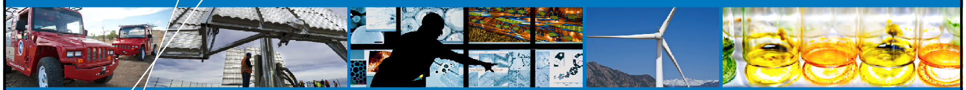
Xiong, X., Navon, I., and Uzunoglu, B. (2007). A note on the particle filter with posterior gaussian resampling. *Tellus A*, 58(4).

Zupanski, M., Fletcher, S. J., Navon, I., Uzunoglu, B., Heikes, R. P., Randall, D. A., Ringler, T. D., and Daescu, D. (2006). Initiation of ensemble data assimilation. *Tellus A*, 58(2):159–170.

Bahri Uzunoğlu IEA Wind Topical Expert Meeting 82

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Uncertainty related standards and R&D initiatives



Jason Fields

Senior Engineer
National Wind Technology Center
National Renewable Energy Laboratory

IEA Topical Experts Meeting 82-
Uncertainty Quantification of Wind Farm Flow Models
Visby, Sweden June 12, 2015

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Agenda

- IEA TEM on Uncertainty & Finance
- IEC 61400-15 Overview
- A2e & PRUF

NATIONAL RENEWABLE ENERGY LABORATORY 2

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

IEA TEM on Uncertainty & Finance

IEA TEM-Uncertainty & Finance

TEM Goals

- **Explore the intersection of project and portfolio related risks with technical drivers**
- **Explore country or region specific finance models, incentives and risk drivers**
- **Facilitate the exchange of information on project structures and risk mitigation approaches**
- **Discuss best practices for decision information tools/processes**
- **Determine desire for future collaborative work in this area which would:**
  - Generate a catalog of projects risks and associated magnitudes
  - Define actionable improvements in risk quantification and mitigation strategies
  - Develop best practice guidelines for decision information tools/processes

NATIONAL RENEWABLE ENERGY LABORATORY 4

IEA TEM-Uncertainty & Finance

Meeting Venue: Europe (TBD)
Potentially Netherlands

In conjunction with IEA Task 26:
Cost of Energy meeting

Meeting Timing:
October 27-29, 2015

NATIONAL RENEWABLE ENERGY LABORATORY 5

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

IEC 61400-15

"Assessment of Wind Resource, Energy Yield and Site Suitability input conditions for wind power plants"

IEC 61400-15

- **New standard, new group. 1st meeting in March 2014**
- **Expected to be issued ~2018**
- **Intended to compliment other IEC standards**
  - 61400-1 (Design)
  - 61400-12 (Power Performance Testing)
- **Committee mostly consists of European and US delegates (up to 6 per country)**

- Some of the Companies Represented:
  - Vestas
  - GE
  - Siemens
  - Gamesa
  - Senvion
  - Enercon
  - DTU
  - AWS Truepower
  - RES
  - Sgurr
  - Leosphere
  - Deutsche WindGuard
  - Anemos
  - NREL
  - EDF EN
  - DNV GL

NATIONAL RENEWABLE ENERGY LABORATORY 7

Foundational Work

Existing related standards & best practices

- IEC 61400-1,3 Wind Turbine: Design Requirements
- IEC 61400-12-1 Power Performance Testing
- IEC 61400-26 Availability: Technical Specification
- MEASNET "Evaluation of site specific winds"

Other documents/collaborations

- Consortium Loss & Uncertainty definitions
- Wind Resource Assessment: A Practical Guide to Developing a Wind Project
- IEA Wind Task 32 Remote Sensing
- IEA Wind Task 31 Windbench and Wakebench
- IEA Task 11 75th meeting on complex terrain
- Power Curve Working Group

NATIONAL RENEWABLE ENERGY LABORATORY 8

Who will use this standard?

- **Developers:** **To have a source of guidelines by which to develop wind assessment campaigns and to understand the importance of their choices.**
- **Consultants/IE's: To have a set of standard criteria and project data which need to be considered and reported on.**
- **Banks/Investors: To have a standard by which to judge or qualify an independent energy assessment, and to compare assessments from multiple IE's**
- **Manufacturers:** **To have a set of standard criteria and input data which from which loading and suitably can determinations can be calculated with confidence.**

NATIONAL RENEWABLE ENERGY LABORATORY 9

Goals – Normative (Required)

- **Define standards for reporting**
  - A checklist of items that must be considered in an assessment
  - Report must cover the checklist and explain how each item was considered
  - Example: Wind speed predictions at turbine locations
- **Define IEC uncertainty model**
  - Explicit calculation of uncertainty
  - Provides benchmark for readers
  - Organizations can still use their own uncertainty calculation but would need to also report the IEC calculation and explain differences
  - Used as a tool to show what activities can reduce uncertainty
    - Met towers, High quality anemometers, Remote Sensing
    - Wind plant design optimization
- **Define turbine suitability load calculation inputs**
  - Each manufacturer asks for different datasets to run their loads model
  - Standardize the data to improve quality and transparency

