Estimation of Wind Turbine Power Curves

A simple way to include turbulence

Emil Hedevang

Siemens Wind Power
Borupvej 16, 7330 Brande, Denmark
emil.soerensen@siemens.com

Aarhus University
Thiele Centre for Applied Mathematics in Natural Science
Department of Mathematical Sciences
Ny Munkegade 118, 8000 Aarhus C, Denmark
emil@imf.au.dk

May 2011

SIEMENS

Scope and scale

One turbine is standing in free wind, not in wake of another wind turbine. The meteorology mast is placed somewhere upstream, approximately 3 rotor diameters away.

Problem to solve

How much power does the wind turbine produce at a given mean wind speed?

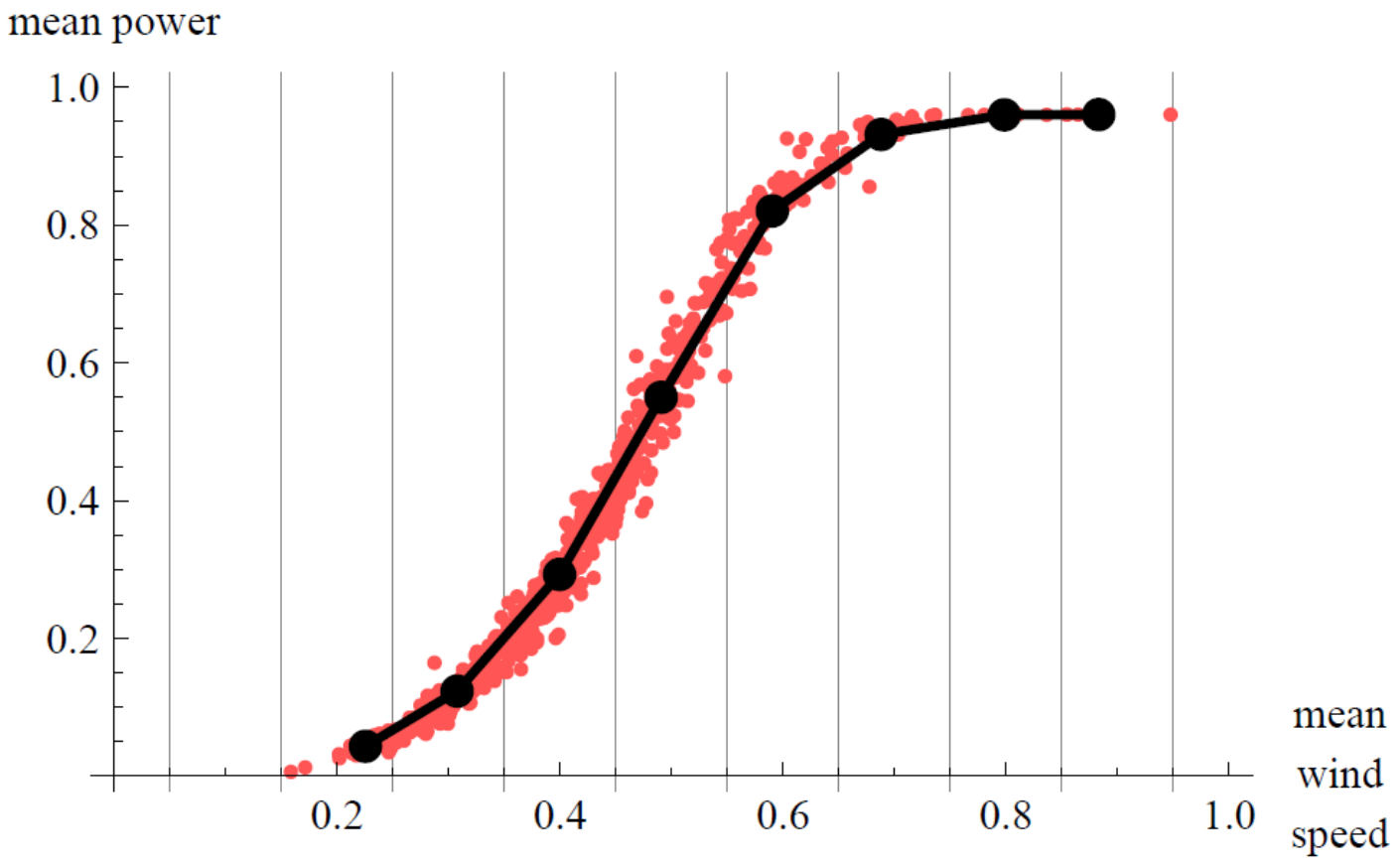
Input data to solve the problem

Ten minute statistics consisting of

- mean wind speed and mean power
- standard deviation of wind speed and power
- temperature, pressure, etc.

The IEC power curve

Bin the data and take means of means. This method does not take turbulence intensity into account.



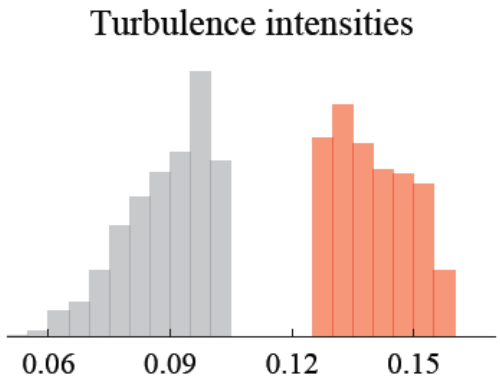
SIEMENS

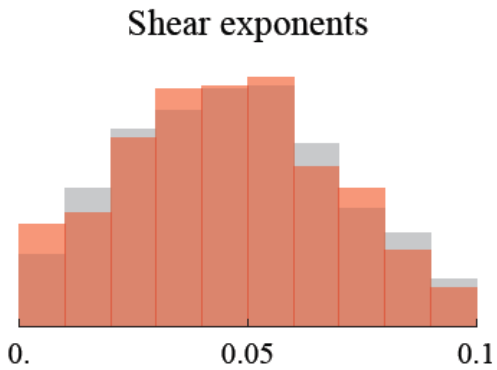
Does turbulence intensity matter at all?

From a larger data set two smaller are formed based on turbulence intensity and shear exponent.

- **Gray:** Low turbulence intensity
- **Red:** High turbulence intensity
- **Both:** Low shear exponent

The low shear makes it unnecessary to correct for vertical wind shear as otherwise described in [Wagner et al.].

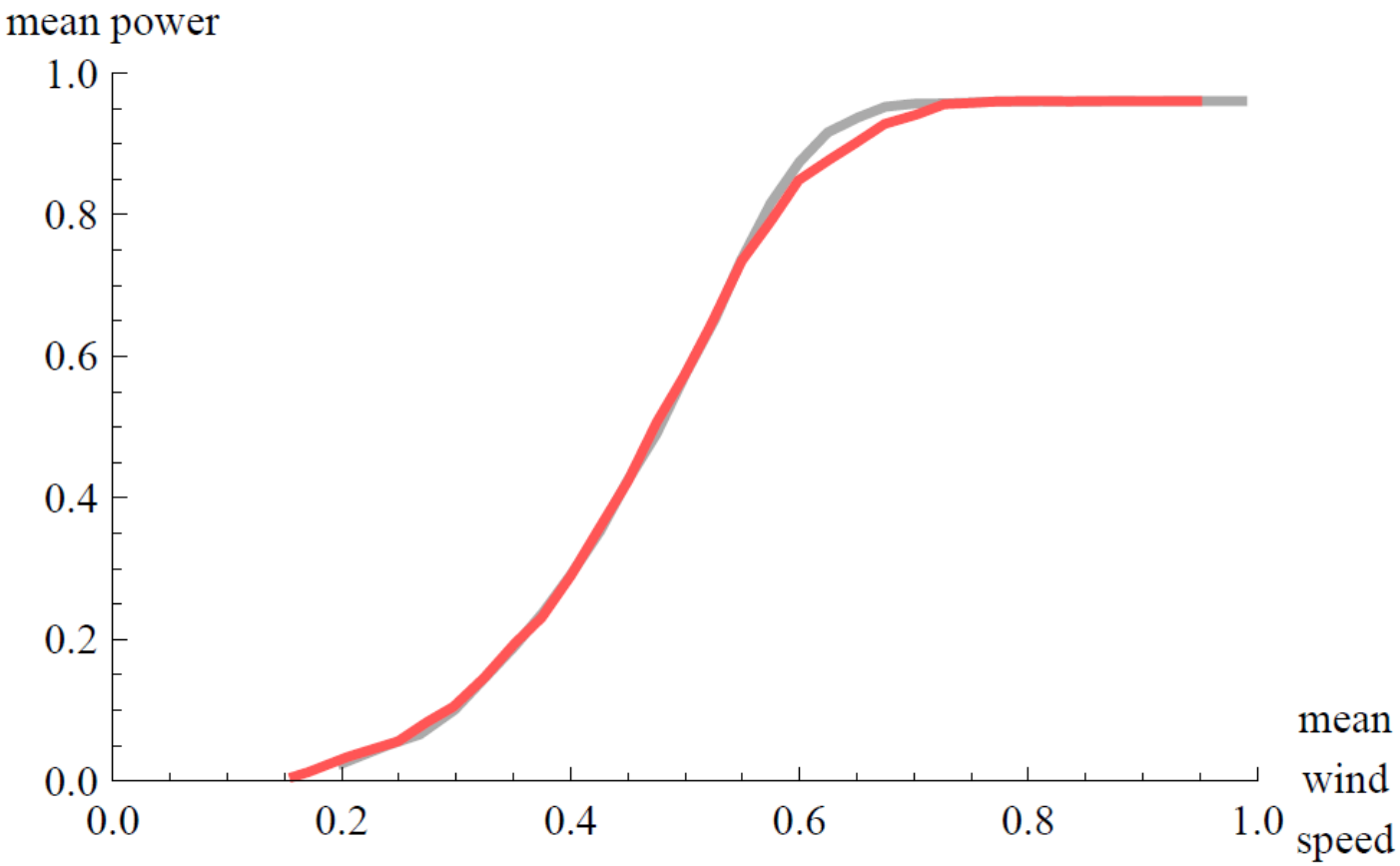




SIEMENS

Yes, turbulence intensity does matter!

These are the IEC power curves for the two data sets.

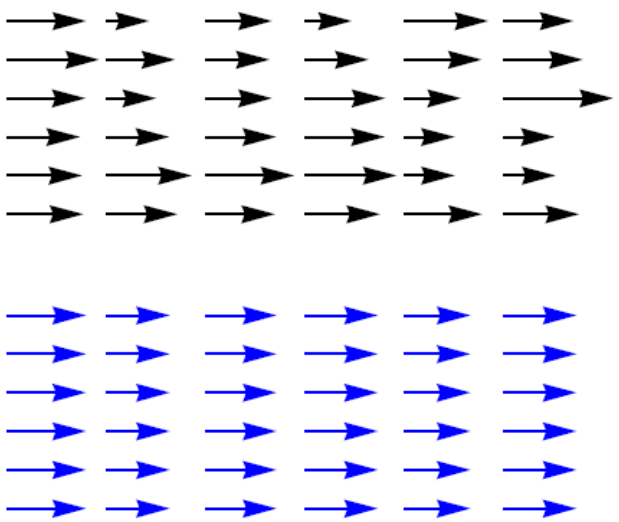


SIEMENS

Some simplifying assumptions

Equivalent wind speed

Assume that the real wind field which fluctuates in both space and time can be replaced by an equivalent wind field that fluctuates only in time (a time series) such that the power produced is the same.



Instantaneous response

Assume that the wind turbine adjusts instantaneously to changes in the wind.

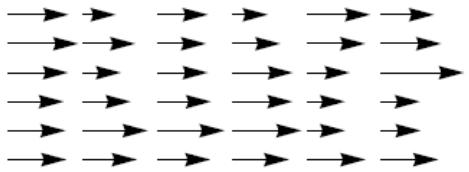
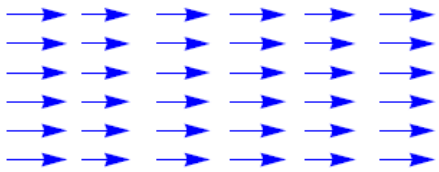
SIEMENS

What is the equivalent wind speed?

Suppose we can get from the point measurement at the meteorology mast to the equivalent wind speed by scaling the fluctuations. What should the scale factor be?

Example: Average the fluctuating longitudinal wind velocity component u_1 over the rotor disk and add the mean wind speed:

$$v(x) = \mu_u + \frac{1}{\text{rotor area}} \int_{\text{rotor}} u_1(x, y, z)\, dy\, dz$$

$\mu_u + u_1 =$  $v =$ 

Then with a rotor radius of 50 meters and an integral length of 150 meters we get $\sigma_v \approx 0.76\,\sigma_u$ under the additional assumption of isotropic von Kármán turbulence.

SIEMENS

Ready, set, estimate!

Instantaneous response and **equivalent wind** implies

$$\text{instantaneous power} = P_0(v(t))$$

$$\text{mean power} = \int_0^\infty P_0(u) f(u)\, du$$

- P_0 instantaneous power curve ("zero turbulence power curve")
- $v(t)$ equivalent wind speed at time t
- f the p.d.f. of the equivalent wind speeds

Renormalised power curve: $P_I(V) = \int_0^\infty P_0(u) f_{V,I}(u)\, du$

Ready, set, estimate P_0!

SIEMENS

Ready, set, estimate!

Input: n data points consisting of

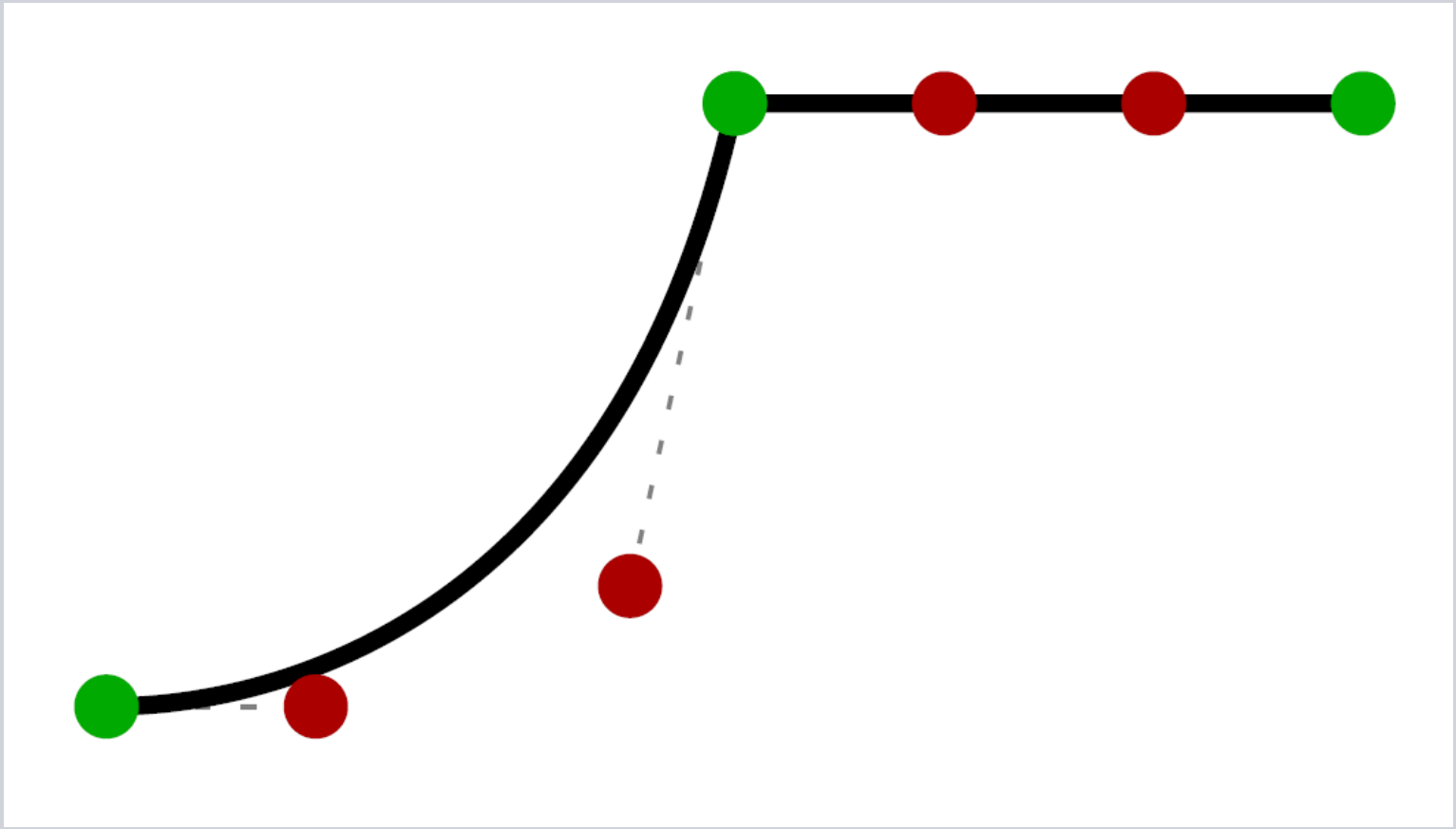
- μ_{P_i} mean power
- σ_{P_i} standard deviation of power
- f_i p.d.f. of equivalent wind speeds
  - mean wind speed and standard deviation
  - equivalent scale factor $k \leq 1$ such that $\sigma_v = k \cdot \sigma_u$
  - compare with [Albers]

Output: $$\hat{P}_0 = \arg\min_{P_0} \frac{1}{2} \sum_{i=1}^{n} \left(\mu_{P_i} - \int_0^\infty P_0(u) f_i(u)\, du \right)^2$$

Note that σ_{P_i} is not used directly here, but instead used indirectly to guess f_i from the meteorology mast's wind data.

SIEMENS

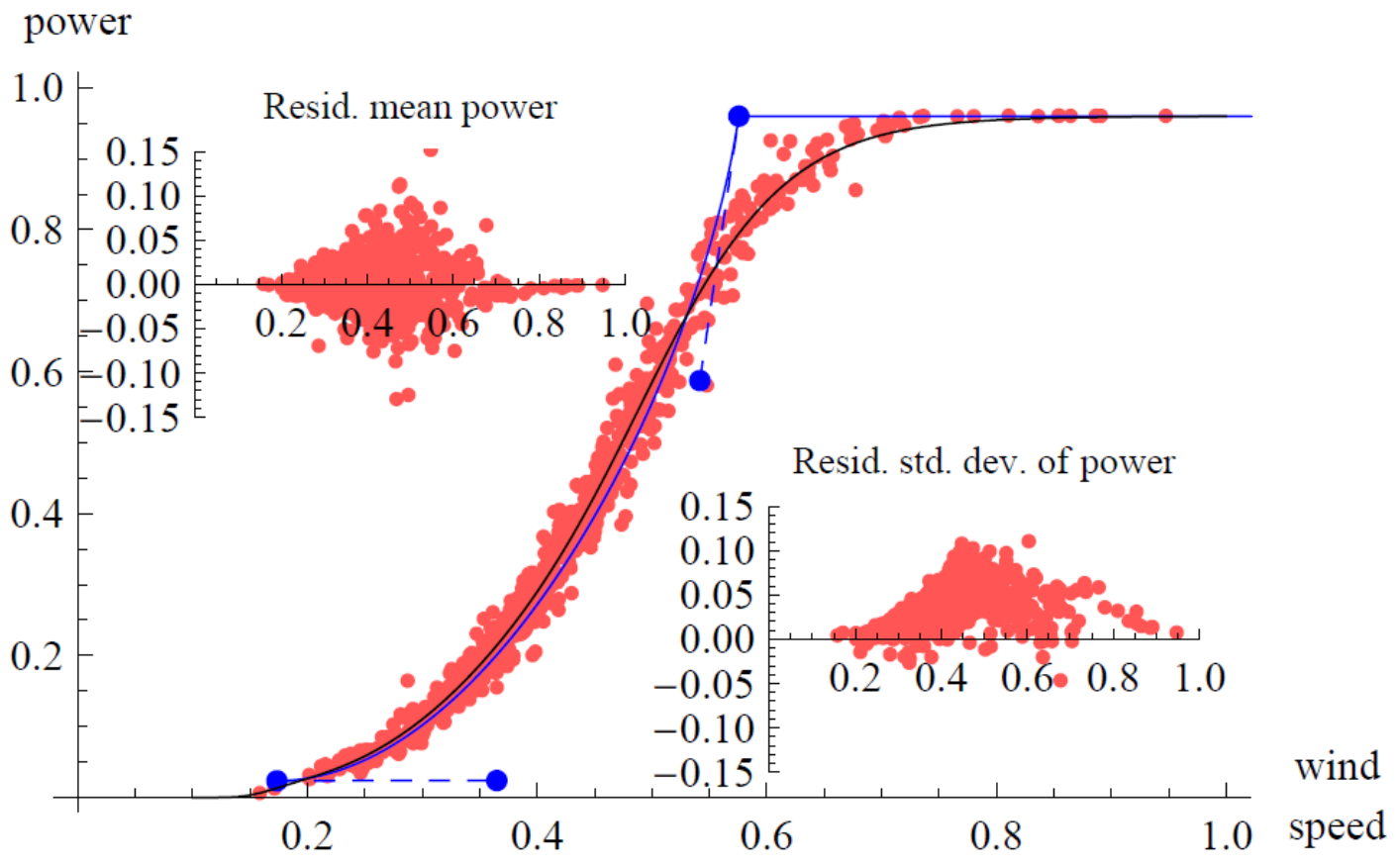
Parametrizing the instantaneous power curves



SIEMENS

Results: High turbulence intensity (14%), k = 1.00

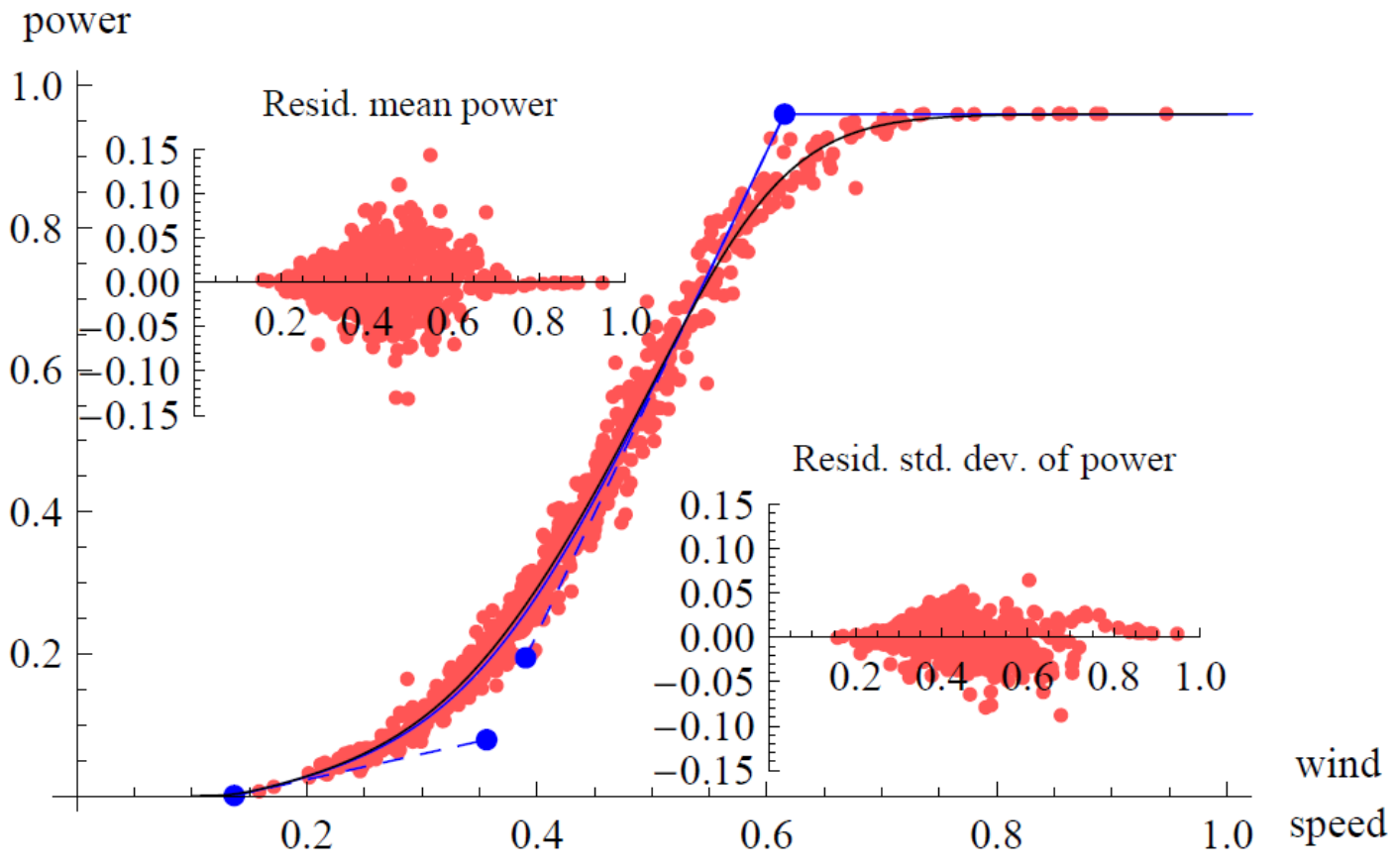
When $k = 1$, residual standard deviation of power is over-predicted, and mean power is under-predicted at high wind speeds.



