On the Sensitivity of Numerical Wind Field Modeling

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WindSim AS

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WindSim AS

Variation in Annual Energy Production, AEP

Parameter sensitivities in the AEP calculation

Pre-processing

Processing, Simulations
- Cosine hill

Post-processing
- Ridge

Conclusion
## WindSim AS

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>VECTOR AS; CFD consulting</td>
</tr>
<tr>
<td>1993</td>
<td>Oil &amp; Gas</td>
</tr>
</tbody>
</table>
| 1997 | Wind Energy  
   - Wind resource assessment, Norwegian Wind Atlas  
   - Micro-siting |
| 2003 | WindSim, PC software for simulation of local wind fields |
| 2005 | VECTOR AS was divided in two companies  
   - WindSim AS; Sale, support and development of WindSim  
   - VECTOR AS; Consulting |

*WindSim office: Jarlsø, 3124 Tønsberg, Norway*
AEP – lower than estimated

Wind farm owners frequently experience that the annual energy production (AEP) from their wind farms are lower than the estimated production.

This serious problem is now addressed by the wind energy sector world wide.

CFD simulations are used to get more accurate simulation results.

What are the important lessons learned, what parameters affect the quality of results?
AEP variation within a wind farm

Simple terrain - Denmark

Complex terrain - Norway
Simple terrain

Location: Torrild, Denmark, simple terrain
Wind farm: 15 Bonus 150 kW turbines with 30 meters hub height, height variation within the wind farm is 6 meters
Climatology: February to October 2000, measurement height 30 meters, mean wind speed 5.6 m/s
Models: Nesting, 20x20 km into 2x2 km with resolution 20x20 meters, number of cells is 200 000

Digital terrain model with elevation in meters. Left side 20x20 km model, right side 2x2 km model with a 20x20 meters grid resolution
There is no simple coincidence between high wind speed areas and high altitude areas. Simulations shows that areas west of the wind farm display the best wind conditions. This area has terrain gradients perpendicular to the main wind directions, giving significant speed-ups.
Simple terrain – AEP

The difference in energy output between the various turbines is 25%. Wake effects is not included.
Simple terrain – Optimization

Alternative locations along the grey lines would according to simulation give a 10% increase in AEP

Wind resource map at 30 meters height

Complex terrain – AEP

Location: Norway, complex terrain
Wind farm: 2 MW turbines with 80 meters hub height, height variation within the wind farm is in the order of 100 meters.

Digital terrain model with elevation (m). Annual energy production based on simulations, AEP (MWh/y)

The production varies between 8468 and 4356 MWh/y according to the simulations. The difference in energy output between the various turbines is in the order of 100%.
AEP variation within a wind farm

Summary:

Large variations within a wind farm in both simple and complex terrain.

Next:

Parameter sensitivities
AEP – Estimation procedure

Pre-processing
- Terrain
- Climatology

Post-processing
- Increase the power
- Resources

Simulations

Processing
Terrain conversion

Conversion from contour lines to a regular grid will smooth the grid.

Original elevation contour lines

Elevation contour lines after conversion to a regular grid with 30x30meters resolution
Simulation method

The method is based on the solution of the Reynolds Averaged Navier-Stokes equations, given in standard notation by:

\[
\begin{align*}
\frac{\partial U_i}{\partial x_i} &= 0 \\
\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} &= -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \left( \nabla \cdot \mathbf{u} \right)_{ij} + F_i
\end{align*}
\]

Solving the non-linear transport equations for mass, momentum and optionally also the energy makes the method suitable for simulations in both complex terrain, and in situations with complex local climatology.

*Transport of the turbulent kinetic energy in an idealized 2D sinusoidal terrain, illustrating the development of a turbulent boundary layer.*
Streamlines over 2D ridge with average slope angle of 5.7, 11.3 and 21.8 degrees.

