VALIDATION AND COMPARISON BETWEEN CFD AND LINEAR WASP MODEL PERFORMANCE IN VERTICAL PROFILE ESTIMATION USING MEASUREMENTS FROM A 65M TALL MAST

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Summary

The study examines the resource modeling capabilities of modern CFD software (WindSim) on a difficult and rugged site to estimate the wind velocity distribution vertical profile at different wind directions and during different seasons. Cross-predictions between different measuring heights are used. Two comparison sessions were set up for two different year-seasons. All comparison results were extrapolated with WaSP results. Accurate, fine grid was used around the measuring mast. Results show superiority of the CFD model.

1. Introduction & Objectives

Many wind energy projects are proceeding to the constructional phase in eastern Mediterranean and Balkans region. In Greece particularly, more than 1.000 MW (year 2010) is operating while tenths of GW of projects are currently under licensing procedure and final installation planning. One of the most important factors during the development stage of a project is without doubt wind resource modeling. In particular, the most critical question in projects that have already license and are under final design/development, is how vertical wind shear profile is valuated when measurements are taken from lower than hub height masts (common practice). The answer to such a critical question is very difficult in rugged and mountainous terrain.

Many questions can arise from this occasion: When developers want to estimate the average wind velocity and generally the wind potential at hub height, how certain can they be when CFD software is used combined with measurements from lower mast Vs measurements directly from a mast at hub height? In addition, is the performance of CFD commercial software (WindSim) better than the performance of WAsP linear model? How tall measurement mast should be erected in order to get a good picture of vertical wind shear profile?

The objective thus of this study is to give an initial but otherwise clear answer to these questions. It differs from many other past studies because the measurement mast is installed in a site, neighboring with both the sea and tall (often snow covered) mountains. The results can thus be used by the developers and RES financing sources as an initial guide on judging uncertainties of vertical wind-profile prediction with the scientifically most promising simulation tools, namely CFD.

2. Methodology

The procedure and methodology [3],[4] that was chosen for the study can be summarized as follows:

- Select a geographical region that complies with all the prerequisites to be characterized as “difficult” for wind flow modeling. Meaning that it should have a generally rugged terrain (but not technically inadequate for a wind park), some common climatology affecting factors (sea or tall mountains around).
- Operate a tall met mast of 65m height, able to collect reliable measurements, meeting IEC 61400 standards.
- Gather data for a large enough period of time.
- Setup digital terrain model. In our case, it is created with the combination of:
    - Data from the SRTM project of Nasa & European Space Agency for the general area.
    - The abovementioned data was corrected by contour lines of 4m isodistance that were derived from 1:5000 topographical maps for an area ~1km around the mast. Digital terrain models established both for height and roughness.

- Run WindSim CFD v4.9.1. (based on RANS equations). The use of nesting technique is a necessity due to the fine grid that was chosen for the micro-model (15x15m) combining with the large extent of the modeled region (see §3.).
- Run a conventional WAsP model [1] to generate comparable wind-shear vertical profiles.
- Compare predictions of WindSim in different heights (transferred climatologies) with actual measurements (original climatologies) using 30m.a.g.l as the reference height.
- Compare WindSim results with WAsP values and Exponent Law values.

The procedure reflects in reality the transformation of wind measurements from original measuring height to hub height within an imaginary Wind Farm that usually is carried out during site-calibration procedure or due diligence studies. It is in other words the crucial task that wind project developers and financing organisations are faced with.

3. Description of Study Area

The validation study took place in Central Greece. The study area is surrounded by two high mountains in the North-East and in the North-West leaving a valley in the North, which is parallel to North-South and is margined by sea in the South.

The study area extend is 11.8X8.5km^2. The area has a typical Mediterranean climate. In this part of Greece, northern is the principal wind direction and thus the northern Meltemi winds dominate each summer period. In the warmer days local thermal induced wind might be a common phenomenon.

In general the wind potential of the area is quite strong. In fact, the whole study area resembles a gigantic constricted tube whereas the wind particles are accelerated in the middle of it due to the Venturi effect and makes the validation project if not more difficult, but for sure more interesting. (See picture 1).