SIEMENS

Results: High turbulence intensity (14%), k = 0.75

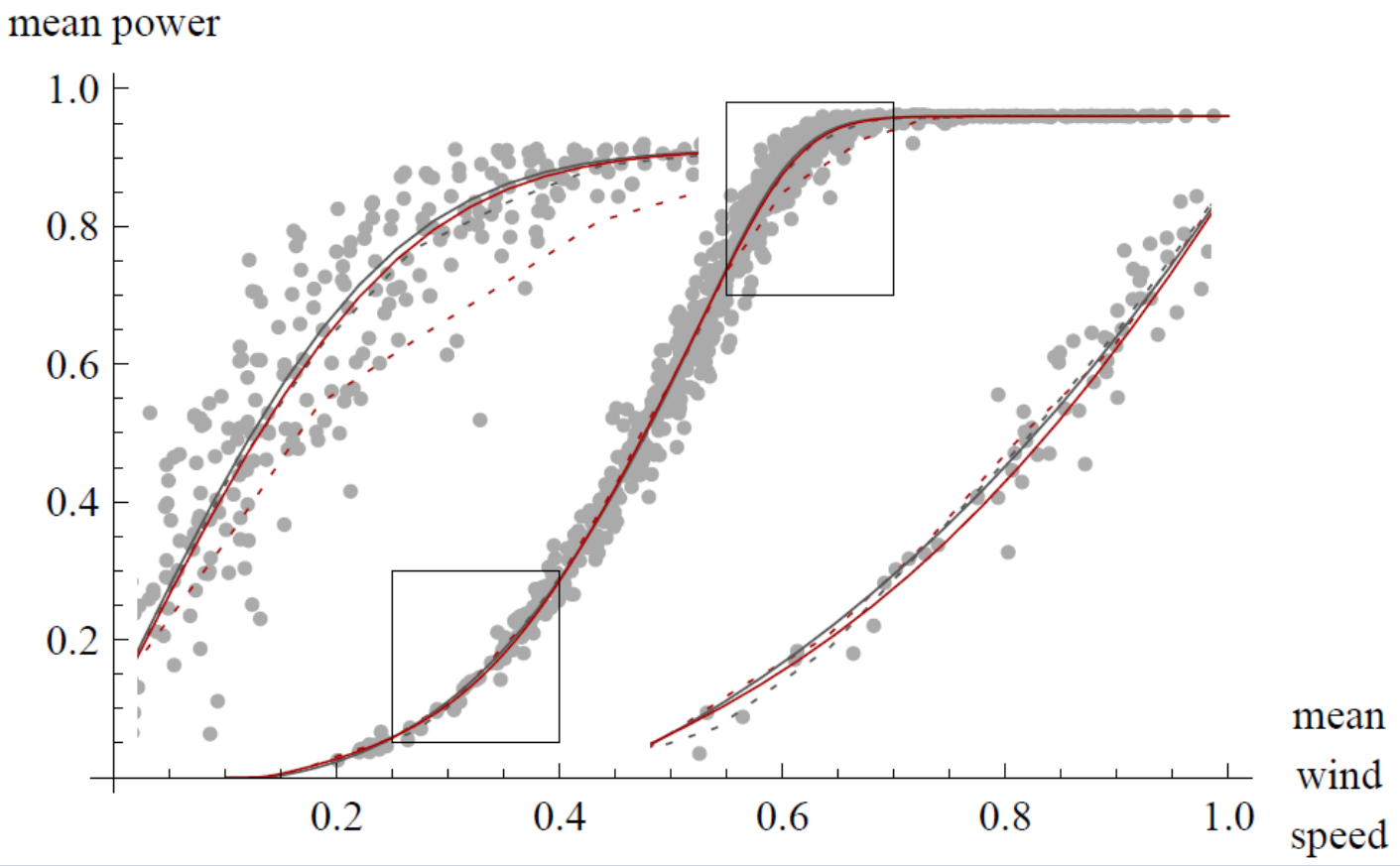
When $k = 0.75$, the problems disappear. Some scatter in the residuals remains, however.



SIEMENS

Renormalize to low turbulence intensity (8.9%)

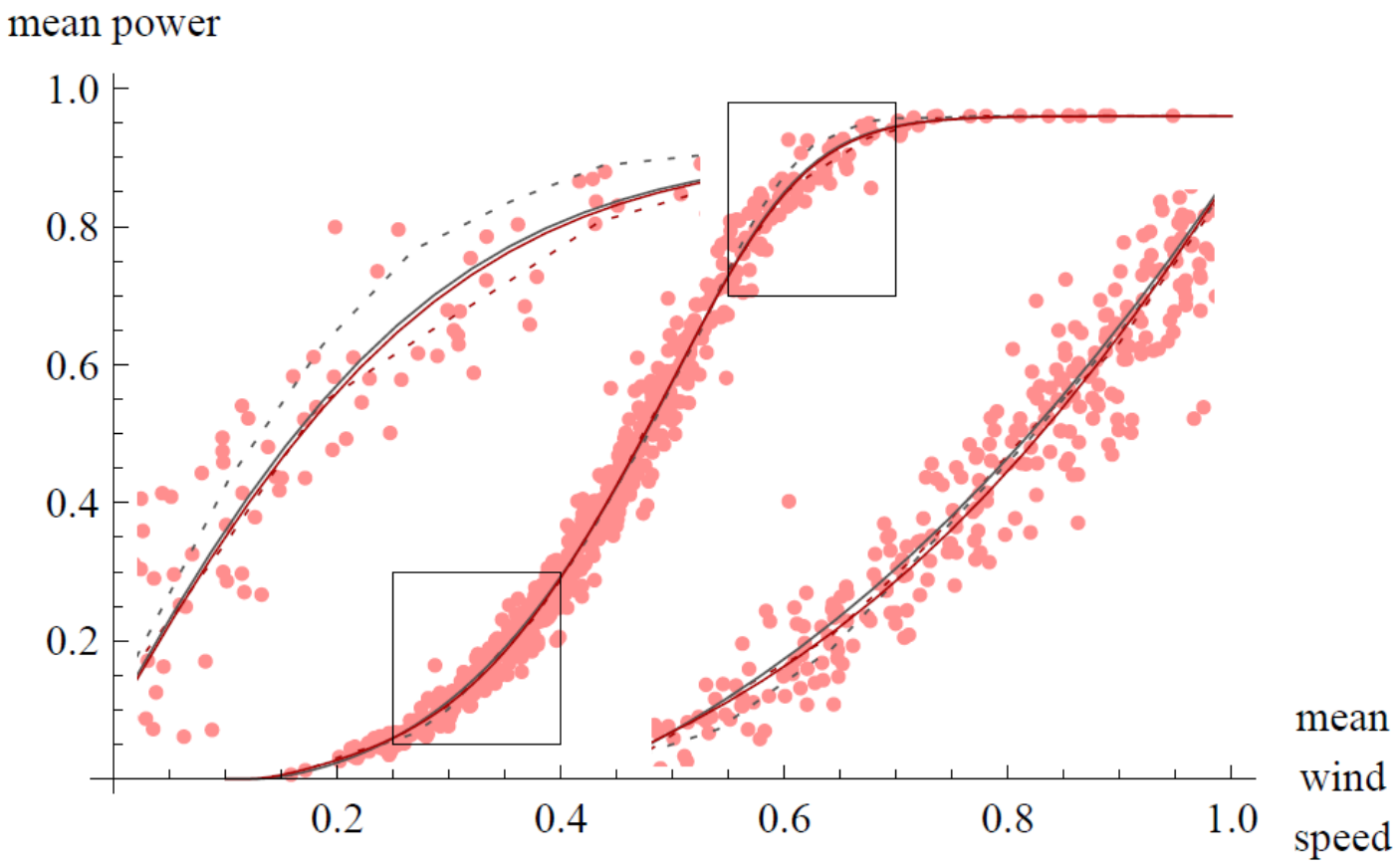
Gray curve is slightly above red curve around 0.3 and 0.6, probably due to differences in mean wind speed distributions. This can be addressed by assigning weights to data points.



SIEMENS

Renormalize to high turbulence intensity (14%)

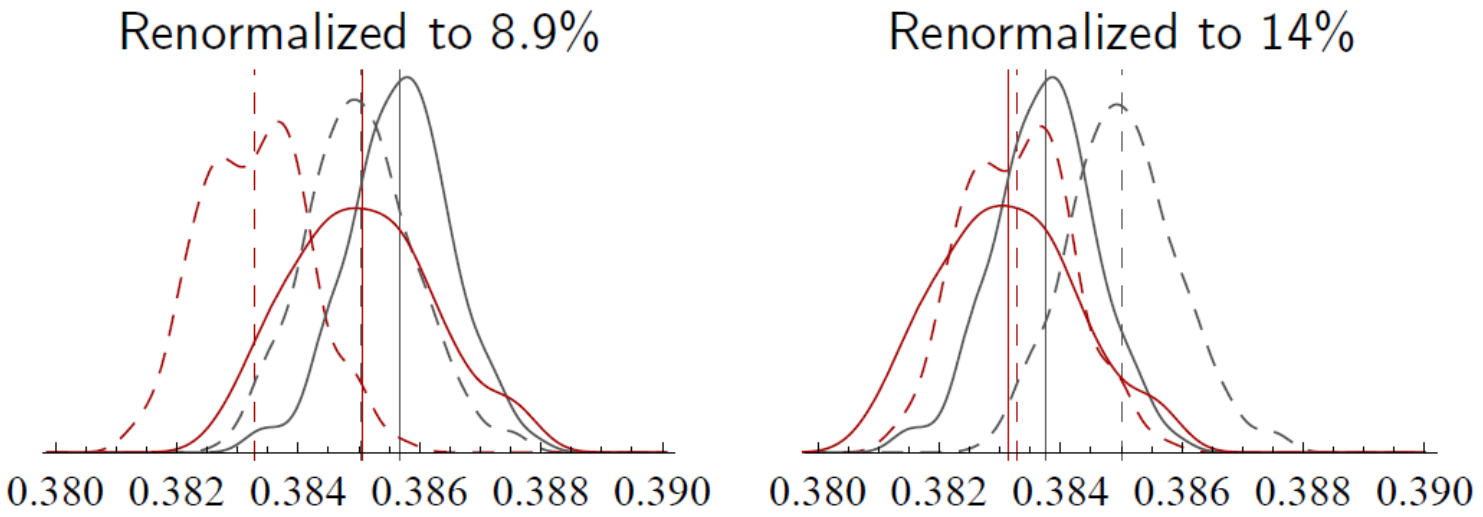
The difference is slightly less pronounced at higher turbulence intensities.



SIEMENS

Bootstrapping AEP for mean wind speed = 8 m/s

Change in AEP for the renormalized power curves is approximately a third of the change in AEP for the IEC power curves. This can without doubt be improved even further.



SIEMENS

Conclusion

Assumptions

- Equivalent wind speeds (Gaussian distribution)
- Instantaneous response
- Bézier representation

Implications

- Decrease dependence of the power curve and the AEP of the atmospheric conditions through renormalization of power curves.
- Decrease uncertainty in rotor comparisons.
- Works well with just ten minute statistics.
- Can also work with less data.
- Nested optimization problem, the outer is non-linear, the inner is simple.

SIEMENS

Future work

- The modelling and algorithmic framework supports non-parametric distributions of equivalent wind speeds with no added computational overhead.
- Extend and generalize the model loosen the assumptions. (LIDAR, non-instantaneous turbine response, non-parametric power curve). Compare with [Anahua et al.].
- Provide a robust standard that everyone can use.
- Put weights on data points to address the effect of different mean wind speed distribution of different data sets.
- Estimate turbulence intensity from power statistics as a part of wind farm wake analysis.

SIEMENS

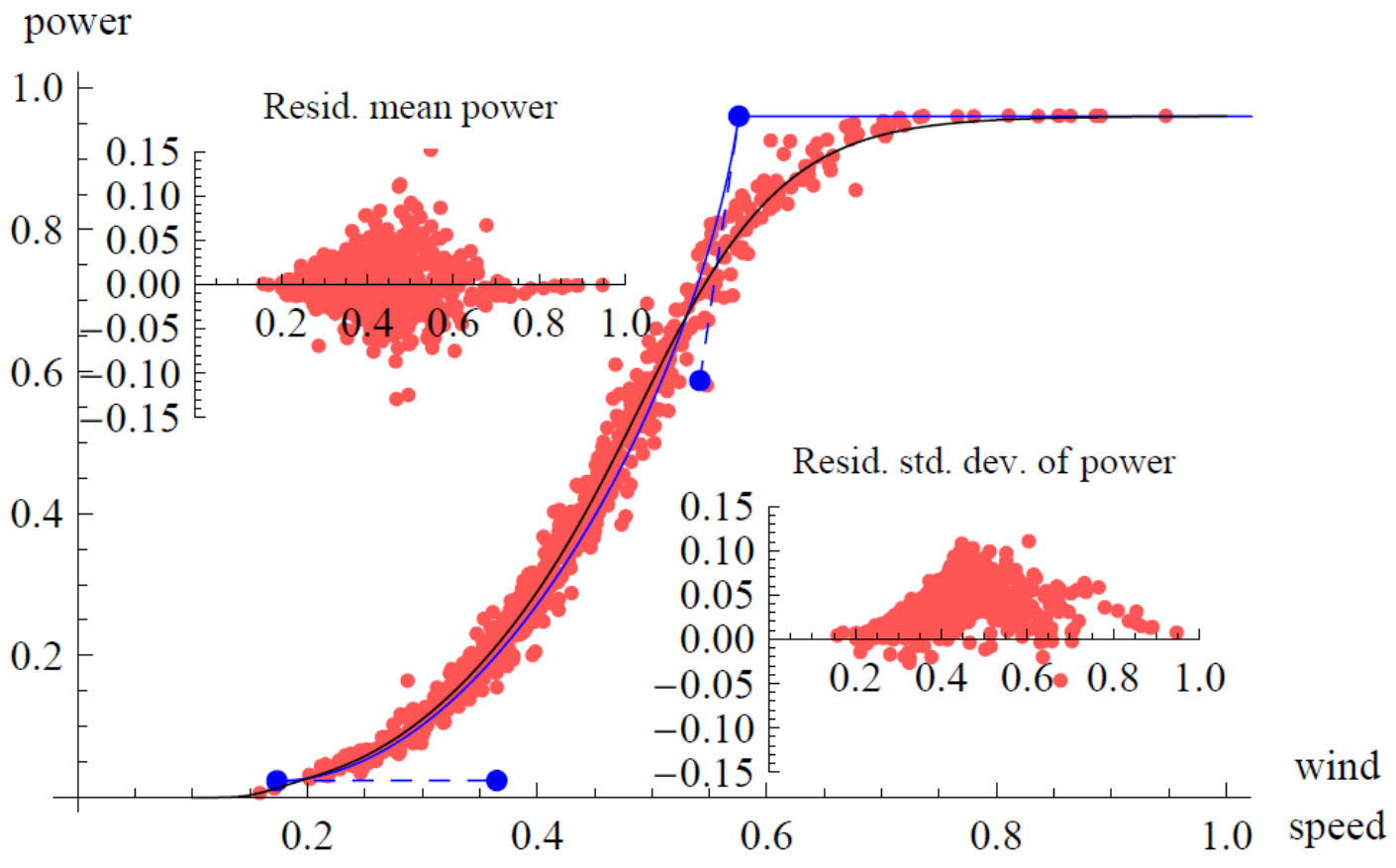
References

- Wagner et al. *The influence of the wind speed profile on wind turbine performance measurements*, Wind Energy, 2009.
- Albers. *Turbulence Normalisation of Wind Turbine Power Curve Measurements*, Deutsche WindGuard Consulting GmbH, 2009.
- Anahua et al. *Markovian Power Curves for Wind Turbines*, Wind Energy, 2008.

SIEMENS

Results: High turbulence intensity (14%), k = 1.00

When $k = 1$, residual standard deviation of power is over-predicted, and mean power is under-predicted at high wind speeds.



GL Garrad Hassan

Wind Plant Layout Optimization using an Integrated Energy Production and Loading Model

Graeme McCann – 24th May 2011

Presentation Overview

Wind Plant Layout Optimization

1. The current industry approach
   - the weaknesses
2. An alternative approach
   - the potential benefits

Wind plant layout optimization – THE CURRENT APPROACH

Turbine Manufacturer designs to:

- Maximize turbine performance
- Minimize turbine loading
- Minimize unit cost

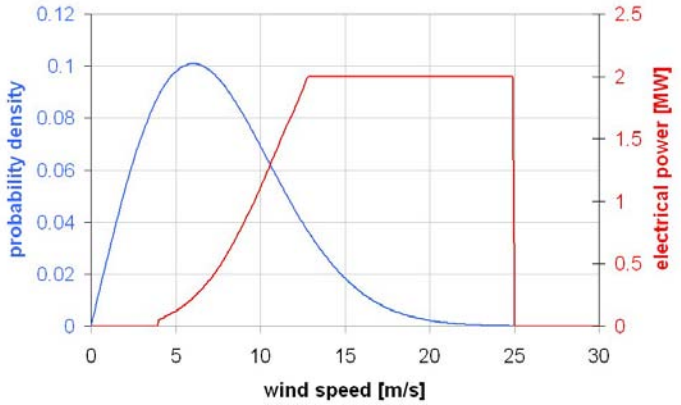
Farm Developer designs to:

- Maximize plant energy production
- Ensure turbine site suitability
- Minimize balance of plant cost
- Satisfy constraints (eg. noise)

Wind plant layout optimization – THE CURRENT APPROACH

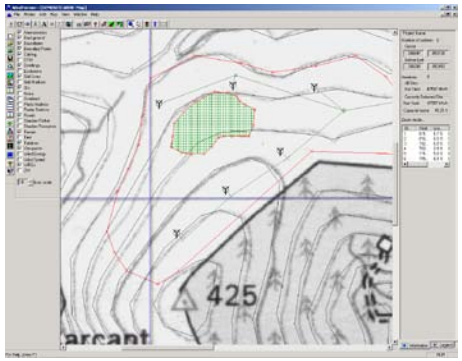
Turbine Manufacturer:

1. provides dynamic power curve data
2. defines turbine type class (eg. class IEC II-A)



Farm Designer:

3. quantifies design constraints (eg. site area, access etc)
4. computes layout for optimum energy production (AEP-opt)
4. compares site conditions with turbine type class
5. based on AEP-opt, calculates cost of energy



Turbine Layout Design Goals:

1. MAXIMUM ENERGY PRODUCTION

2. TURBINE SITE SUITABILITY

Wind plant layout optimization – THE CURRENT APPROACH

WEAKNESSES

1. Turbine **SITE SUITABILITY** based on external conditions, not loads

2. Cannot optimize the **COST OF ENERGY** with this approach

$$COE_{OPT} \neq \frac{ICC \times FCR + O\,\&\,M}{AEP_{OPT}}$$

Wind plant layout optimization – AN ALTERNATIVE APPROACH

A new approach to wind farm design

1. Rigorous approach to turbine **SITE SUITABILITY**

2. Optimization of the **COST OF ENERGY**

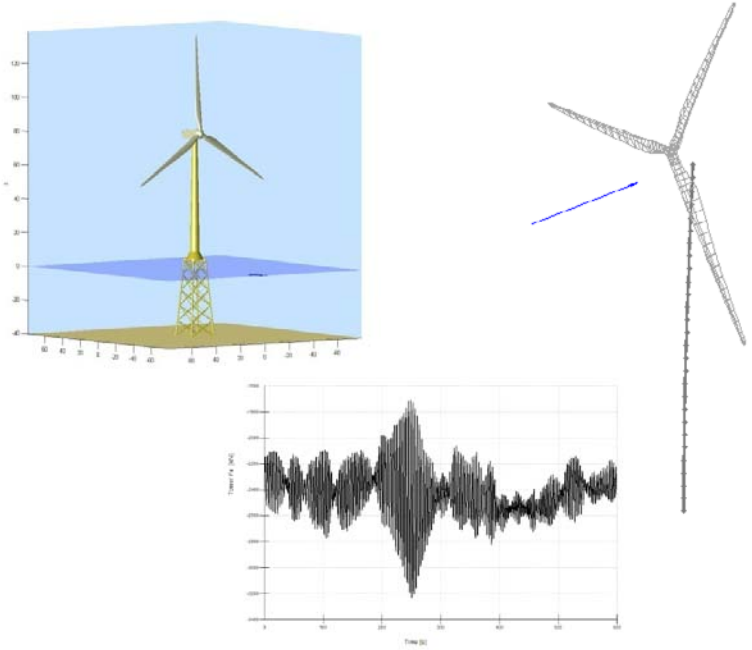
using an integrated energy production and load model

Wind plant layout optimization – AN ALTERNATIVE APPROACH

Integrated energy production and load model?

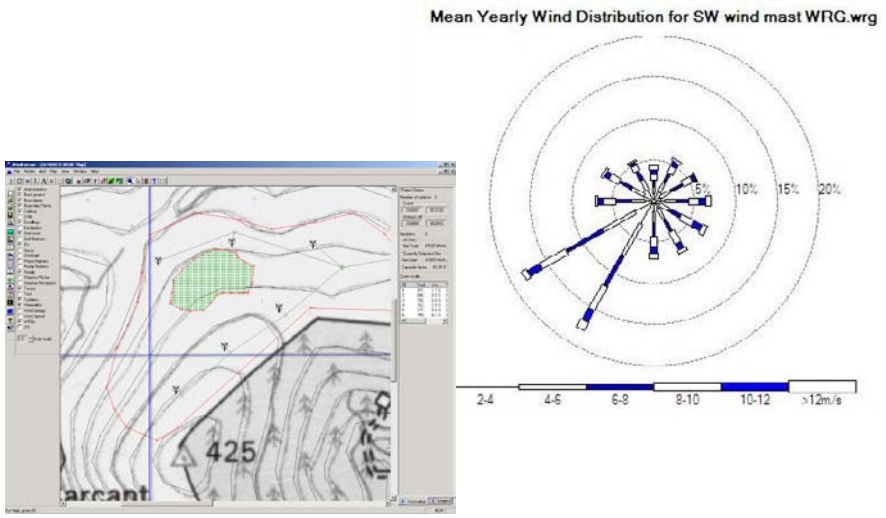
Wind Turbine design tools

- Aero elastic modelling
- Load calculation and dynamic response



Wind Plant design tools

- Wind flow modelling
- Wake modelling
- Plant energy production

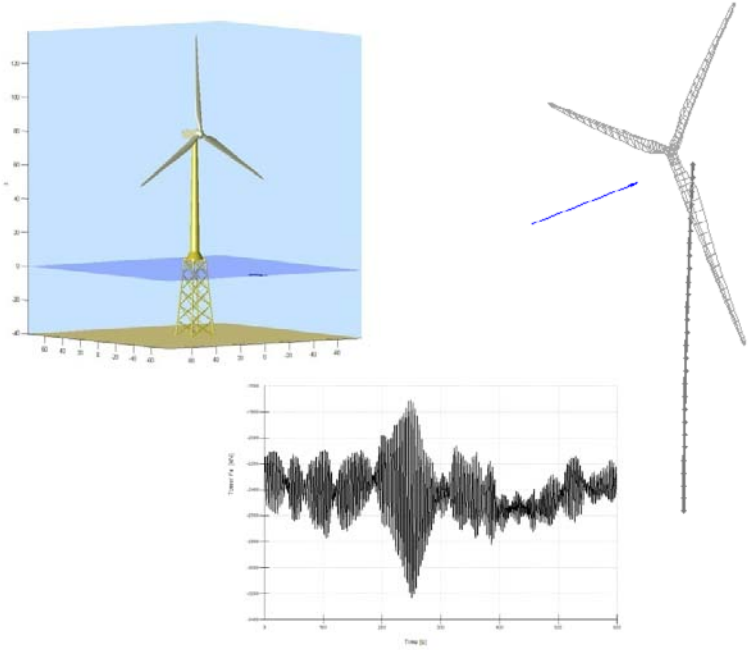


Wind plant layout optimization – AN ALTERNATIVE APPROACH

Integrated energy production and load model?