NATIONAL RENEWABLE ENERGY LABORATORY 10

Goals – informative (Recommended)

- **Provide industry consensus best practices, including multiple approaches to common problems**
  - Measurement (Local Site Conditions)
    - Measurement strategy
    - Measurement parameters
    - Measurement Devices
      - Meteorological Towers and Instrumentation
      - Remote Sensing
    - Data Management
    - Production data from nearby projects
    - Alternative valid measurements
  - Data Analysis
    - Traceability and Calibration
    - Quality control of data
  - Wind Resource Modeling
    - Gap Filling
    - Long-Term
    - Vertical Extrapolation
    - Horizontal Extrapolation
    - Validation (all of the above)
  - Wind Plant Energy Yield Modeling
    - Ideal Energy Yield
    - Wake
    - Losses
  - Statistical description of measurements
    - Frequency Distributions
    - Wind Roses
    - 12x24
    - 8760
    - Weibull

NATIONAL RENEWABLE ENERGY LABORATORY 11

IEC 61400-15 Early results

- **Universal Site Suitability Input Form**
- **Standard Loss Framework**
- **Standard Uncertainty Framework**

Big Deal!

- One form to rule them all
- Universal site suitability input form eliminates need for reprocessing and reformatting of data for every turbine OEM.
- Site suitability format largely agreed upon amongst major Turbine OEM's. Currently being socialized up the chain now
- Includes wind speed and direction frequency distributions, TI summaries, coherent turbulence information, Extreme wind estimations and extreme turbulence models amongst other parameters

NATIONAL RENEWABLE ENERGY LABORATORY 12

IEC 61400-15 Early results

- Universal Site Suitability Input Form
- Standard Loss Framework
- Standard Uncertainty Framework

Task 31 and UQ TEM input desired!

IEC 61400-15 DRAFT Loss Categories for Precosntrcution Energy Estimates

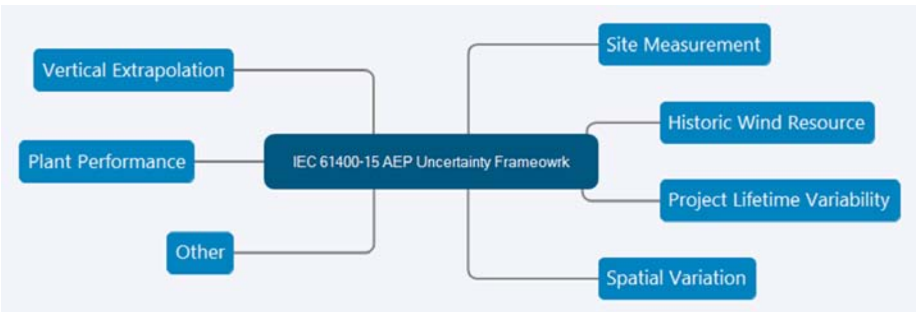
First Level loss category	Second Level Loss category
Availability	Turbine Availability
	Balance of Plant Availability
	Grid Availability
Wake Effect	Internal Wake Effects
	External Wake Effects
	Future Wake Effects
Electrical	Electrical Efficiency
	Facility Parasitic Consumption
Turbine Performance	Sub-Optimal Performance
	Generic Power Curve Adjustment
	Site-specific Power Curve Adjustment
	High Wind Hysteresis
Environmental	Icing
	Degradation
	Environmental Shut down
	Exposure
Curtailments / Operational Strategies	Directional Curtailment / Wind Sector Management
	Grid Curtailment
	Environmental / Permit Curtailment
	Owner-directed Operational Strategies