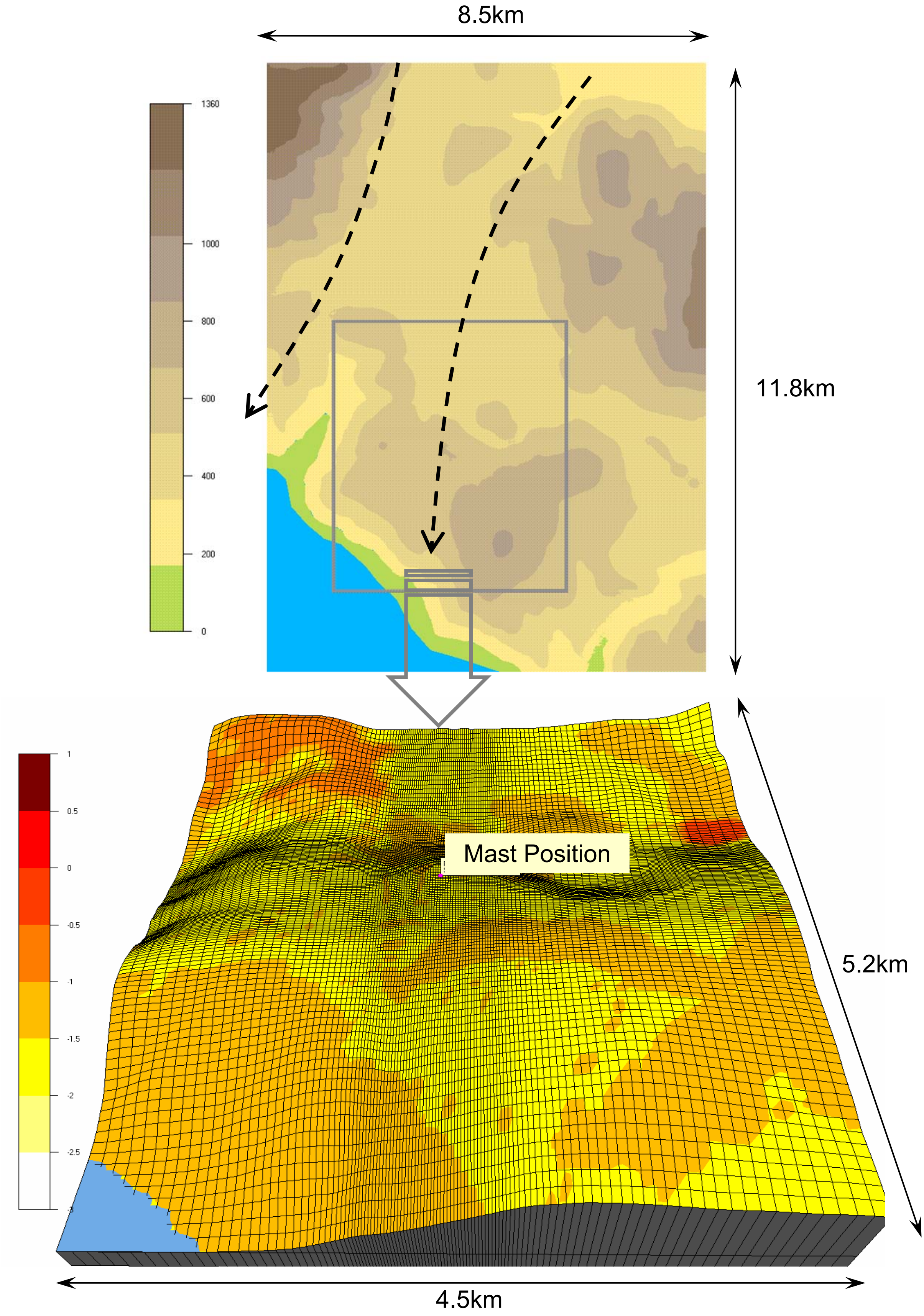
It is very interesting to mention that inclination angles in the main wind direction do not exceed 28^o. (See §5.1.a. 22^o is the limit for linear models). Another important terrain characteristic is that around and close to the mast (<100m), terrain looks rather flat with gentle slopes. In the south the gently shaped terrain continues for approximately 800m.