Upstream speed-up, (speed hill top)/(speed inlet)

Cosine hill – terrain data

Elevation:
\[ z = H \cos^2(\pi \sqrt{x^2 + y^2}/2L) \]
\[ z = 0 \]
where

\[ H = 200 \text{ meters} \]
\[ L = 400 \text{ meters} \]

The maximum inclination angle is 40°

Roughness heights:
\[ z_0 = z_{\text{land}} \]
\[ z_0 = z_{\text{sea}} \]
Cosine hill - climatology

<table>
<thead>
<tr>
<th>Sector</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>10.33</td>
</tr>
<tr>
<td>A</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>7.77</td>
</tr>
<tr>
<td>Frequency</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Mean speed</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>7.50</td>
</tr>
</tbody>
</table>

*Weibull (k,A), frequency (-) and mean wind speed (m/s) versus sector.*
Cosine hill – model input

**Grid:**
- Resolution – Cell size in the horizontal plane
- Height – Distance from the hill top to the upper boundary
- NZ – Number of cells in the z-direction
- Factor – Distribution factor for refining the grid towards the ground

**Roughness:**
- $Z_{\text{land}}$ – Roughness height for areas with elevation larger than 0
- $Z_{\text{sea}}$ – Roughness height for areas with elevation equal to 0

**Boundary conditions:**
- BL Height – Boundary layer height
- BL Speed – Speed above the boundary layer
- Nesting – Initial and boundary conditions obtained by nesting

**Physical models:**
- Transient – Inclusion of the transient term in the transport equations
- Temp. – Inclusion of the transport equation for temperature
- Turb. mod. – Turbulence closure

**Solution procedure:**
- Iterations – Number of iteration performed in the solution procedure
- Solver – Segregated versus Coupled solver
Cosine hill – reference case

<table>
<thead>
<tr>
<th>Terrain</th>
<th>Resolution</th>
<th>Height</th>
<th>NZ</th>
<th>Factor</th>
<th>#cells</th>
<th>$z_{land}$</th>
<th>$z_{sea}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40x40</td>
<td>1500</td>
<td>20</td>
<td>0.1</td>
<td>139986</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Wind Fields

<table>
<thead>
<tr>
<th>BL Height</th>
<th>BL Speed</th>
<th>Iterations</th>
<th>Solver</th>
<th>Nesting</th>
<th>Turb. mod.</th>
<th>Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>10.0</td>
<td>300</td>
<td>Seg.</td>
<td>No</td>
<td>k-eps</td>
<td>No</td>
</tr>
</tbody>
</table>

Reference case ID 1000

Resolution:
40x40 meters, approximately 140 000 cells

Vertical direction:
Height 1500 meters, 20 cells, distribution factor of 0.1. Distribution of the first 5 nodes in z-direction: 6.8, 23.7, 47.0, 76.8, 113.0 meters

Blocking:
Setting the height of the computational domain to 1500 meters above the highest point in the terrain, gives a blocking less than 2%.
# Cosine hill – cases

<table>
<thead>
<tr>
<th>ID</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>1001</th>
<th>1002</th>
<th>1100</th>
<th>1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>40x40</td>
<td>40x40</td>
<td>20x20</td>
<td>40x40</td>
<td>40x40</td>
<td>40x40</td>
<td>40x40</td>
</tr>
<tr>
<td>Height</td>
<td>1500</td>
<td>1500</td>
<td>1000</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>NZ</td>
<td>20</td>
<td>20</td>
<td>30</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Factor</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>#cells</td>
<td>139986</td>
<td>139986</td>
<td>425971</td>
<td>139986</td>
<td>139986</td>
<td>139986</td>
<td>139986</td>
</tr>
<tr>
<td>(z_{\text{land}})</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>(z_{\text{sea}})</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.001</td>
</tr>
<tr>
<td>BL Height</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>250</td>
<td>1000</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>BL Height</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Iterations</td>
<td>300</td>
<td>1500</td>
<td>3000</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Nesting</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Turb. mod.</td>
<td>k-eps</td>
<td>k-eps</td>
<td>k-eps</td>
<td>k-eps</td>
<td>k-eps</td>
<td>k-eps</td>
<td>k-eps</td>
</tr>
<tr>
<td>Temp.</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Cosine hill cases, changes to the reference case ID 1000 are marked with red.
Cosine hill – ID 2000

<table>
<thead>
<tr>
<th></th>
<th>WECS_40</th>
<th>WECS_60</th>
<th>WECS_80</th>
<th>AEP (Gwh/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream_clim_10</td>
<td>1.98</td>
<td>1.93</td>
<td>1.91</td>
<td>19.16</td>
</tr>
<tr>
<td>Upstream_clim_30</td>
<td>1.58</td>
<td>1.55</td>
<td>1.53</td>
<td>15.27</td>
</tr>
<tr>
<td>Upstream_clim_50</td>
<td>1.45</td>
<td>1.42</td>
<td>1.40</td>
<td>13.04</td>
</tr>
<tr>
<td>Downstream_clim_10</td>
<td>2.67</td>
<td>2.61</td>
<td>2.57</td>
<td>18.56</td>
</tr>
<tr>
<td>Downstream_clim_30</td>
<td>2.14</td>
<td>2.09</td>
<td>2.07</td>
<td>19.66</td>
</tr>
<tr>
<td>Downstream_clim_50</td>
<td>2.01</td>
<td>1.97</td>
<td>1.94</td>
<td>19.34</td>
</tr>
</tbody>
</table>