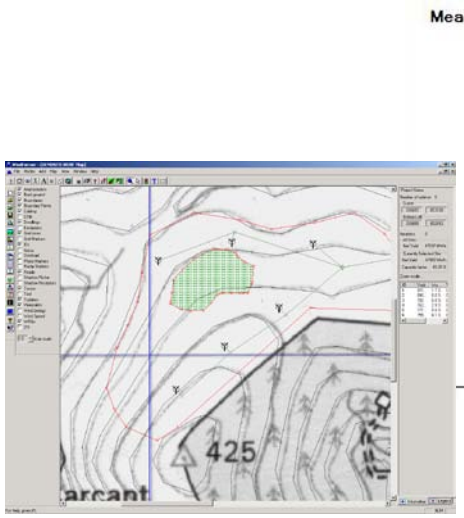
Wind Turbine design tools

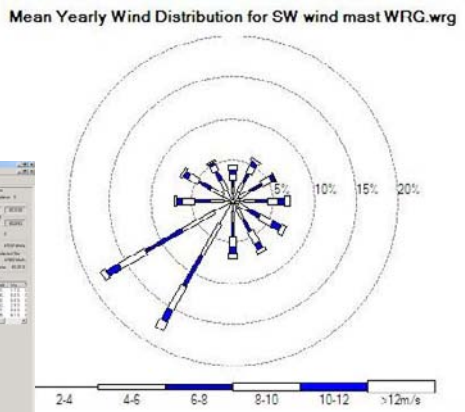
- Aero elastic modelling
- Load calculation and dynamic response



Wind Plant design tools

- Wind flow modelling
- Wake modelling
- Plant energy production





Wind plant layout optimization – AN ALTERNATIVE APPROACH

Integrated energy production and load model?

Wind Turbine design tools

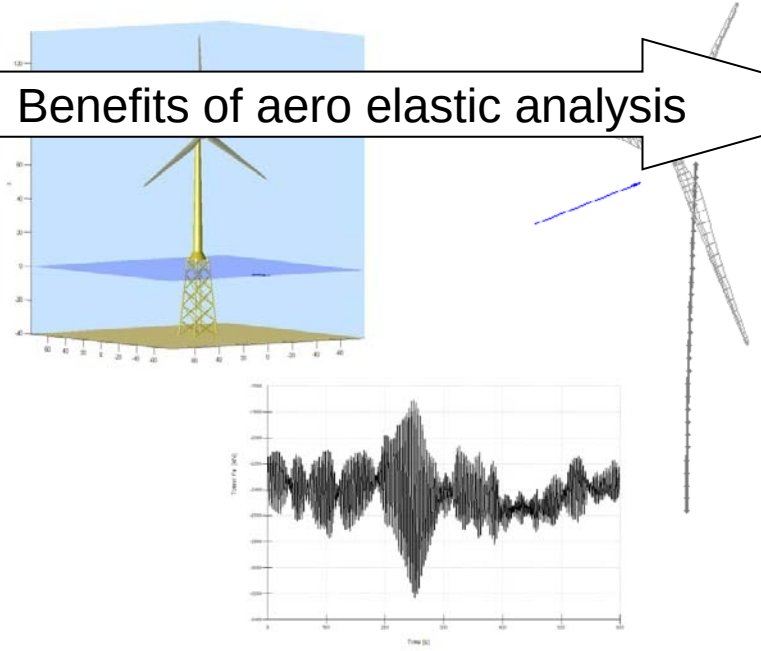
- Aero elastic modelling
- Load calculation and dynamic response

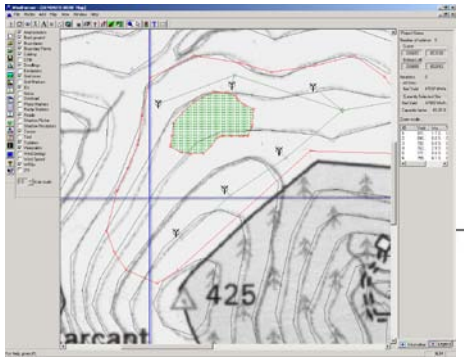
Wind Plant design tools

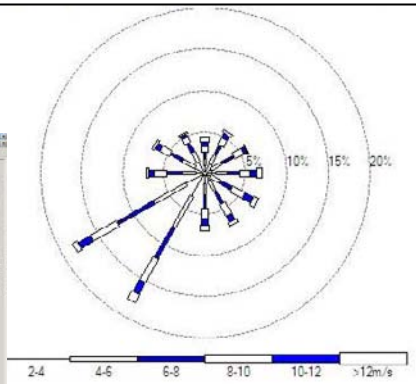
- Wind flow modelling
- Wake modelling
- Plant energy production

Benefits of aero elastic analysis

Commercial and technical barriers





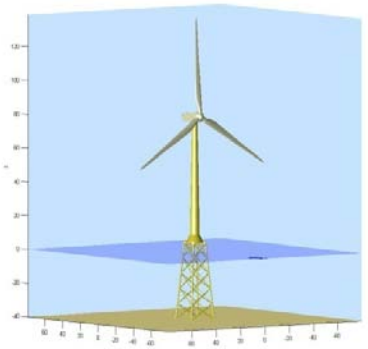


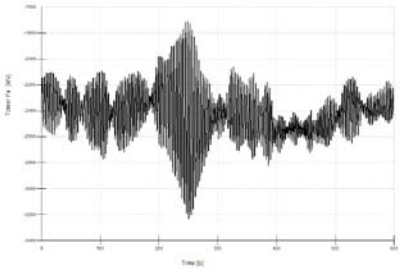
Wind plant layout optimization – AN ALTERNATIVE APPROACH

Integrated energy production and load model?

Wind Turbine design tools

- Aero elastic modelling
- Load calculation and dynamic response

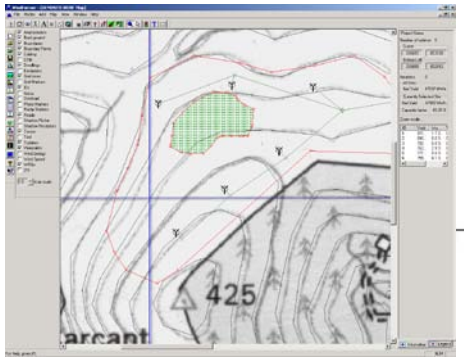


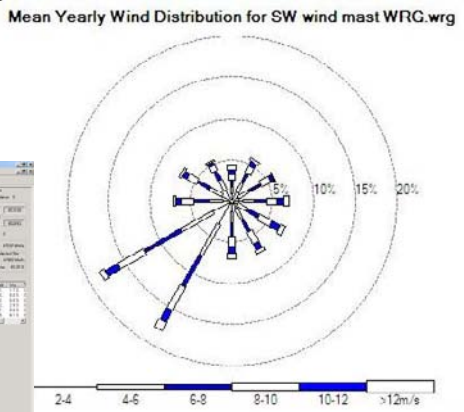


Benefits of aero elastic analysis

Wind Plant design tools

- Wind flow modelling
- Wake modelling
- Plant energy production

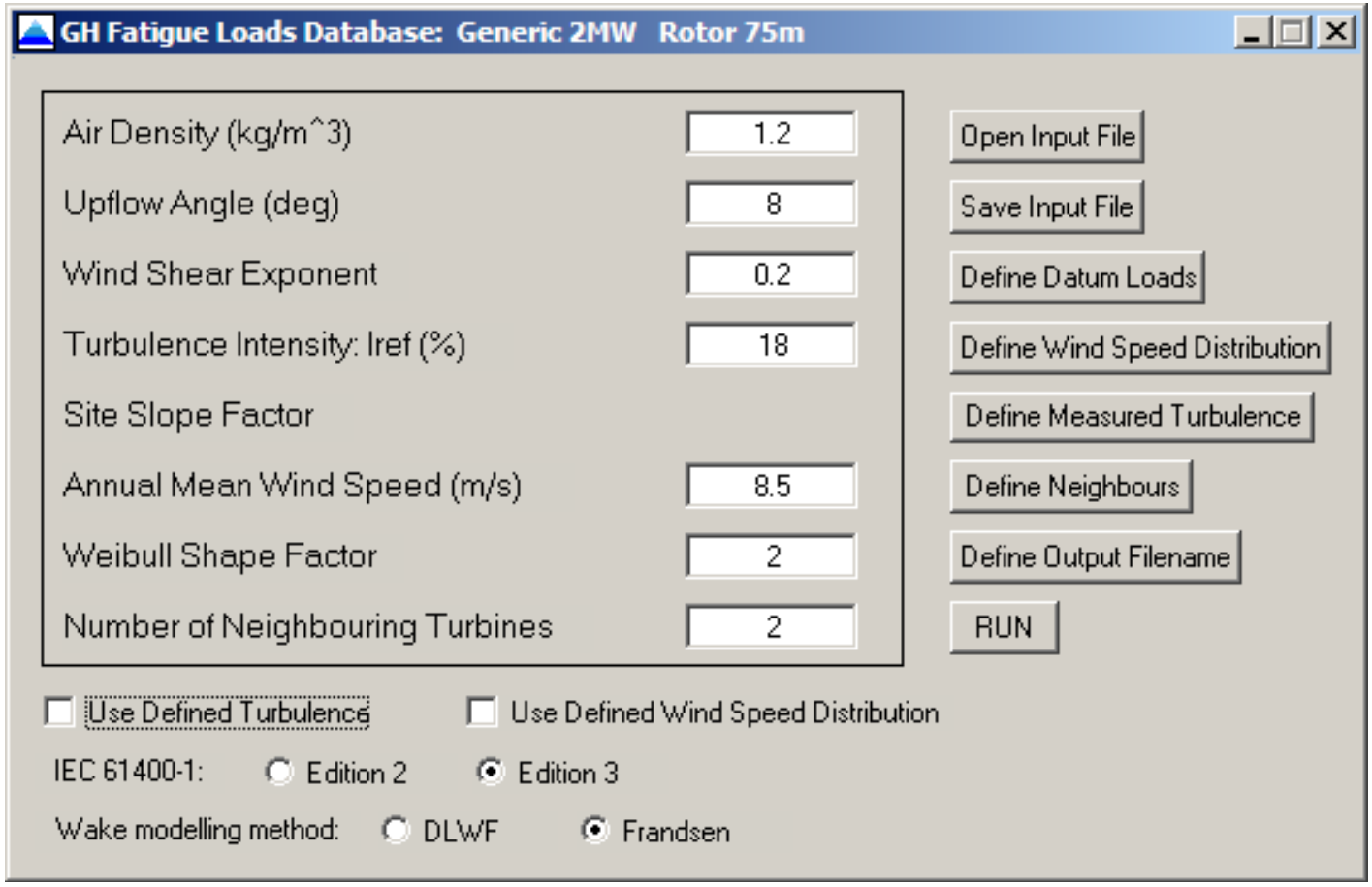


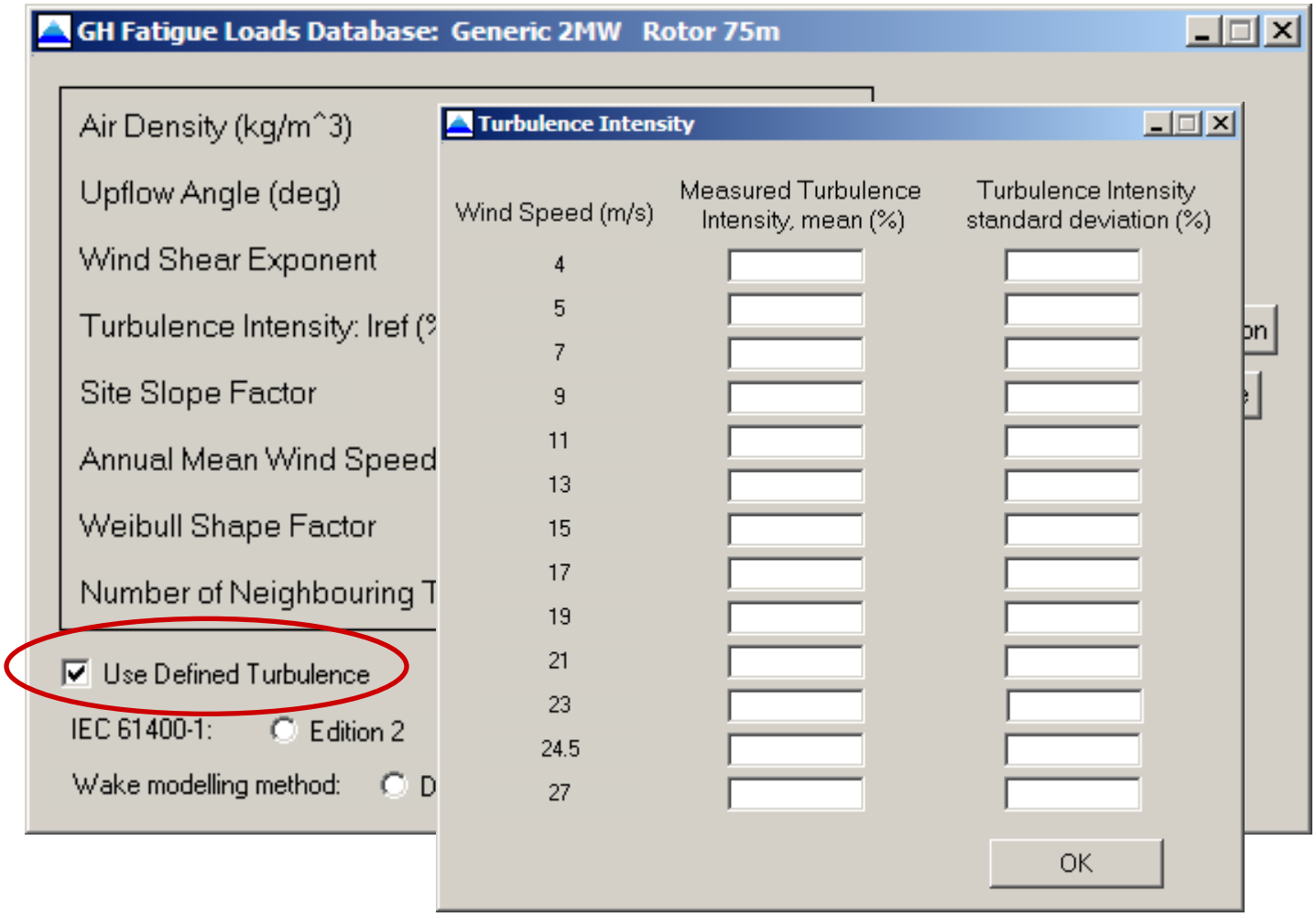


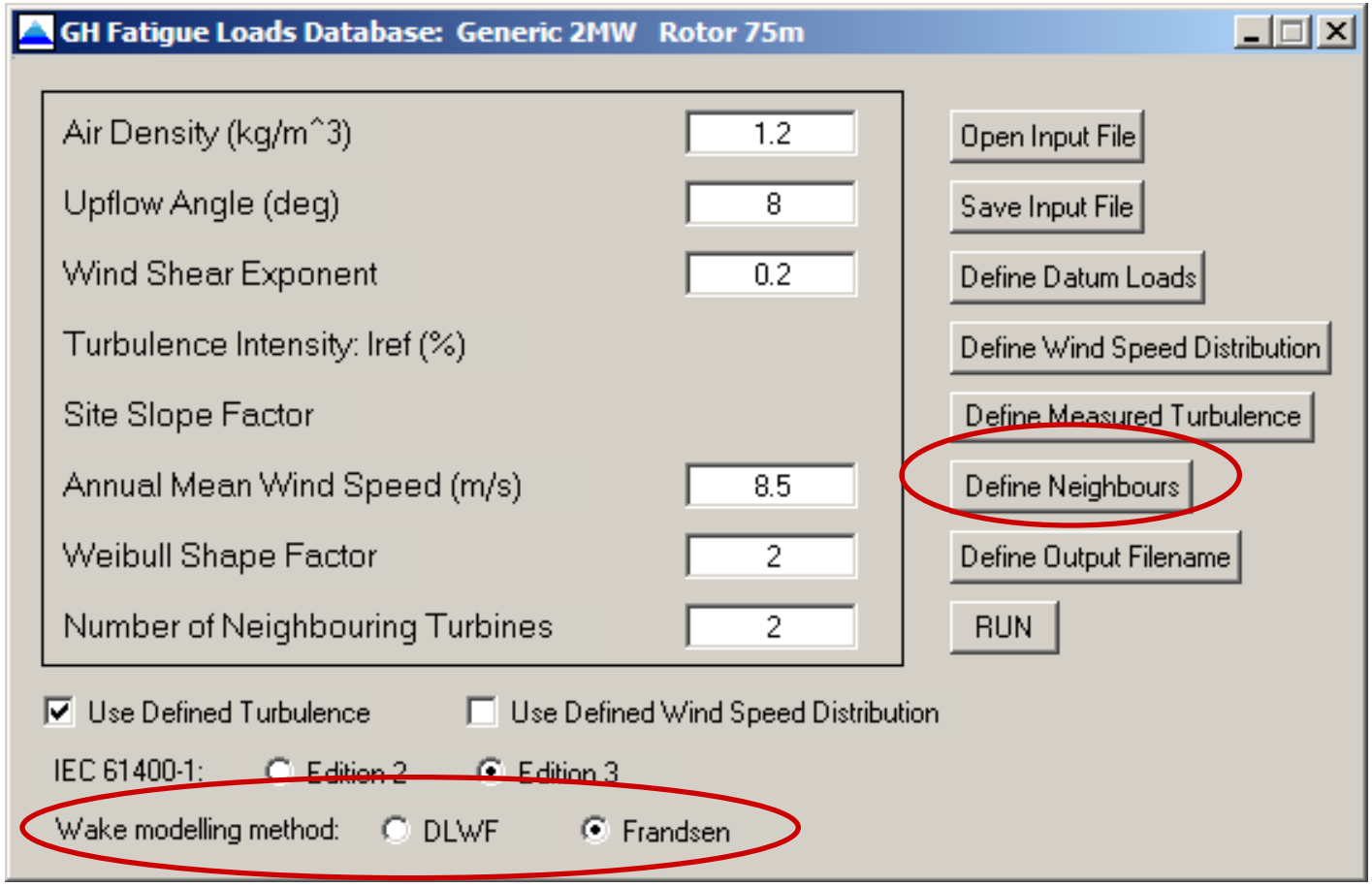
Fatigue load databases

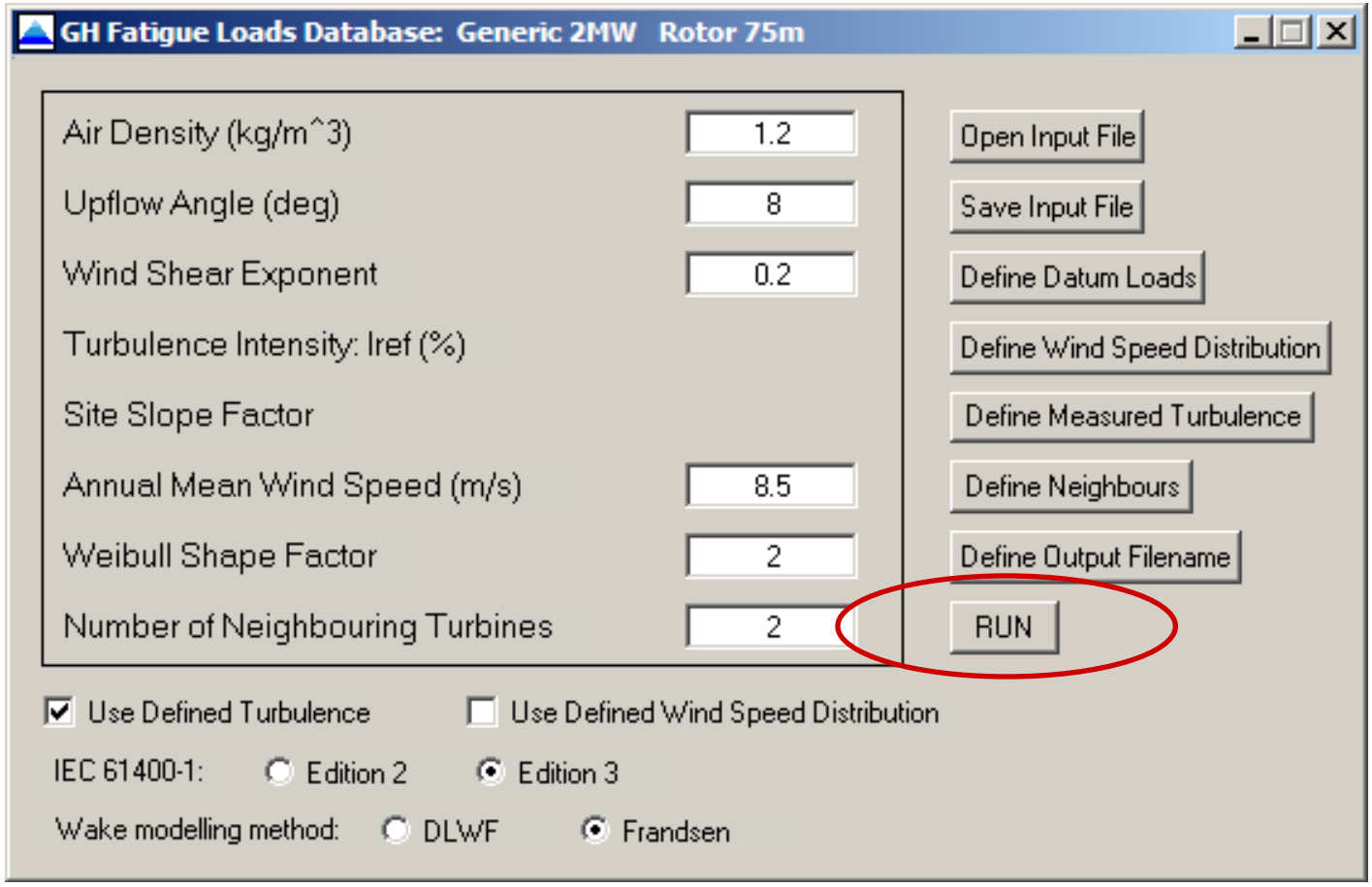
Database of damage equivalent fatigue loads for a specific turbine