*Version 1.0 dated February 26, 2015

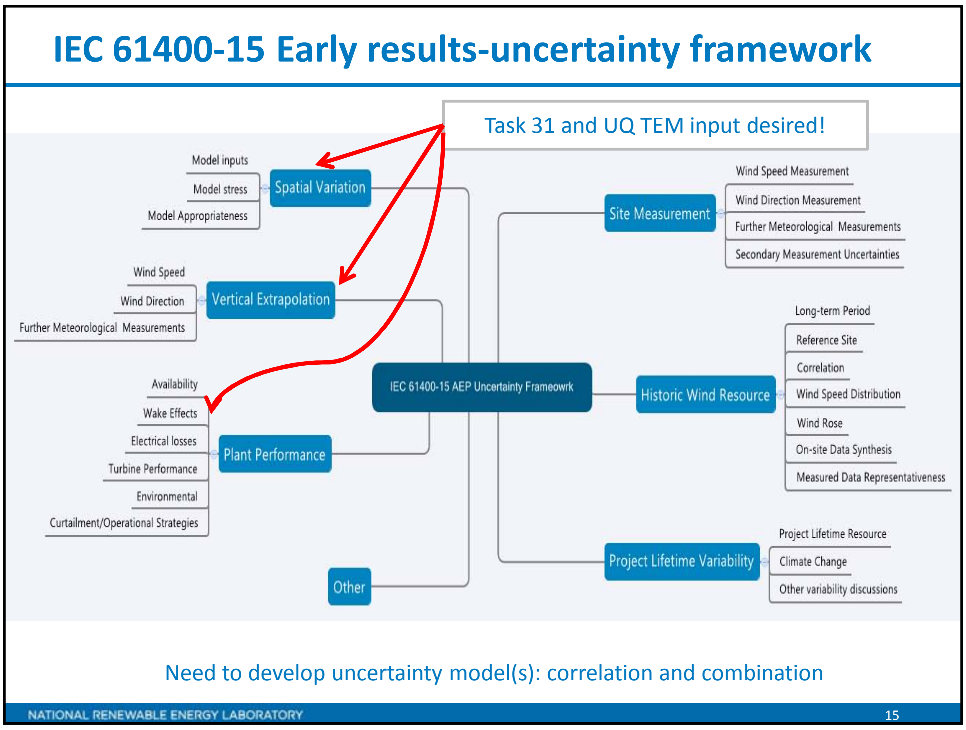
NATIONAL RENEWABLE ENERGY LABORATORY 13

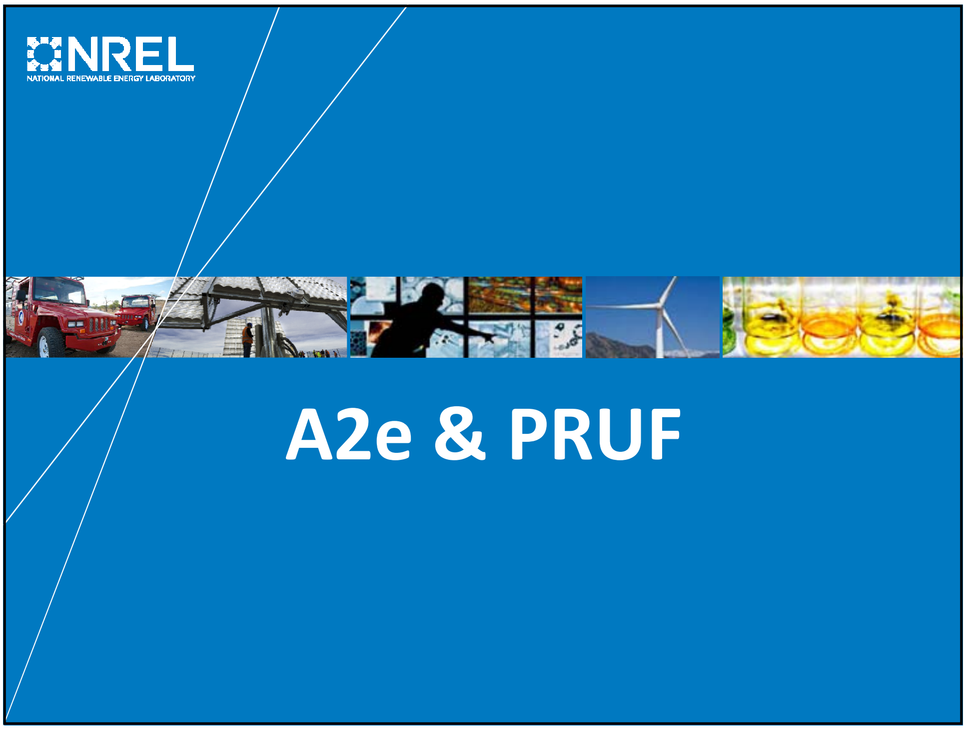
IEC 61400-15 Early results

- Universal Site Suitability Input Form
- Standard Loss Framework
- Standard Uncertainty Framework



NATIONAL RENEWABLE ENERGY LABORATORY 14


IEC 61400-15 Early results-uncertainty framework
Task 31 and UQ TEM input desired!
Model inputs
Model stress
Model Appropriateness
Spatial Variation
Wind Speed
Wind Direction
Further Meteorological Measurements
Vertical Extrapolation
Availability
Wake Effects
Electrical losses
Turbine Performance
Environmental
Curtailment/Operational Strategies
Plant Performance
Other
IEC 61400-15 AEP Uncertainty Frameowrk
Site Measurement
Wind Speed Measurement
Wind Direction Measurement
Further Meteorological Measurements
Secondary Measurement Uncertainties
Historic Wind Resource
Long-term Period
Reference Site
Correlation
Wind Speed Distribution
Wind Rose
On-site Data Synthesis
Measured Data Representativeness
Project Lifetime Variability
Project Lifetime Resource
Climate Change
Other variability discussions
Need to develop uncertainty model(s): correlation and combination
NATIONAL RENEWABLE ENERGY LABORATORY
15


