Wind Energy Simulation

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Content

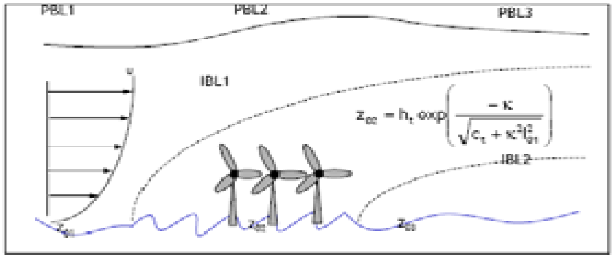
- Background
- Why CFD
- Who should be using CFD
- Process automation
  - Meshing/ Modelling / Reporting
- Case Studies
  - Single wake
  - Multiple wakes and forestry (Blacklaw wind farm)
  - Multiple wakes offshore
  - Complex terrain (Bolund)
- Conclusion

Background

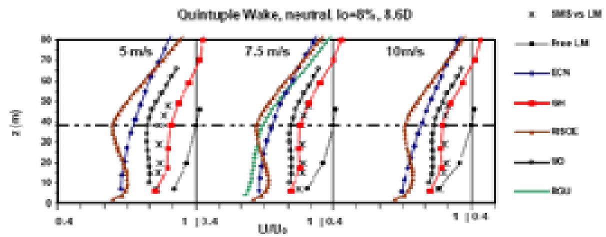
- Wind Industry faced with the need to consider more difficult sites for Wind Farms:
  - Terrain with complex orography
  - Large wind farms where multiple-wake effects are relevant
  - Dense forests
- Simple linearised tools (and parameterised models) have limitations for these cases
- CFD increasingly being used
  - Need for tools that can be used reliably by non CFD specialists
  - Automation of simulation process required
- Driven by customer needs for practical prediction capability

N-S Solvers vs. Linearised models

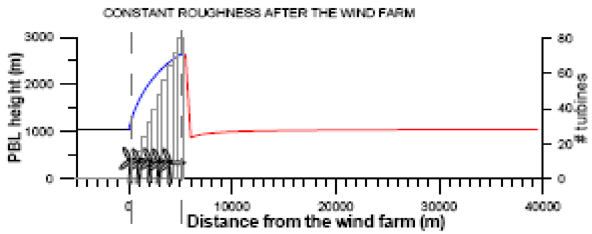
- **Advantages of Navier-Stokes solvers as compared to linearised models:**
  - Accurate prediction of turbulence:
    - flow turbulence is modeled or resolved using RANS/LES
  - Better prediction of multiple-wake effects:
    - accurate geometry description and wake prediction from multiple installations
    - no limit to number of wind turbines considered
  - Separation/shade effects due to complex terrain
    - complex terrain is resolved
    - shading effects, recirculation and separation are captured



Ref. 3



Ref. 1



Ref. 1

N-S Solvers vs. Linearised Models

- **Advantages of Navier-Stokes solvers as compared to linearised models:**
  - Possibility of computing unsteady peak loads
    - important for structural loads
- **Some perceived drawbacks of CFD:**
  - It can be CPU intensive
  - Needs experienced users for the production of reliable data

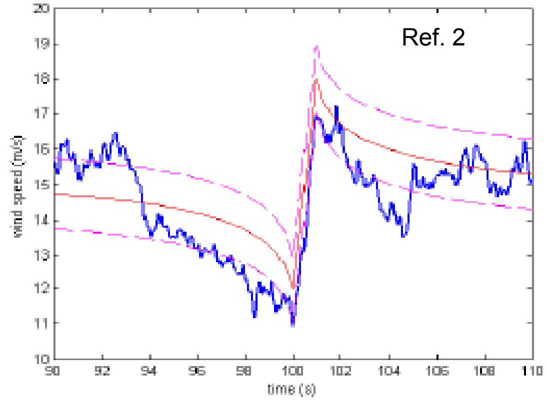


Figure 9: An example of a gust with a velocity jump of 6 m/s at t=100 s to 101 s. The smooth curve indicates the (theoretically) mean gust shape; the dotted lines indicate the standard deviation of the gust shape.

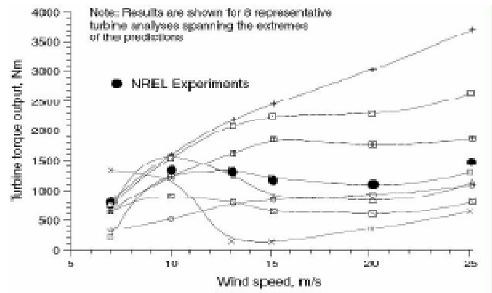


Figure 6: Representative 'in the blind' predictions of turbine power output as a function of wind speed compared to experimental measurements, Leishman 2002.

1. Barthelmie, R.J et al., Modelling and measurements of wakes in large wind farms, Journal of Physics: Conference Series 75 (2007) 012049.
2. Van Kuik, V.A.M. et al., The status of wind energy, 4th European and African Conference on Wind Engineering, Prague, 11-15 July 2005.
3. Barthelmie, R.J et al., Modelling Uncertainties in power prediction offshore, IEA, Risoe, March 2004.

Limitations of Linearised Models

- Linearised models operate outside their recommended envelope when flow separation occurs:
- Measured by Ruggedness Index (RIX), percentage area over a radius of 3500m where slope > 0.3
- Equivalent to 16.7° critical angle

'If the RIX is > 0%, parts of the terrain are steeper than 0.3 and flow separation may occur in some sectors. This situation is generally outside the performance envelope of WAsP and prediction errors may be expected. Large RIX values will lead to large errors in the flow modelling. '

Mortensen, Landberg and Troen, WAsP Utility Programs Manual, Sept 2004, Riso National Laboratory

Alaiz Hill

- Complex Terrain, RIX 16%

‘As it is shown, CFD extrapolates wind speed between masts more accurately in almost all cases giving an average absolute error of 1.75% significantly less than the others: 5.67% for WAsP Engineering and 5.41% for WAsP.’

D. Cabezón, A. Iniesta, E. Ferrer, I. Martí, ‘*Comparing linear and non linear wind flow models*’, http://www.ewec2006proceedings.info/allfiles2/825_Ewec2006fullpaper.pdf

Influence of Forestry

- Forestry has a big influence on flow separation
  - Increases tendency for flow to separate
  - Critical angle for recirculation reduced by ~ ¼° per metre of tree height
    - 12m trees -> critical angle ~14°
    - 20m trees -> critical angle ~12°

P. Stuart, I. Hunter, R. Chevallaz-Perrier, G. Habenicht, *'Predicting and Understanding the Breakdown of Linear Flow Models '* , http://ewec2009proceedings.info/proceedings/index.php?page=info2&id=151&id2=619&ordre=45&tr=&searchin=&what=&searchtext=&day=4&top=&fil1=&fil2=&fil2&ord1=&sess=#top

Ross, AN; Vosper, SB (2005), '*Neutral turbulent flow over forested hills*', Q J ROY METEOR SOC, 131, 1841-1862. doi:10.1256/qj.04.129.

Who should be using CFD

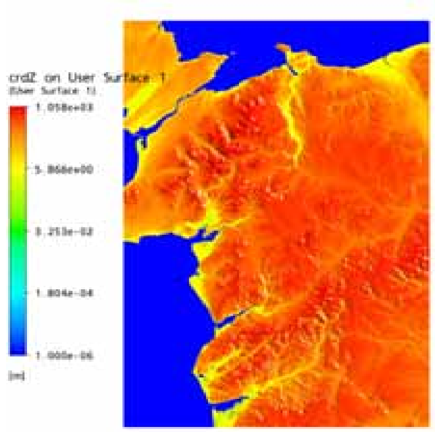
- Wind Farm Developers
  - Initial resource assessment
    - Is this a good place for a wind farm
  - Detailed layout planning
    - Number of turbines, locations
    - Effect of wakes, forestry management
- Investors
  - Will there be a return on investment (ROI)
- Turbine manufacturer
  - Turbulence levels, leading to turbine failure
  - IEC guidelines for turbulence intensity

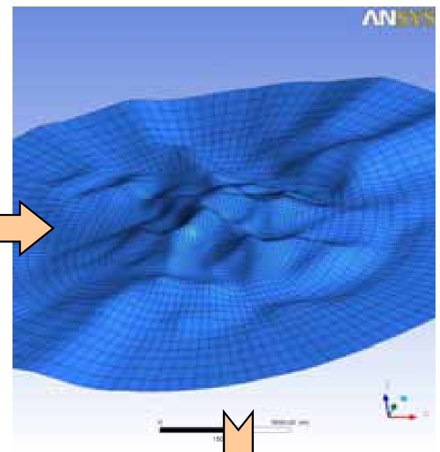
Tools for Automated Solution

- WindModeller: set of tools wrapped around ANSYS commercial CFD products:
  - To allow non-CFD experts to perform wind farm analyses in automated way
  - Driving ANSYS CFX or FLUENT flow solver
  - Provide access to State Of The Art CFD software
  - Customised setup and post-processing scripts can easily be altered by the user to further develop the tools
  - Allows advanced user to encapsulate their own expertise
  - Fast turnaround on modern multi-core systems

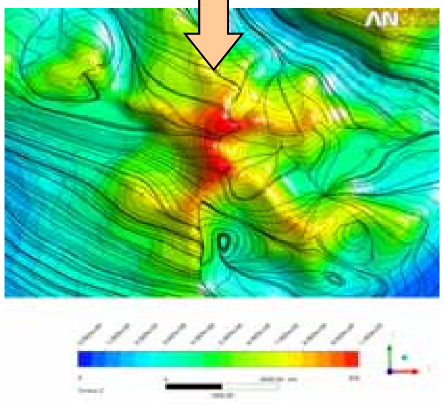
Tools for Automated Solution

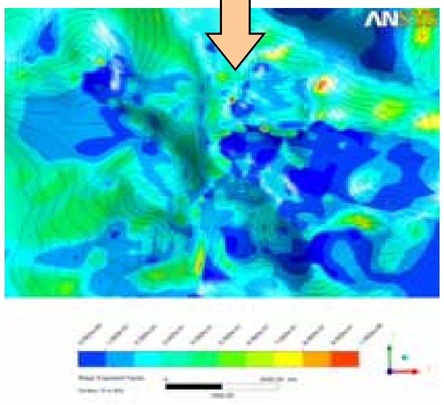
- Objective
  - From Map to Mesh to CFD to Report
  - Data Extraction and Automation of Analysis

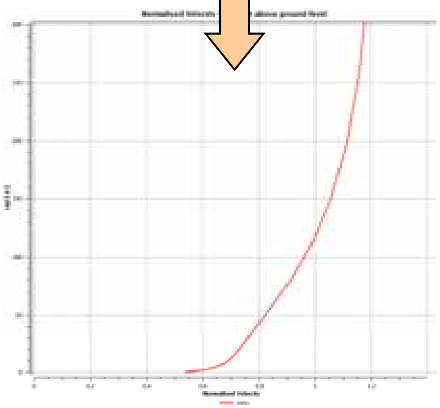


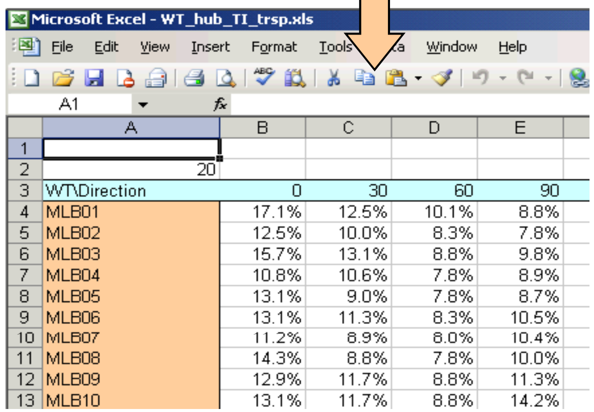


CFD solution + automated post-processing







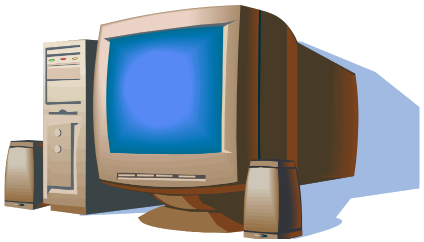


	A	B	C	D	E
1					
2	20				
3	WT\Direction	0	30	60	90
4	MLB01	17.1%	12.5%	10.1%	8.8%
5	MLB02	12.5%	10.0%	8.3%	7.8%
6	MLB03	15.7%	13.1%	8.8%	9.8%
7	MLB04	10.8%	10.6%	7.8%	8.9%
8	MLB05	13.1%	9.0%	7.8%	8.7%
9	MLB06	13.1%	11.3%	8.3%	10.5%
10	MLB07	11.2%	8.9%	8.0%	10.4%
11	MLB08	14.3%	8.8%	7.8%	10.0%
12	MLB09	12.9%	11.7%	8.8%	11.3%
13	MLB10	13.1%	11.7%	8.8%	14.2%

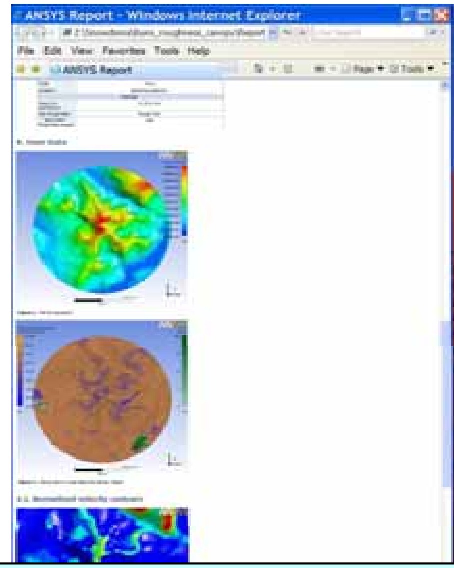
WindModeller: Simulation Process

- Wind farm simulation process from user perspective
  - Set up analysis on desktop computer (either via GUI or command line)
  - Submit job to:
    - Run possible large number of cases on the local machine or on a remote server
    - Postprocess results to automatically generate reports/summary data files
  - Possibility to perform additional post-processing on individual results files using CFD Post

Setup on desktop



Run on local or remote computer

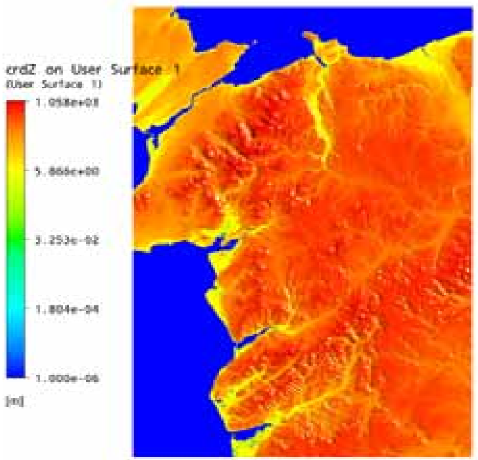


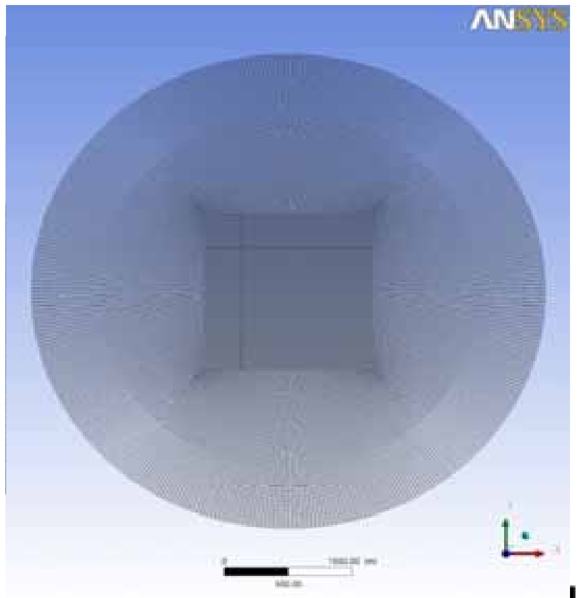
Report as html file

ANSYS

Meshing Approach

- Current recognised terrain format
  - .map files (WAsP format)
  - Generic point data file (.csv)
    - X,Y,Z (DTM/DEM)
  - SRTM (Shuttle Radar Topography Mission), freely available, 90m resolution (finer resolution in the US)
  - OS NTF and DXF data (UK)
  - STL
- Terrain converted to tesselated format (STL)
- Meshing with custom tools
  - Fixed mesh structure, hexahedral mesh (5 or 9 blocks), aimed at process automation
  - Template mesh morphed onto STL terrain representation
  - Fast, robust