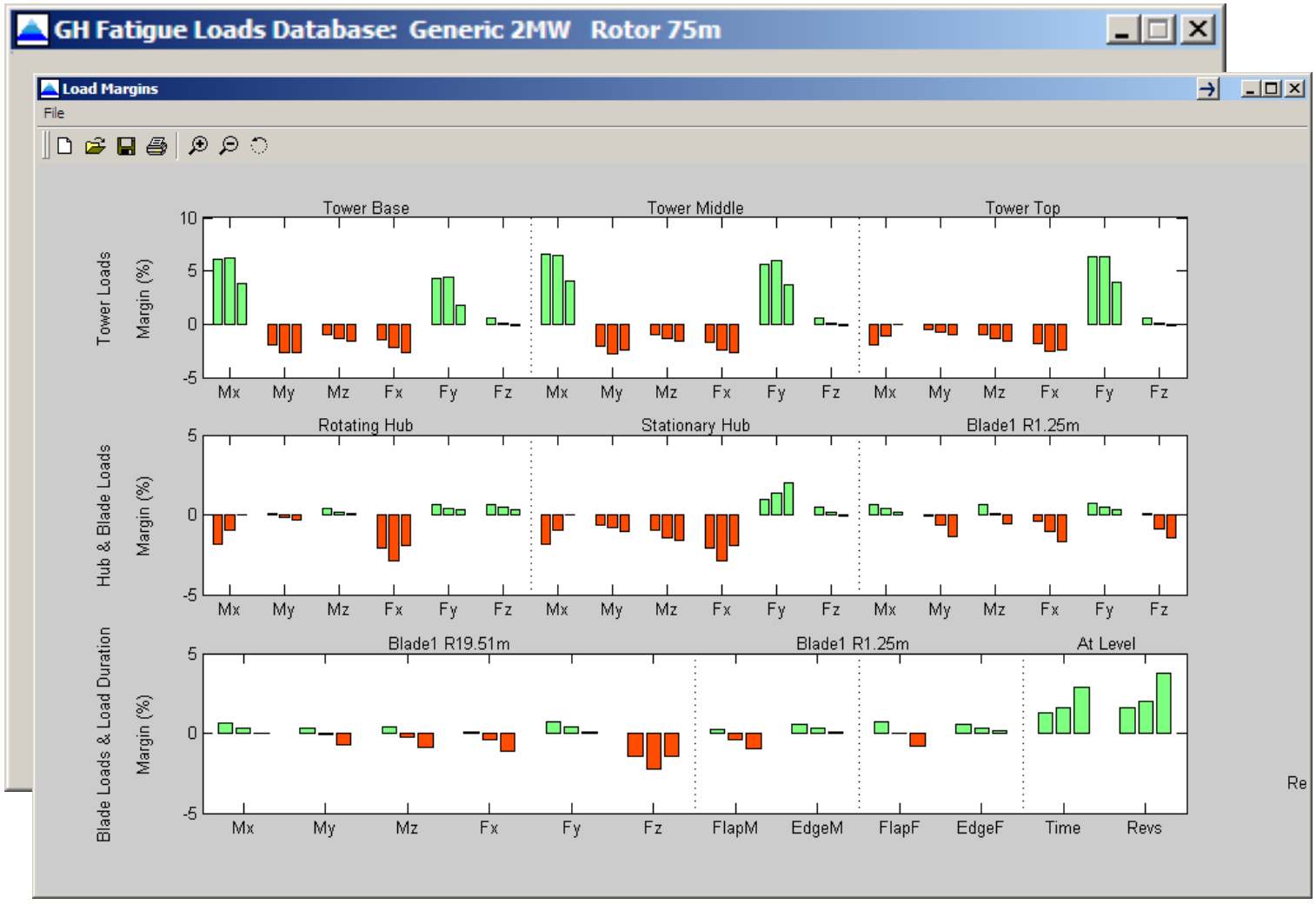
- Created from ~20,000 time domain **aero elastic simulations**
- Lifetime fatigue loads provided as a function of external site conditions and inter-turbine wake affects
- Loads reported in an instant for a wide range of components
- **Load data** can be **normalized** and **encrypted** to protect turbine manufacturers' data


GH Fatigue Loads Database: Generic 2MW Rotor 75m
Air Density (kg/m^3)
1.2
Upflow Angle (deg)
8
Wind Shear Exponent
0.2
Turbulence Intensity: Iref (%)
18
Site Slope Factor
Annual Mean Wind Speed (m/s)
8.5
Weibull Shape Factor
2
Number of Neighbouring Turbines
2
Open Input File
Save Input File
Define Datum Loads
Define Wind Speed Distribution
Define Measured Turbulence
Define Neighbours
Define Output Filename
RUN
Use Defined Turbulence
Use Defined Wind Speed Distribution
IEC 61400-1:
Edition 2
Edition 3
Wake modelling method:
DLWF
Frandsen


GH Fatigue Loads Database: Generic 2MW Rotor 75m
Air Density (kg/m^3)
Upflow Angle (deg)
Wind Shear Exponent
Turbulence Intensity: Iref (%
Site Slope Factor
Annual Mean Wind Speed
Weibull Shape Factor
Number of Neighbouring T
Use Defined Turbulence
IEC 61400-1: Edition 2
Wake modelling method: D
Turbulence Intensity
Wind Speed (m/s)
Measured Turbulence Intensity, mean (%)
Turbulence Intensity standard deviation (%)
4
5
7
9
11
13
15
17
19
21
23
24.5
27
OK


GH Fatigue Loads Database: Generic 2MW Rotor 75m
Air Density (kg/m^3)
1.2
Upflow Angle (deg)
8
Wind Shear Exponent
0.2
Turbulence Intensity: Iref (%)
Site Slope Factor
Annual Mean Wind Speed (m/s)
8.5
Weibull Shape Factor
2
Number of Neighbouring Turbines
2
Open Input File
Save Input File
Define Datum Loads
Define Wind Speed Distribution
Define Measured Turbulence
Define Neighbours
Define Output Filename
RUN
Use Defined Turbulence
Use Defined Wind Speed Distribution
IEC 61400-1:
Edition 2
Edition 3
Wake modelling method:
DLWF
Frandsen


GH Fatigue Loads Database: Generic 2MW Rotor 75m
Air Density (kg/m^3)
1.2
Upflow Angle (deg)
8
Wind Shear Exponent
0.2
Turbulence Intensity: Iref (%)
Site Slope Factor
Annual Mean Wind Speed (m/s)
8.5
Weibull Shape Factor
2
Number of Neighbouring Turbines
2
Open Input File
Save Input File
Define Datum Loads
Define Wind Speed Distribution
Define Measured Turbulence
Define Neighbours
Define Output Filename
RUN
Use Defined Turbulence
Use Defined Wind Speed Distribution
IEC 61400-1:
Edition 2
Edition 3
Wake modelling method:
DLWF
Frandsen

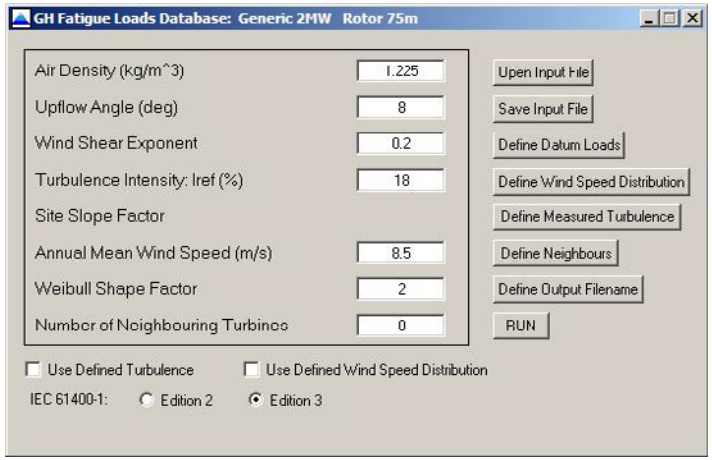

GH Fatigue Loads Database: Generic 2MW Rotor 75m
Load Margins
File
Tower Base
Tower Middle
Tower Top
Tower Loads
Margin (%)
10
5
0
-5
Mx
My
Mz
Fx
Fy
Fz
Rotating Hub
Stationary Hub
Blade1 R1.25m
Hub & Blade Loads
Blade1 R19.51m
Blade1 R1.25m
At Level
Blade Loads & Load Duration
FlapM
EdgeM
FlapF
EdgeF
Time
Revs

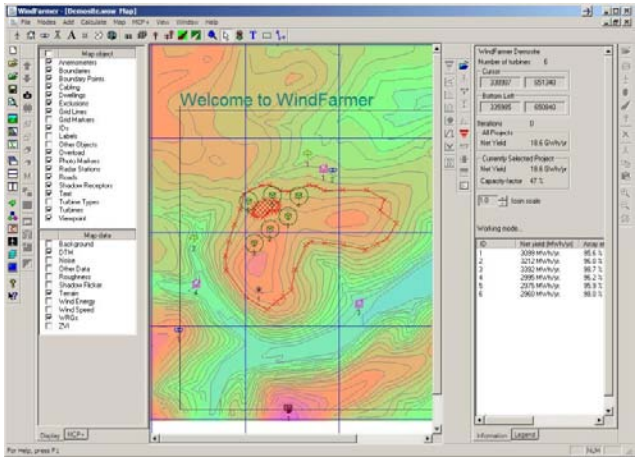
Fatigue load database – WindFarmer integration

LOAD DATABASE

WIND FARM DESIGN TOOL

Site conditions





Load output

CHALLENGE 1: Turbine site suitability

Turbine design type class:

Class:	I-B
Annual mean wind speed:	10 m/s
Design TI at 15 m/s:	16 %
Flow inclination:	8°
Wind shear:	0.2
Air density:	1.225 kg/m^3

Wind farm site conditions:

Class:	-
Annual mean wind speed:	8.5 m/s
Design TI at 15 m/s:	13 %
Flow inclination:	8°
Wind shear:	0.16
Air density:	1.19 kg/m^3

CHALLENGE 1: Turbine site suitability

Turbine design type class:		Wind farm site conditions:	
Class:	I-B	Class:	-
Annual mean wind speed:	10 m/s	Annual mean wind speed:	8.5 m/s
Design TI at 15 m/s:	16 %	Design TI at 15 m/s:	13 %
Flow inclination:	8°	Flow inclination:	8°
Wind shear:	0.2	Wind shear:	0.16
Air density:	1.225 kg/m^3	Air density:	1.19 kg/m^3

Based on comparison of site conditions, can state turbine is suitable

CHALLENGE 1: Turbine site suitability

Turbine design type class:

Class:	I-B
Annual mean wind speed:	10 m/s
Design TI at 15 m/s:	16 %
Flow inclination:	8°
Wind shear:	0.2
Air density:	1.225 kg/m^3

Wind farm site conditions:

Class:	-
Annual mean wind speed:	10.6 m/s
Design TI at 15 m/s:	14.2 %
Flow inclination:	6°
Wind shear:	0.18
Air density:	1.213 kg/m^3

CHALLENGE 1: Turbine site suitability

Turbine design type class:		Wind farm site conditions:	
Class:	I-B	Class:	-
Annual mean wind speed:	10 m/s	Annual mean wind speed:	10.6 m/s
Design TI at 15 m/s:	16 %	Design TI at 15 m/s:	14.2 %
Flow inclination:	8°	Flow inclination:	6°
Wind shear:	0.2	Wind shear:	0.18
Air density:	1.225 kg/m^3	Air density:	1.213 kg/m^3

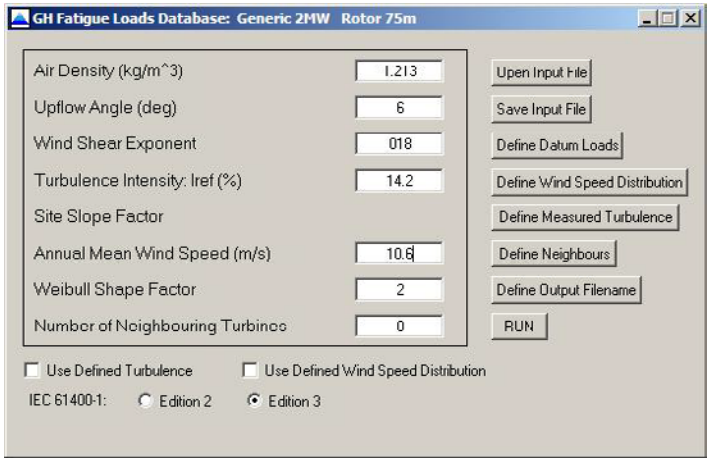
?

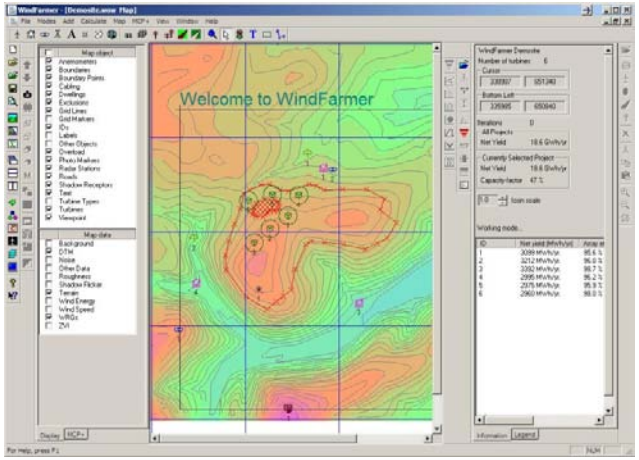
Based on comparison of site conditions, CANNOT state turbine suitability

Farm designers may be forced to reject possible layouts simply due to a lack of rigor in the site-suitability assessment

CHALLENGE 1: Turbine site suitability based on LOADS

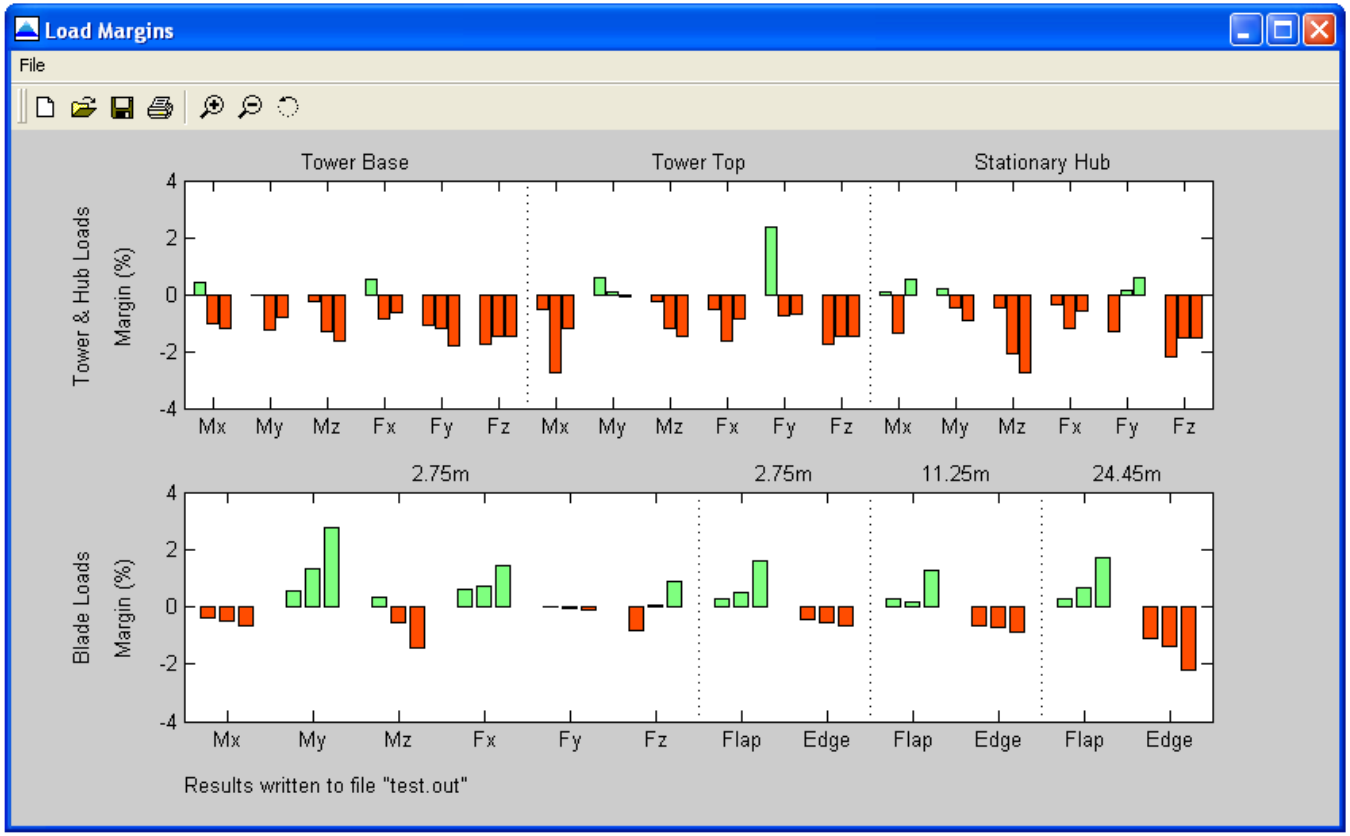
Load data





Site conditions

CHALLENGE 1: Turbine site suitability based on LOADS



Load margins for each turbine location on site automatically calculated by load database

CHALLENGE 1: Turbine site suitability based on LOADS

Turbine ID	Load Test	Blade root Mx (%)	Blade root My (%)	Rev at level (%)	Tower top Fx (%)	Yaw bearing Mz (%)	Stationary Hub My (%)
1	pass	5.9	2.45	24.1	3.07	10.0	10.9
2	pass	5.4	0.98	23.5	0.112	7.5	8.5
3	pass	5.4	1.00	23.5	0.0284	7.5	8.4
4	pass	5.7	2.34	23.8	1.97	9.2	10.2
5	pass	5.6	1.48	23.8	1.59	8.7	9.6
6	fail	5.1	0.104	23.3	-1.09	6.5	7.4
7	fail	5.1	0.112	23.3	-1.17	6.4	7.4
8	pass	5.5	1.37	23.6	0.67	8.1	9.0
9	pass	5.7	1.58	23.8	1.72	8.9	9.8
10	fail	5.2	0.221	23.3	-0.94	6.6	7.6
11	fail	5.2	0.244	23.3	-0.98	6.6	7.6
12	pass	5.6	1.53	23.6	0.90	8.3	9.3
13	pass	6.2	3.3	24.3	4.6	11.4	12.3
14	pass	5.7	1.96	23.8	1.75	9.0	10.0
15	pass	5.7	2.01	23.8	1.75	9.0	10.0
16	pass	6.2	3.5	24.2	4.2	11.1	12.0

Load margins for each turbine location on site automatically calculated by load database

CHALLENGE 2: Cost of Energy Optimization

Current wind farm layout design tools calculate:

AEP = fn(X $_{\text{turbine positions}}$)

To compute optimal COE also need:

ICC, O&M = fn(X $_{\text{turbine positions}}$)

$$COE_{OPT} \neq \frac{ICC \times FCR + O\,\&\,M}{AEP_{OPT}}$$

CHALLENGE 2: Cost of Energy Optimization

ICC, O&M = fn (X $_{\text{turbine positions}}$) ?

- Choice (and cost) of turbine will depend on site-specific fatigue loading
- Electrical cable costs will vary as a function of turbine positions
- Turbine foundation costs will vary as a function of turbine position:
  - fatigue loading
  - water depth (offshore)
  - soil properties
- Reliability, and hence O&M costs, will vary as a function of fatigue loading

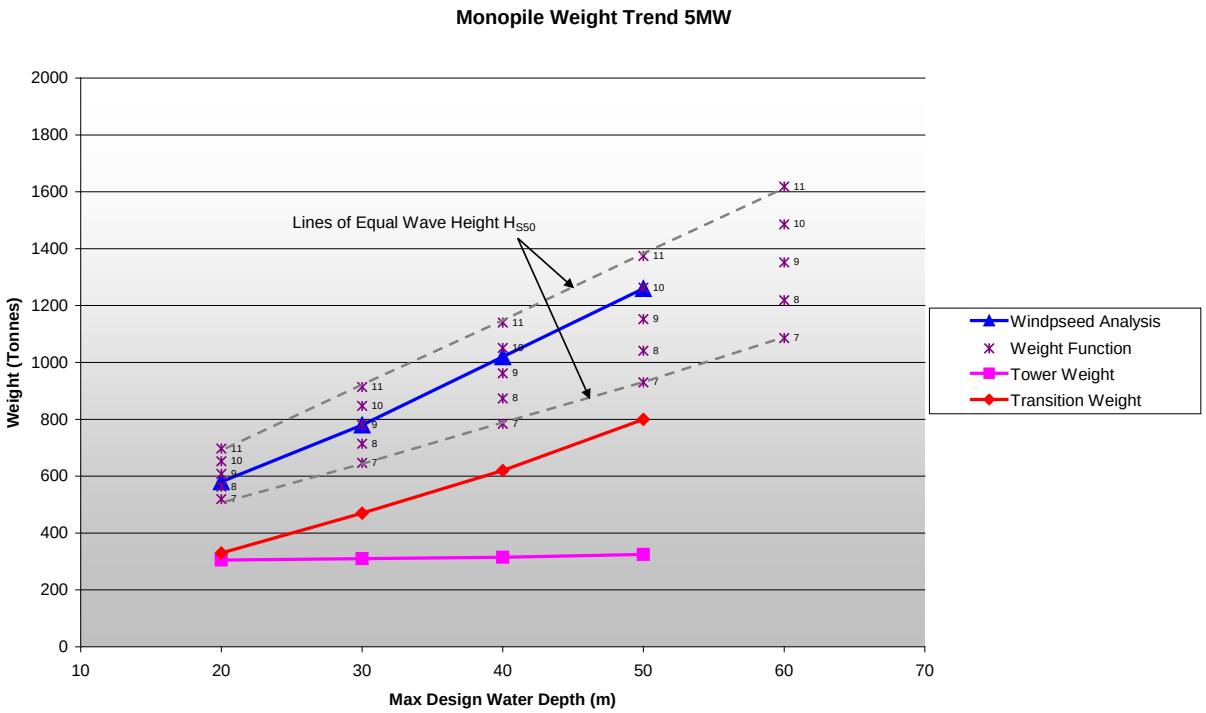
$$COE = \frac{ICC \times FCR + O\,\&\,M}{AEP}$$