NREL
NATIONAL RENEWABLE ENERGY LABORATORY
A2e & PRUF

A2e

ATMOSPHERE
TO ELECTRONS
U.S. DEPARTMENT OF ENERGY

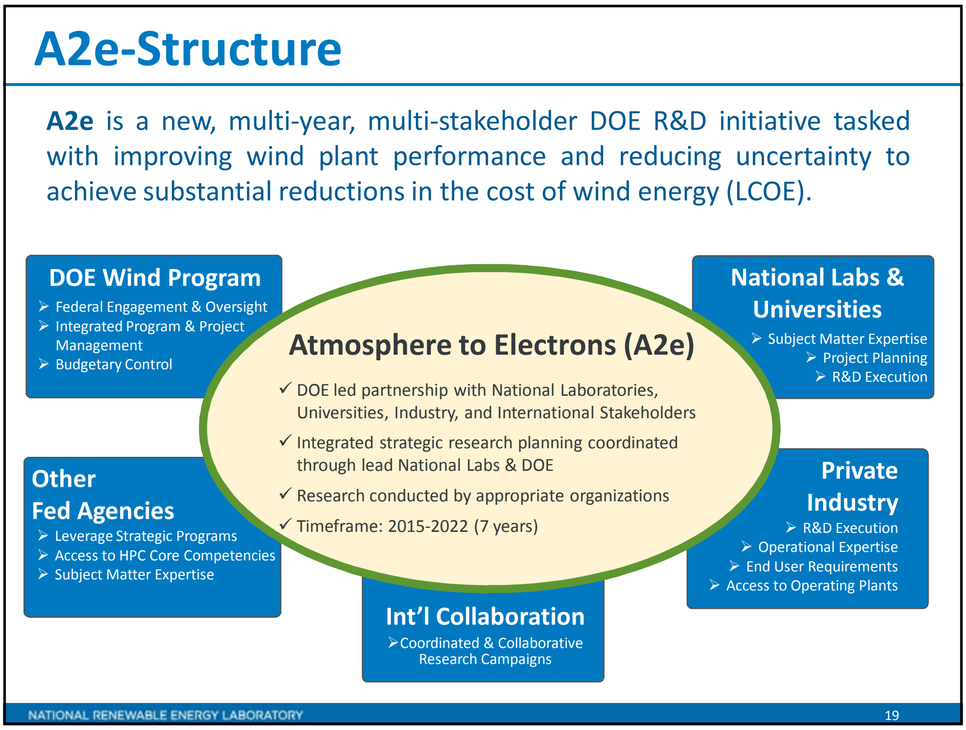
NATIONAL RENEWABLE ENERGY LABORATORY 17

What is A2e?

1 ***A Technology R&D Initiative*** to enable design and deployment of ***Next Generation Wind Power Plants***

2 ***A Novel DOE Management Construct*** leveraging a diverse expertise and stakeholder groups

NATIONAL RENEWABLE ENERGY LABORATORY 18


A2e-Structure
A2e is a new, multi-year, multi-stakeholder DOE R&D initiative tasked with improving wind plant performance and reducing uncertainty to achieve substantial reductions in the cost of wind energy (LCOE).
DOE Wind Program
Federal Engagement & Oversight
Integrated Program & Project Management
Budgetary Control
National Labs & Universities
Subject Matter Expertise
Project Planning
R&D Execution
Atmosphere to Electrons (A2e)
DOE led partnership with National Laboratories, Universities, Industry, and International Stakeholders
Integrated strategic research planning coordinated through lead National Labs & DOE
Research conducted by appropriate organizations
Timeframe: 2015-2022 (7 years)
Other Fed Agencies
Leverage Strategic Programs
Access to HPC Core Competencies
Subject Matter Expertise
Private Industry
R&D Execution
Operational Expertise
End User Requirements
Access to Operating Plants
Int'l Collaboration
Coordinated & Collaborative Research Campaigns
NATIONAL RENEWABLE ENERGY LABORATORY
19