4. Measurement Station

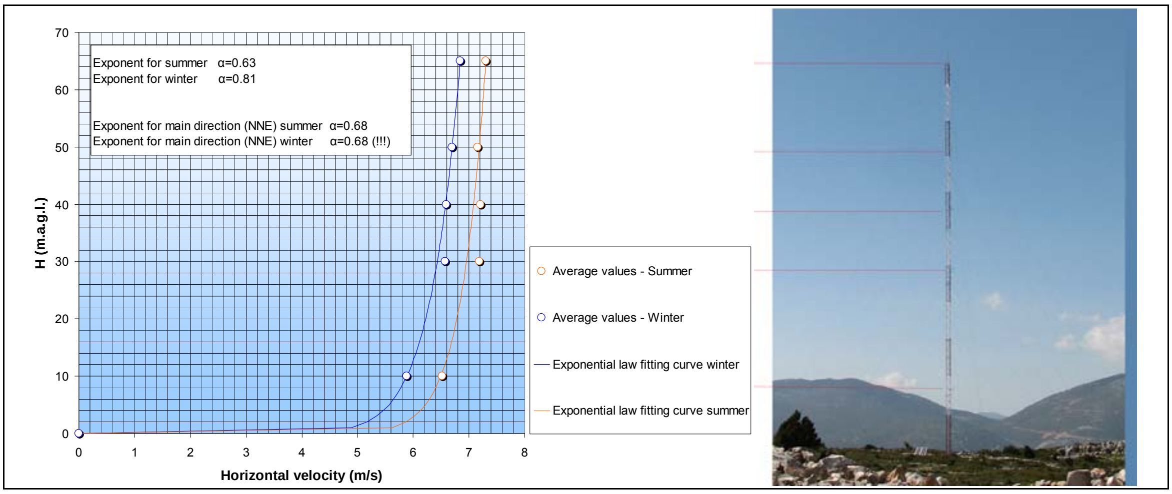
The anemological mast of 64m height was installed on April 2008 for more detailed estimation of the wind potential of an already licensed project, thus it was suitable for the purpose of this study.

The measuring station was installed in accordance with IEC-61400-12-1 by the accredited laboratory of Istos Renewables. All anemometers were calibrated by a Measnet member lab and in addition control anemometer was installed for in situ comparison at the top of the mast. The measurement campaign lasted for a whole year. Measuring data was filtered in order to avoid no valid values that occur due to icing on instruments or lightning storms.

Before determining and selecting the most suitable measuring periods of year to use for the validation study, the measuring data was examined in order to find any differences in the vertical wind-shear profile between winter and summer months (i.e. conventional winter months for measurements: Dec, Jan, Feb, Mar / summer: Jun, Jul, Aug, Sept). As it is easy to be distinguished from picture 3, there is no significant difference in the shape of wind-shear profile between winter and summer months. Furthermore for main direction (NNE) the vertical wind-shear profile gives exactly the same exponential factor $\alpha=0.68$. This similarity actually implies than NNE winds are always induced by the same (non locally thermal / seasonally affected) wind pattern.



Picture 1 & 2: The area of validation study, where nesting technique was used (grey). In the upper picture the arrows stand for the Venturi effect caused be the valley. The lower area is the micro-model where the roughness height (in log scale) is depicted.



Picture 3: The average vertical wind-shear profiles, (summer vs. winter).

4.1. Filtering & Analysis of Data

The measurement data has been automatically & manually inspected and filtered, identifying inconsistencies and missing data. The missing data is only a very little percentage of the whole volume of data (3.6%) caused mainly due to power shortage and icing of instruments. After filtering, five frequency tables of measurements that refer to each measuring height are derived.

5. Wind Field Simulation

In global wind energy study subject, two types of Wind Field Models dominate: linearised (ie WaSP) and CFD (ie WindSim) models. Linearised are very famous because they require very limited computer power, they are fast and easy to use. But what are their limitations? In the following paragraph the main characteristics of both types of models are presented:

5.1. Presentation of Wind Field Models

a. Linearised Models

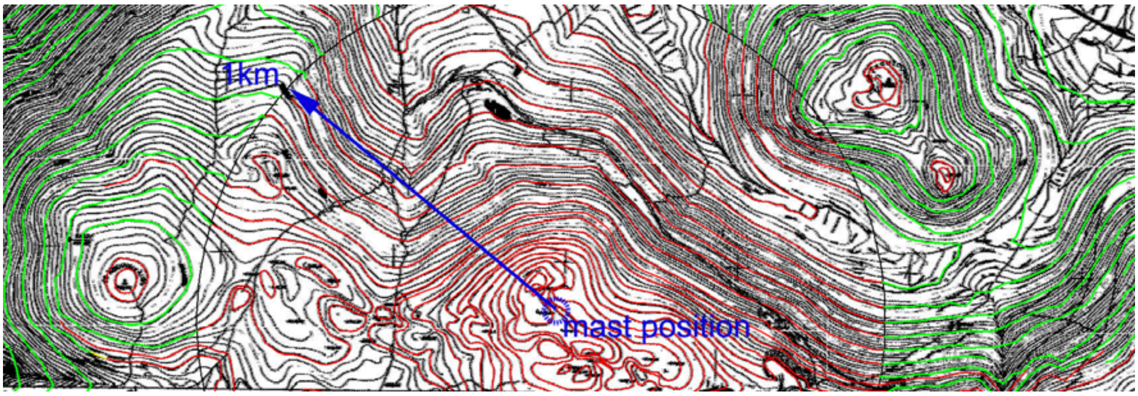
Linearised models are based on linearised solutions of the dynamic equations for boundary layer flow perturbed by terrain (simplified steady-state solutions of the Navier-Stokes equations - e.g. linearisation techniques). The theory of Jackson and Hunt (1975) provided a basis for numerical modeling of 2D steady-state turbulent flow over a low hill of gentle slope. [2]
The governing momentum equations are linearised using scale analysis and assuming uniform rough surface and small slope.
The terrain shape is analysed in terms of Fourier components [2]; the equations are thus solved in Fourier space; the Fourier transform is numerically inverted to give the solution in real space. For that purpose terrain model is developed around the anemometry mast using polar coordinate system. Simple closure assumptions are normally used to model the Reynolds stresses. Moreover the linearised theory can be extended in order to model the effect on the wind field of roughness length variations.
Application of the theory to the wind energy sector led to the development of two most popular microscale modelling products: WAsP (Troen and Petersen, 1989) and MsMicro (Walmsley et al. 1990).
According to bibliography[2] linearised models fail to predict and describe correctly the lee region where turbulent wake and separation develop. Further tests and applications proved the linearised theory to give reasonably good results on the upstream side and on the top of hills with H/L≤0.3-0.4, which corresponds to maximum inclinations of 22°.

b. CFD non linearised models (especially WindSim)

As already known, the most general equations that govern the fluid flow in the Atmospheric Boundary Layer are the Navier-Stokes equations. These equations express the physical principles of conservation of mass, momentum and energy. WindSim CFD software solves the non-linear transport equations for mass, momentum and energy by the means of finite volume method.
The finite volume method for discretises the governing analytical equations over each finite volume. In particular, WindSim solves the RANS equations. RANS (Raynolds Averaged Navier Stokes) equations are deduced from the Navier-Stokes equation, using a time averaging procedure. In this way all the turbulence is modelled and only the time averaged variables are found with the simulations. These equations aren't linear and thus the only way to solve them is to use an iterative method. WindSim initiates a core code constituted by the solver Phoenics.

5.2. Orography Data and improvement.

The digital terrain data in this project derived from publicly available sources (SRTM & D4W). Grid resolution from those sources cannot be considered fine. The best grid dimensions obtained were 90x90m (corresponds to the length of 3" of a longitudinal degree). Knowing from experience that this alone stands for a basic inaccuracy source [7], our team purchased 1:5000 topographical maps of the area. The low resolution grid data were converted to contour altitude isolines. Now the satellite low resolution data could be corrected for an area ~1km around the mast by contour lines of 4m isodistance derived from the topographical maps. The result was a DTM with grid resolution of 6x6m. The positioning of the mast on the Digital Terrain Model was carefully accomplished by GPS data and cross-checked with photographs and on-site observations.



Picture 4: Improving the DTM by citing topographical maps on satellite data (green).