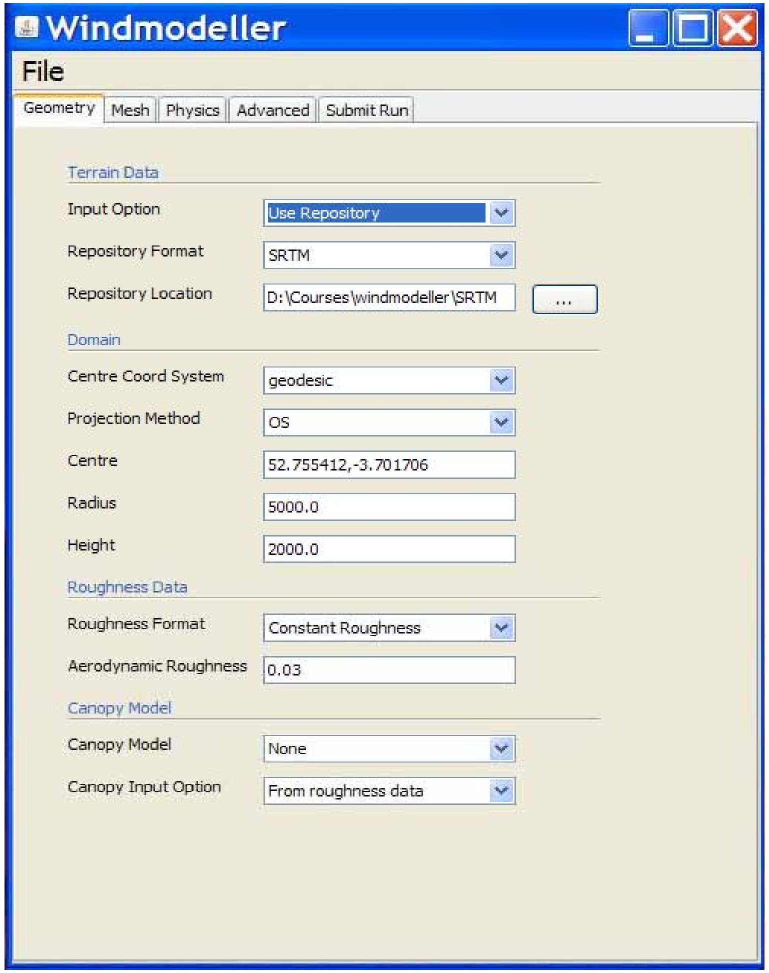




Meshing: User Input

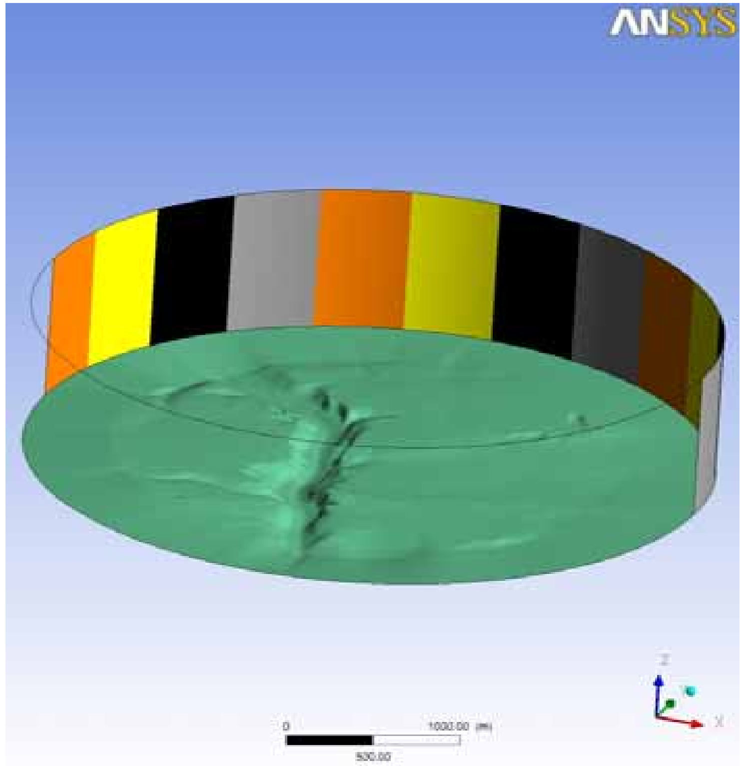
User input:

- Radius and height of domain
- Coordinates of the centre of the domain
- Type of terrain data, type of coordinates used.
- Horizontal and vertical grid resolution (geometric progression used in the vertical)



Setup

- Outer surface divided into 24 regions
  - 12 for inlet b.c.
  - 12 for outlet b.c.
- Setup automated to run for e.g. 12 wind directions
  - Easy to do more directions
- Selection of surfaces defining inlet/outlet automated in script running cases for various wind directions
- → meshing done only once



Flow Modelling in WindModeller

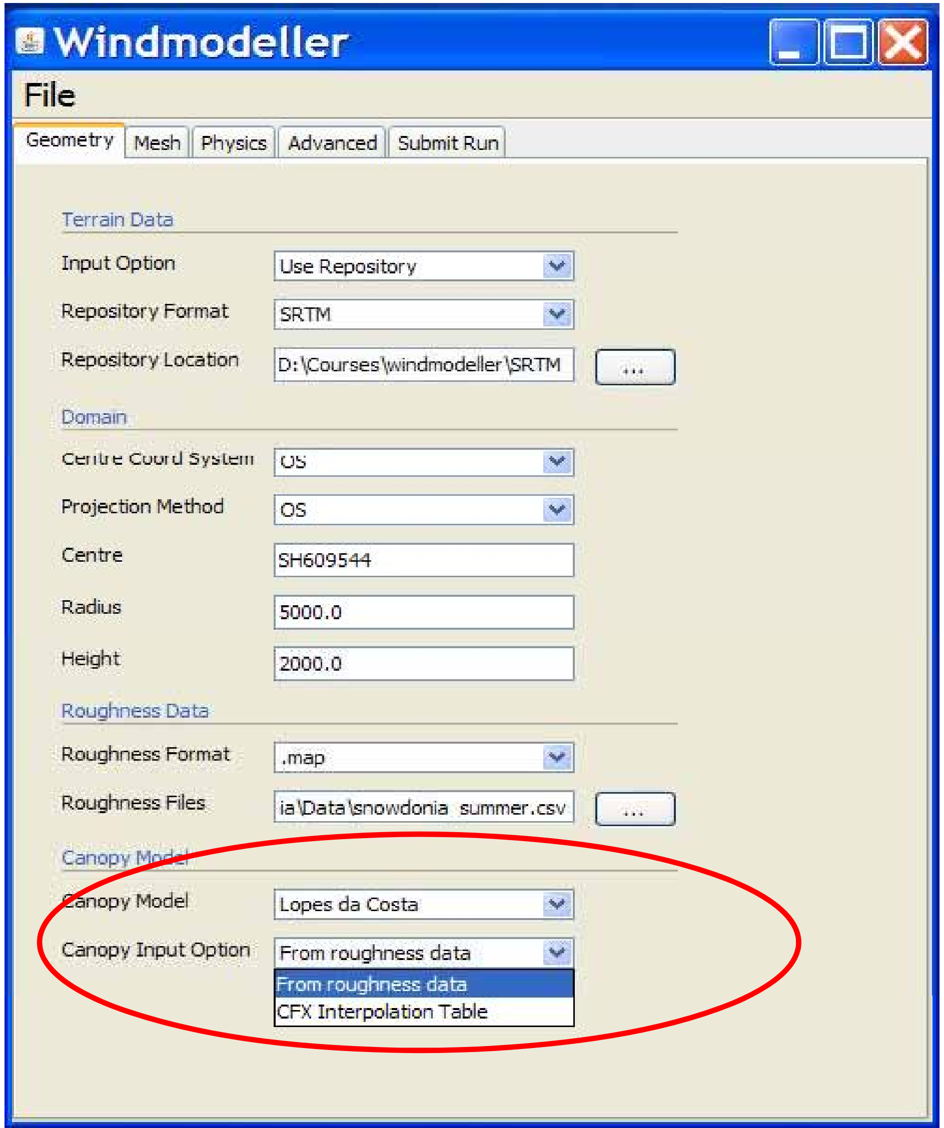
- Atmosphere modelled as:
  - incompressible fluid (Air at 15C),
  - assuming neutral stability (i.e. no effect of temperature included),
  - solving for steady state RANS
- Turbulence modelled via two-equation model
  - Shear Stress Transport (SST) turbulence model or k- ε.
- Ground modelled as rough wall (spatially variable roughness)
- Inlet boundary conditions
  - Classical constant-shear Atmospheric Boundary Layer profiles (Durbin & Petterson Reif, Richards and Hoxey):

$$u = \frac{u_*}{\kappa} ln(\frac{z}{z_0}) \qquad k = \frac{u_*^2}{C_\mu^{1/2}} \qquad \varepsilon = \frac{u_*^3}{\kappa z}$$

- Additional physics:
  - **Forest canopy model** (resistive term in momentum equation + additional source terms in turbulence model)
  - **Multiple wake model** (actuator disk model)

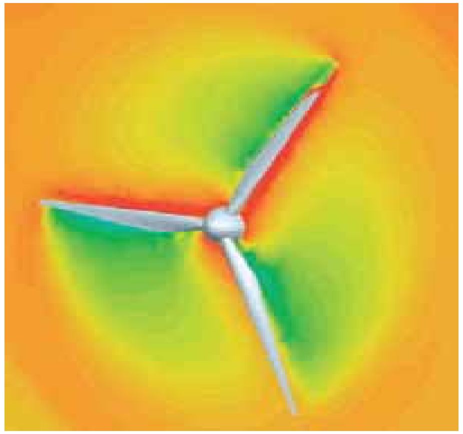
Switching on the Forest Canopy Model in GUI

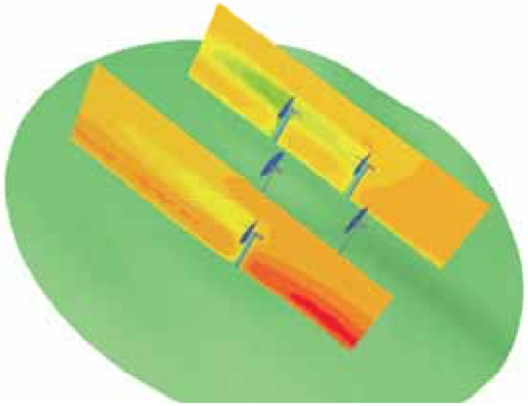
- Select ‘Canopy Model’. Options are:
  - None
  - Svensson
  - Lopes da Costa
  - Resistance in momentum only
- Enter ‘Canopy Input Option’
  - From roughness data
  - CFX Interpolation Table



Wake Modelling

- Hierarchy of Wake Models available in ANSYS CFD
- Resolved blade models
- Virtual Blade Models
- Simple Actuator Disk Models
  - Provide practical model for calculations with many turbines
  - Input is turbine thrust curve, turbine diameter, turbine hub height
  - Provides momentum sink in cylindrical volume surrounding each turbine
  - Basis of Models for WindModeller

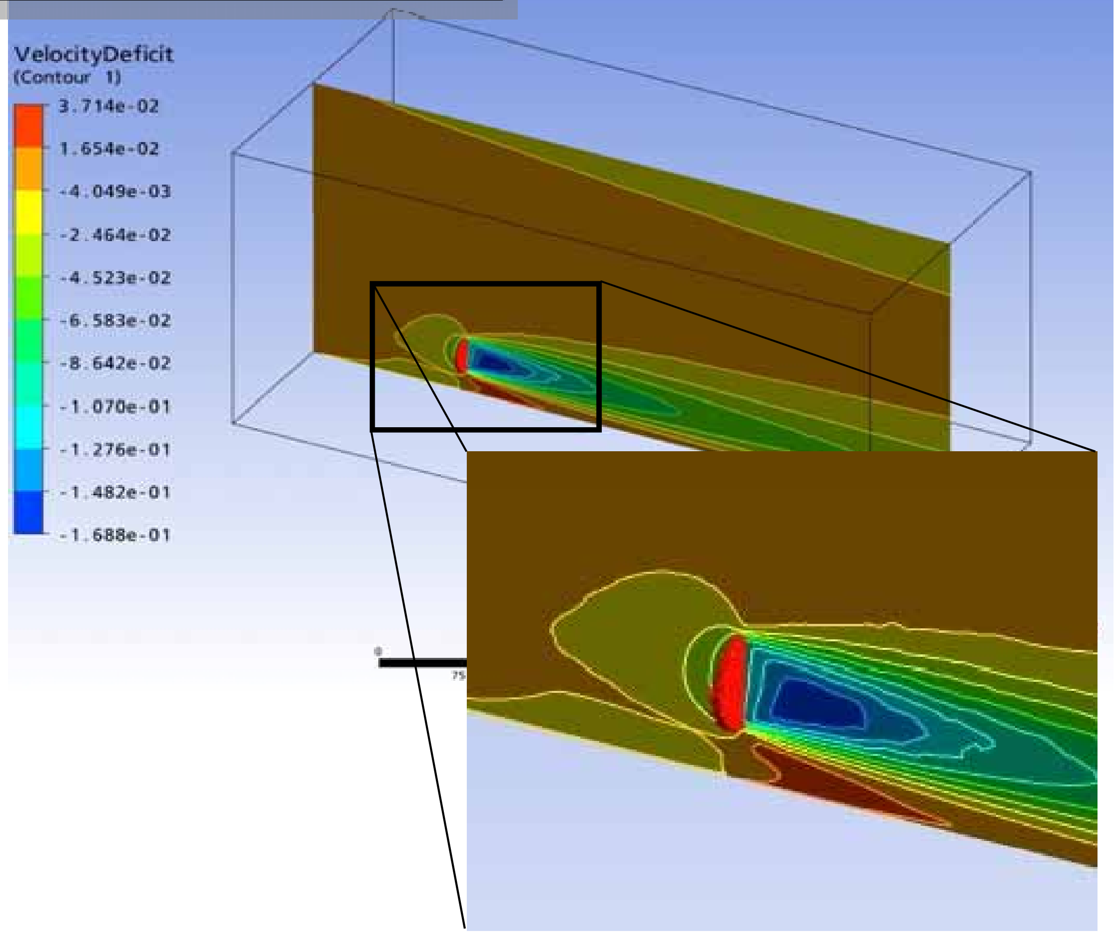




Simple Wake Model

- Wind turbine represented by momentum sink (constant thrust per volume) within identified rotor disk.
- Wind turbine orientation parallel to wind direction at inlet
- Works on any type of mesh
- Best results will be obtained with resolution that captures the wind turbine
- User input:
  - Coordinates of hub location, WT diameter, WT thrust and power curve