Initial, high-priority strategic initiatives
Strategic Planning Areas
1. Performance Risk, Uncertainty, and Finance (PRUF)
– Jason Fields(NREL)
2. High Fidelity Modeling
– Dr. David Womble (SNL), Dr. Steve Hammond (NREL)
3. Experimental Measurement Campaigns
– Dr. Scott Schreck (NREL), Dr. Jon White (SNL)
– Dr. Jim Wilczak (NOAA)
4. Data Archive and Portal
– Chitra Sivaraman (PNNL)
5. Integrated Wind Plant Control
– Dr. Kathryn Johnson (Colorado School of Mines/NREL)
– Dr. Dave Wilson (SNL)
6. Wind Plant Reliability
– Dr. Carsten Westergaard (SNL Contractor)
– Dr. Jonathan Keller (NREL)
7. Aeroacoustics and Propagation
– Dr. Pat Moriarty (NREL)
8. Integrated Wind Plant Design and Analysis
– Sandy Butterfield (Boulder Wind Consulting)
Jointly planned within a comprehensive Verification and Validation Planning Group
Technology programs build off of V&V, HFM, and Experiment
NATIONAL RENEWABLE ENERGY LABORATORY
20

Performance risk, uncertainty, and finance (PRUF)

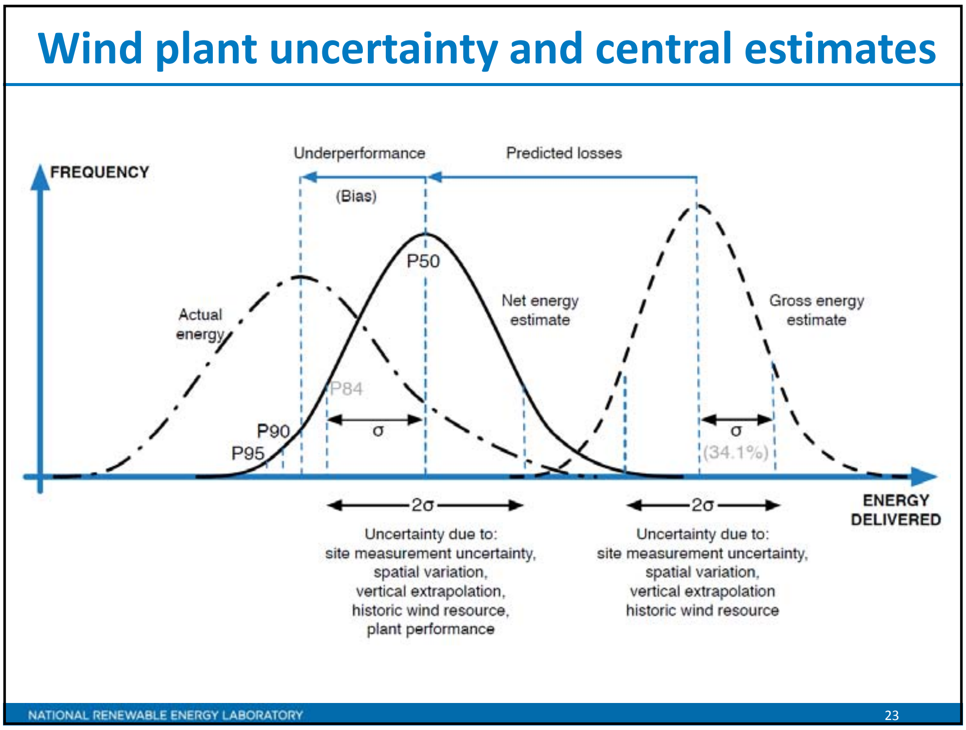
The primary objective of PRUF *is to increase the value of wind energy by lowering the risk and uncertainty associated with developing, investing in, owning, and operating wind power plants.*