5.3. Roughness

The whole region of this study is very complicated concerning the roughness. As described in paragraph 3, the sea area to the south part corresponds to roughness height of 0.001m. In the inland area, the roughness height which dominates is 0.03m (corresponds to open grass-land with few busses). But there are many areas with steep rocks or villages that have a roughness height from 0.3m up to 0.8m. Main roughness data was taken from Data4Wind database, tuned to some level according to actual local observations.

5.4. WindSim Modelling

Due to the large domain size, the nesting technique was used. Flow fields were solved using 16 direction sectors in both the meso-scale, and the micro-scale model. The WindSim version used was 4.9.1. At first the wind conditions for the meso model were determined with the following parameters:

Domain size: 8.5x11.2 km	Vertical nodes: 30, height distribution factor: 0.1
Model height: 8.319 m	Number of nodes: 346 860
Grid spacing x-y: 90 m	Iterations: 100
Boundary condition at top: fix pres.	Physical model: Disregard temperature (neutral conditions)

To get more accurate results the results of the meso-model are used as an input (boundary conditions) to the micro-model engaged:

Area size: 4.5x5.2 km	Vertical nodes: 60, height distribution factor: 0.07
Model height: 5.083m	Number of nodes: 873 600
Grid spacing x-y: 18x18m (6m is the resolution of DTM)	Iterations: 100
Boundary condition at top: fix pres.	Physical model: Disregard temperature

Measured wind data was imported to each measuring height in the form of frequency-direction tables (wind-roses). The micro model had a refinement grid area close to the mast with fine resolution of 18m x 18m. (see picture 2).

The predictor climatology was chosen to be at the 30m above ground level height and then it was transferred by vertical translation to 10m, 40m, 50m and 65m.a.g.l., using the micro model results.

The predicted climatologies at each level are then compared with the original one.

The comparisons were repeated for each sector and so the process generated 4x16=64 comparisons.

5.5. WAsP Modelling

In order to provide a reference and comparison measure for CFD, the study includes a similar “conventional” WAsP based analysis. The model is based on WAsP 8.0 engine, set up through the WindPro 2.5 frontend. The procedure followed to establish the WAsP model was a “by the book” approach. The same grid data file used in WindSim is imported and converted to contours with the built-in map editor, with a separation of 5m height.

Apart from the recurring procedures, calculations were quite speedy, due to the fact that only measurement positions were subject to predictions, one of the advantages of the WAsP modeling.

6. Results

After transferring the reference climatology from 30m.a.g.l. to each other measuring level, the results of comparisons between predictions and measurements were calculated. The procedure was to calculate for each sector the differences between:

- Measured Average Velocity and predicted Average Velocity for each predicted measuring height i.e. 10, 30, 40, 50, 65m.a.g.l. as generated by WindSim. Totally 64 comparisons were carried out (ie. 4 predicted heights X 16 sectors = 64 predictions).
- Measured Average Velocity and predicted Average Velocity for each predicted measuring height i.e. 10, 30, 40, 50, 65m.a.g.l. as generated by WAsP.
- Finally, the accuracy of transferred wind-rose predictions were compared to the results of simplistic exponential law fit with given values the measured velocities at 10m.a.g.l. and 30m.a.g.l.

The aforementioned comparisons per sector were weighted according to the blow frequency of each sector and thus a polar diagram is created in order to generate comparable errors.

At last, a comparison between the theoretical energy productions of a dummy windturbine calculated with real measurements at 65m (hypothetical hub-height) and of the same dummy windturbine calculated with predicted wind-roses.

6.1. Average Wind Speed for overall sectors

This comparison shows the general performance of the different models. In the next diagram measurements from all directions are plotted against estimations.

Quantification of the performance of the examined models is done by the implementation of the following functions:

$$\overline{|Error|} = \frac{\sum_{i=1}^{n} \left| V_{real,i} - V_{pred,i} \right|}{n} \quad (1)$$

, where i goes for each different predicted measuring height.

$$std(Errors) = \sqrt{\frac{SSR}{n-1}} = \sqrt{\frac{\sum_{i=1}^{n} (V_{real,i} - V_{pred,i})^2}{n-1}} \quad (2)$$

Quantification should have a practical meaning and should be easily translated to useful information for a potential user of the models. Therefore, it was preferred to count in only errors from 30m.a.g.l. and above, since most project developers in Greece have measurements from a short mast (perhaps 30m) and want to estimate the vertical wind-shear profile and the wind velocity at hub height. Practically we ignore errors at 10m.a.g.l., because they are out of interest.