$$F_i = Thrust = C_T \frac{1}{2} \rho A_D U_\infty^2$$

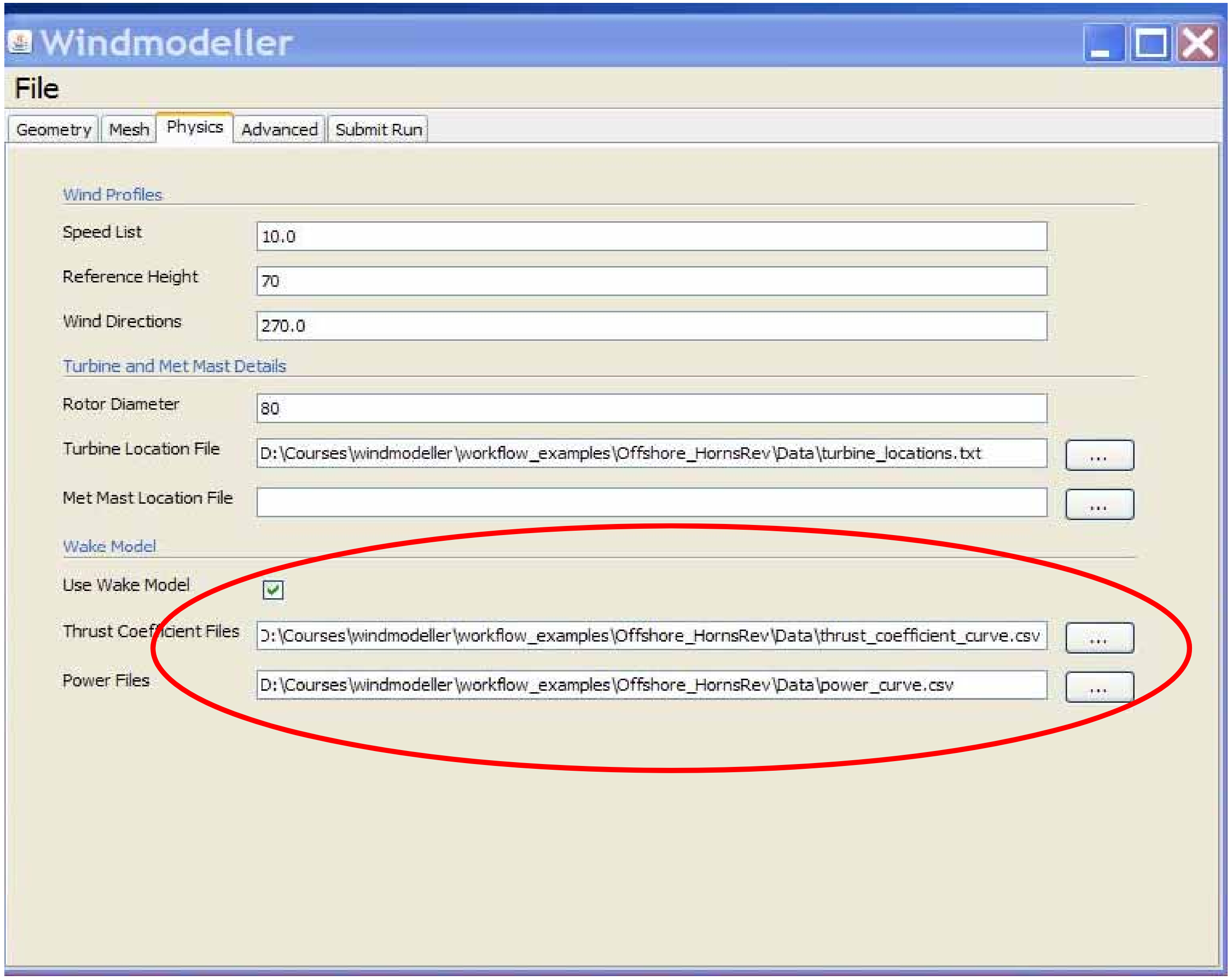


Mesh Adaption to Resolve WT rotor

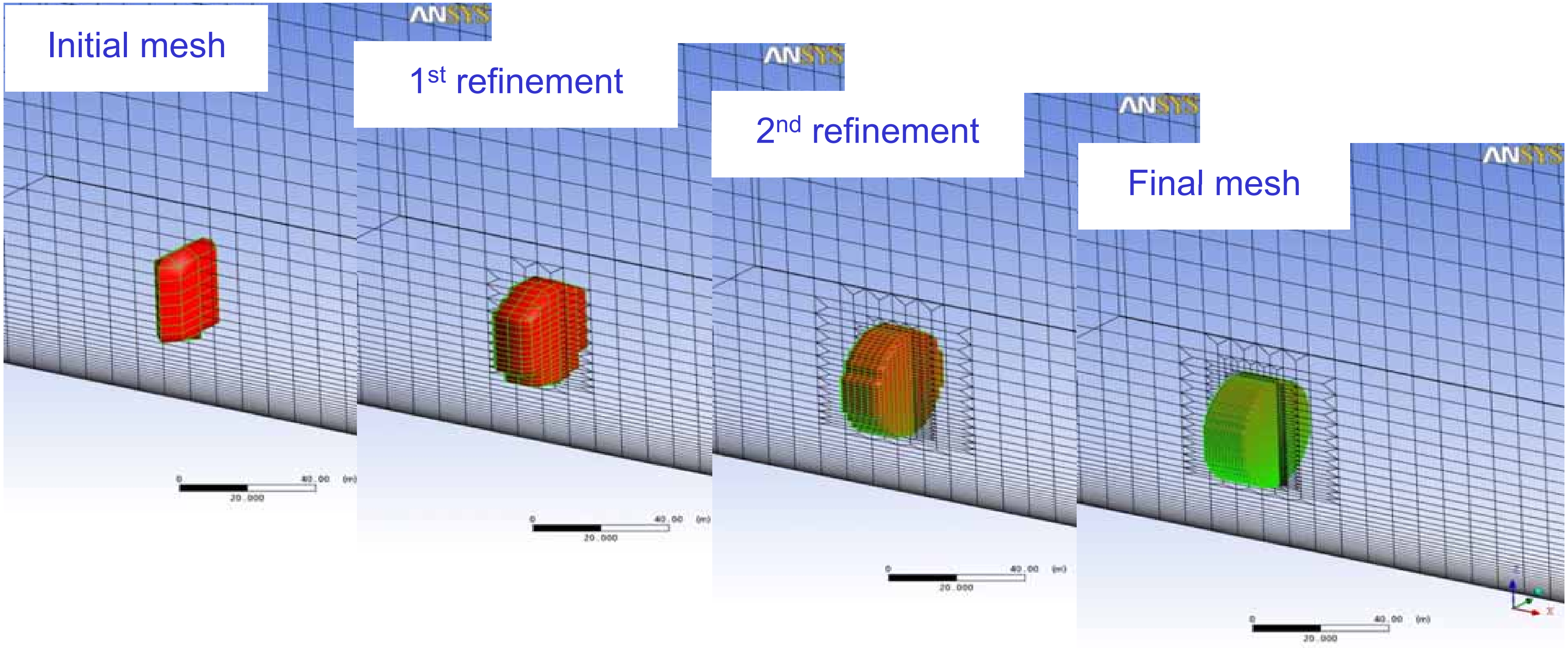
- Two ways to resolve wind turbine rotor:
  - Resolve rotor in initial mesh
    - Requires meshing for each wind direction
    - Difficult to keep good quality boundary layer mesh when rotor is present
  - Resolve rotor with mesh adaption during solution stage
    - Adaption criteria based on gradients of additional variable defining the wind turbine location
    - Advantage:
      - only one initial mesh (i.e. no need to provide wind direction dependent mesh)
      - Easier to preserve boundary layer mesh in most of domain

Enabling Multiple Wake Model in GUI

- Select 'Use Wake Model'
- Provide path to files containing:
  - Wind turbine locations
  - Thrust Coefficient
  - Power curve
- Mesh adaption included automatically

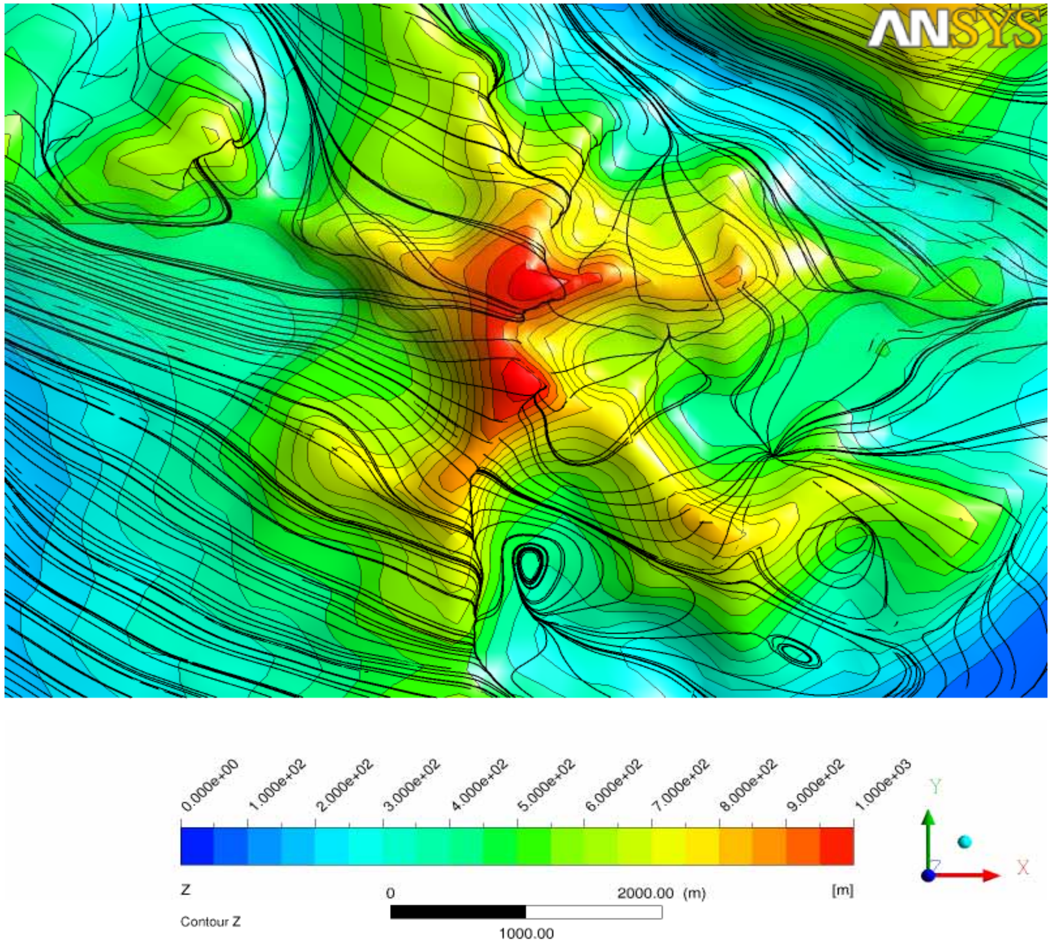


Mesh Adaption on WT Rotor



Post-Processing in WindModeller

- As part of the automated approach WindModeller can generate:
  - Plots of streamlines (identification of recirculation zones)
  - Plots at constant height AGL and profiles at wind turbine/mast locations for quantities such as normalised velocity, turbulence intensity, shear exponent factor
  - Exported data tables of similar quantities at wind turbine/mast locations
  - Export to Google Earth (.kml files)
  - Automated report in html format



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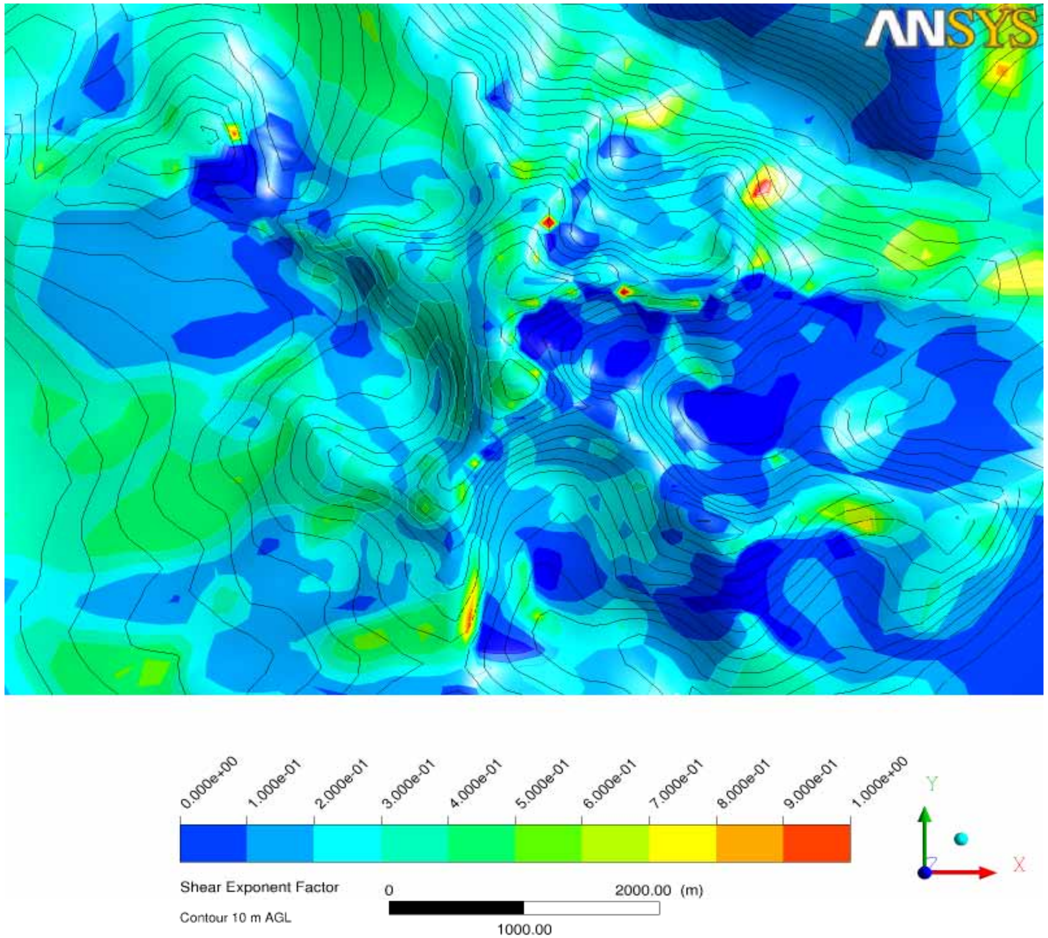

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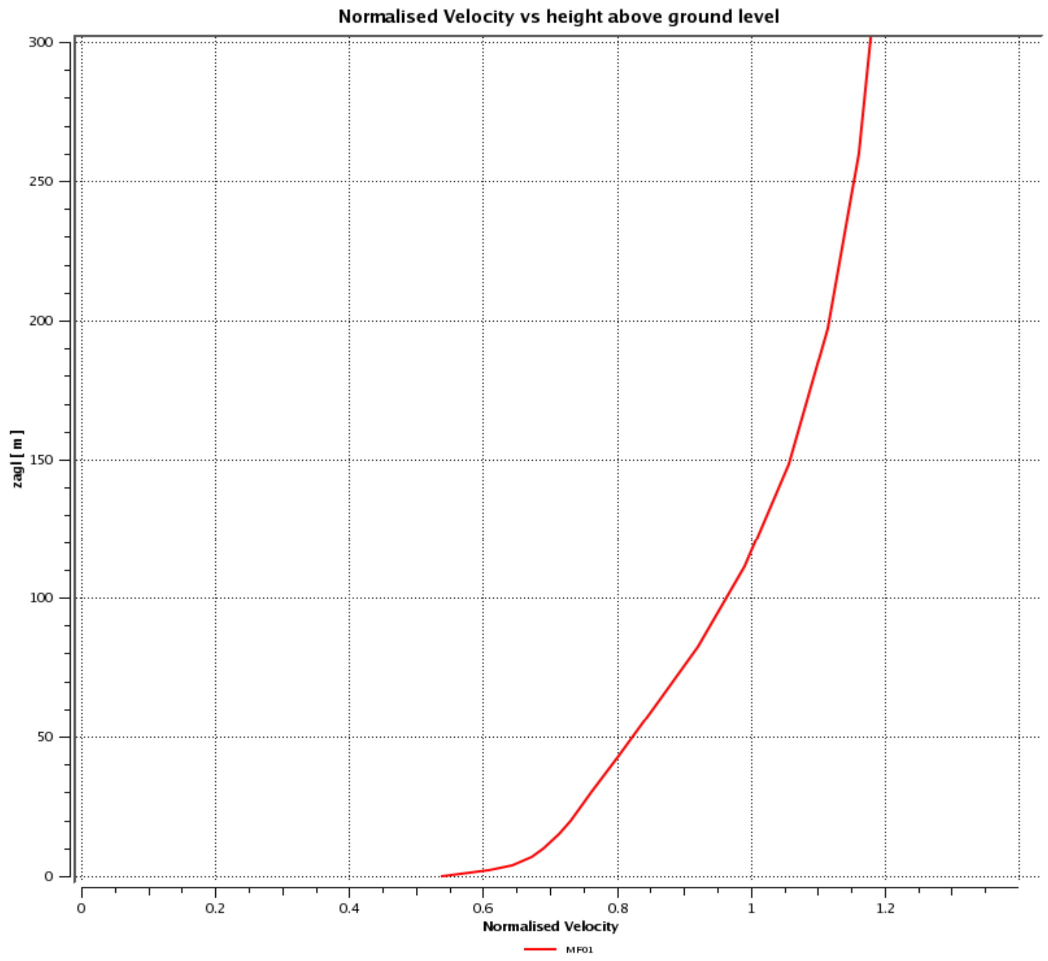

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Microsoft Excel - WT_hub_TI_trsp.xls

	A	B	C	D	E
1					
2	20				
3	WT\Direction	0	30	60	90
4	MLB01	17.1%	12.5%	10.1%	8.8%
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6	MLB03	15.7%	13.1%	8.8%	9.8%
7	MLB04	10.8%	10.6%	7.8%	8.9%
8	MLB05	13.1%	9.0%	7.8%	8.7%
9	MLB06	13.1%	11.3%	8.3%	10.5%
10	MLB07	11.2%	8.9%	8.0%	10.4%
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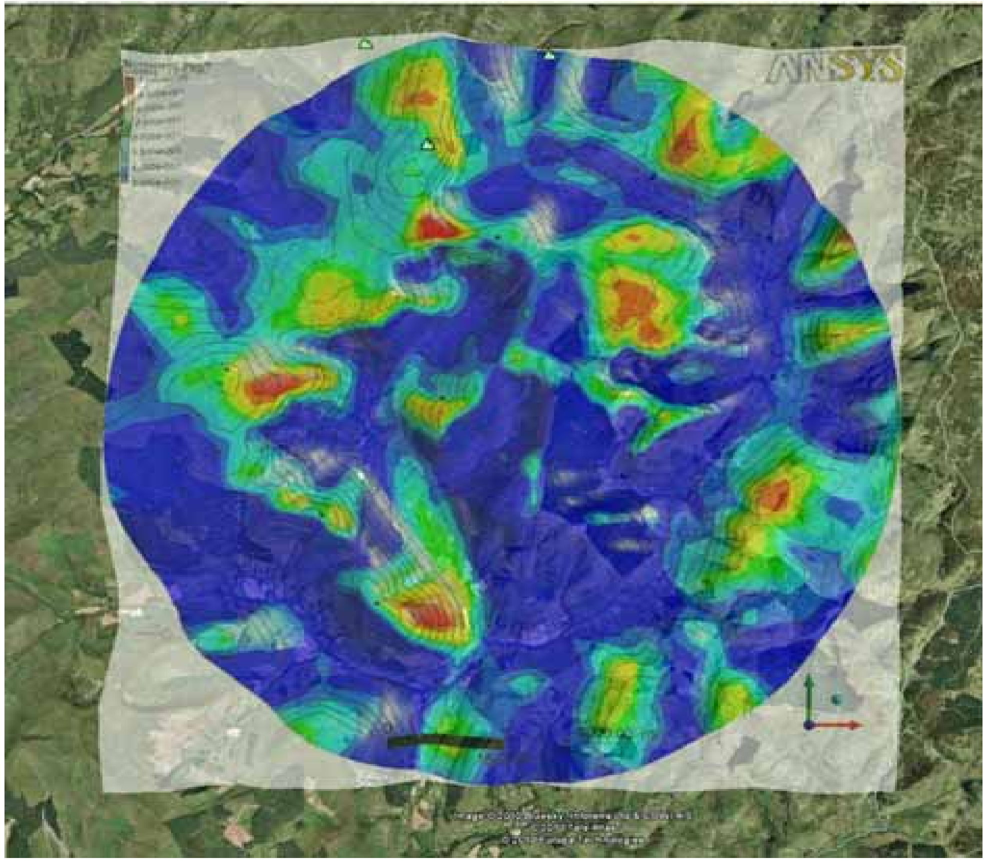
  - Automated report in html format