CHALLENGE 2: Cost of Energy Optimization

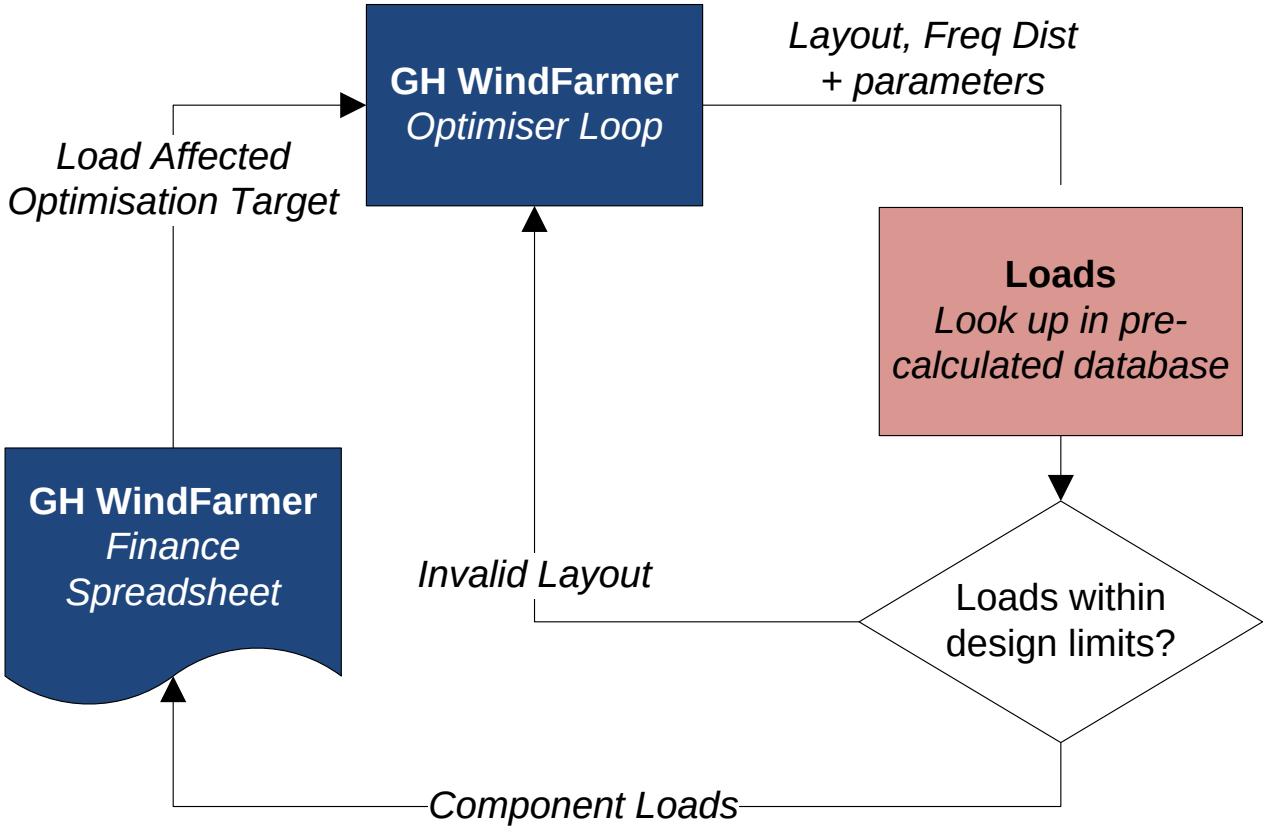
COST MODELS

Published results available from industrial research projects, eg:

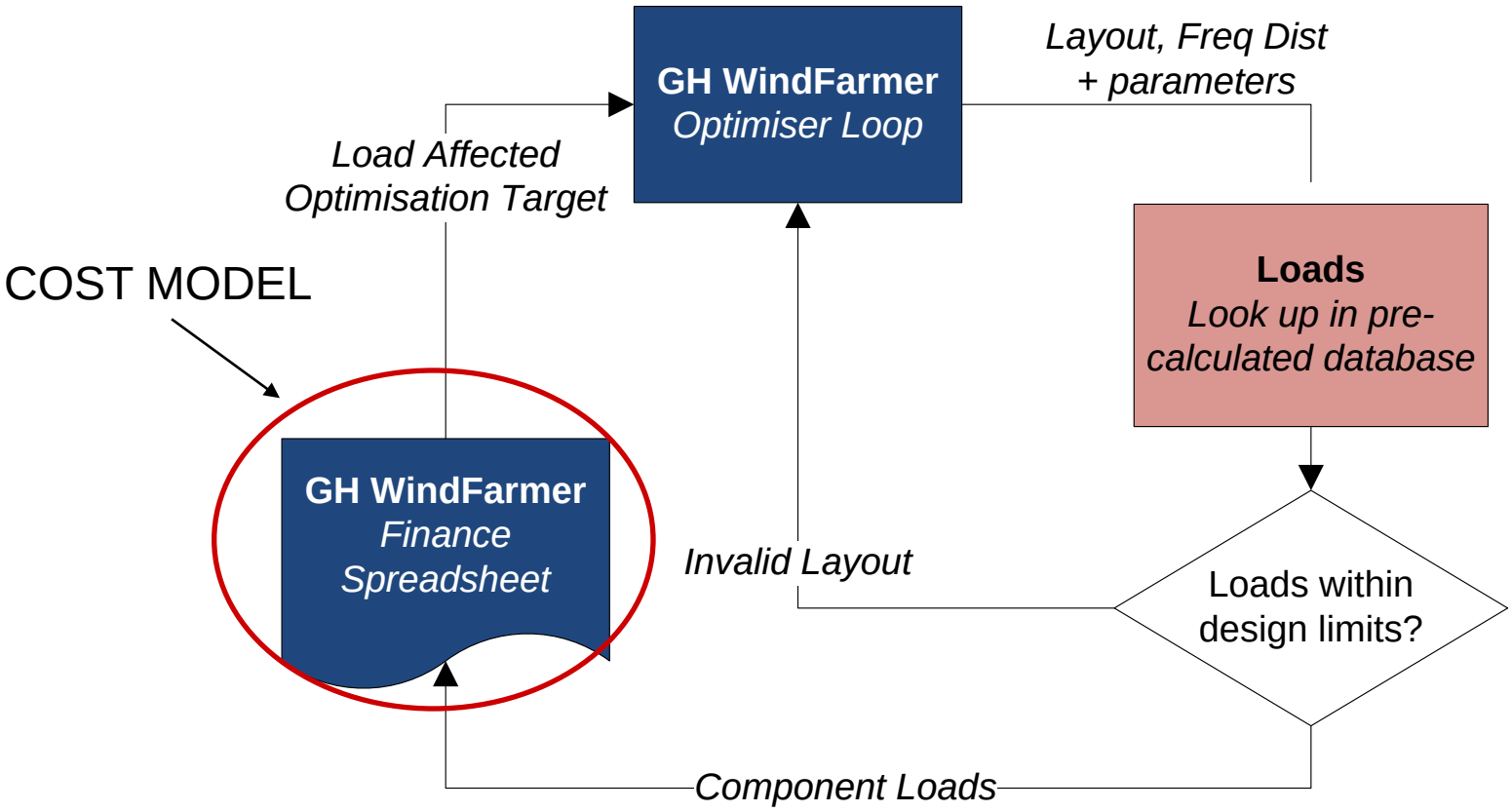
- UPWIND
- RELIAWIND
- TOPFARM
- WINDSPEED



CHALLENGE 2: Cost of Energy Optimization



CHALLENGE 2: Cost of Energy Optimization



CHALLENGE 2: Cost of Energy Optimization Test Cases

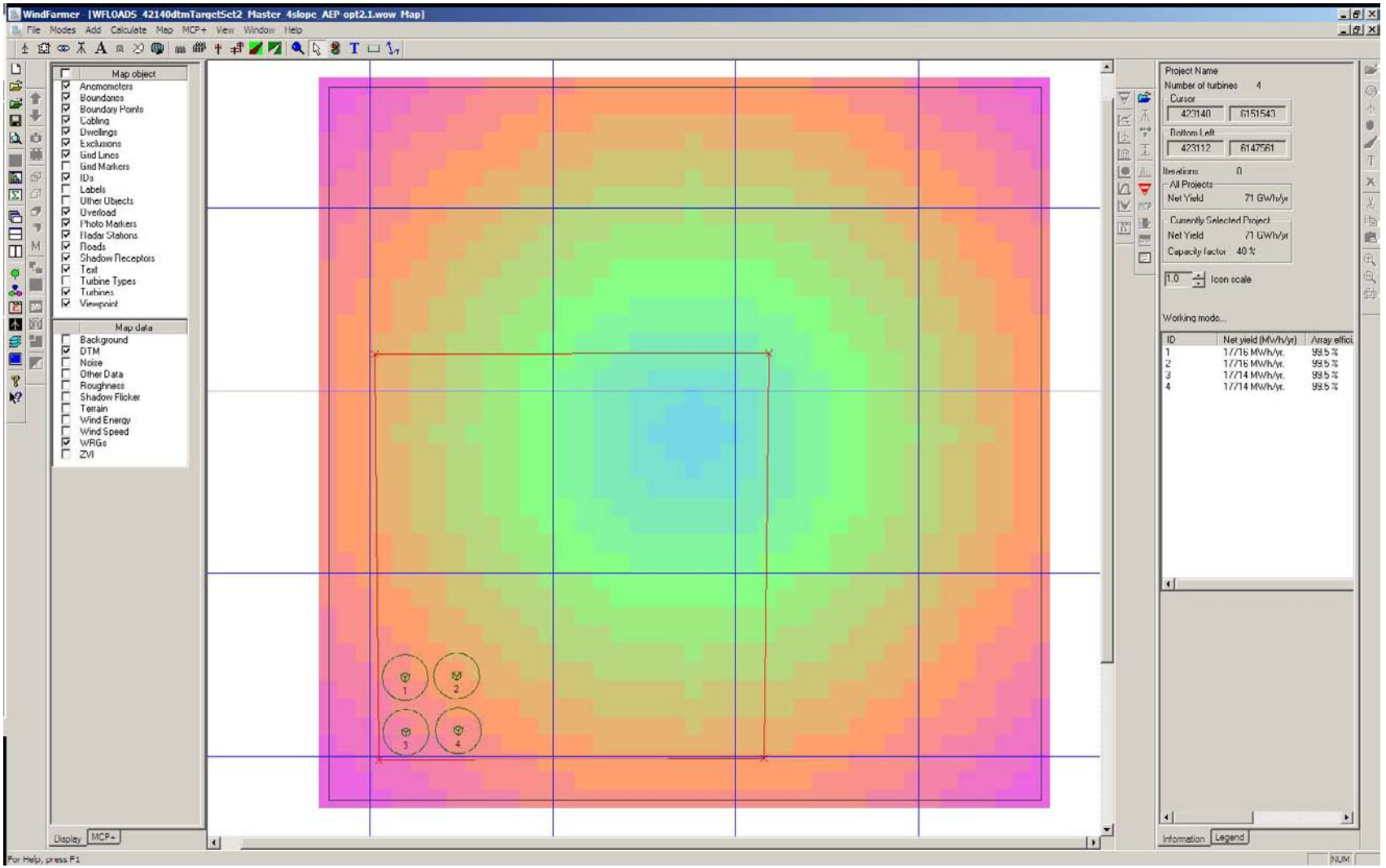
Example 1:

- Four 5MW wind turbines
- Offshore site (simplified sea-bed)
- Dynamic foundation cost model (loads and water depth)
- Cable cost model
- O&M cost model

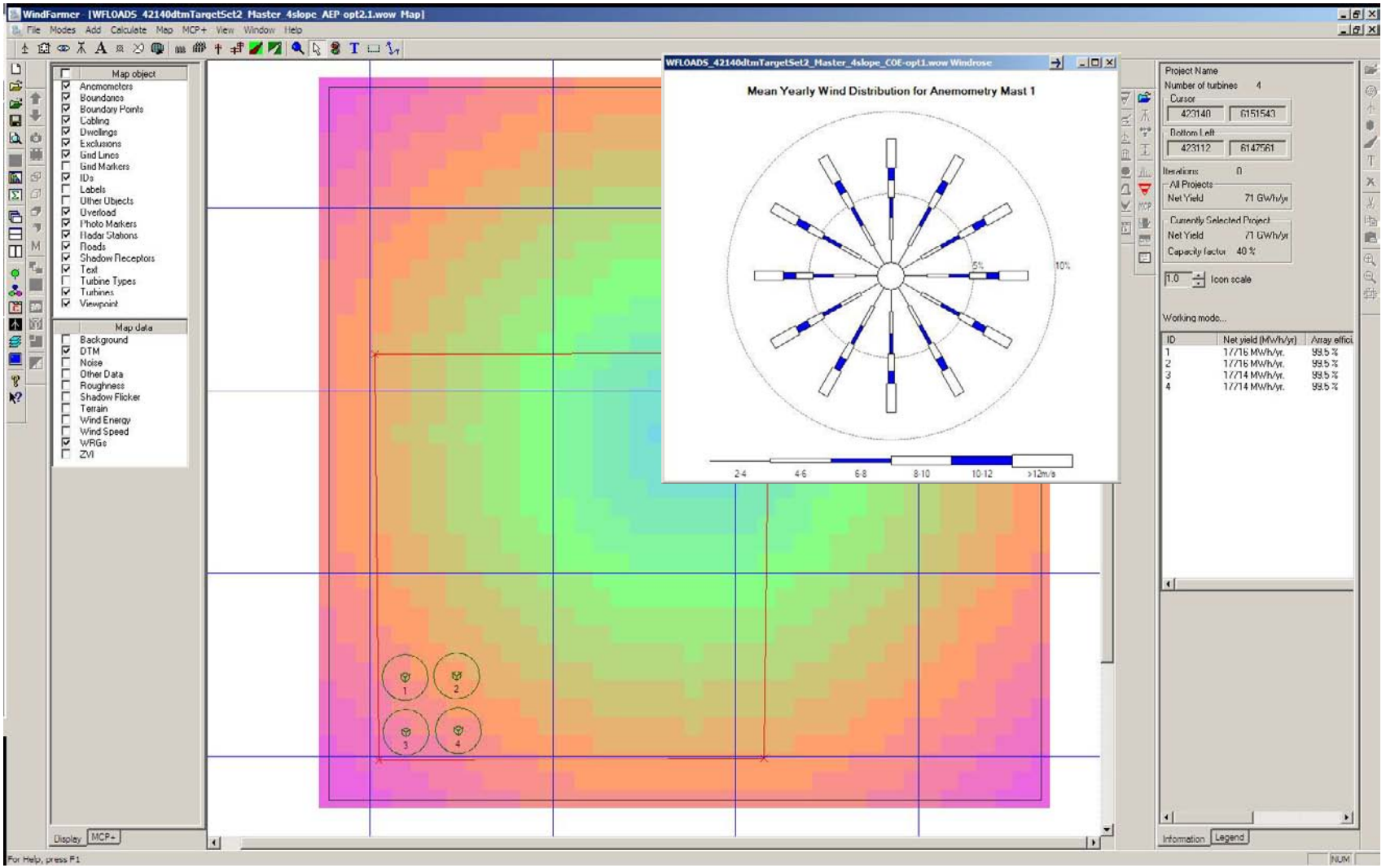
Example 2:

- Sixteen 5MW wind turbines
- Offshore site (complex sea-bed)
- Dynamic foundation cost model (loads and water depth)
- Cable cost model
- O&M cost model

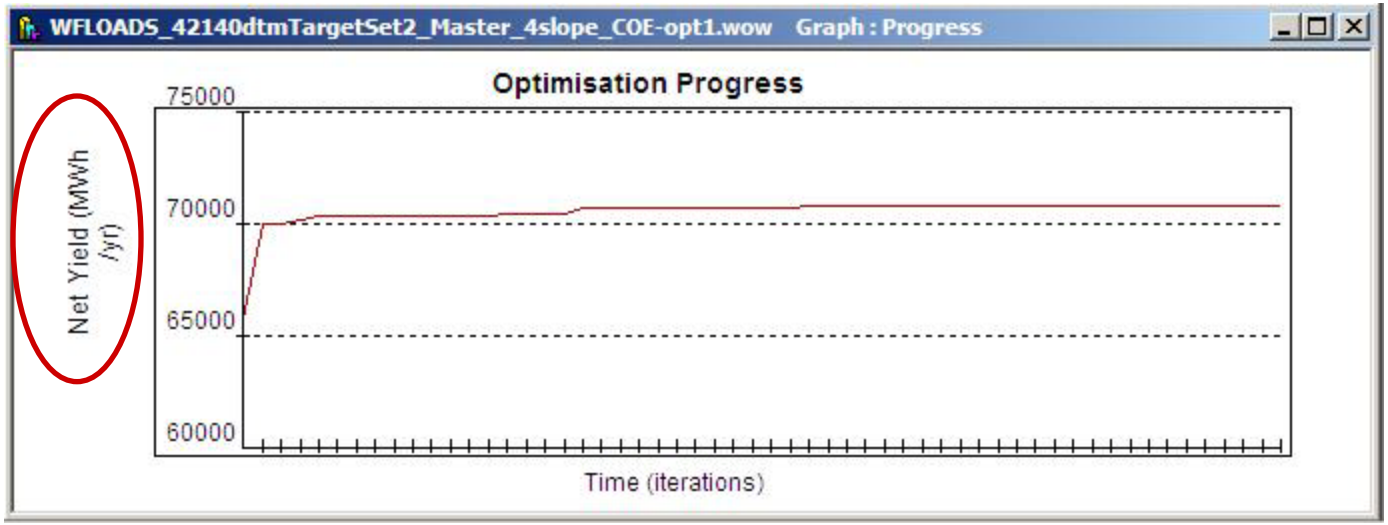
COE optimization: Example 1 - Simple 4-turbine



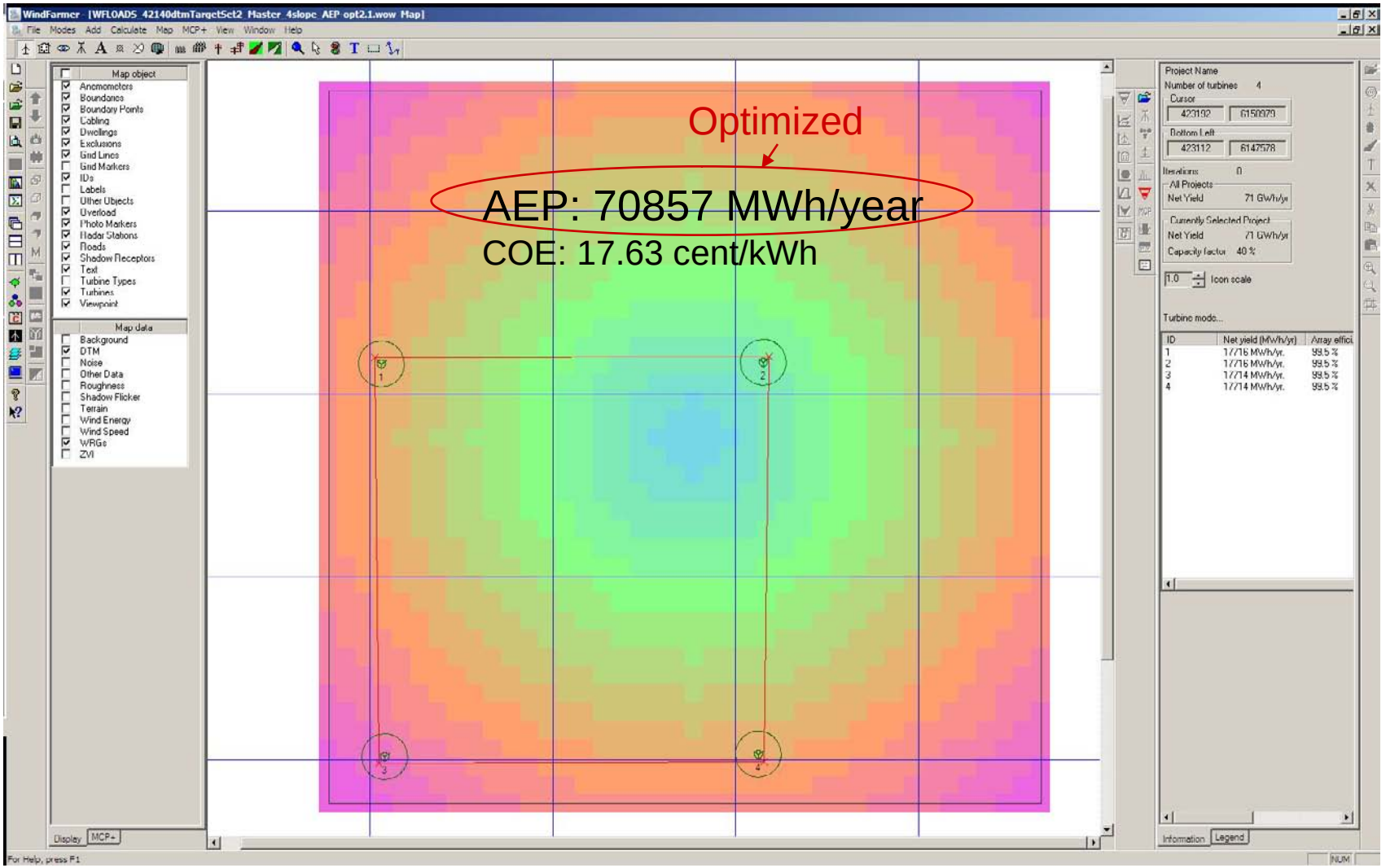
COE optimization: Example 1 - Simple 4-turbine



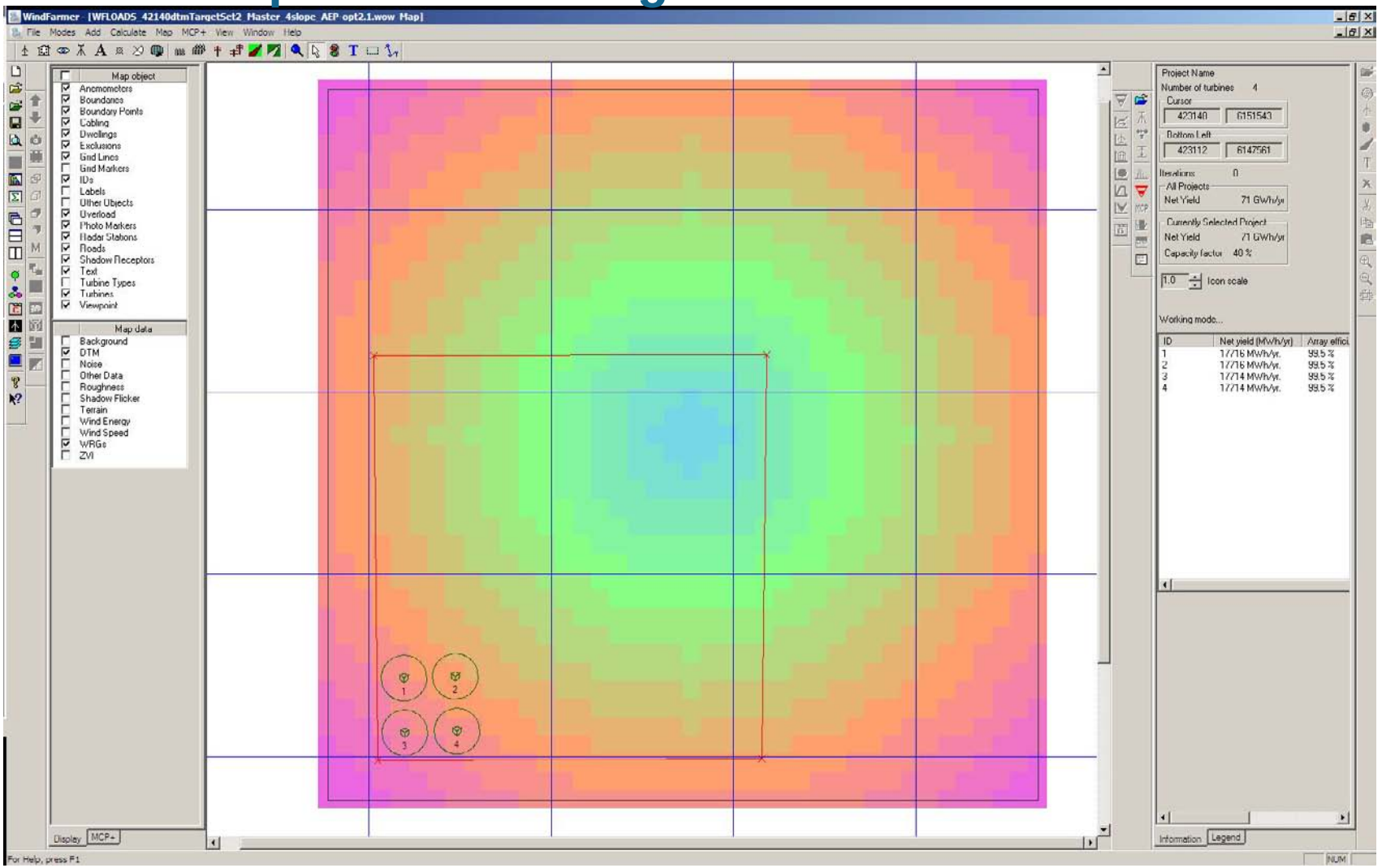
Test 1: Optimization Target = AEP



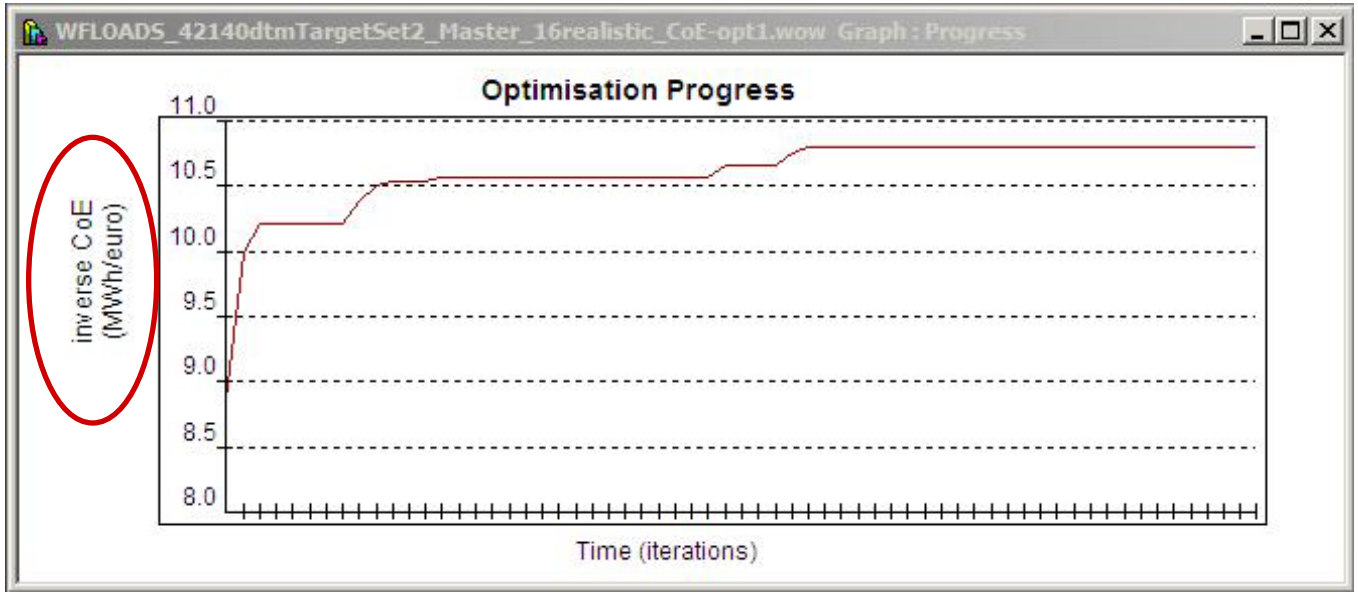
Test 1: FINAL LAYOUT (Optimization Target = AEP)