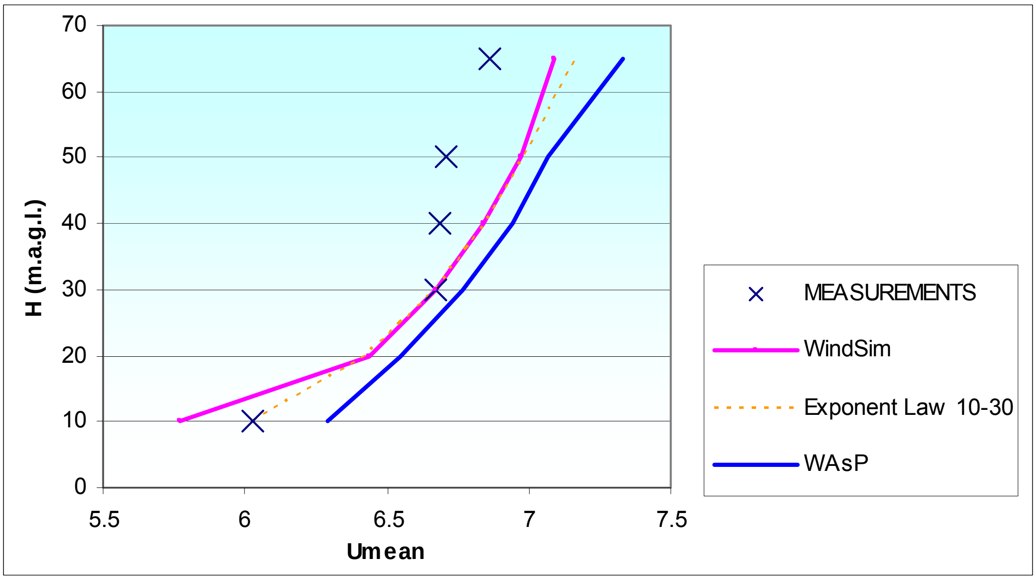


Diagram 1: Measurements from all sectors vs estimations from WindSim and other models.

So, according to the results shown in Diagram 1 and implementing the equations (1) & (2) for 40, 50 and 65m levels we obtain the following table:

MODEL:	***WindSim***		***WAsP***		***Exponential Law fitting 10-30m.a.g.l.***	
Average(|Errors|)	***0.22m/s***	***3.3%***	***0.37m/s***	***5.4%***	***0.25m/s***	***3.6%***
Std(Errors)	***0.27m/s***	***3.9%***	***0.45m/s***	***6.5%***	***0.31m/s***	***4.5%***
Error @65m.a.g.l.	***+0.23m/s***	***3.3%***	***+0.47m/s***	***6.8% (!!!)***	***+0.30m/s***	***4.4%***

Table I

6.2. Analysis of the Sector-wise Estimation Performance .

The former procedure is carried out for each of the 16 sectors. Below, table II shows the comparison results per sector only for WindSim & Exponential Law fitting. Except for standard deviations of errors, the errors at 65m are laid over for both models ($e_{@65m}$).