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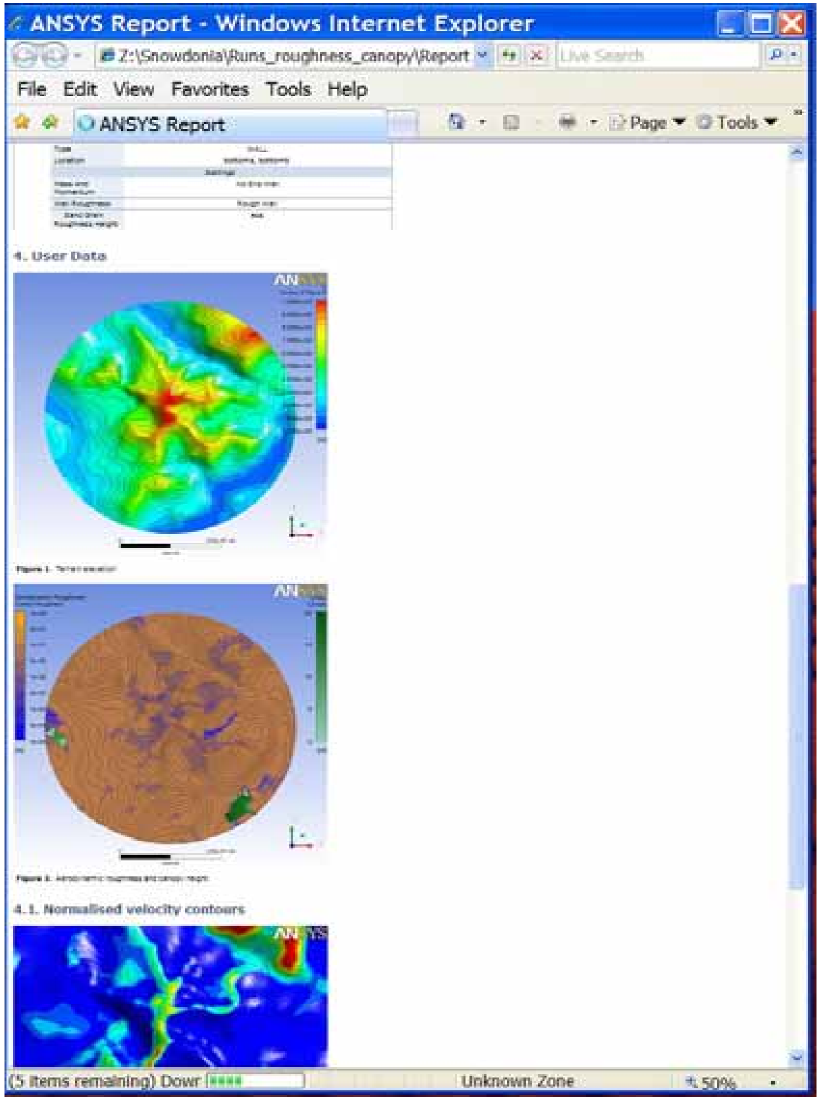
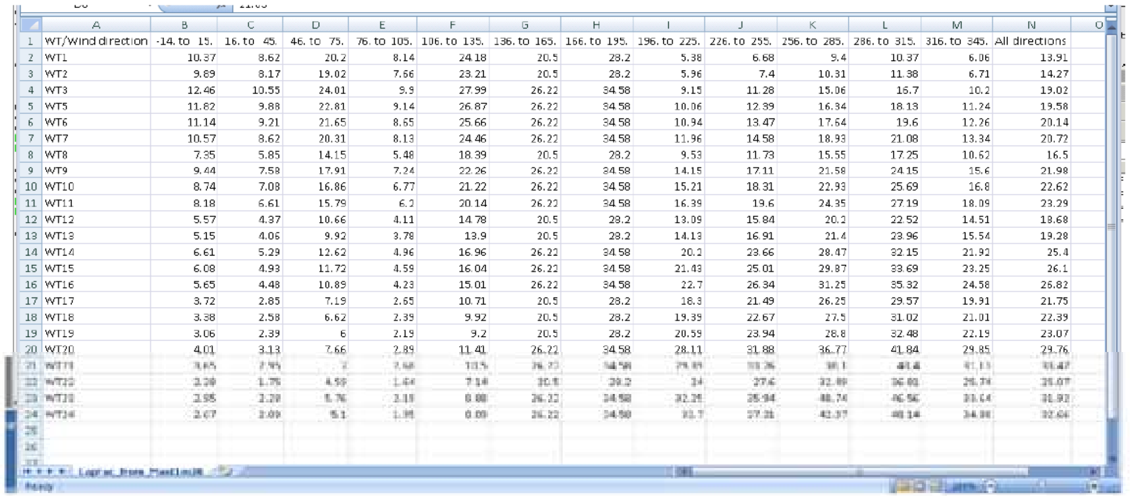
  - Exported data tables of similar quantities at wind turbine/mast locations
  - Export to Google Earth (.kml files)
  - Automated report in html format, including the above



Energy Assessment

- **Automated Energy Assessment**
- **Wind data for input:**
  - **Time series or Frequency tables**
- **Allows for multiple masts and with / without wake calculations**
- **Masts before or after wind turbines installed**



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	WT/Wind direction	-14. to 15.	16. to 45.	46. to 75.	76. to 105.	106. to 135.	136. to 165.	166. to 195.	196. to 225.	226. to 255.	256. to 285.	286. to 315.	316. to 345.	All directions
2	WT1	10.37	8.62	20.2	8.14	24.18	20.5	28.2	5.38	6.68	9.4	10.37	6.06	13.91
3	WT2	9.89	8.17	19.02	7.66	23.21	20.5	28.2	5.96	7.4	10.31	11.38	6.71	14.27
4	WT3	12.46	10.55	24.01	9.9	27.99	26.22	34.58	9.15	11.28	15.06	16.7	10.2	19.02
5	WT5	11.82	9.88	22.81	9.14	26.87	26.22	34.58	10.06	12.39	16.34	18.13	11.24	19.58
6	WT6	11.14	9.21	21.65	8.65	25.66	26.22	34.58	10.94	13.47	17.64	19.6	12.26	20.14
7	WT7	10.57	8.62	20.31	8.13	24.46	26.22	34.58	11.96	14.58	18.93	21.08	13.34	20.72
8	WT8	7.35	5.85	14.15	5.48	18.39	20.5	28.2	9.53	11.73	15.55	17.25	10.62	16.5
9	WT9	9.44	7.58	17.91	7.24	22.26	26.22	34.58	14.15	17.11	21.58	24.15	15.6	21.98
10	WT10	8.74	7.08	16.86	6.77	21.22	26.22	34.58	15.21	18.31	22.93	25.69	16.8	22.62
11	WT11	8.18	6.61	15.79	6.2	20.14	26.22	34.58	16.39	19.6	24.35	27.19	18.09	23.29
12	WT12	5.57	4.37	10.66	4.11	14.78	20.5	28.2	13.09	15.84	20.2	22.52	14.51	18.68
13	WT13	5.15	4.06	9.92	3.78	13.9	20.5	28.2	14.13	16.91	21.4	23.96	15.54	19.28
14	WT14	6.61	5.29	12.62	4.96	16.96	26.22	34.58	20.2	23.66	28.47	32.15	21.92	25.4
15	WT15	6.08	4.93	11.72	4.59	16.04	26.22	34.58	21.43	25.01	29.87	33.69	23.25	26.1
16	WT16	5.65	4.48	10.89	4.23	15.01	26.22	34.58	22.7	26.34	31.25	35.32	24.58	26.82
17	WT17	3.72	2.85	7.19	2.65	10.71	20.5	28.2	18.3	21.49	26.25	29.57	19.91	21.75
18	WT18	3.38	2.58	6.62	2.39	9.92	20.5	28.2	19.39	22.67	27.5	31.02	21.01	22.39
19	WT19	3.06	2.39	6	2.19	9.2	20.5	28.2	20.59	23.94	28.8	32.48	22.19	23.07
20	WT20	4.01	3.13	7.66	2.89	11.41	26.22	34.58	28.11	31.88	36.77	41.84	29.85	29.76
21	WT21	3.65	2.95	7	2.68	10.5	26.22	34.58	29.89	33.36	38.1	[illegible]	[illegible]	33.47
22	WT22	3.20	1.75	4.59	1.64	7.14	20.5	28.2	24	27.6	32.89	36.81	25.74	25.07
23	WT23	2.95	2.20	5.76	2.15	8.88	26.22	34.58	32.25	25.94	38.74	46.56	33.64	31.92
24	WT24	2.67	2.09	5.1	1.95	8.09	26.22	34.58	33.7	37.31	42.37	48.14	34.88	32.64

Figure 8. Example table of capacity factors from data at one mast. Note: values were obtained with fictitious tables of simulation results and do not correspond to any actual wind farm.

- **Produces for each wind turbine:**
  - **Tables of Capacity Factors (by directions and overall)**
  - **Wind speed distributions(WAsP .tab files)**

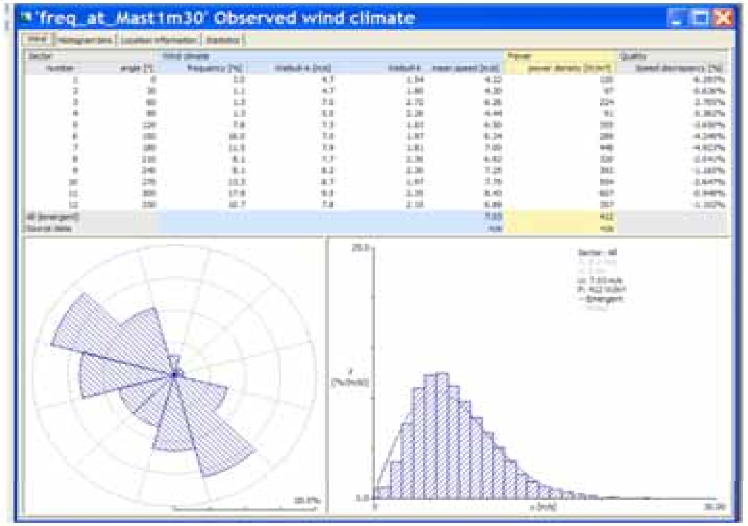


Figure 10. Wind climate obtained from WAsP when opening the .tab files generated by EnergyCalc.

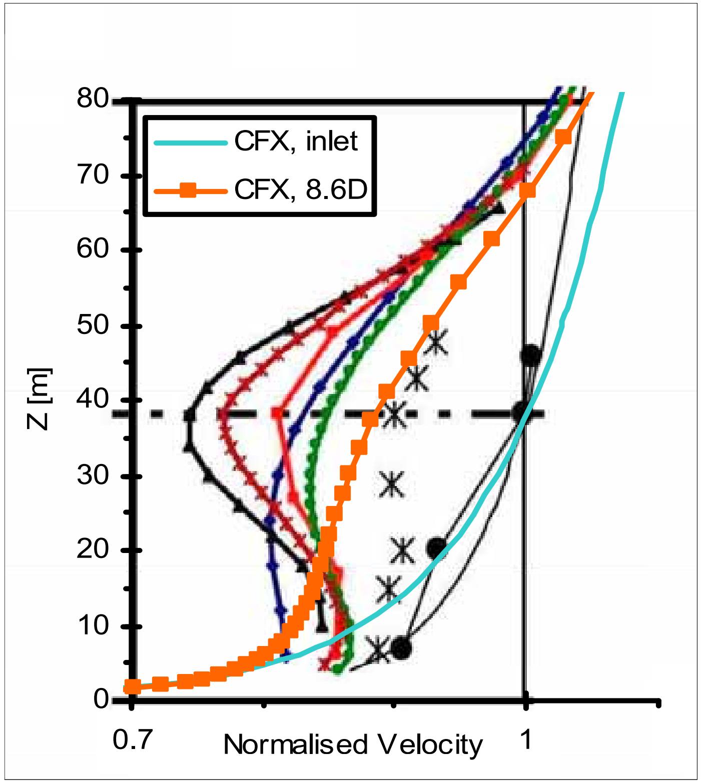
Validation and Case Studies

- Many examples available, ANSYS and Customers.
- Single Turbine wake, offshore (Vindeby, Nibe)
- Blacklaw Wind Farm, Scotland,
  - Wakes, forestry, power assessment
- Bolund Hill, Denmark
  - Complex terrain
- Nant-y-Moch,
  - Complex terrain, forestry
  - Best practice / sensitivity studies
- Large Offshore –> Horns Rev + others

Validation of Actuator Disk Model: Vindeby

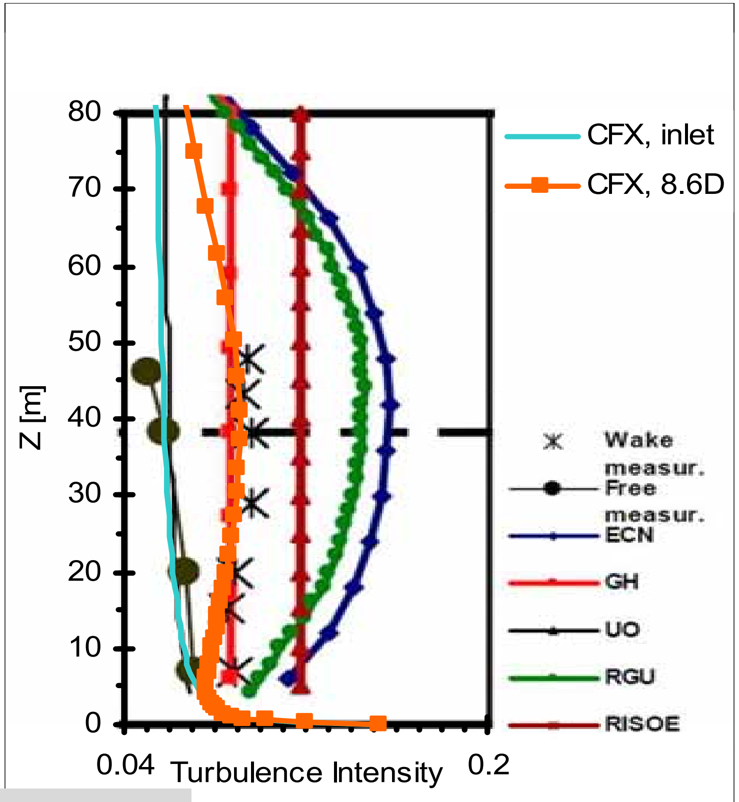
- Compare with wake models and measurements* , turbine 6E
- Good agreement with measurement
- At least as good as the other models, often better.

Normalised velocity, 8.6 Diameters downstream



Run with:
z_0 = 0.001 m
U_{ref} = 7.5 m/s
Z_{ref} = 38 m
WT diameter = 35 m
C_T = 0.76
Ambient TI = 6% (measured)

Turbulence Intensity 8.6 Diameters downstream

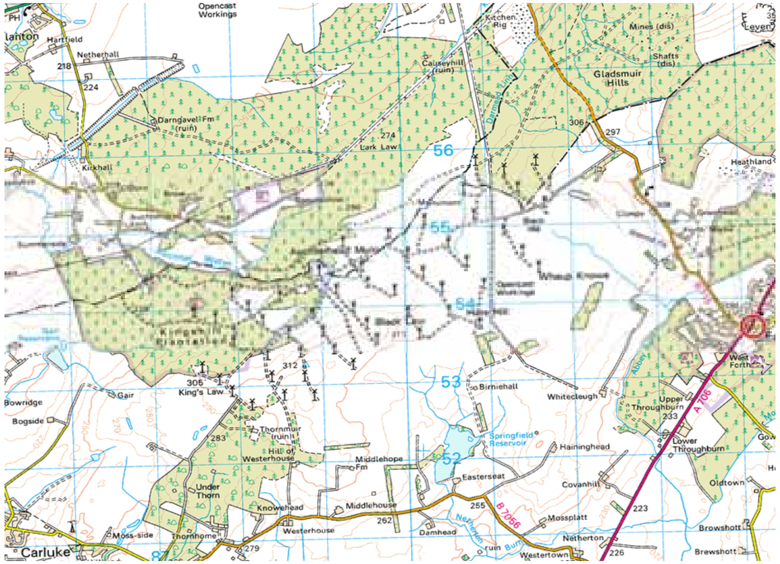


Rados, et al, *'A Comparison of Wake Model Performances in an Offshore Environment'*, http://www.risoe.dk/rispubl/art/2007_49_paper.pdf.