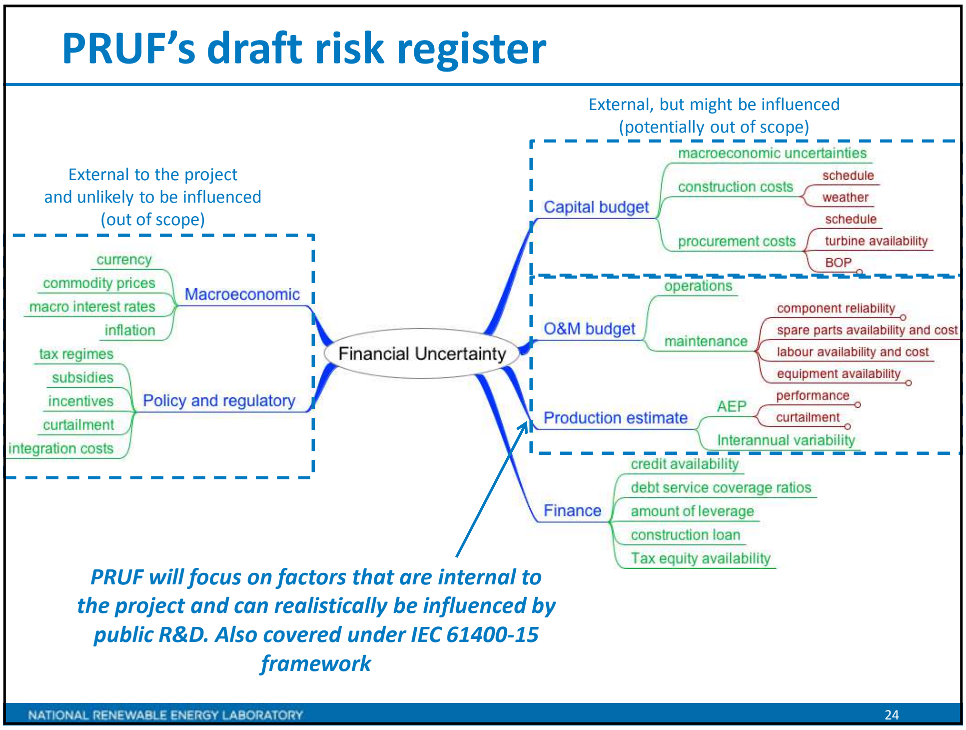
NATIONAL RENEWABLE ENERGY LABORATORY 21

PRUF Outcomes

1. Identify and quantify wind plant risks and uncertainties
2. Identify and communicate financial implications of wind plant risks and uncertainties
3. Mitigate high priority opportunities with targeted research and outreach

NATIONAL RENEWABLE ENERGY LABORATORY 22


Wind plant uncertainty and central estimates
FREQUENCY
Underperformance
(Bias)
Predicted losses
P50
Actual energy
Net energy estimate
Gross energy estimate
P84
P90
P95
σ
σ
(34.1%)
2σ
2σ
ENERGY DELIVERED
Uncertainty due to: site measurement uncertainty, spatial variation, vertical extrapolation, historic wind resource, plant performance
Uncertainty due to: site measurement uncertainty, spatial variation, vertical extrapolation historic wind resource
NATIONAL RENEWABLE ENERGY LABORATORY
23


PRUF's draft risk register
External, but might be influenced (potentially out of scope)
External to the project and unlikely to be influenced (out of scope)
Financial Uncertainty
Macroeconomic
currency
commodity prices
macro interest rates
inflation
Policy and regulatory
tax regimes
subsidies
incentives
curtailment
integration costs
Capital budget
macroeconomic uncertainties
construction costs
schedule
weather
procurement costs
schedule
turbine availability
BOP
O&M budget
operations
maintenance
component reliability
spare parts availability and cost
labour availability and cost
equipment availability
Production estimate
AEP
performance
curtailment
Interannual variability
Finance
credit availability
debt service coverage ratios
amount of leverage
construction loan
Tax equity availability
PRUF will focus on factors that are internal to the project and can realistically be influenced by public R&D. Also covered under IEC 61400-15 framework
NATIONAL RENEWABLE ENERGY LABORATORY
24

Why does uncertainty matter?

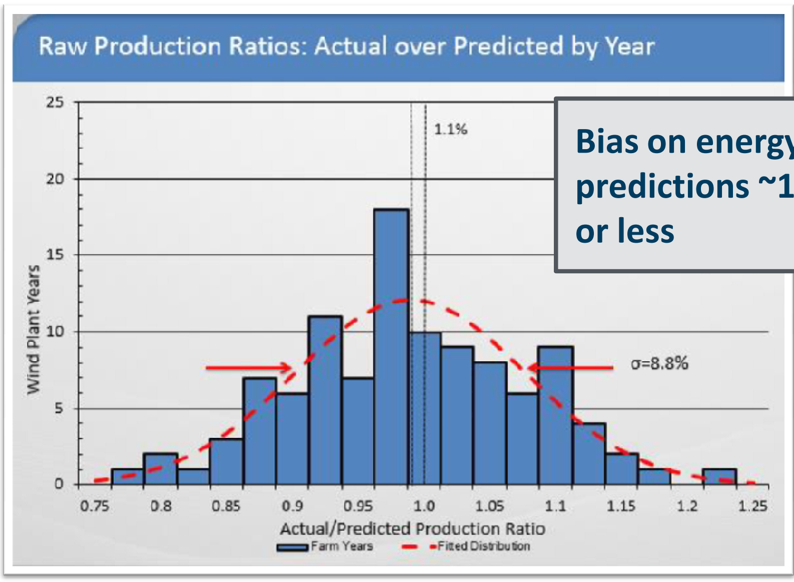
- Industry is concerned about long term impacts of data silos and inaccurate WRA methods
- Broad disagreement on accuracy of energy prediction methods
- No independent validations available
- Inadequate risk assessment and valuation

Recent Example #1
- 200MW project
- Energy estimate uncertainty ~7%
- Two consultant P50 estimates were 3% different
- Difference in project NPV: **$17M**