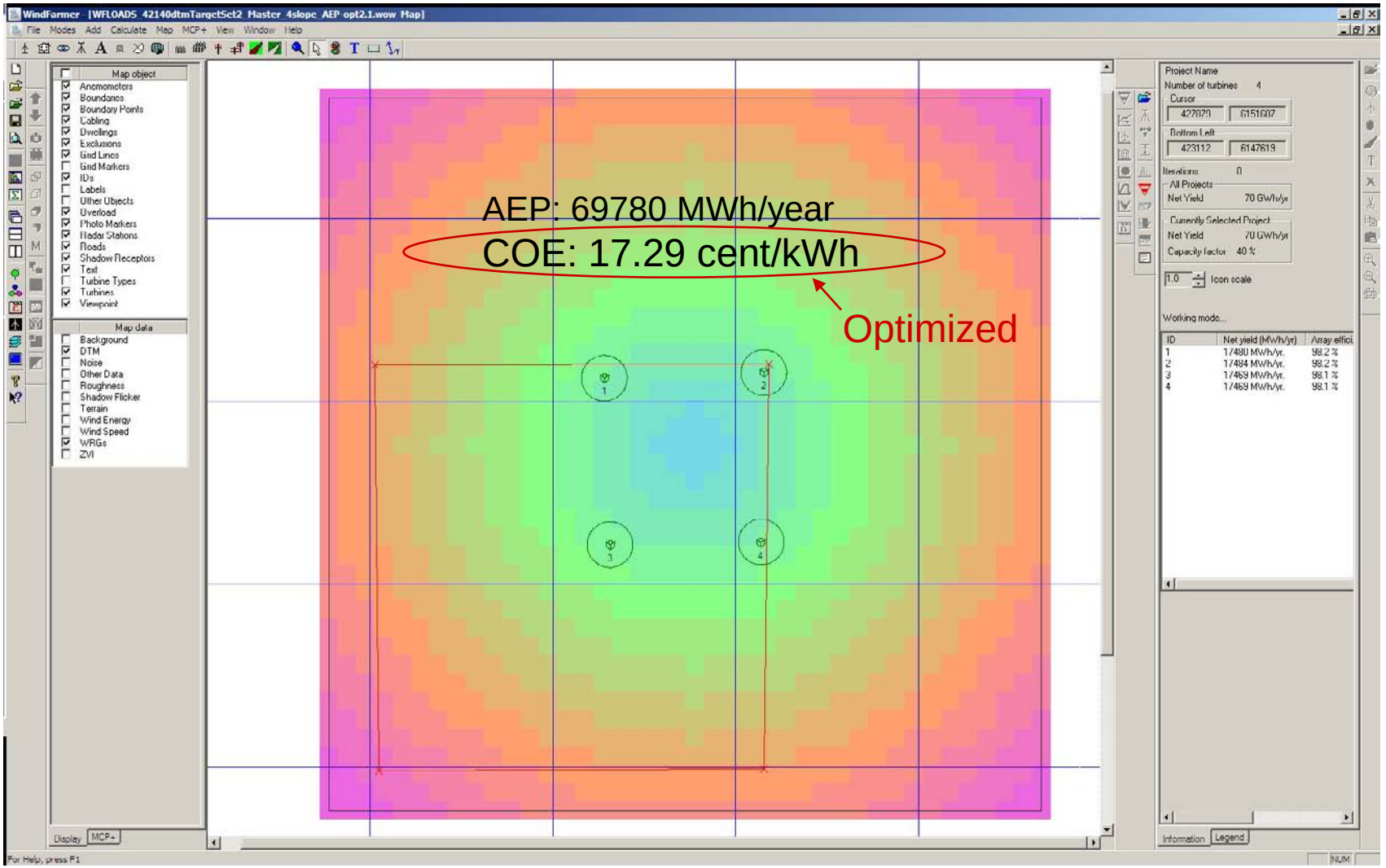
Test 2: Optimization Target = COE



Test 2: Optimization Target = COE



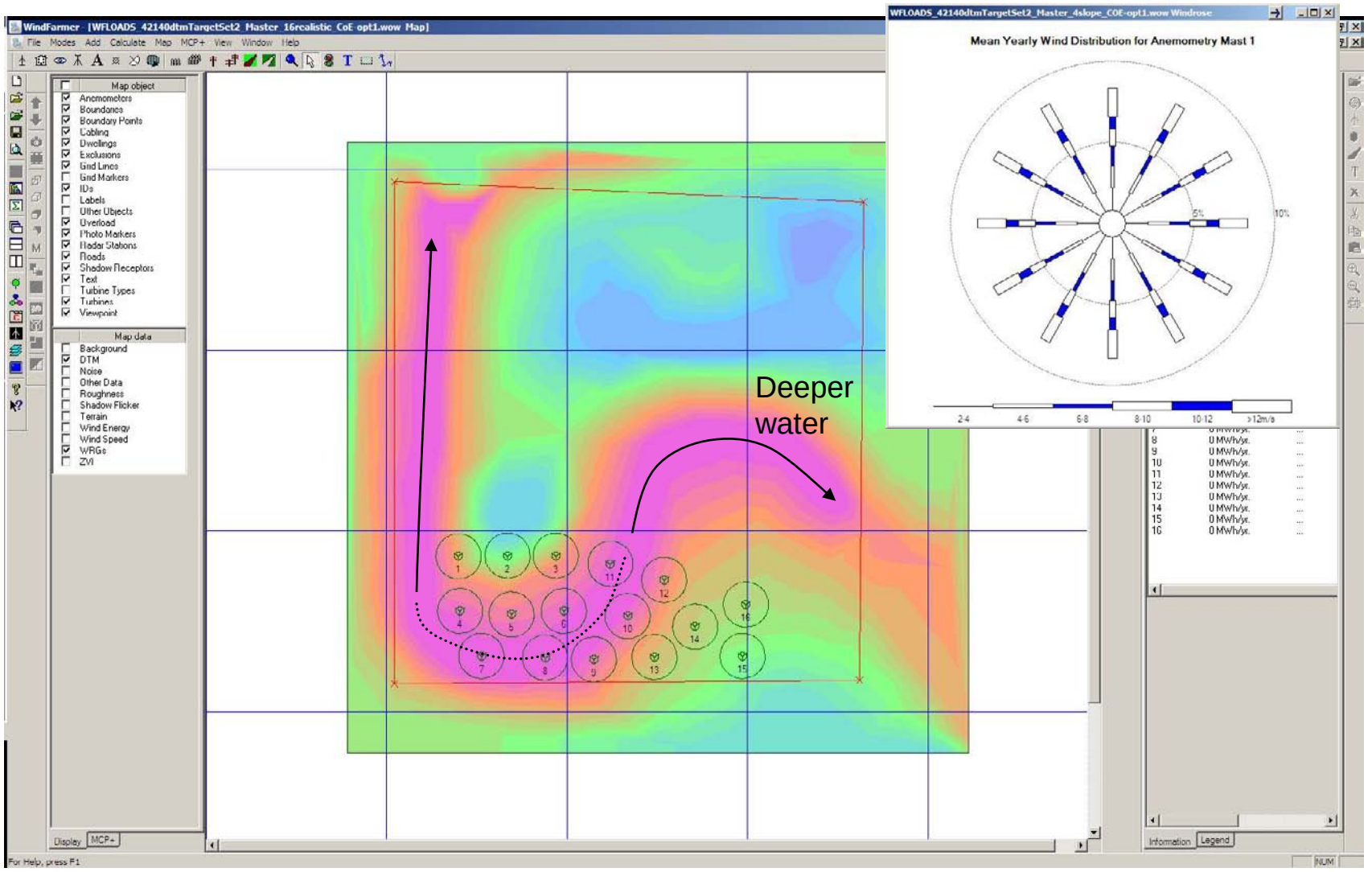
Test 2: FINAL LAYOUT (Optimization Target = COE)



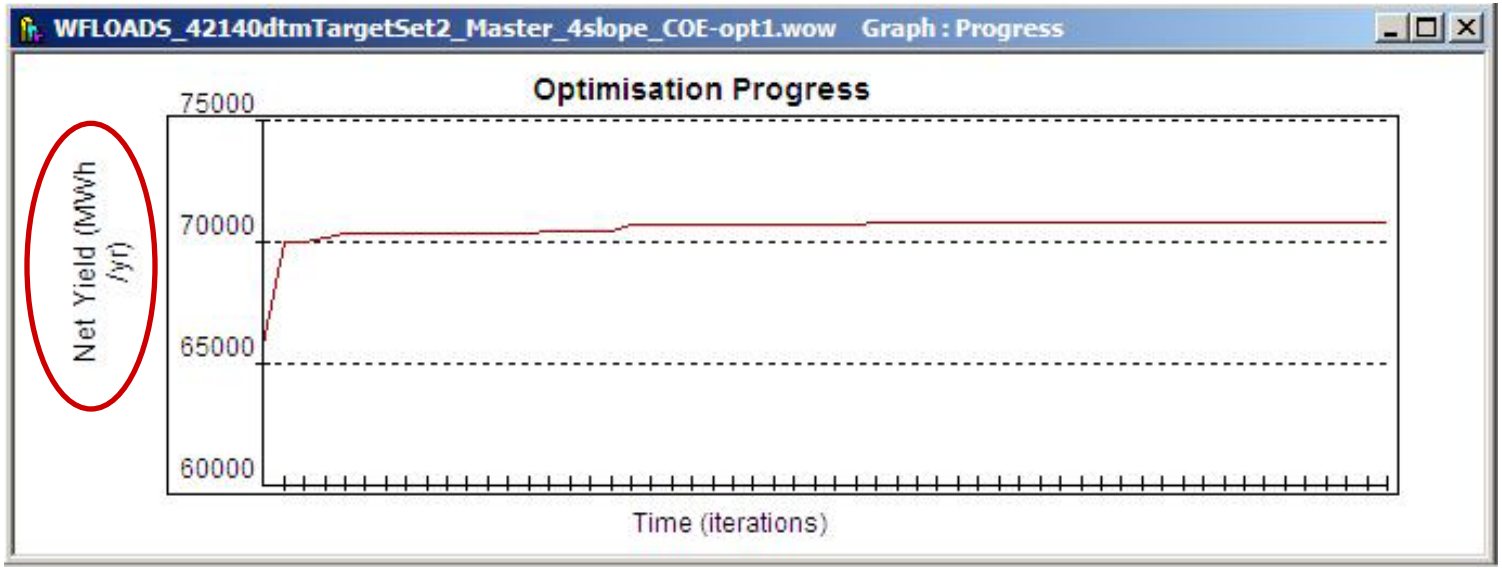
Results Summary - simple 4-turbine test case

Optimization Target:	Target 1 – AEP Optimization	Target 2 – COE Optimization	MARGIN
Annual Energy Production (MWh/year)	70857	69780	-1.5 %
Cost of Energy (cent/kWh)	17.63	17.29	-2.0 %

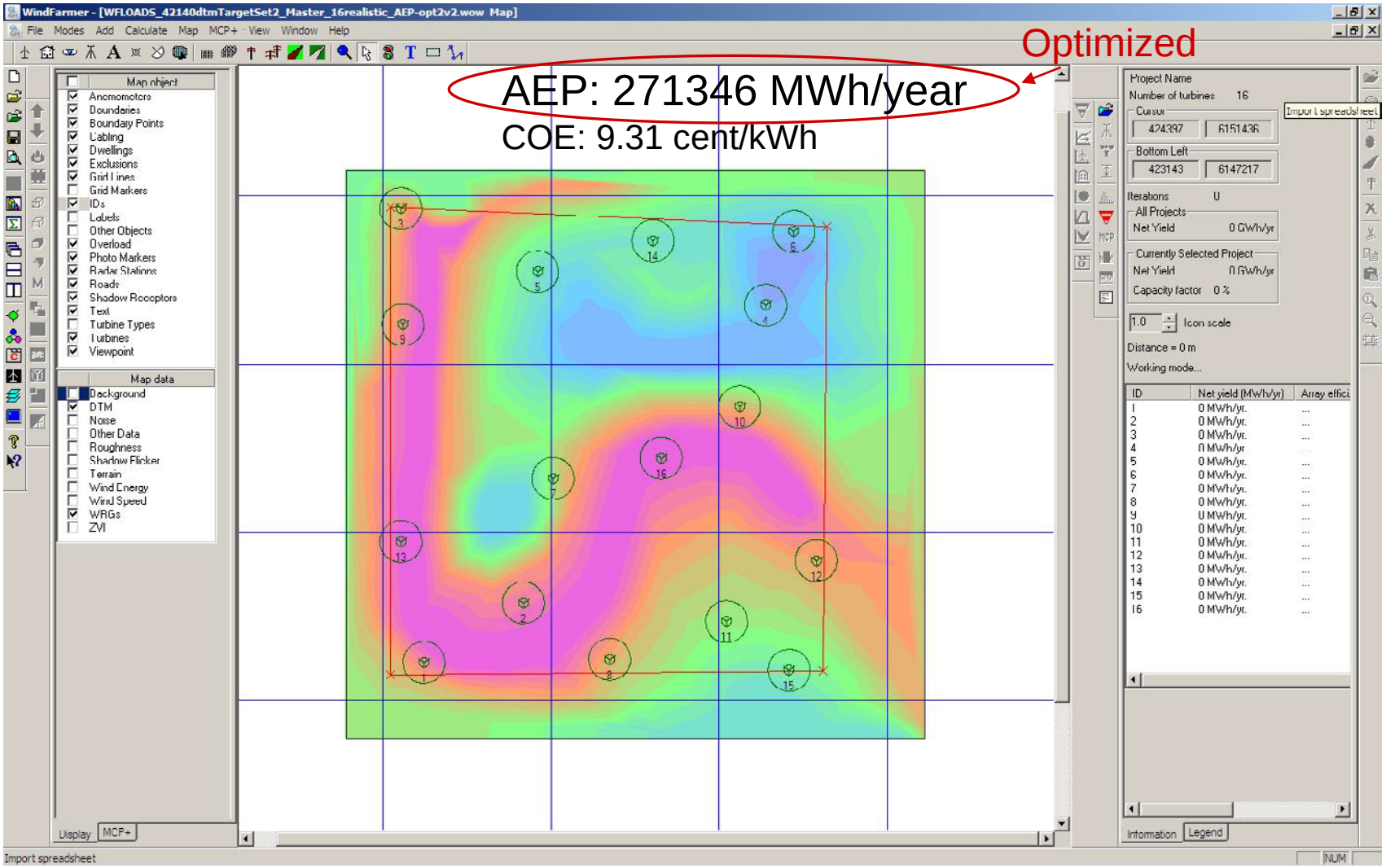
COE optimization: Example 2 - Complex 16-turbine



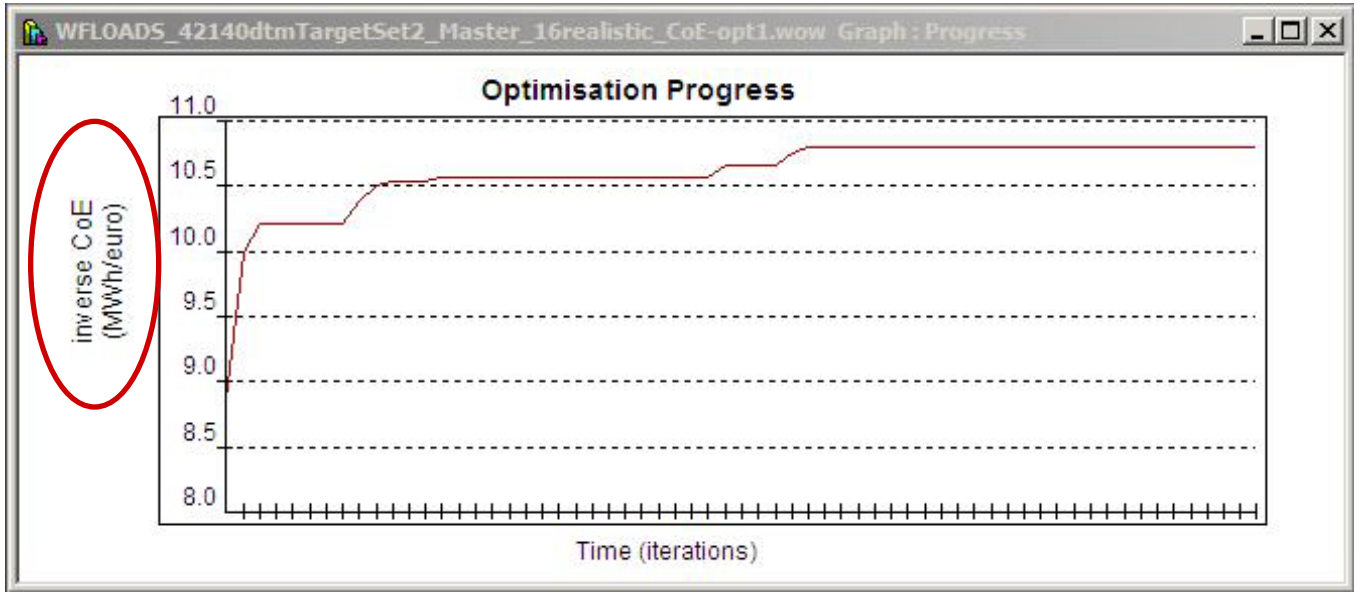
Test 1: Optimization Target = AEP



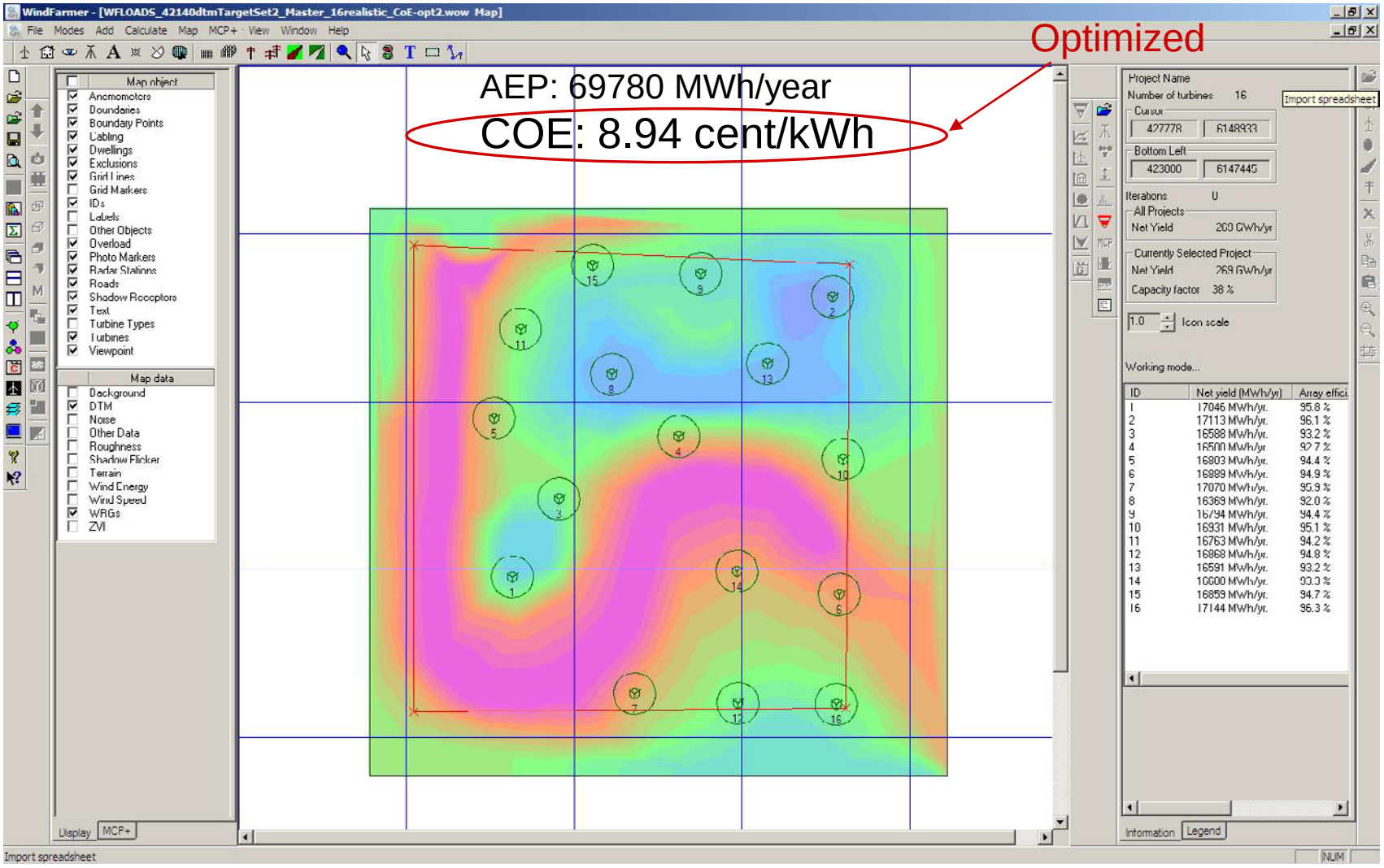
Test 1: FINAL LAYOUT (Optimization Target = AEP)