Speed-up and AEP for case ID 2000

3D velocity vectors 10 meters above the ground
# Cosine hill – ID 3000

<table>
<thead>
<tr>
<th>Location</th>
<th>WECS_40</th>
<th>WECS_60</th>
<th>WECS_80</th>
<th>AEP (Gwh/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream_clim_10</td>
<td>1.88</td>
<td>1.84</td>
<td>1.82</td>
<td>18.51</td>
</tr>
<tr>
<td>Upstream_clim_30</td>
<td>1.55</td>
<td>1.51</td>
<td>1.50</td>
<td>14.73</td>
</tr>
<tr>
<td>Upstream_clim_50</td>
<td>1.43</td>
<td>1.40</td>
<td>1.38</td>
<td>12.62</td>
</tr>
<tr>
<td>Downstream_clim_10</td>
<td>2.43</td>
<td>2.38</td>
<td>2.35</td>
<td>19.25</td>
</tr>
<tr>
<td>Downstream_clim_30</td>
<td>2.30</td>
<td>2.25</td>
<td>2.22</td>
<td>19.61</td>
</tr>
<tr>
<td>Downstream_clim_50</td>
<td>2.35</td>
<td>2.30</td>
<td>2.22</td>
<td>19.49</td>
</tr>
</tbody>
</table>

**Speed-up and AEP for case ID 3000**

3D velocity vectors 10 meters above the ground
## Cosine hill

<table>
<thead>
<tr>
<th>Downstream climatology</th>
<th>10</th>
<th>30</th>
<th>50</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEP1000/2000 %</td>
<td>103.66</td>
<td>86.98</td>
<td>83.51</td>
<td>Increase the number of iterations</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Upstream climatology</th>
<th>10</th>
<th>30</th>
<th>50</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEP1000/2000 %</td>
<td>99.32</td>
<td>99.67</td>
<td>100.77</td>
<td>Increase the number of iterations</td>
</tr>
<tr>
<td>AEP1000/3000 %</td>
<td>102.81</td>
<td>103.33</td>
<td>104.12</td>
<td>Finer resolution - separation</td>
</tr>
<tr>
<td>AEP1000/1001 %</td>
<td>99.37</td>
<td>98.70</td>
<td>99.85</td>
<td>Reduced boundary layer height</td>
</tr>
<tr>
<td>AEP1000/1002 %</td>
<td>100.42</td>
<td>101.13</td>
<td>100.84</td>
<td>Increased boundary layer height</td>
</tr>
<tr>
<td>AEP1000/1100 %</td>
<td>115.33</td>
<td>115.74</td>
<td>112.02</td>
<td>Sea surface roughness</td>
</tr>
<tr>
<td>AEP1000/1200 %</td>
<td>102.64</td>
<td>101.13</td>
<td>101.94</td>
<td>Finer resolution vertical direction</td>
</tr>
</tbody>
</table>

- Slower convergence downstream
- Separation requires 20x20 meters resolution, 40° inclination
- Less sensitive to boundary profile
- Very sensitive to roughness changes
- No significant changes with a finer grid in z-direction
Cosine hill – forest

<table>
<thead>
<tr>
<th>ID</th>
<th>No forest</th>
<th>Forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. res.</td>
<td>15x15</td>
<td>15x15</td>
</tr>
<tr>
<td>Height</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>NZ</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Factor</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>#cells</td>
<td>460350</td>
<td>460350</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Z_{land}</th>
<th>No forest</th>
<th>Forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z_{sea}</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>BL Height</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>BL Height</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Iterations</td>
<td>400</td>
<td>4000</td>
</tr>
<tr>
<td>Solver</td>
<td>Coupled</td>
<td>Seg.</td>
</tr>
<tr>
<td>Nesting</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Turb. mod.</td>
<td>k-eps</td>
<td>k-eps</td>
</tr>
<tr>
<td>Temp.</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Setting for two similar cases with and without a forest

Differences in AEP with and without a forest

<table>
<thead>
<tr>
<th>Downstream climatology</th>
<th>10</th>
<th>30</th>
<th>50</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEP (No forest)/(forest) %</td>
<td>117.24</td>
<td>126.09</td>
<td>129.44</td>
<td>Large sensitivities to vegetation</td>
</tr>
</tbody>
</table>
AEP parameter sensitivities - processing

Summary:

Some processing parameters display large AEP sensitivities.