Ter@tec

Blacklaw Wind Farm

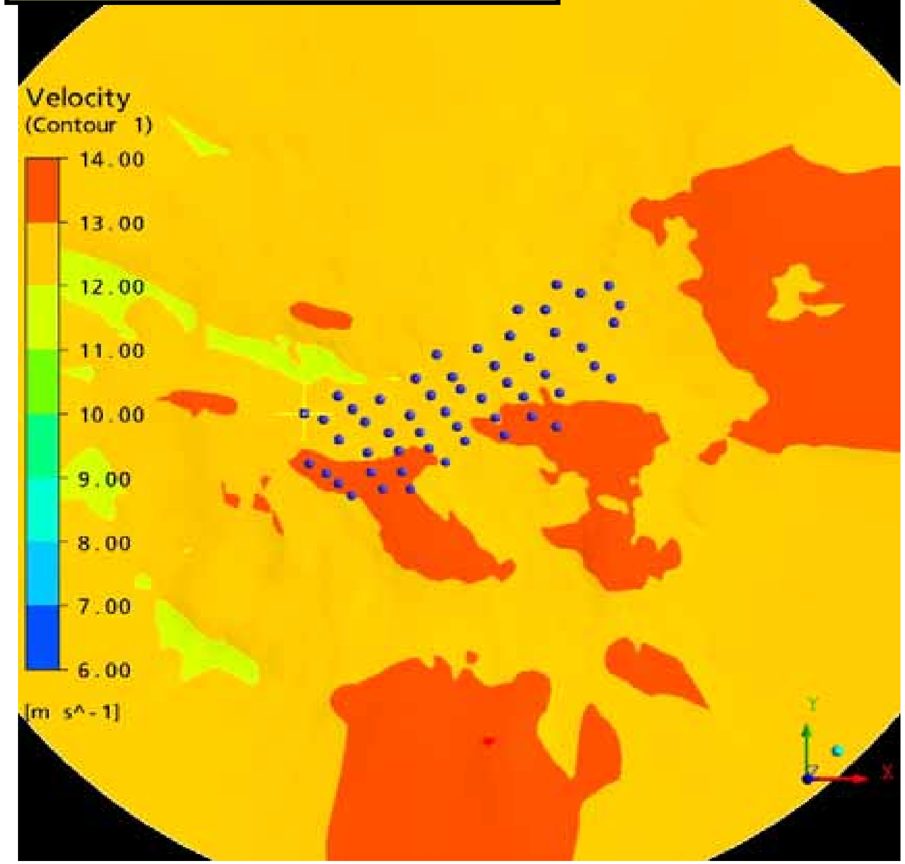
- Central Scotland
  - Former open cast coal site
- Operated by Scottish Power Renewables
- Largest operating windfarm in the UK (Jan 2006),
- 54 Siemens Turbines
- Total installed power capacity of 125 megawatts (2.3 MW each)
- Small height variations (170m) across farm



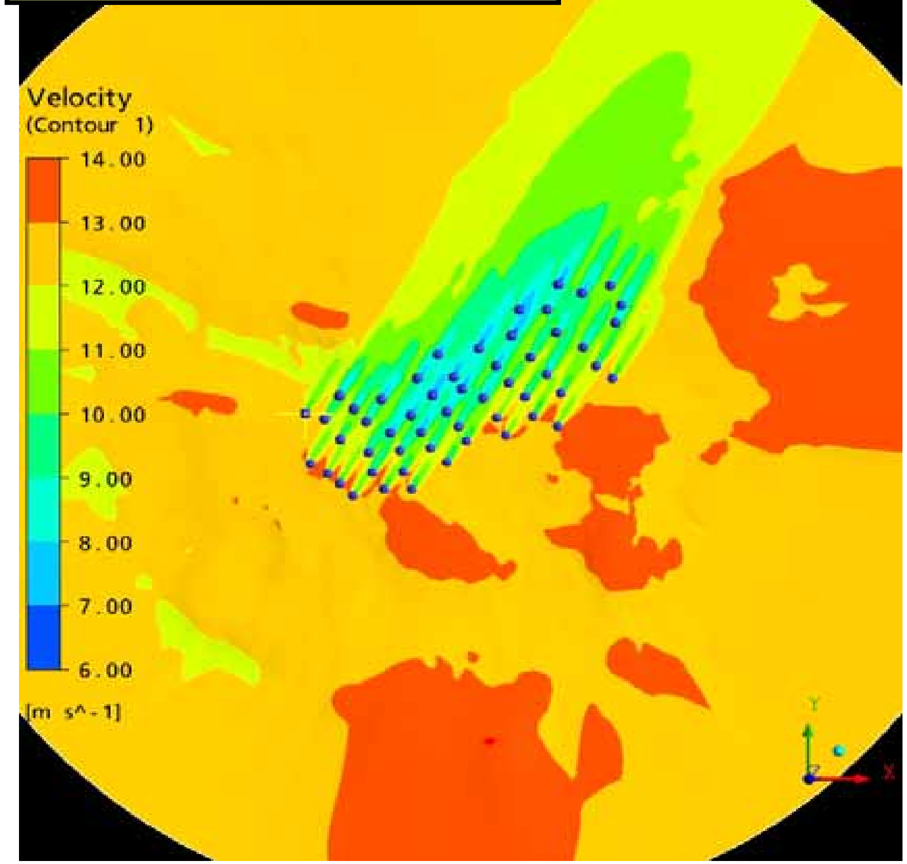
C. Montavon, I. Jones, C. Staples, C. Strachan, I. Gutierrez, 2009, Practical issues in the use of CFD for modelling wind farms, http://www.ewec2009proceedings.info/allfiles2/70_EWEC2009presentation.pdf

Multiple Wakes Example: Wind Farm

Without wind turbines

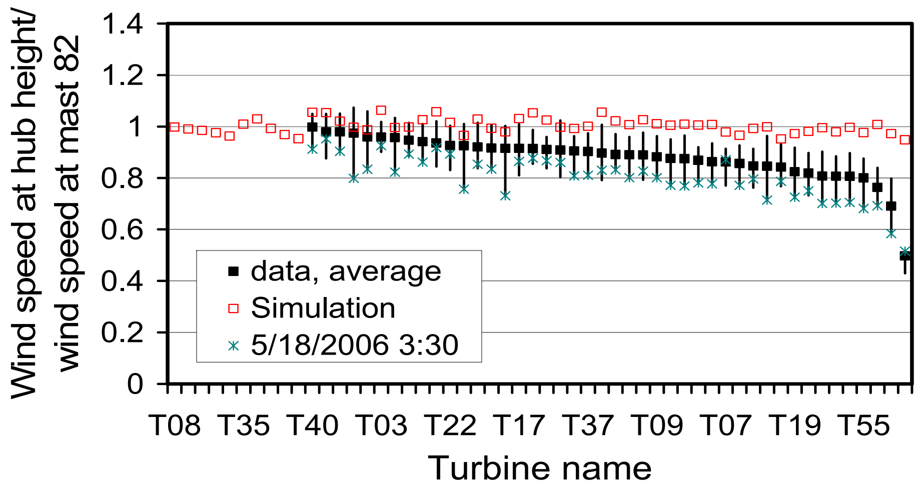


With wind turbines

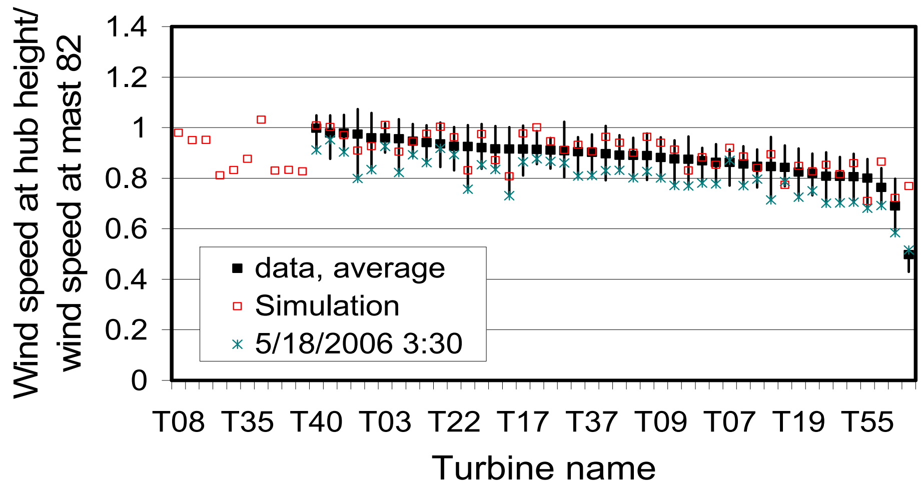


Comparison with Data

Without wakes



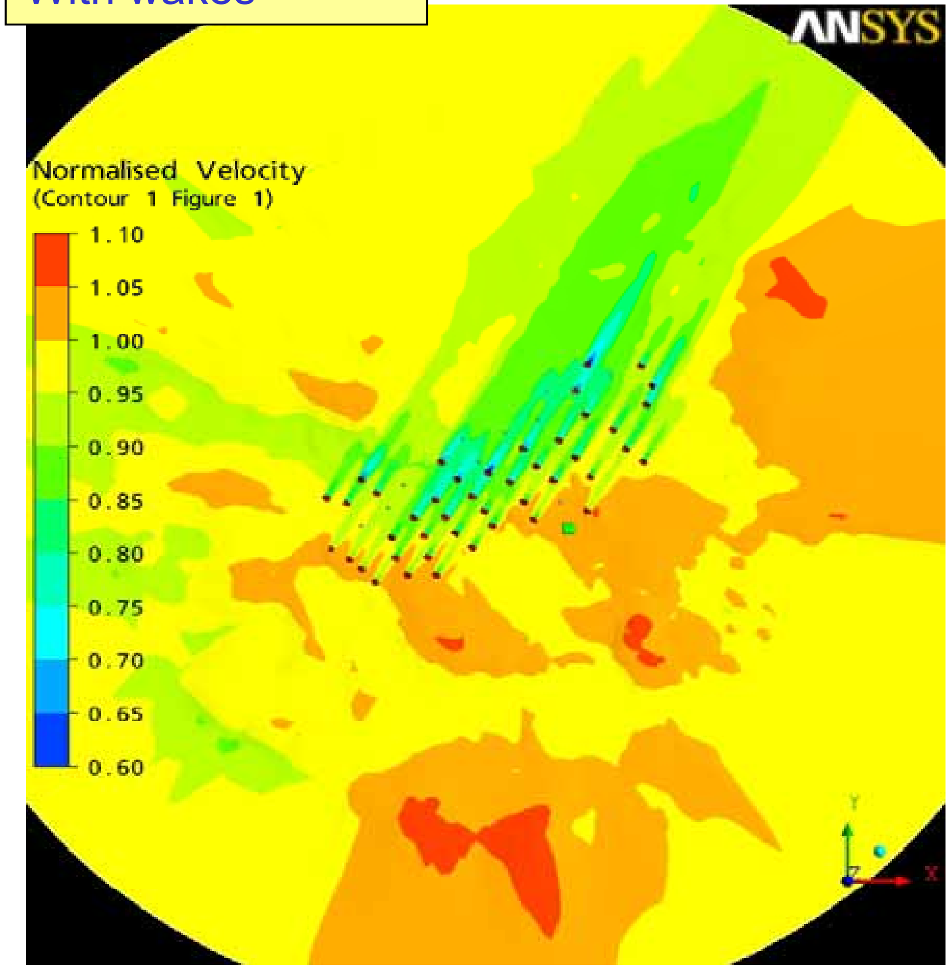
With wakes



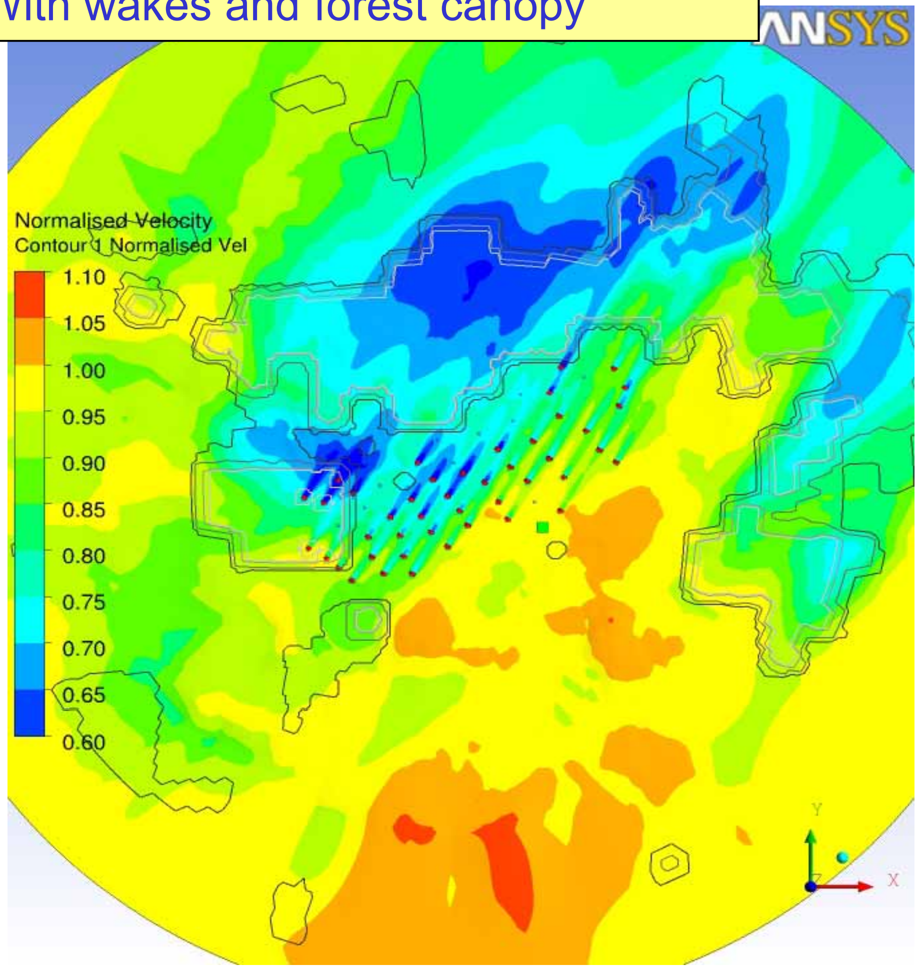
- Wake model significantly improves the prediction of wind speed distribution on site.
  - Wakes persist for several kilometres