Recent Example #2
- 200MW project
- Two consultant P50 estimates were identical
- P95 estimates ~1% different
- Difference in project NPV: **$1.5M**

NATIONAL RENEWABLE ENERGY LABORATORY 25

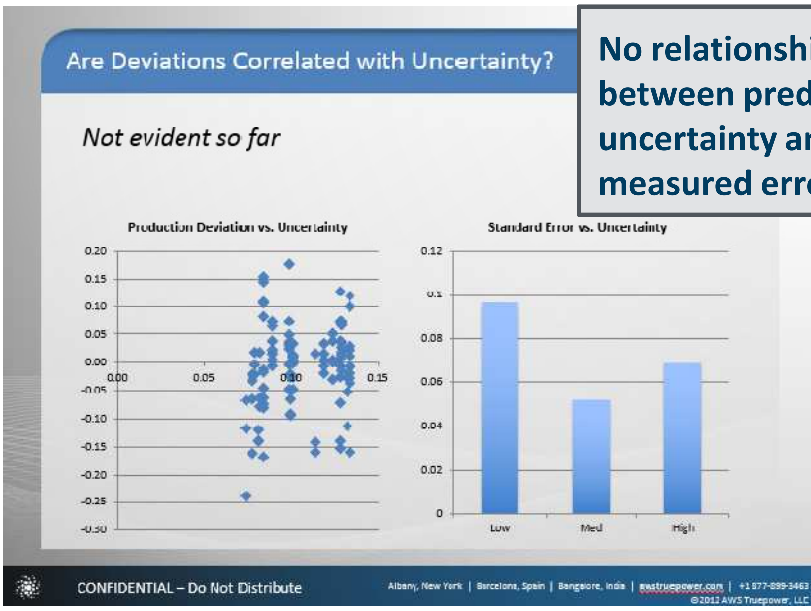
General consensus is that P50 bias is fine



Bias on energy predictions ~1% or less

NATIONAL RENEWABLE ENERGY LABORATORY 26

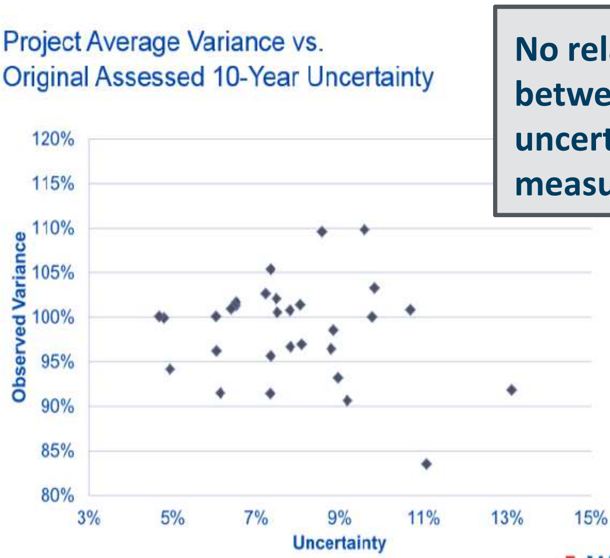
Uncertainty is a different story



No relationship between predicted uncertainty and measured error

NATIONAL RENEWABLE ENERGY LABORATORY 27

Uncertainty is a different story



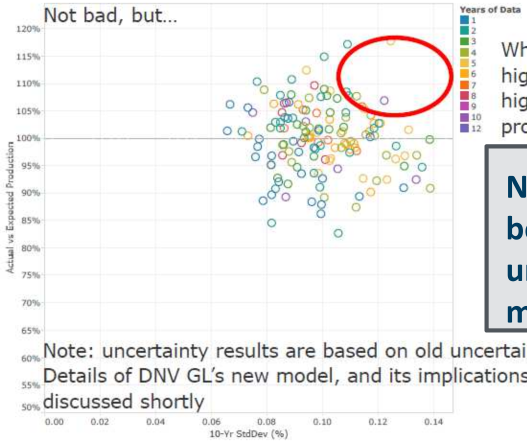
No relationship between predicted uncertainty and measured error

WSP

NATIONAL RENEWABLE ENERGY LABORATORY 28

Uncertainty is a different story

Results look good overall, but are we getting it right for the right reason?



Where are the high-uncertainty high-performance projects?