N sector

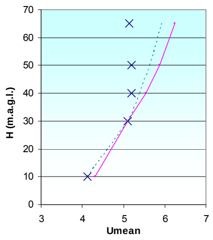
frequency=12.2%

$s|_{WindSim}$ = 0.77m/s

$e_{@65m}$= 1.1m/s

$s|_{Exp. Law}$ = 0.53m/s

$e_{@65m}$= 0.79m/s



NNE sector

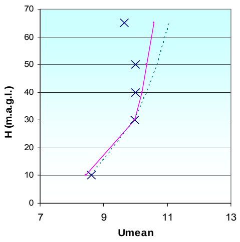
frequency=22.4%

$s|_{WindSim}$ = 0.60m/s

$e_{@65m}$= 0.95m/s

$s|_{Exp. Law}$ = 0.93m/s

$e_{@65m}$= 1.41m/s



NE sector

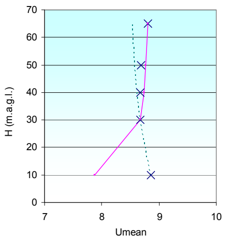
frequency=12.3%

$s|_{WindSim}$ = 0.06m/s

$e_{@65m}$=-0.01m/s

$s|_{Exp. Law}$ = 0.17m/s

$e_{@65m}$=-0.27m/s



ENE sector

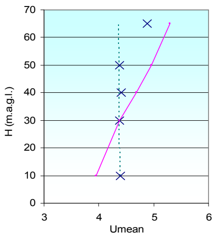
frequency=1.9%

$s|_{WindSim}$ = 0.44m/s

$e_{@65m}$= 0.41m/s

$s|_{Exp. Law}$ = 0.30m/s

$e_{@65m}$= -0.51m/s



E sector

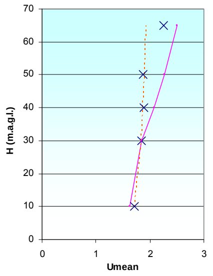
frequency = 0.6%

$s|_{WindSim}$ = 0.29m/s

$e_{@65m}$= 0.24m/s

$s|_{Exp. Law}$ = 0.19m/s

$e_{@65m}$= -0.32m/s



ESE sector

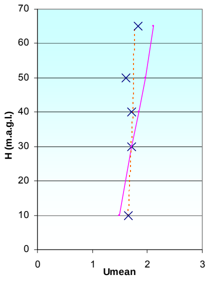
frequency = 0.6%

$s|_{WindSim}$ = 0.27m/s

$e_{@65m}$= 0.28m/s

$s|_{Exp. Law}$ = 0.09m/s

$e_{@65m}$= -0.06m/s



SE sector

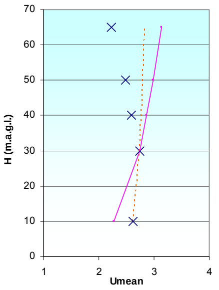
frequency = 1.1%

$s|_{WindSim}$ = 0.62m/s

$e_{@65m}$= 0.91m/s

$s|_{Exp. Law}$ = 0.40m/s

$e_{@65m}$= 0.60m/s



SSE sector

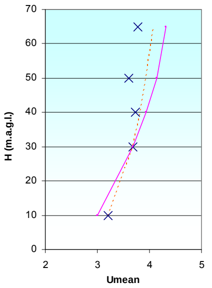
frequency = 2.3%

$s|_{WindSim}$ = 0.46m/s

$e_{@65m}$= 0.54m/s

$s|_{Exp. Law}$ = 0.27m/s

$e_{@65m}$= 0.30m/s



S sector

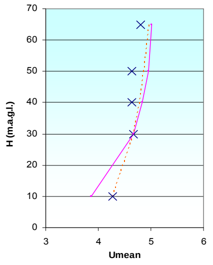
frequency = 12.1%

$s|_{WindSim}$ = 0.24m/s

$e_{@65m}$= 0.21m/s

$s|_{Exp. Law}$ = 0.18m/s

$e_{@65m}$= 0.17m/s



SSW sector

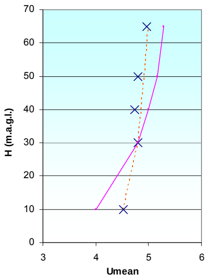
frequency = 15.5%

$s|_{WindSim}$ = 0.32m/s

$e_{@65m}$= 0.32m/s

$s|_{Exp. Law}$ = 0.10m/s

$e_{@65m}$= 0.02m/s



SW sector

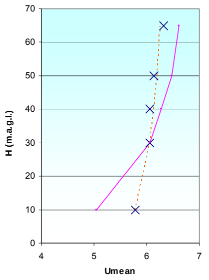
frequency = 9.9%

$s|_{WindSim}$ = 0.29m/s

$e_{@65m}$= 0.29m/s

$s|_{Exp. Law}$ = 0.07m/s

$e_{@65m}$= -0.06m/s



WSW sector

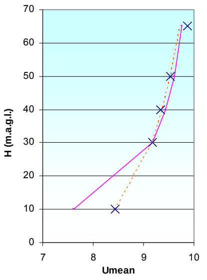
frequency = 5.2%