Effect of Forestry, Normalised Velocity

With wakes

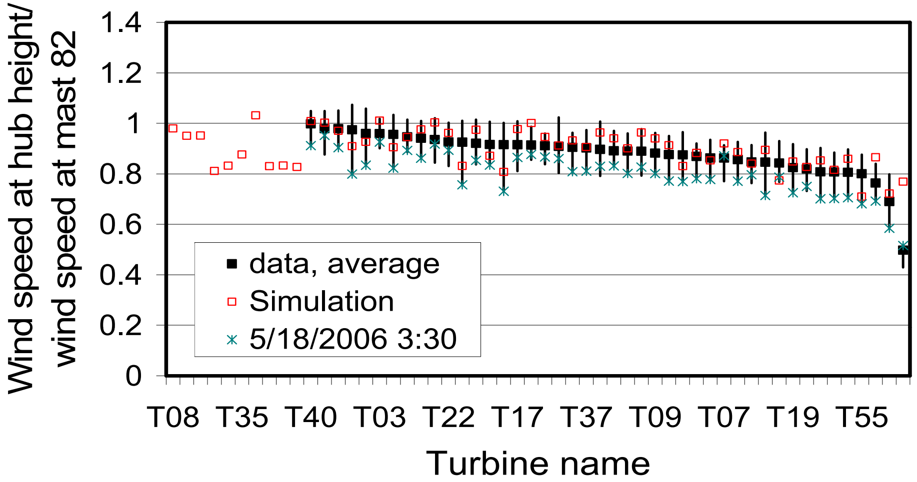


With wakes and forest canopy

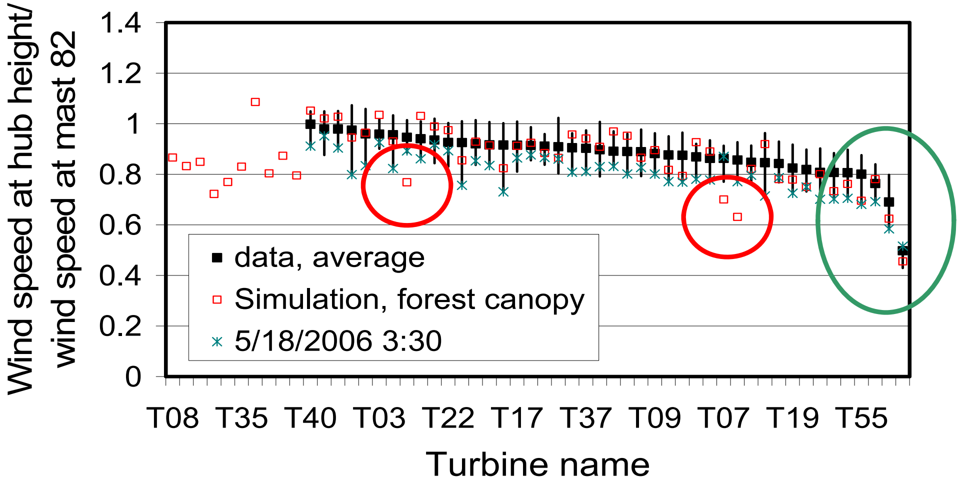


Effect of Forestry

With wakes



With wakes and forestry

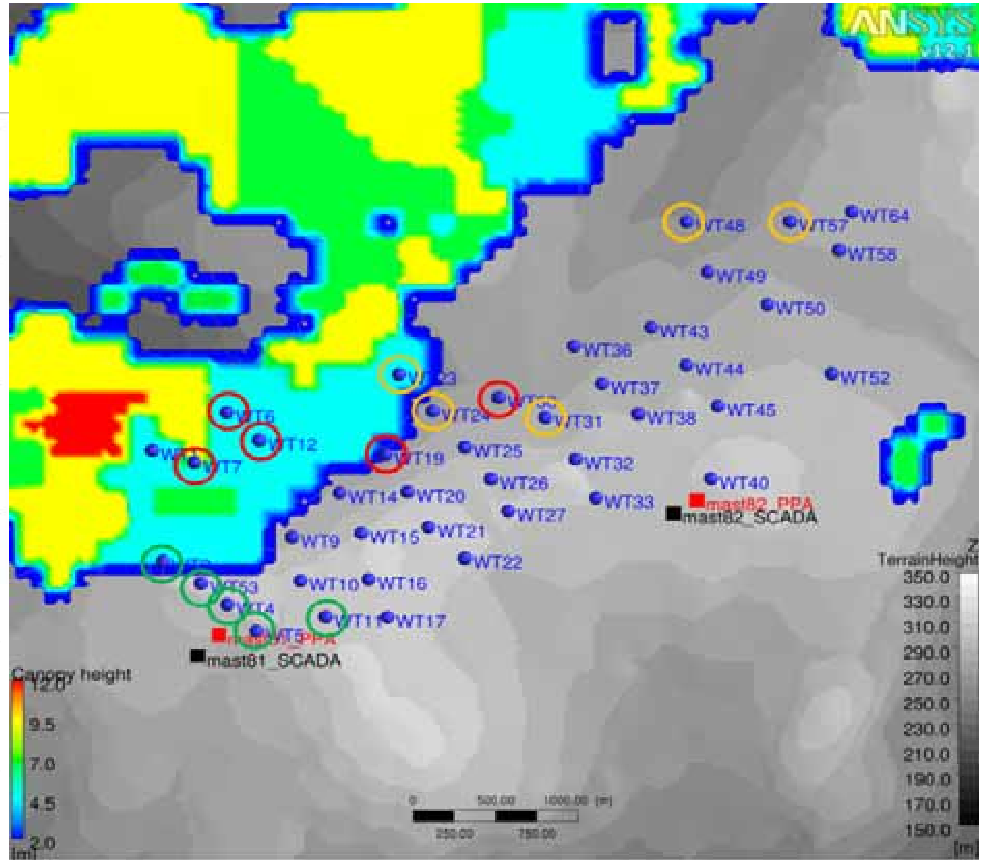


- Modelling forest canopy improves prediction for some machines (green circle) but degrades prediction for some other (red circle)
- Most likely cause: too coarse representation of forest canopy
- Other possible issue: use of single loss coefficient, rather than using spatially varying leaf area index

Power Prediction

- Further Work
  - More detailed forestry and met. data
  - Annual Capacity Factor vs SCADA data
- Normalised Power Outputs
- Acknowledge Scottish Power Renewables and SgurrEnergy

R. Spence, C. Montavon, I. Jones, C. Staples, C. Strachan, D. Malins, 2010, Wind modelling evaluation using an operational wind farm site, http://www.ewec2010proceedings.info/allfiles2/517_EWEC2010presentation.pdf



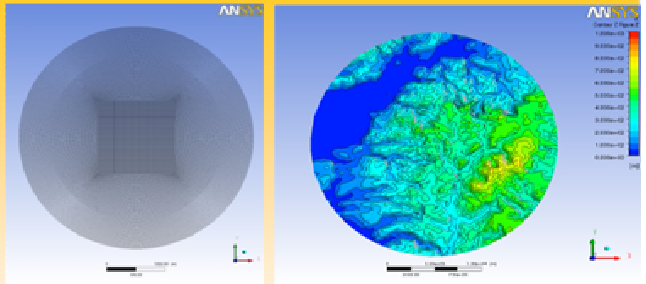
ANSYS

Nant y Moch I

- Central Wales
- Lots of small hillocks, 30° slopes
- Complex forestry
- 9 Met Masts

Figure 2: Map of Nant-y-Moch site, showing contours and forestry: Ordnance Survey © Crown Copyright 2008, License number 100048580

Scripted hex meshing:
- Terrain data from NTF, SRTM or MAP format.
- 9-block mesh topology, mesh height smoothed in outer blocks, projected onto terrain surface.
- User controls horizontal and vertical resolution, radius and height of domain.
- Terrain extended automatically beyond the physical boundaries, to allow flow to adjust to terrain and roughness variations near the physical boundary.

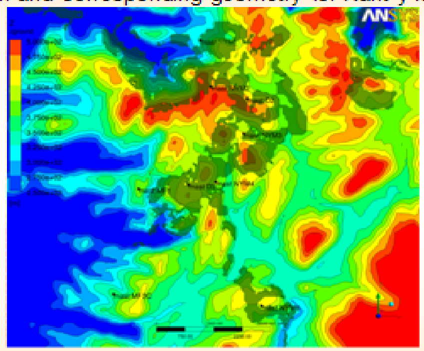


Template mesh and corresponding geometry for Nant y Moch.

Roughness and Forestry:
- Surface roughness modelled via roughness height, eg from .map file.
- Forestries are modeled via resistance terms.
- Svensson model (Svensson & Häggkvist, 1990) or the Lopes da Costa model (Lopes da Costa, 2007).
- Source Term in the Momentum equation, K_{loss} is product of leaf area index and drag coefficient.

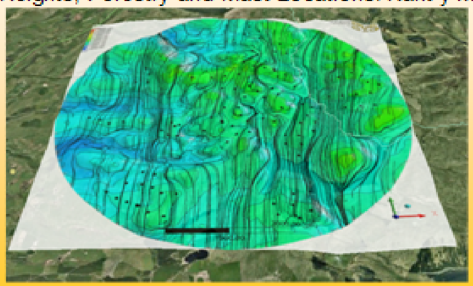
$$F_i = -\frac{1}{2}\rho\alpha C_D |U|U_i = -K_{loss}\frac{\rho}{2}|U|U_i$$

- In the Lopes da Costa model, additional terms are added to the equations to account for turbulence production and dissipation.



Detail of Heights, Forestry and Mast Locations: Nant y Moch.

Automated postprocessing:
- Standardised plots (e.g. turbulence intensity, normalised velocity at hub height or on vertical sections, surface streamlines)
- Exported data at predefined locations (e.g. met mast, turbine hub)
- Standardised html report
- Option for output to Google Earth (.kml)



Surface Streamlines superimposed in Google Earth for Nant y Moch.

Figure 3: Outline of the WindModeller approach.

Nant y Moch: Sensitivity Study

- Horizontal cells of 53 metres required for grid convergence with forestry, (3 Million nodes).
- If no forestry modelling grid convergence at one million cells, adequate simulations with coarser meshes.
- The forestry loss coefficient:
  - analyses suggest 0.025/0.03 appropriate.
  - Lopes da Costa model better results than the Svensson model.
  - Simulations sensitive to canopy height, use 0.75 of the tree height.
- Using 15° or finer sectors and averaging per 30° sector gives marked improvement in comparison with data.

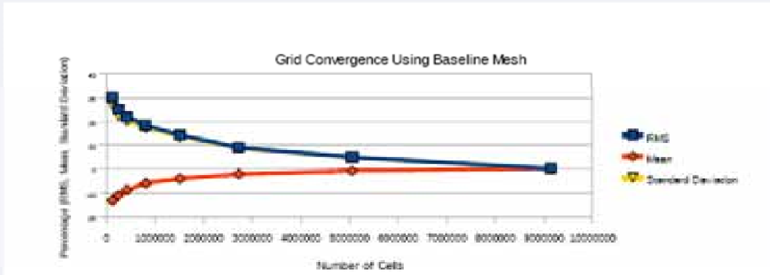


Figure 6: Results from grid convergence exercise on a case with forestry, showing grid convergence for 3Million cells and above.

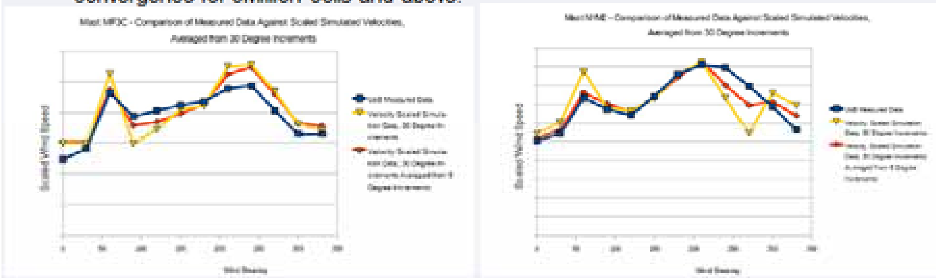


Figure 7: Comparison between measured and predicted normalised wind speeds. Predicted wind speeds from 5° sectors averaged over 30° sectors provides better match than wind speed from 30° degree sectors.

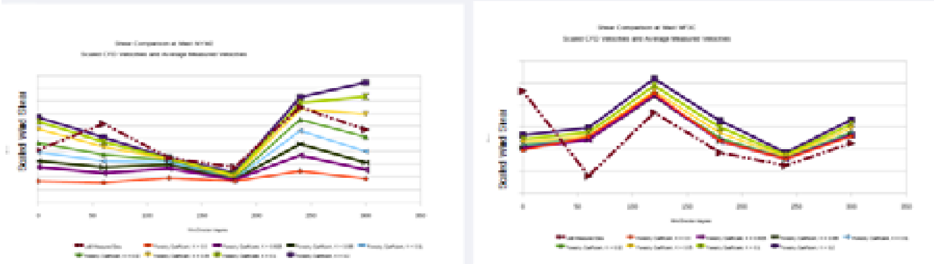


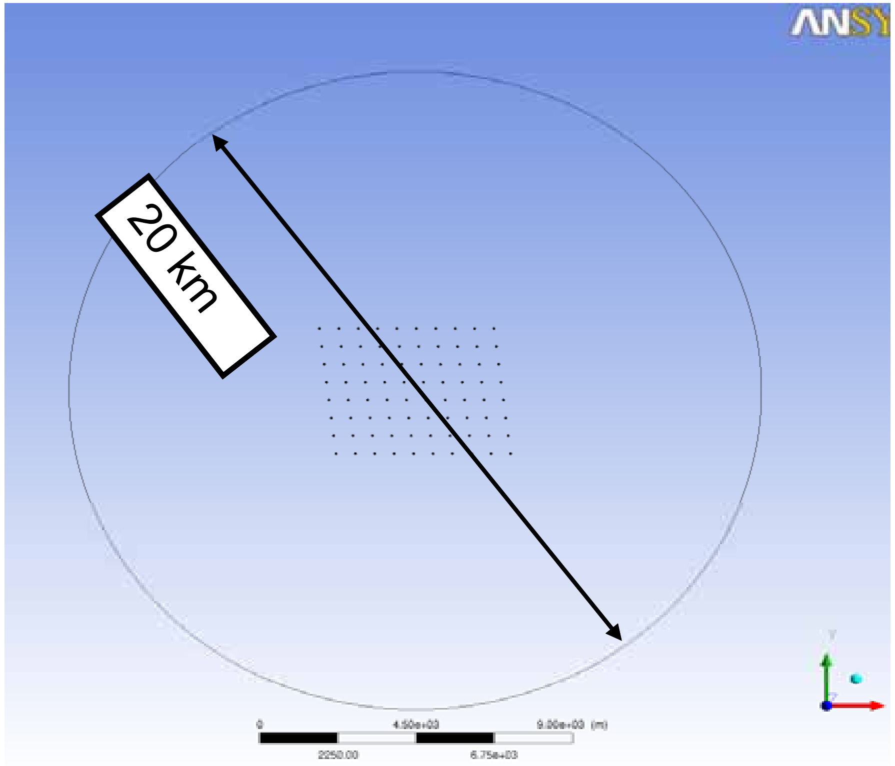
Figure 8: Comparison between measured and predicted wind shear for a range of forestry loss coefficients, showing better agreement for lower values of the loss coefficient. Note that the CFD results are not averaged over 5° sectors.

Results courtesy SSE Renewables and Bristol University. EWEC 2010 paper.

C.A. Montavon, G. Ryan, C.B. Allen, P. Housley, C.J. Staples, I.P. Jones, 2010, Comparison of meshing approaches and RANS turbulence models performance for flows over complex terrain,http://www.ewec2010proceedings.info/allfiles2/421_EWEC2010presentation.pdf

Offshore Wind Farms: Modelling Large Arrays

- Case Study: Horns Rev
- 8x10 WT, 80m diameter, Hub height 70m.
- Turbine spacing: 7 diameters
- Domain size:
  - 10 km radius
  - 1.0 km height
- Wind turbine thrust curve: Vestas V80
- ABL boundary layer profiles at inlet

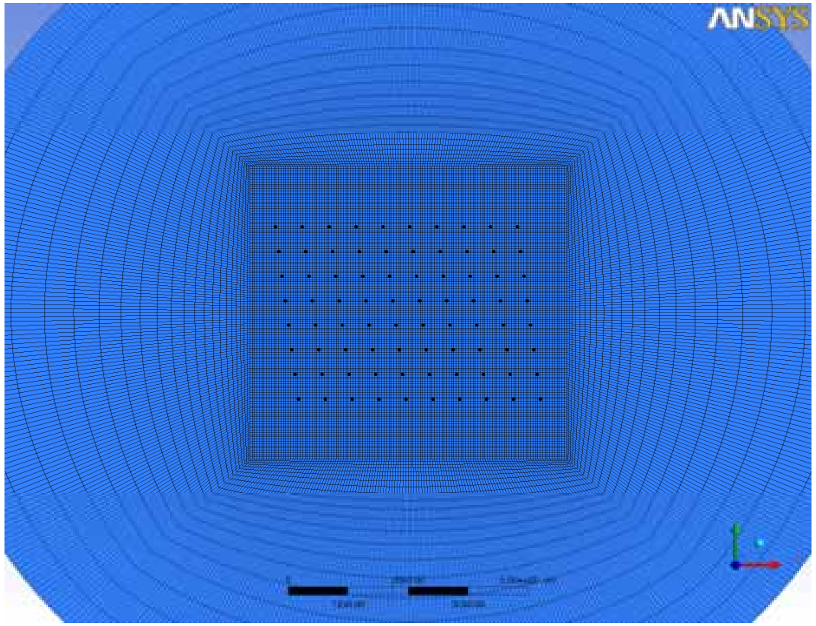


$$u = \min\left[\frac{u_*}{\kappa} ln(\frac{\tilde{z}}{z_0}), u_{geo}\right] \quad k = \frac{3}{2}\left(u_{ref} TI_{inlet}\right)^2 \quad \varepsilon = \frac{u_*^3}{\kappa \tilde{z}}$$

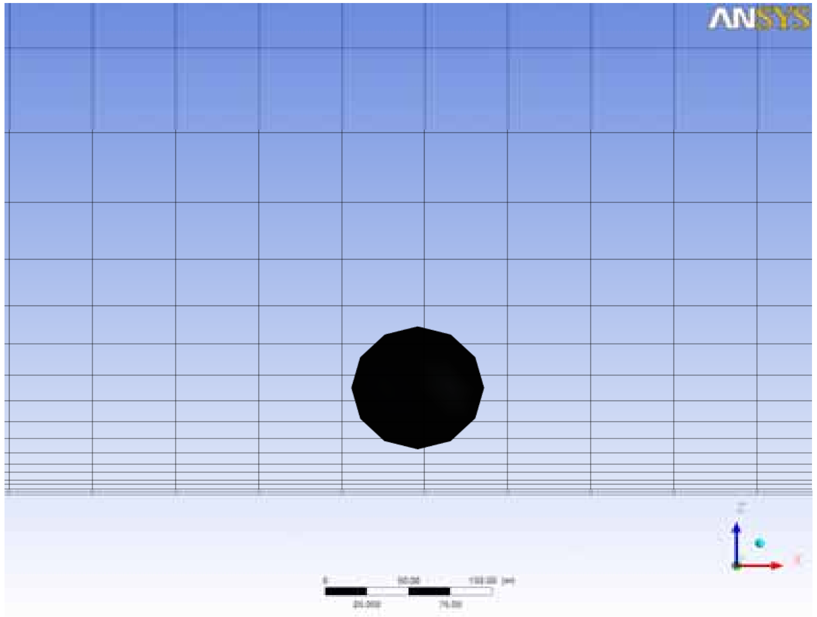
$$\tilde{z} = \max\left[z - z_{ground}, z_0\right] \qquad C_\mu = \left(\frac{u_*^2}{k}\right)^2$$

Mesh characteristics

- Hexahedral mesh
- Non-uniform in horizontal and vertical planes
- Background mesh before adaption ~690 k nodes