No relationship between predicted uncertainty and measured error

5 DNV GL © 2014 03 December 2014 DNV·GL

NATIONAL RENEWABLE ENERGY LABORATORY 29

Implications

1. ***North American uncertainty estimates do not correlate with measured performance variation***

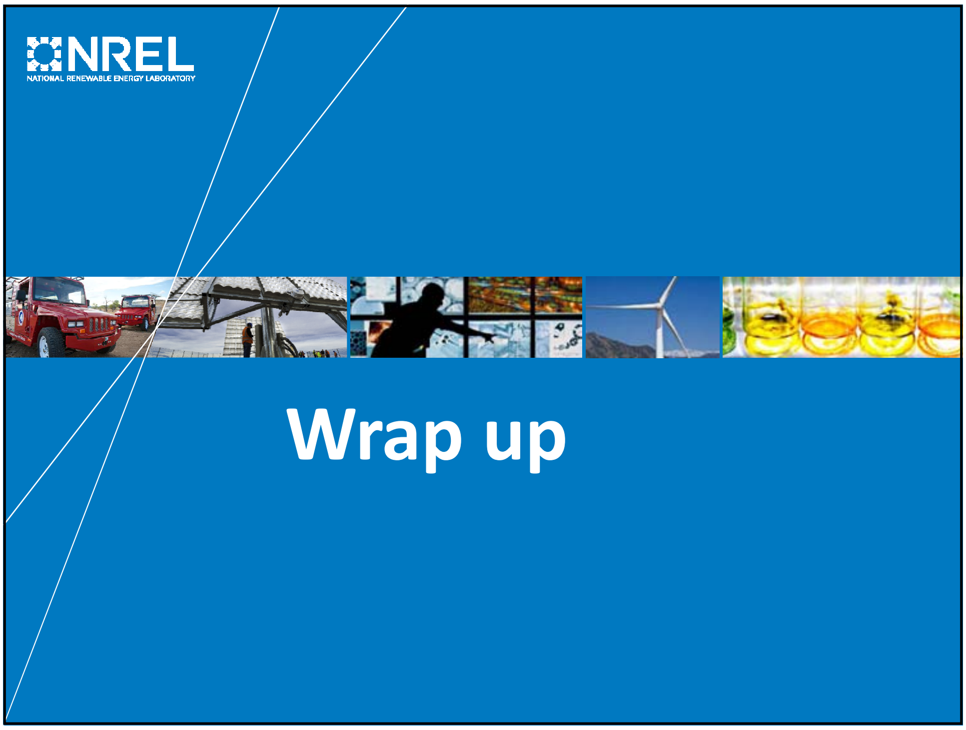
2. ***Quantifying project risk based upon technical uncertainty estimation is not a valid approach based upon those results***

NATIONAL RENEWABLE ENERGY LABORATORY 30

What is PRUF going to do about it?

1. ***Develop common reporting formats and definitions (IEC 61400-15)***
2. ***Create a modular uncertainty & risk characterization framework***
    1. ***Investigate correlated uncertainty interactions***
    2. ***Understand how uncertainties permeate through to investors***
3. ***Perform a detailed validation of pre-construction energy estimate practices (100+ projects)***
4. ***Create a performance uncertainty working group***
    1. ***Platform for detailed R&D on uncertainty practices***
    2. ***Safe space for interaction/collaboration between investment community and technical energy assessors***

NATIONAL RENEWABLE ENERGY LABORATORY 31



Key Questions for IEA Task 31 and TEM participants

1. ***What is the median and range of wind plant wake losses and wind plant wake loss uncertainty? (by project size, turbine layout, atmospheric conditions, etc .)***
2. ***What is the potential to reduce the wake losses? How?***
3. ***What is the potential to refine the wake loss uncertainty? How?***
4. ***Same question for other losses and uncertainties. Specifically wind speed and wind speed distribution uncertainty from flow model. And all parameters that feed into wind speed e.g. temperature stratification***

NATIONAL RENEWABLE ENERGY LABORATORY 33

Conclusions

- **IEA TEM on Uncertainty & Finance coming up in the fall**
- **A2e & PRUF have major activities ongoing to develop uncertainty & risk modeling framework**
  - Uncertainties and how they combine
  - Uncertainties and how they map to financial implications and decisions for investors
  - Survey of experts forthcoming
  - Performance uncertainty working group – cross of technical and finance TEMs
- **IEC 61400-15 "the WRA standard"**
  - Site Suitability input form gaining traction
  - First drafts of loss and uncertainty categories are complete
  - Next steps to tackle actual AEP uncertainty model

NATIONAL RENEWABLE ENERGY LABORATORY 34

Acknowledgements

- National Renewable Energy Lab (NREL)
  - Andrew Clifton, Aaron Smith, Paul Veers, Maureen Hand,
- US Department of Energy (DOE)
  - John Meissner
- International Colleagues
  - International Electro-technical committee (IEC) 61400-15 committee

NATIONAL RENEWABLE ENERGY LABORATORY 35

Contact Information

Jason Fields
NREL-National Wind Technology Center
Jason.fields@nrel.gov
303-384-7150
http://www.nrel.gov/wind/

NATIONAL RENEWABLE ENERGY LABORATORY 36