Test 2: Optimization Target = COE



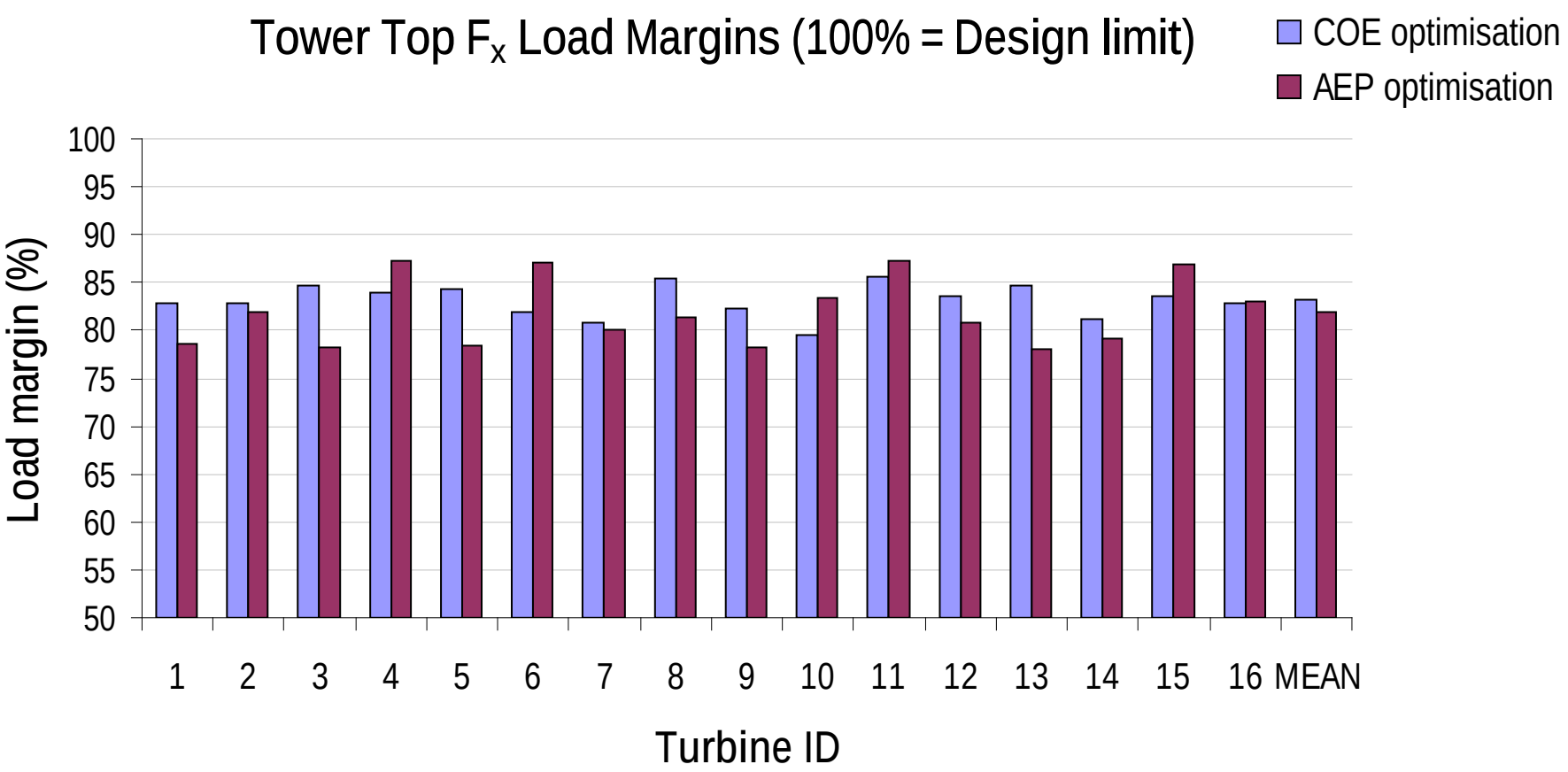
Test 2: FINAL LAYOUT (Optimization Target = COE)



Results Summary - complex 16-turbine test case

Optimization Target:	Target 1 – AEP Optimization	Target 2 – COE Optimization	MARGIN
Annual Energy Production (MWh/year)	271346	268810	-1.0 %
Cost of Energy (cent/kWh)	9.31	8.94	-4.1 %

Loads Summary - complex 16-turbine test case



Presentation Review

Wind Plant Optimization

1. Development of integrated energy and loading models using ‘plug-in’ fatigue load databases

2. Rigorous turbine site-suitability assessment

3. Potential to optimize plant Cost of Energy

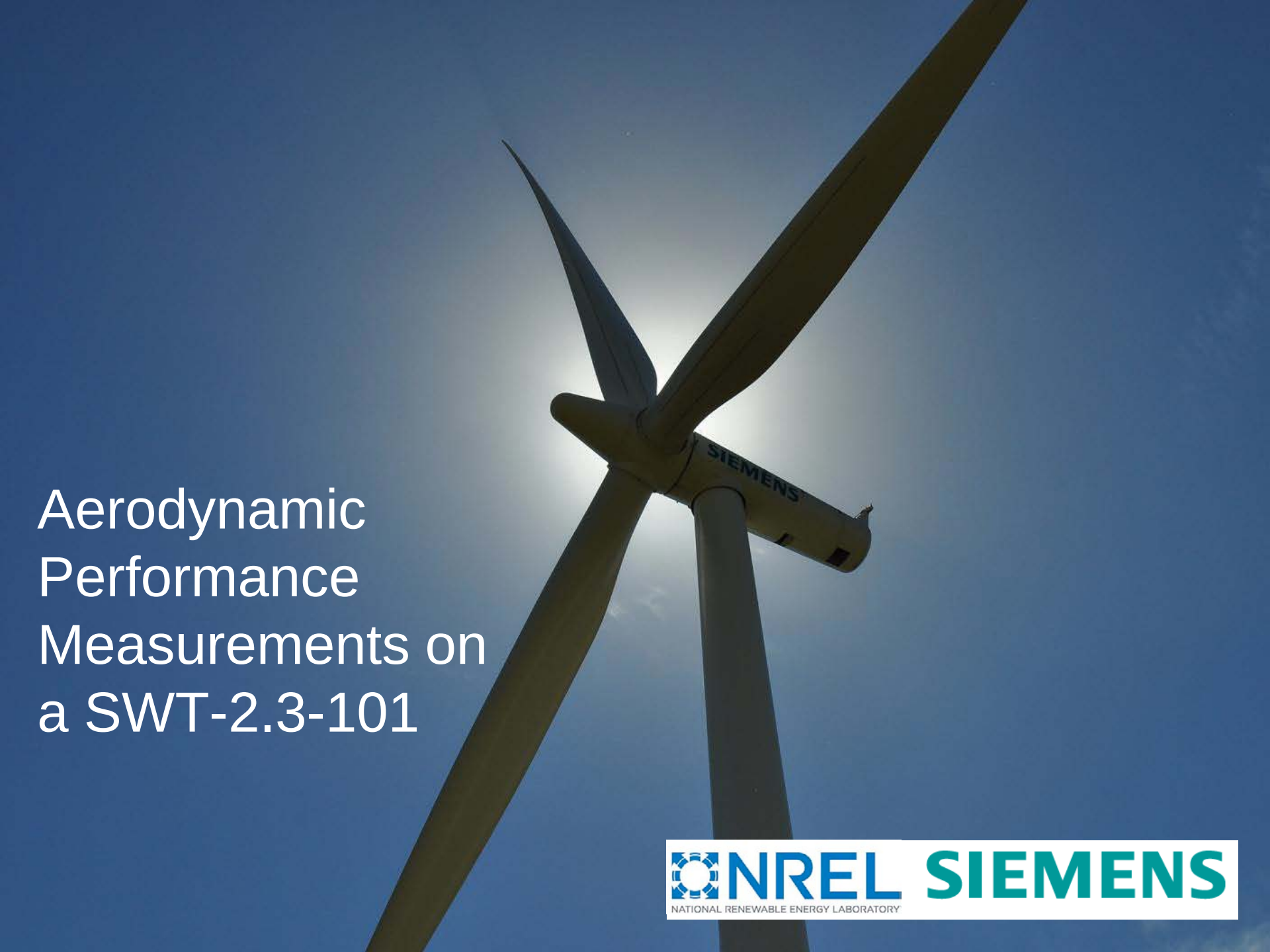
Acknowledgements

- The TOPFARM European Research Project Consortium
- Tim Camp and John King (GL-GH): fatigue load database development
- Kevin Dodson and Malcolm Heath (GL-GH): Load database / wind farm design tool integration

Thank you for your attention

Graeme McCann Load Analysis Engineer, GL Garrad Hassan

graeme.mccann@gl-garradhassan.com



Aerodynamic Performance Measurements on a SWT-2.3-101

NREL NATIONAL RENEWABLE ENERGY LABORATORY

SIEMENS

Overview

- Introduction
- Objectives
- Turbine
- Inflow measurement
- Loads testing
- B-49 Structural Testing
- Noise testing
- Flow visualization
- Aerodynamic testing
- Other tests

Cooperative **R**esearch **A**nd **D**evelopment **A**greement

Department of Energy (DOE) / National Renewable Energy Laboratory (NREL), Siemens Wind Power (SWP)

- NREL call for proposal for CRADA partnership with industry to erect utility scale wind turbine (Sept 2007)
- Siemens selected in competitive procurement as partner (May 2008)
- SWT-2.3-101 wind turbine is featured
- National Wind Technology Center (NWTC), Golden Colorado
- Budget: DOE/NREL $5M
  SWP $9M
- Time plan: 1/1 2009- 31/12 2011

Commissioning Ceremony, October 19th, 2009

Objectives

- Study the performance of SWT-2.3-101
  - Load Response
  - Structural characteristics
  - Noise emission
  - Aerodynamic performance
  - Severe wind environment
    - High atmospheric turbulence
    - High wind events
    - Extreme wind ramps.
- Advanced measurement techniques
- Validation datasets
  - Improve and develop design codes
- Leverage skills and resources of National Wind Technology Center and Siemens for mutual benefit

Siemens SWT 2.3-101

NREL NATIONAL RENEWABLE ENERGY LABORATORY SIEMENS

Rotor	
Diameter	101 m
Swept Area	8,000 m^2
Rotor Speed	6-16 rpm
Power Regulation	Pitch regulation with variable speed

Blades	
Type	B49
Length	49 m

Aerodynamic brake	
Type	Full-span pitching
Activation	Active, hydraulic

Transmission system	
Gearbox type	3-stage planetary/helical
Gearbox ratio	1:91
Gearbox oil filtering	inline and offline
Gearbox cooling	Separate oil cooler
Oil volume	Approximately 400 l

Mechanical brake	
Type	Hydraulic disk break

Generator	
Type	Asynchronous
Nominal power	2,300 kW
Voltage	690 V
Cooling System	Integrated heat exchanger

Yaw system	
Type	Active

Monitoring system	
SCADA system	WebWPS
Remote control	Full turbine control

Tower	
Type	Cylindrical and/or tapered tubular
Hub height	80 m or site-specific

Operational data	
Cut-in wind speed	3-4 m/s
Rated power at	12-13 m/s
Cut-out wind speed	25 m/s
Maximum 3s gust	55 m/s (standard version)
	60 m/s (IEC version)

Weights	
Rotor	62 tons
Nacelle	82 tons
Tower for 80 m hub height	162 tons

Grid connection	
Type	type-4

Inflow

80m met tower

- 6 levels of cup anemometers and directional vanes
  - 3m, 15m, 37m, 58m, 78m, 80m
- Sonic anemometer at 37m
- Thermometers at 58m and 3m
- Barometer
- North-East of dominant wind direction at ~2 diameters (2D)

Lidar (CU-Boulder)

- NRG Systems WINDCUBE®
- Upstream in dominant wind direction at ~ 2.8 D

135m met tower

- 6 levels of cup anemometers and directional vanes
  - 3m-134m
- 6 levels of sonic anemometers with 3-axis accelerometers
  - 15m-130m
- Thermometers at 4 levels
  - 3m-134m
- Barometer
- Precipitation sensor
- Service lift
- Upstream in dominant wind direction at 2D.

Sodar

- Second Wind Triton®
- Scintec SFAS®

Loads Tests

NREL SIEMENS
NATIONAL RENEWABLE ENERGY LABORATORY

Objective

- Study loading at high wind and high turbulence
  - Normal operation, idling, cut-in and cut-out
- Validate aeroelastic and CFD codes

Instrumentation

- Blades, tower and nacelle are instrumented with strain gages and accelerometers
  - Tower: 12m above base, 12m below yaw gear
  - Nacelle: main shaft
  - Blades:
    - ~1m, 15m , 25m, 34m, 41m, and 47m

B49 Blade Structural Tests

NREL NATIONAL RENEWABLE ENERGY LABORATORY SIEMENS

Static Load Test: Measure blade deformations

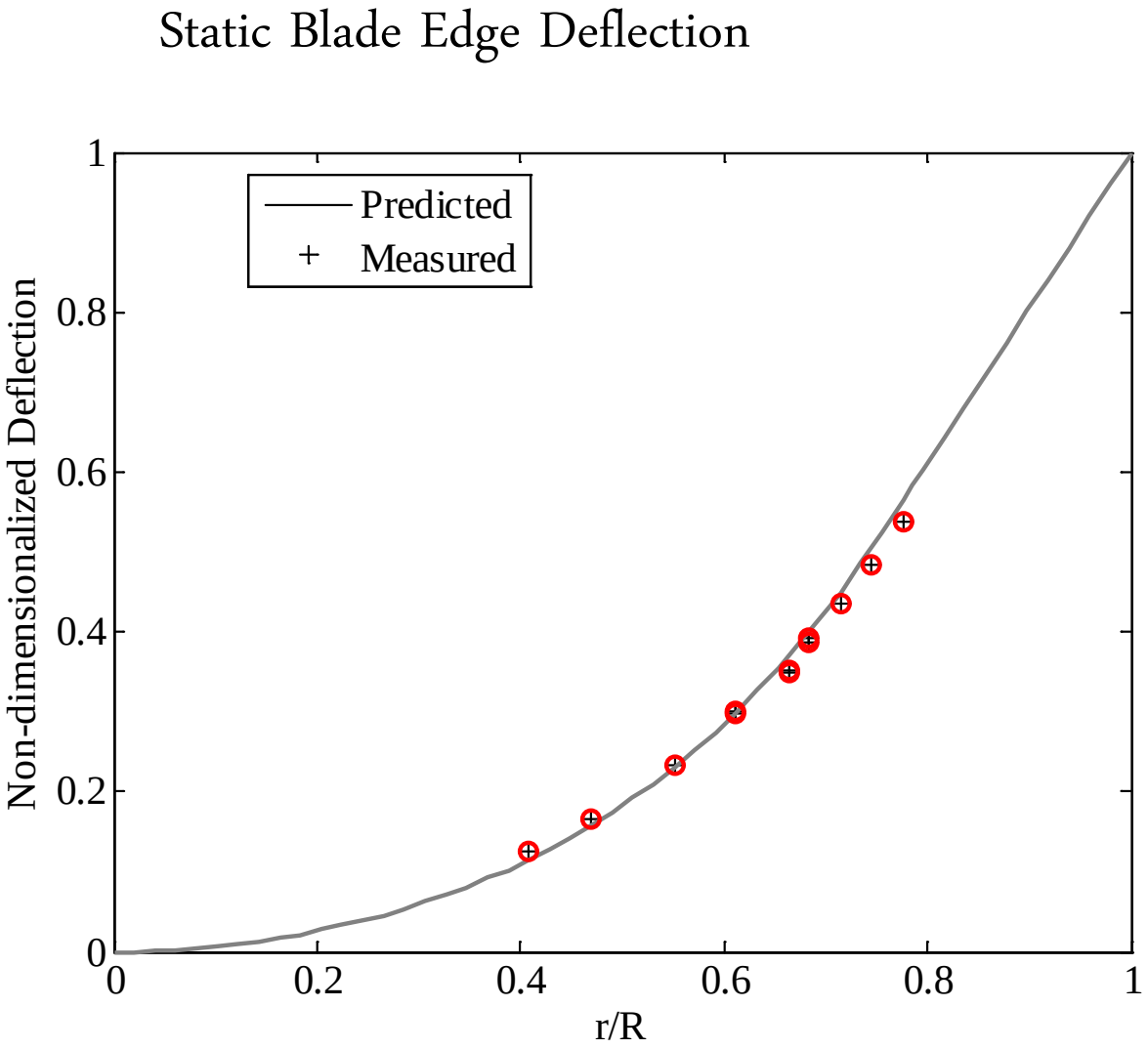
- Flap, edge, and torsion
- Two load positions (38.5m, 47.2m)
- Laser tracker, string pods, and inclinometers
- Test data match well with modeled analyses

Modal Test:

- First two flap, first edge, and first torsion modes
- High fidelity test
- Accelerometers mounted at 10 blade stations
- Impact hammer and snap-back methods for excitation
- Phase I on a softer test stand
  - Observed slightly lower frequencies than modeled results
- Phase II on a more rigid stand
  - May 2011

B49 Blade Structural Tests

NREL SIEMENS
NATIONAL RENEWABLE ENERGY LABORATORY

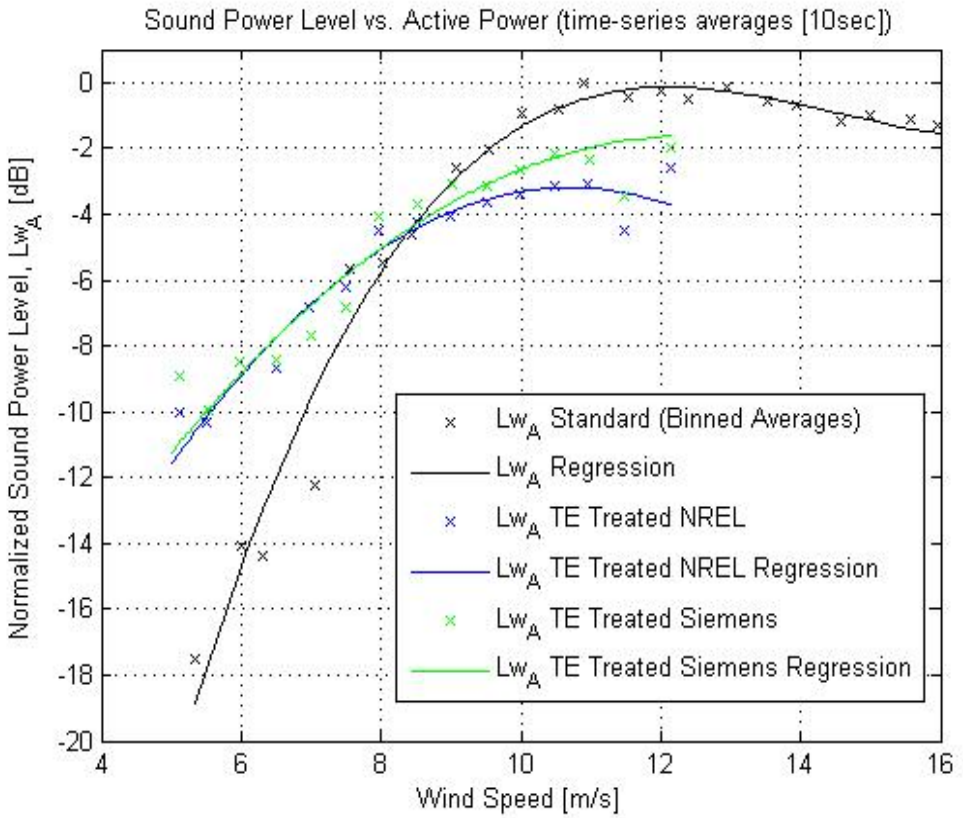


Noise Testing

NREL SIEMENS
NATIONAL RENEWABLE ENERGY LABORATORY

Testing of aeroacoustic noise mitigation devices

- Focus is on trailing edge (TE) noise



- IEC 61400-11 standard noise measurements
- Near field blade passing measurements
  - Comparative measurements of blades in different configurations
- Acoustic Phased Array measurements
  - Source localization and comparative measurements

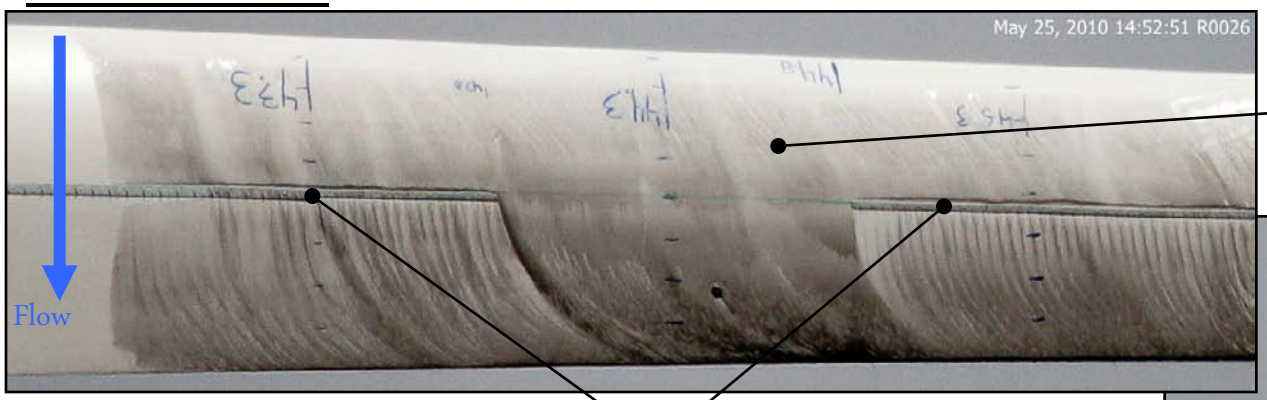
Flow Visualization – Tufts

NREL SIEMENS
NATIONAL RENEWABLE ENERGY LABORATORY

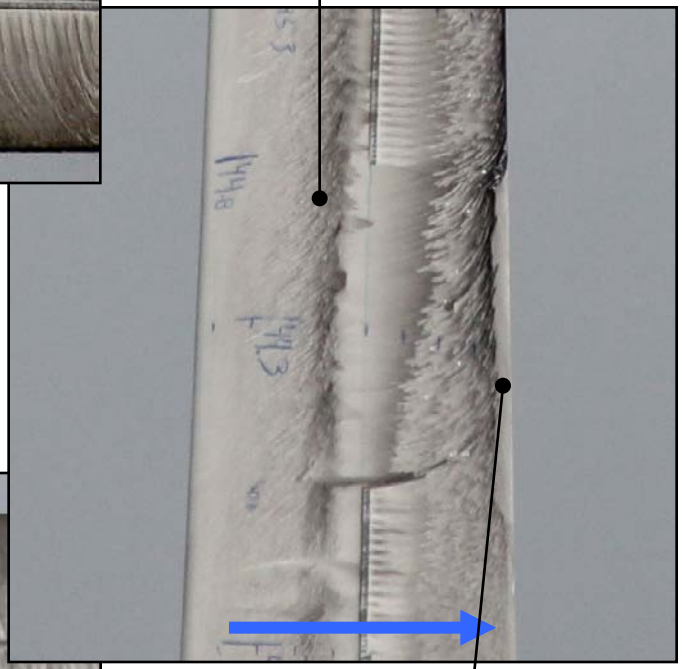
Flow Visualization – Oil

NREL SIEMENS
NATIONAL RENEWABLE ENERGY LABORATORY

Attached Flow



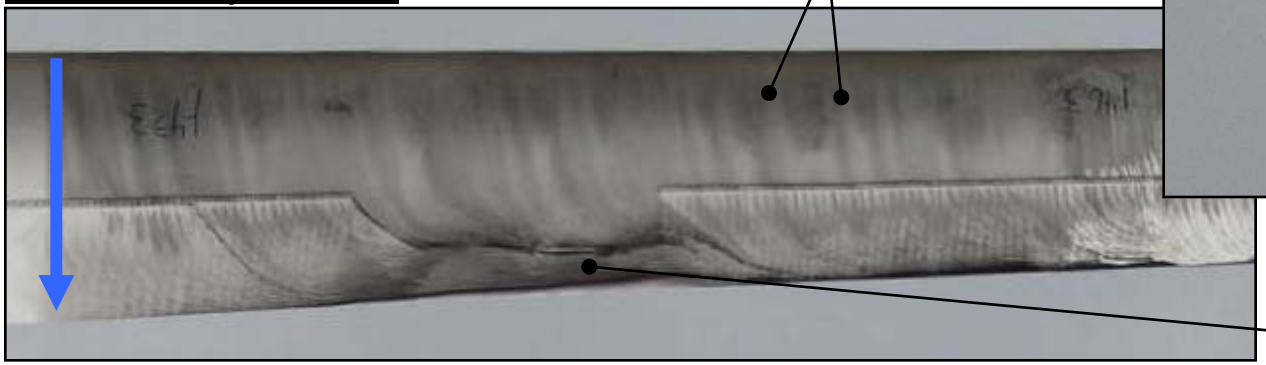
Transition



Vortex Generators

Turbulent Wedge

Forced Separation



Separated Region

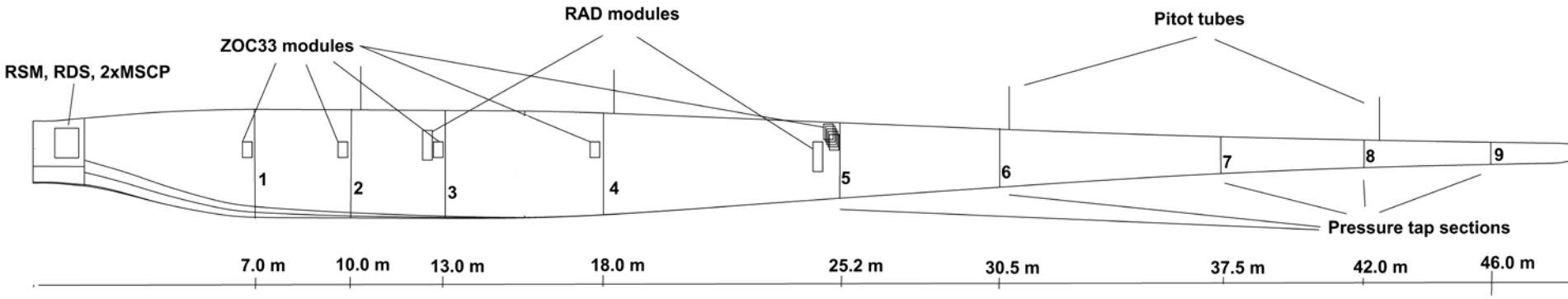
Aerodynamic Testing

Objective

- Gain further insight into aerodynamics SWT-2.3-101 wind turbine.
- Validate and improve aerodynamic design models.