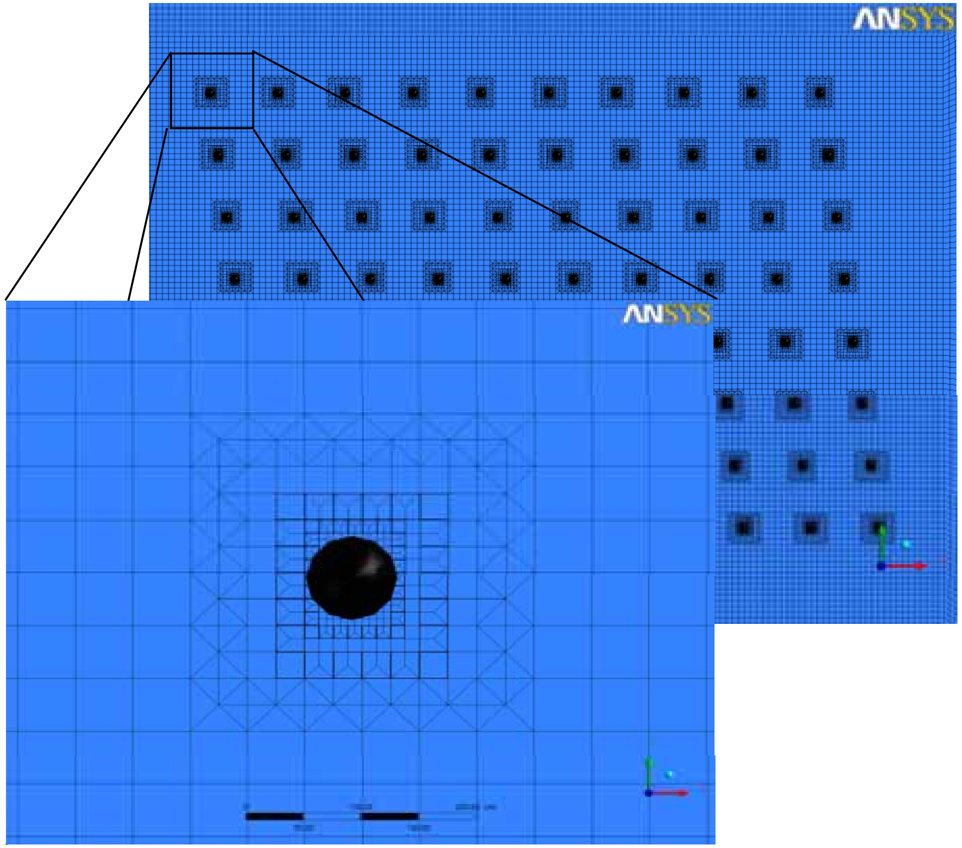
Mesh viewed from above

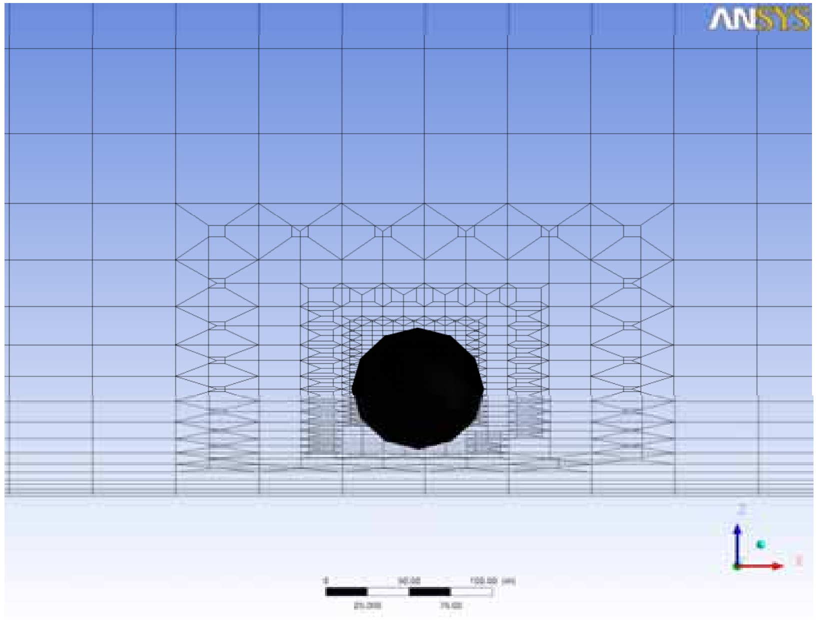


Mesh viewed from upstream

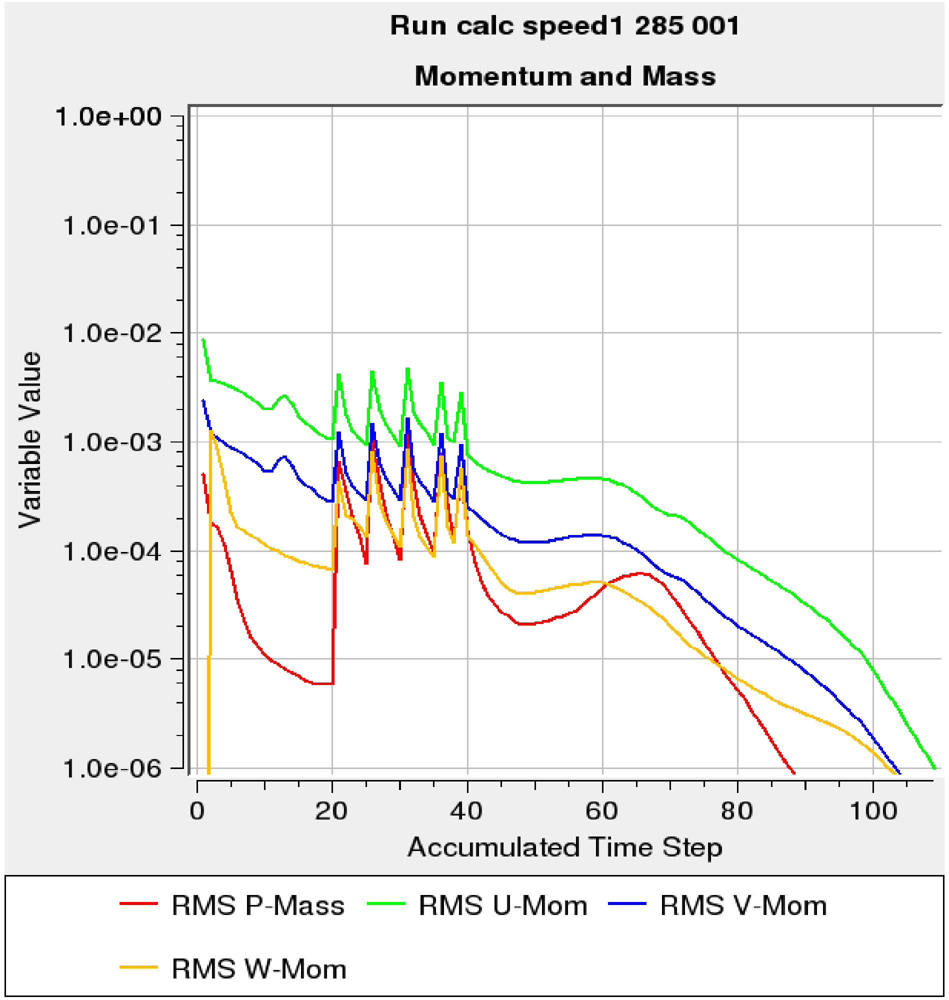
Mesh characteristics

- Mesh after adaption ~1.4M nodes





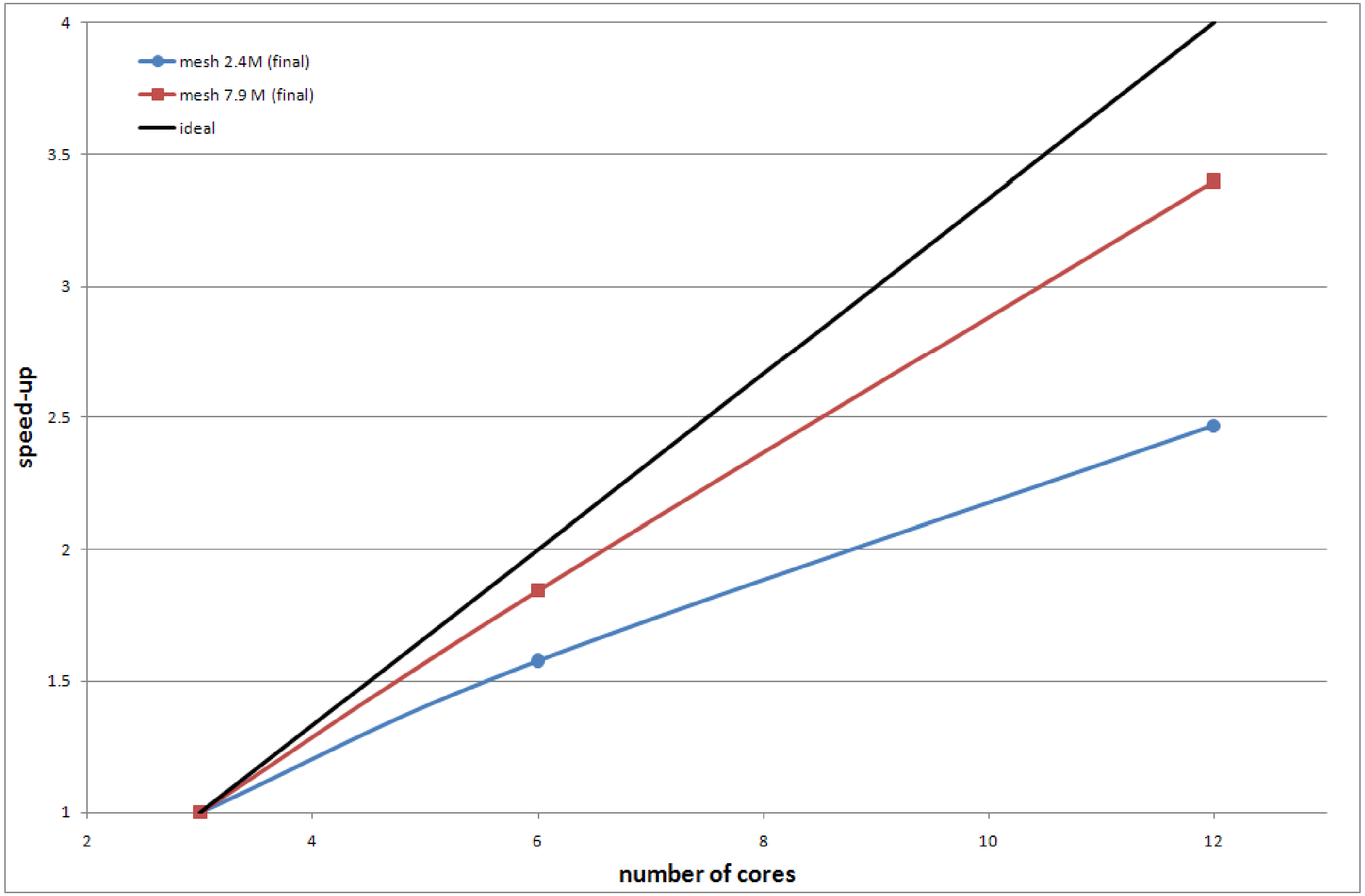
Typical convergence/resource requirements



- **Based on Horns Rev**
- **1.4 M Nodes in final mesh**
- **42 mins / run, start to finish, including I/O, partitioning and adaption.**
- **16 Cores, Intel Xeon X5355 2.66GHz (2 dual processor quad core systems, 16 M Bytes / system)**
- **Typically 60 iterations on final adaption step for convergence, 110 in total.**
- **Very tight convergence criterion, rms residuals < 1E-6. (1E-5 would reduce iterations to 47)**
- **Total time less than 12 hrs start to finish for 15 simulations**

Speed-up with multiple cores

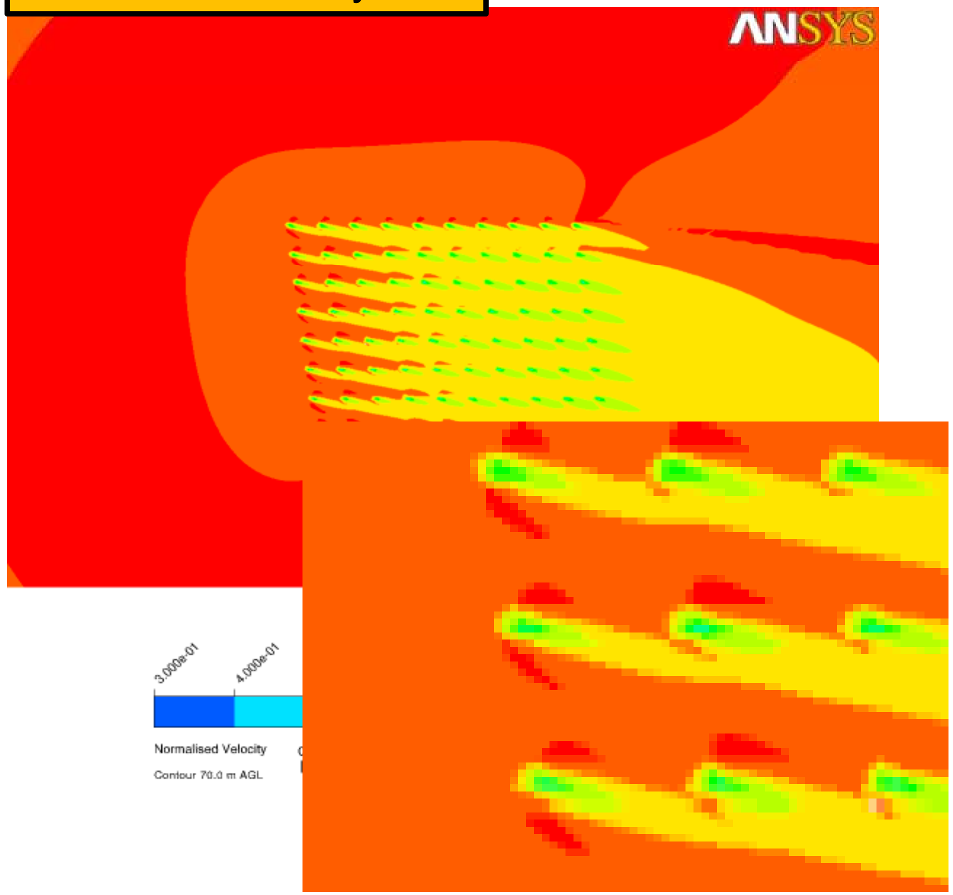
- Speed-up good, but not optimal:
  - Mesh adaption requires more file saving, thus hampering the speed-up



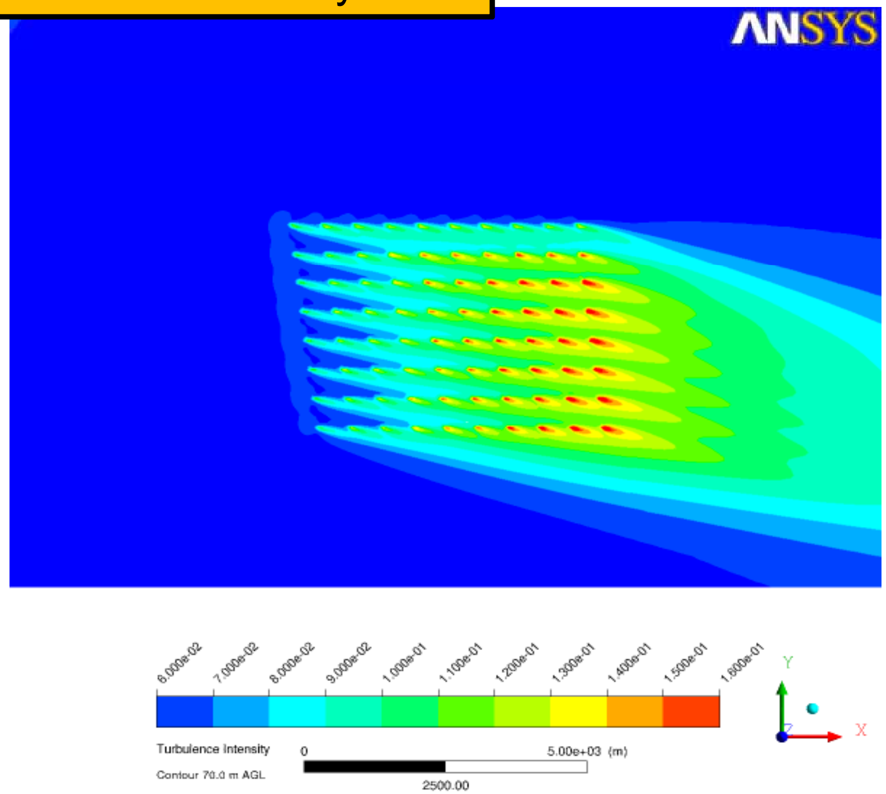
Results at hub height

- U_{ref} = 10 m/s at 70m, z_0 = 0.0001m, upstream TI = 6%
- Wind direction: sector 285