Next:

The AEP procedure requires inclusion of climatology data and turbine characteristics.

We will look at post-processing parameter sensitivities.
AEP sensitivity – Post-processing

- Climatologies represented by frequency distribution

- Power curve correction

The above sensitivities are illustrated with the micro-siting at Hundhammerfjellet a typical ridge situation with negative shear profiles.

\[ \text{\( U_{\text{ref}} \) refers to speed over a flat area, \( U \) refers to the perturbed speed over a hill top. The speed-up is given as } U/U_{\text{ref}} \]
Hundhammerfjellet – 2D ridge

Location: Hundhammerfjellet, Norway

Wind farm: Under construction, 15 turbines, 3-3.5 MW ScanWind, 80 meters hub height, height variation within the wind farm is 60 meters

Climatology: Two measurement masts, 30 and 50 meters high

Models: Nesting, 15x15 km into 9x7.5 km with resolution 30x30 meters, number of cells is 800 000

Digital terrain model with elevation. 9x7.5 km model in grey frame

Hundhammerfjellet, photomontage
The difference in energy output between the various turbines is 23%.

AEP based on climatology Tommerhol is 175.0 GWh/y
AEP based on climatology Hundhammer is 179.0 GWh/y

The discrepancy in estimated AEP is 2.3%.
Climatology transfer

The discrete representation of a climatology as a frequency distribution introduces interpolation errors.

Speed-up: 0.9
Direction shift: -10°

Speed-up: 1.11
Direction shift: 10°
Re-distribution of transferred climatology

The re-distribution imposes a smoothing of the frequency distribution.

Consequently, a transferred climatology which is moved back to its original position will not be reproduced.
The climatology Hundhammeren is moved 1000 meters in the cardinal direction and then back to its original position.
Use the time histories instead of the frequency distribution when post-processing the wind field simulations.
Weighting of climatology data

Summary:

The representation of climatology data by a frequency distribution introduces significant interpolation errors.

Finer resolution, more sectors and bins would reduce the errors, the best would be to use time series.

Next:

Power curve correction
Hundhammerfjellet – negative shear

Speed-ups are observed over hills with maximum wind speed near the ground followed by a region with a negative shear

Wind field from sector 6 (150 degrees), isosurface showing the highest wind speeds below hub height
Energy content – wind profiles

Energy content for logarithmic wind profile

Energy content for wind profile with negative shear
Power curve certification

Certified power curve is established at test site in plane terrain

At complex sites the certified power curve is not valid
Power curve correction procedure

\[
P(z) = \frac{1}{2} \cdot \frac{16}{27} \cdot \rho \cdot \left[ H_r + \left( \frac{D_r}{2} \right)^2 \right] \cdot \sqrt{\left( \frac{D_r}{2} \right)^2 - H_r - z^2} \cdot v(z)^3 \, dz
\]

\[
R = \frac{P(\text{numerical profile})}{P(\text{exponential profile})}
\]

\[
P_{\text{cor}}(\vec{V}, m) = R(\vec{V}, m) \cdot P_{\text{cer}}(\vec{V})
\]

**Power curve correction**

A ridge situation with a negative shear profile could be significantly improved with the correction procedure.

<table>
<thead>
<tr>
<th></th>
<th>No correction</th>
<th>Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 (Experimental/CFD)</td>
<td>77</td>
<td>96</td>
</tr>
</tbody>
</table>

*AEP (GWh/y) for a turbine on a ridge with and without power curve correction*
Conclusion

Calculation of the AEP involves many disciplines, describing complex physical phenomenon. Consequently, a simple calculation procedure can not be set up.

Basic cases show that CFD is clearly more accurate than linear methods.

Important issues

• Grid resolution
• Roughness description
• Climatology description; frequency distribution vs. time-series
• Power curve correction
More information

Booth Number  747

www.windsim.com:
- Paper and presentations
- Free WindSim evaluation copy
- Training courses: 18-20 June 2007
- User meeting: 21-22 June 2007