Instrumentation

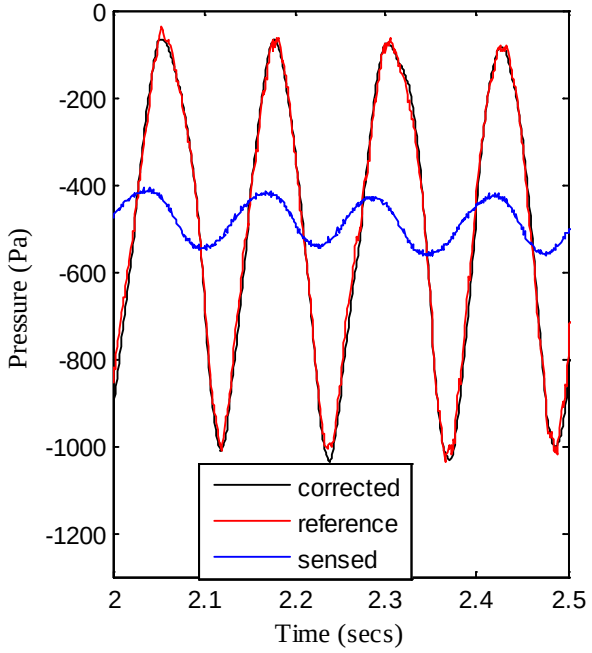
- Nine stations for pressure measurements.
  - Each station has about 60-64 taps.
- Four 5-hole (Pitot) probes for inflow velocity and angle.
- Scanivalve Corporation pressure system acquires data at 25 Hz.
  - Series of post-processing corrections to account for measurement distortions.

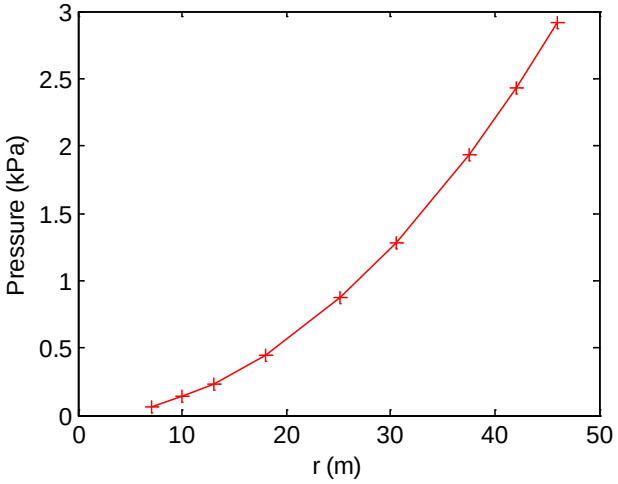


Aerodynamic Testing

Data Post-processing

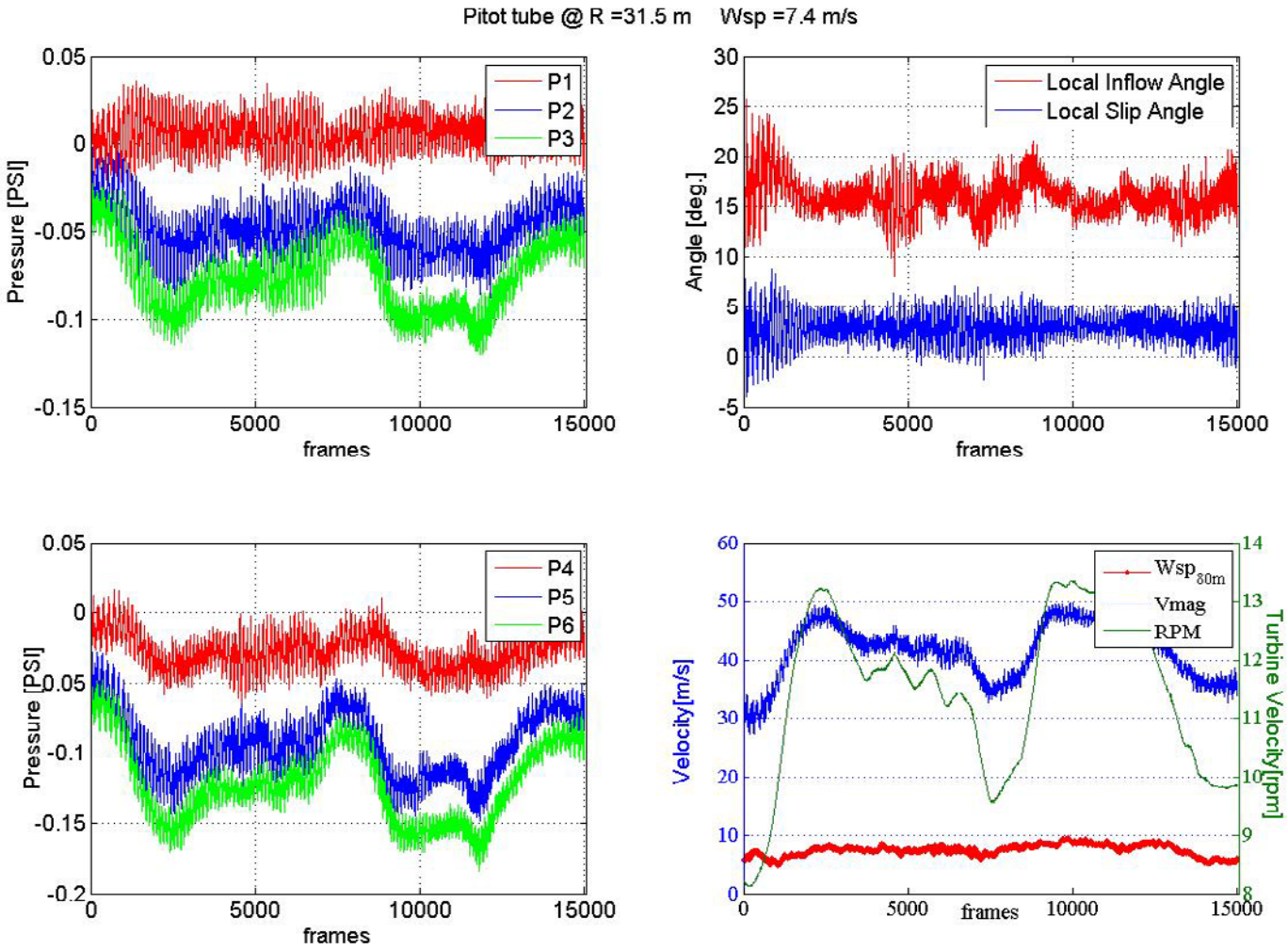
- Reference Pressure Correction
  - Static basket is not exposed to true barometric pressure
- Pressure Reconstruction
  - Measured pressure is damped and has a phase lag relative to surface pressures.
- Hydrostatic Correction
  - Translation of sensor in vertical plane leads to changes in hydrostatic pressure (~10 Pa/m)
- Centrifugal Correction
  - Rotation of the blade causes centrifugal force on column of air in tubing





Aerodynamic Testing – Initial Results

- Local inflow measurements



Measurements are at probe tip and have not been fully corrected.

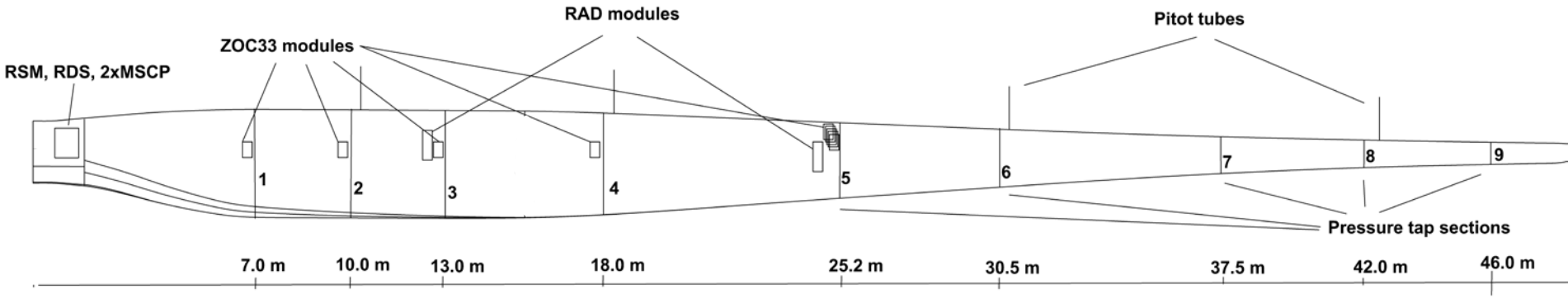
Aerodynamic Testing

Objective

- Gain further insight into aerodynamics SWT-2.3-101 wind turbine.
- Validate and improve aerodynamic design models.

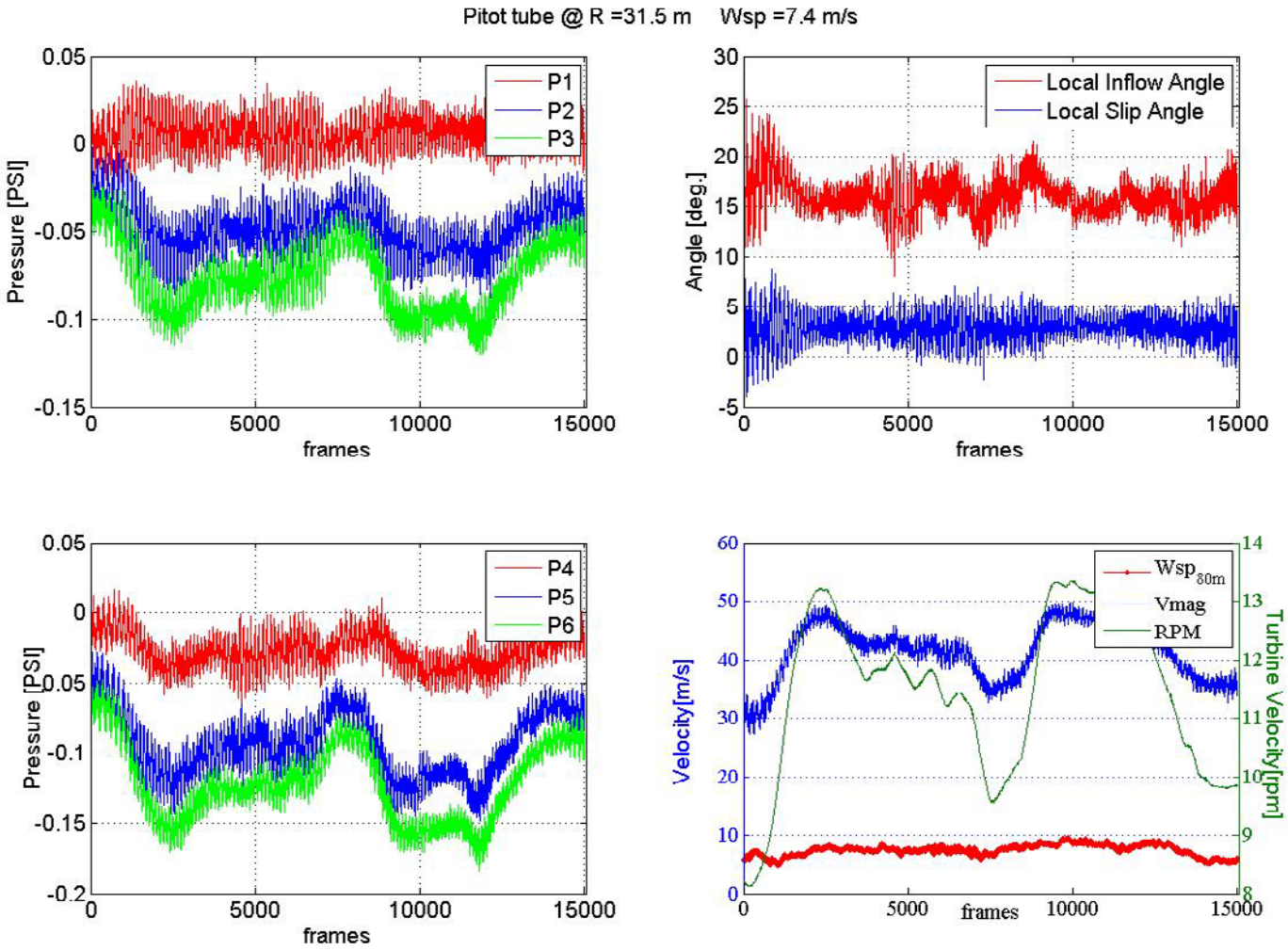
Instrumentation

- Nine stations for pressure measurements.
  - Each station has about 60-64 taps.
- Four 5-hole (Pitot) probes for inflow velocity and angle.
- Scanivalve Corporation pressure system acquires data at 25 Hz.
  - Series of post-processing corrections to account for measurement distortions.



Aerodynamic Testing – Initial Results

- Local inflow measurements

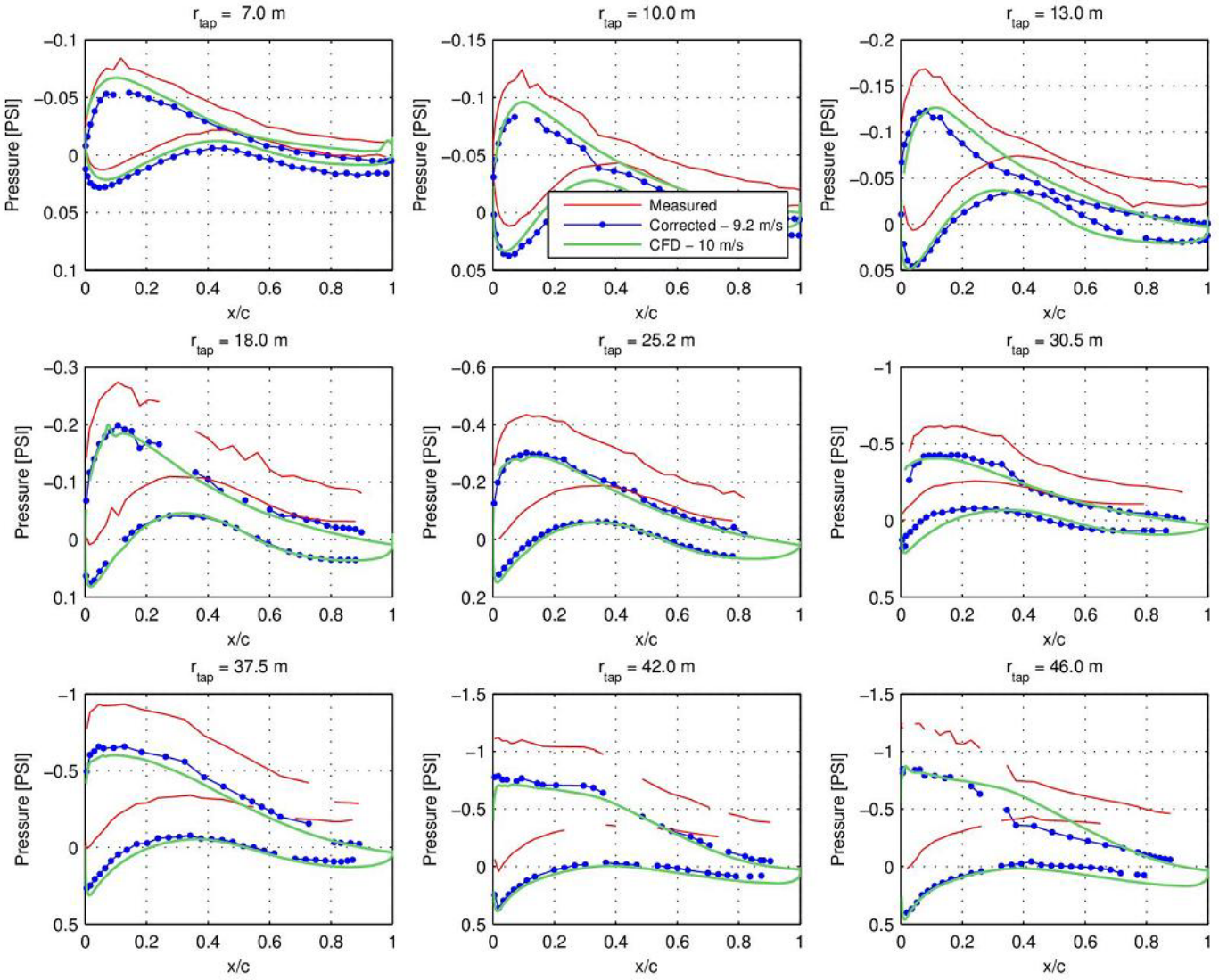


Measurements are at probe tip and have not been fully corrected.

Aerodynamic Testing – Initial Results

NREL SIEMENS
NATIONAL RENEWABLE ENERGY LABORATORY

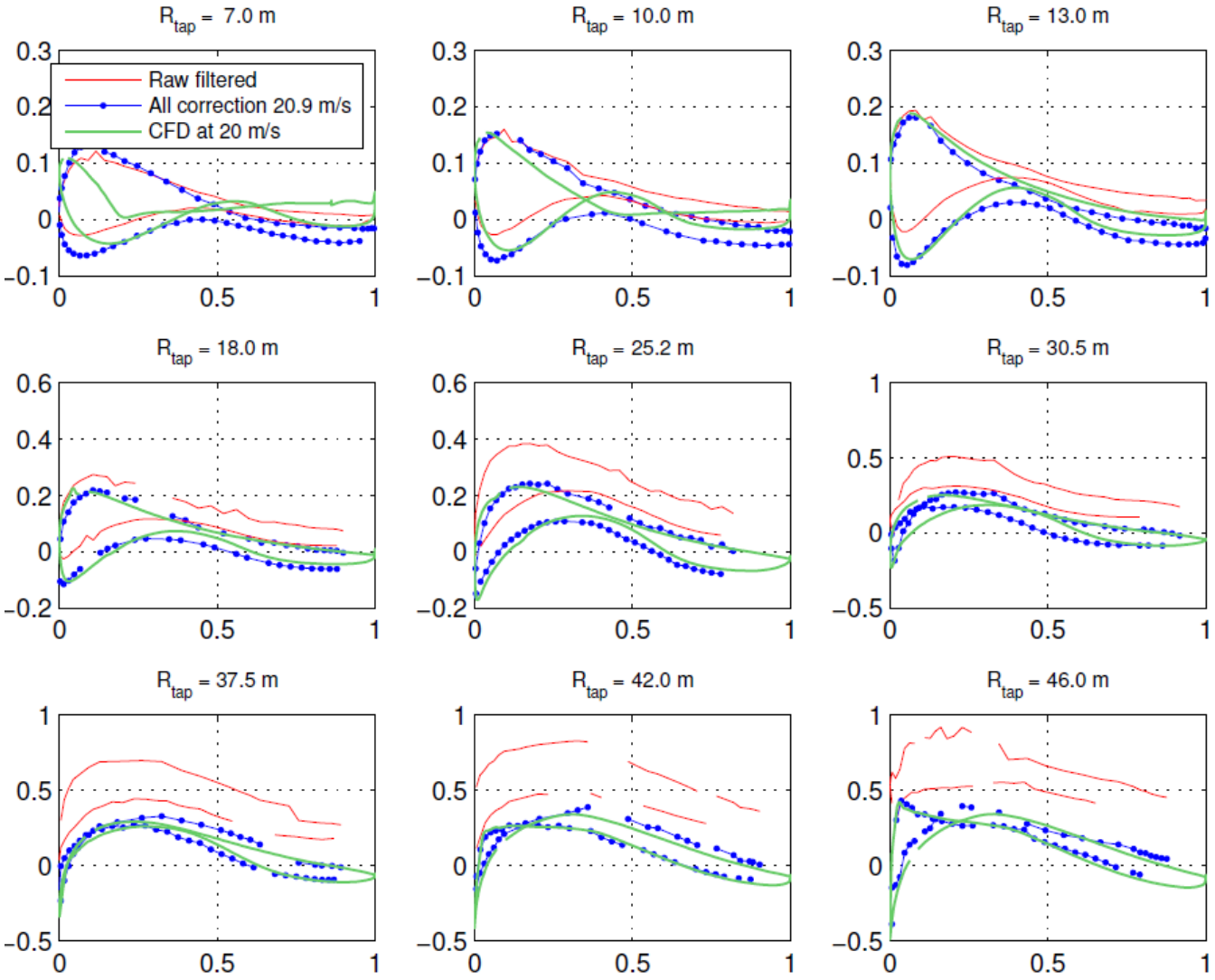
- Surface Pressure Measurements (~ 10 m/s)



Aerodynamic Testing – Initial Results

NREL SIEMENS
NATIONAL RENEWABLE ENERGY LABORATORY

- Surface Pressure Measurements (~ 20 m/s)



Other Testing

NREL SIEMENS
NATIONAL RENEWABLE ENERGY LABORATORY

Independent testing featuring test turbine

- CRADA between Renewable Energy Systems (RES) and NREL to look at foundation loads
- NOAA/LLNL/NREL/CU Turbine Wake and Inflow Characterization Study (TWICS).
  - DOE Wind and Hydropower program - “20% by 2030”

Questions?

Siemens

Paul Medina

Manjinder Singh

Jeppe Johansen

Anna Rivera Jové

Ewan Machefaux

NREL

Lee Fingersh

Scott Shreck

Special thank you

Michael Asheim

Khanh Nguyen

Peter Horsager

Matt Brzezinski

The authors gratefully acknowledge the support of the US DOE Wind and Water Program Office via CRD-08-303