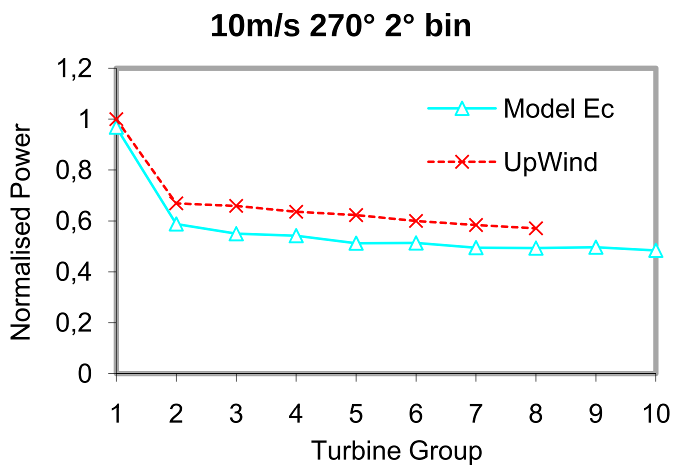
Horizontal velocity



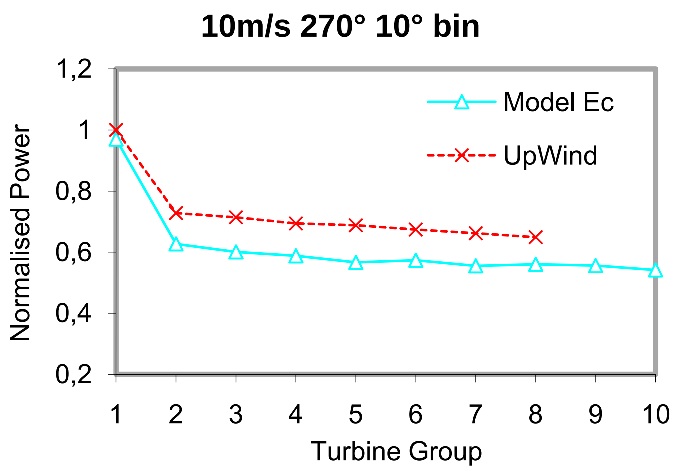
Turbulence intensity

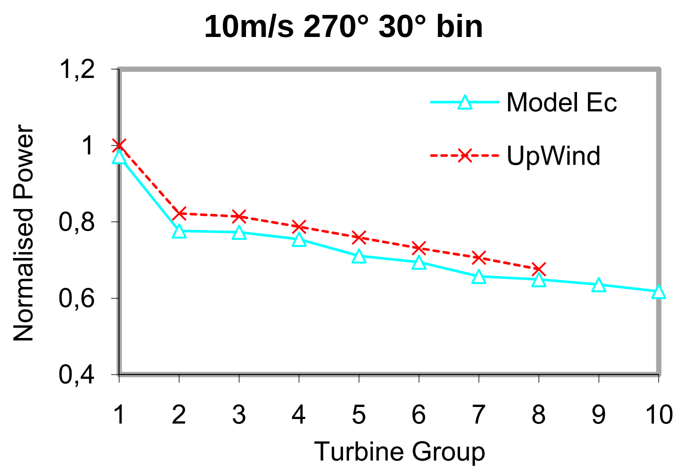


Normalised power down a row



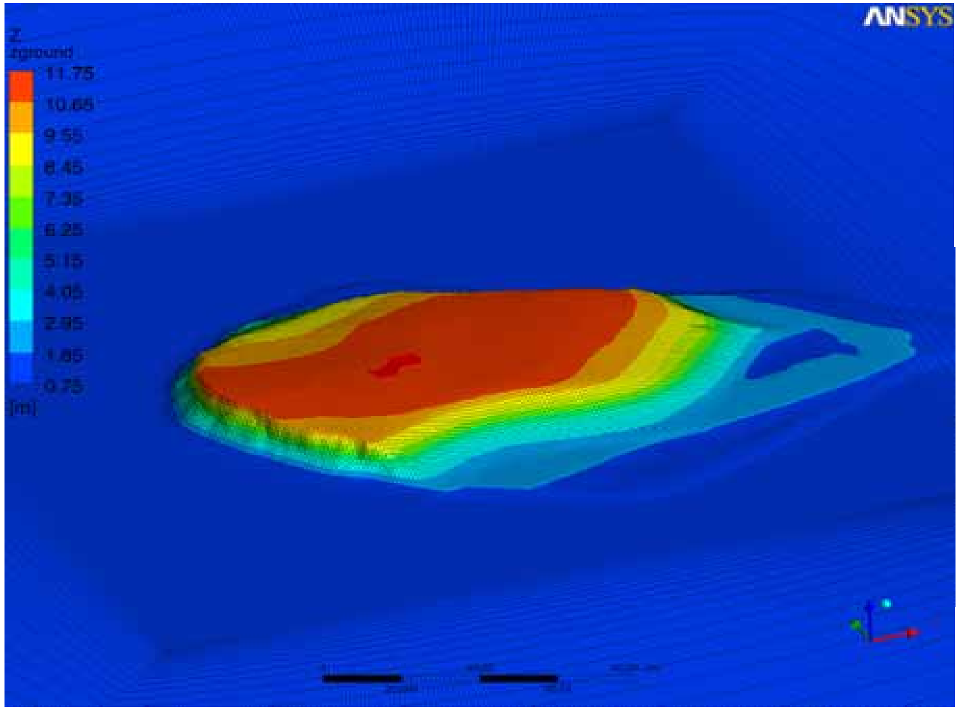
- Sector 270
- Reasonably good prediction
  - Tendency for over-estimation of array losses
  - Good prediction of slope down the row
- Consistent for various bin sizes

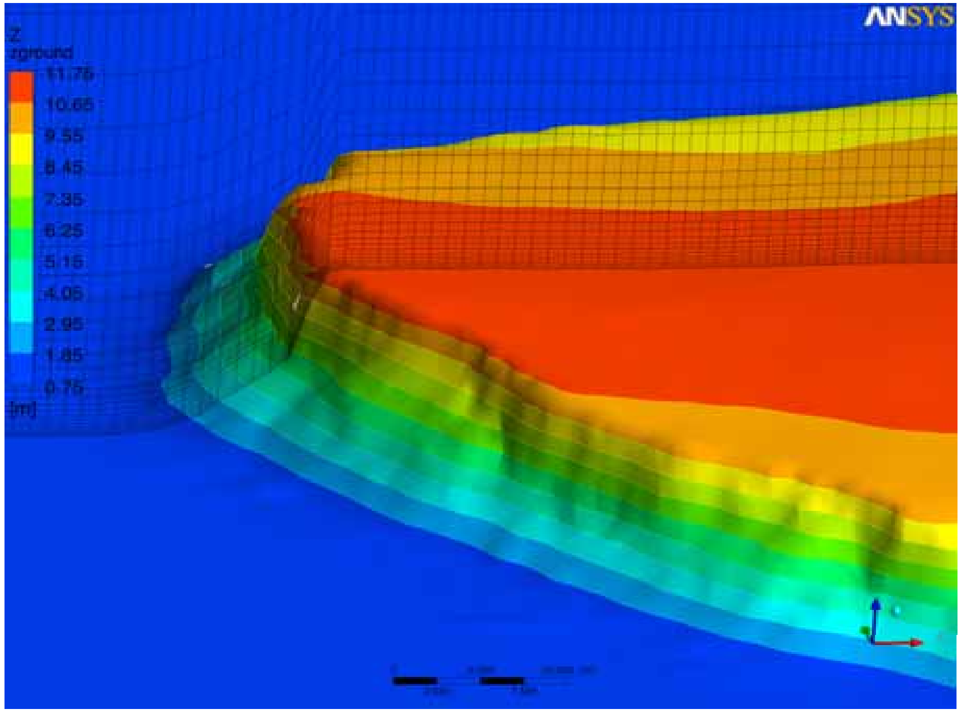




Bolund Hill

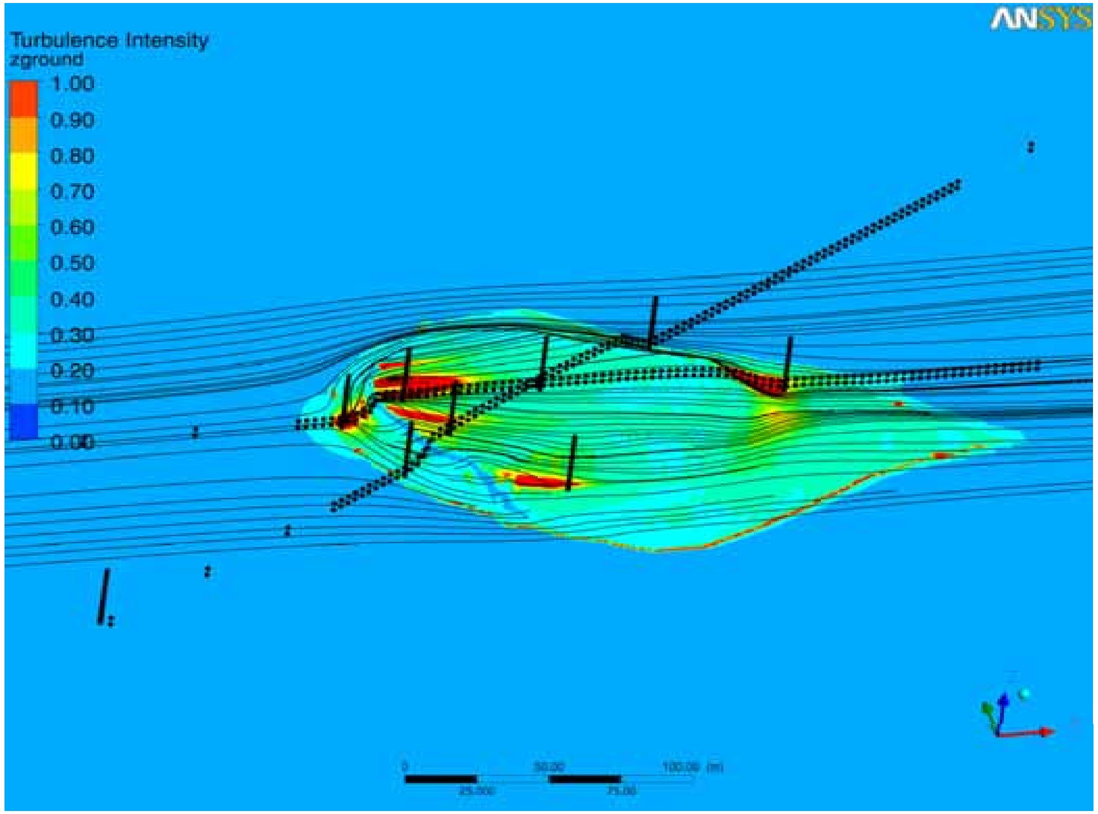
- Off the coast of Denmark
- Small elevation, but very steep cliff





Mast Locations

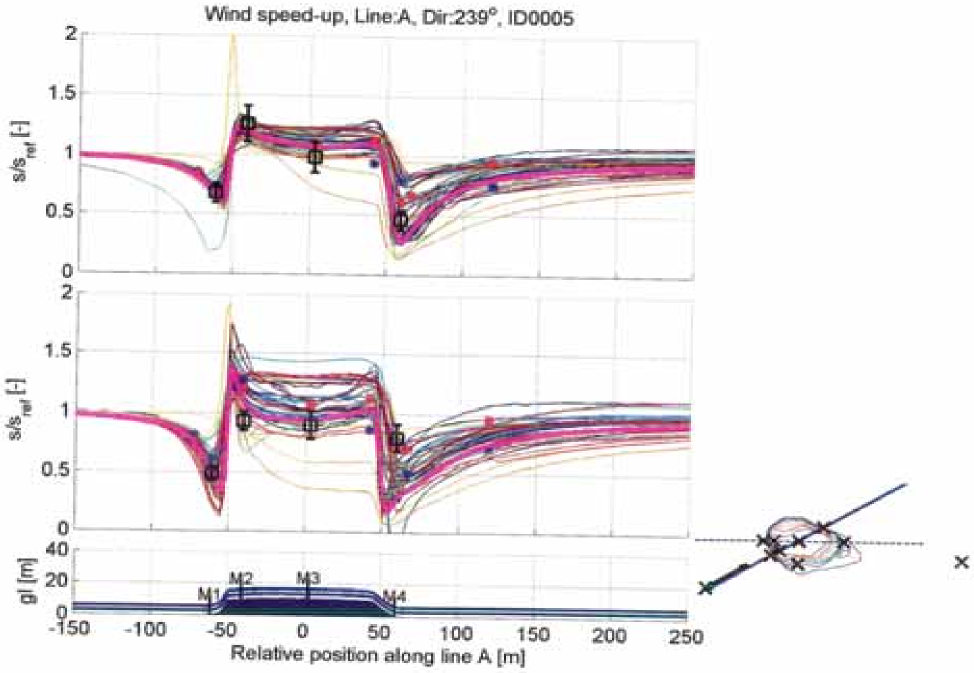
- 10 mast locations
- 2 lines (each with two heights) for CFD output
- Blind test case definition from Risoe
  - 4 wind directions
  - Neutral cases



Bechmann, A., Berg. J., Courtney, M.S., Jørgensen, H.E., Mann J., Sørensen N.N., 2009, The Bolund experiment: Overview and background, Technical Report Risø-R1658(EN), Risø DTU, National Lab., Roskilde, Denmark. http://bolund.risoe.dk.

Comparison with Results – s239
k-ε , Automatic Mesh Generation

Speed up

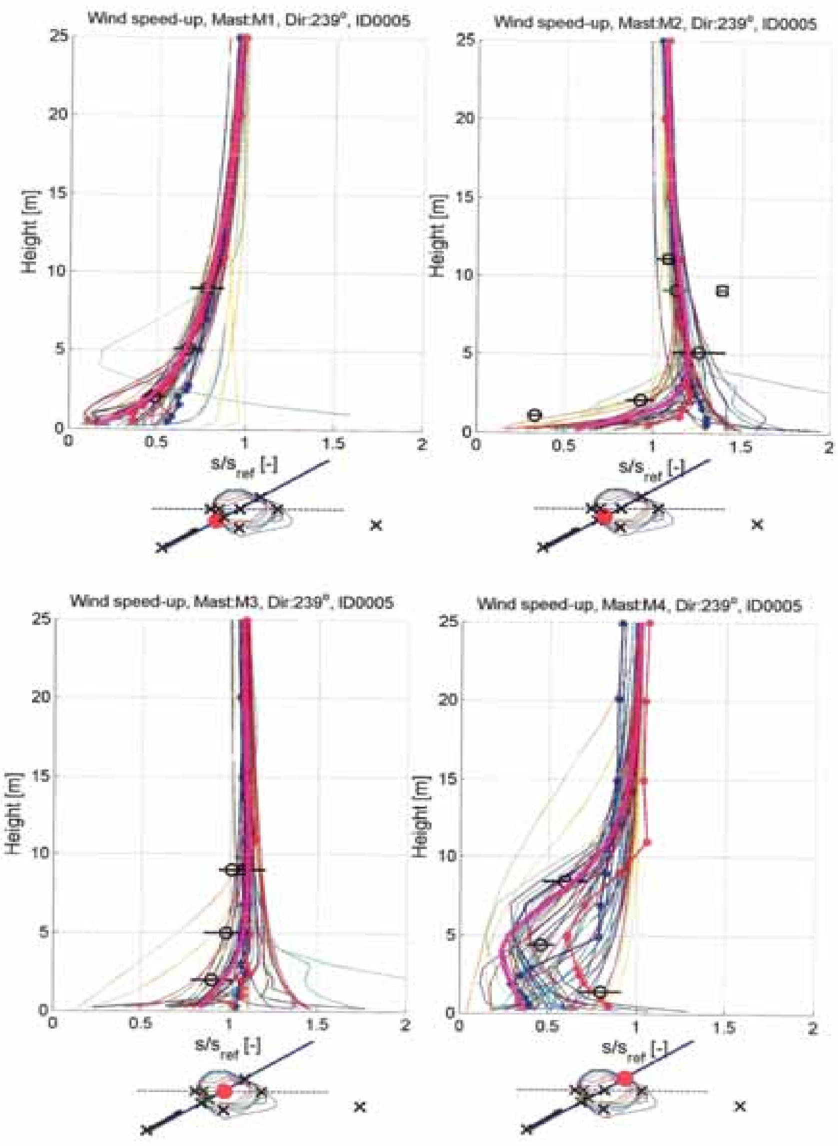


Thick pink line: CFX results, k-ε

Thin lines: other CFD

Black symbols: measurements

Coloured symbols: wind tunnel simulations



Conclusions

- State of the Art CFD tools based on ANSYS CFD software
- Extensive validation and application
- ‘Terrain to mesh to CFD ’ automation with
  - Terrain specification (.map, SRTM, NTF, DXF, STL, .csv point data)
  - Variable roughness
  - Forest canopy model (variable canopy height, constant loss coefficient)
  - Multiple wake model (actuator disk)
- Post-Processing generating:
  - Automated report as html document
  - Plots at constant height Above Ground Level (AGL) and profiles at wind turbine/mast locations for quantities such as normalised velocity, turbulence intensity, shear exponent factor
  - Exported data tables of similar quantities at wind turbine/mast locations
  - Plots of surface-streamlines (identification of recirculation zones)
  - Export to Google Earth (.kml files)
  - Basic energy assessment providing capacity factors and wind distributions at wind turbine locations (WAsP .tab format)
- Technology also being applied to tidal turbines