$s|_{WindSim}$ = 0.10m/s

$e_{@65m}$= -0.12m/s

$s|_{Exp. Law}$ = 0.08m/s

$e_{@65m}$= -0.14m/s



W sector

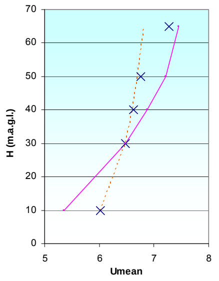
frequency = 1,0%

$s|_{WindSim}$ = 0.32m/s

$e_{@65m}$= 0.19m/s

$s|_{Exp. Law}$ = 0.26m/s

$e_{@65m}$= -0.45m/s



WNW sector ,

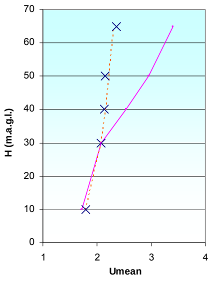
frequency = 0.4%

$s|_{WindSim}$ = 0.79m/s

$e_{@65m}$= 1.0m/s

$s|_{Exp. Law}$ = 0.06m/s

$e_{@65m}$= -0.05m/s



NW sector

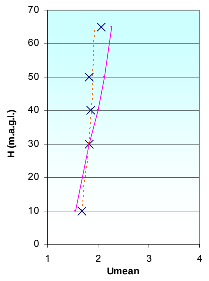
frequency = 0.5%

$s|_{WindSim}$ = 0.22m/s

$e_{@65m}$= 0.2m/s

$s|_{Exp. Law}$ = 0.09m/s

$e_{@65m}$= -0.13m/s



NNW sector

frequency = 1.9%

$s|_{WindSim}$ = 0.68m/s

$e_{@65m}$= 0.88m/s

$s|_{Exp. Law}$ = 0.43m/s

$e_{@65m}$= 0.6m/s

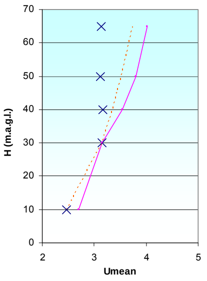
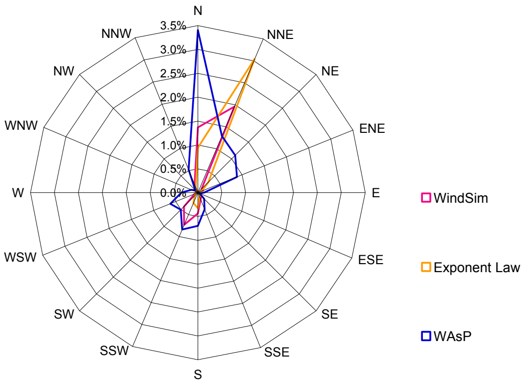


Table II

It can be clearly seen that WindSim is performing very well for dominant wind directions and in the contrary, it performs bad (even worse than the Exp. Law model) for directions with weak winds. By virtue of flat terrain in the south, exp. law performs very well for southerly directions.

6.3. Weighted Errors in vertical profile prediction per sector

Since the evaluated errors in each sector cannot be directly averaged to the overall error, frequency of each sector is a very important weight factor. In diagram 2 the polar chart shows the weighted relative errors for the 3 different models.



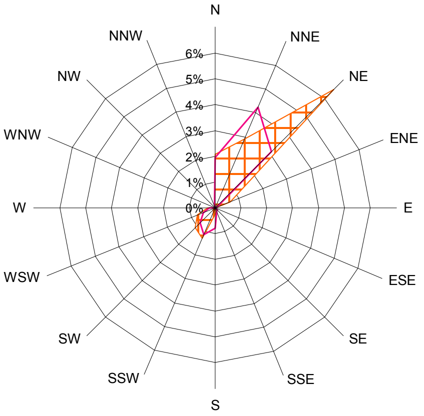


Diagram 2: Polar chart with relative errors in velocity *Diagram 3: Polar chart with relative errors in energy yield*

6.4. Relative Errors in energy content - sectrowise

Judging from all results that are until now presented somebody could suppose that exponent law performs as well as WindSim. But apart from a random case due to the local topography which very close to the mast (<100m) is rather flat, the truth is that in our case exponent law model cannot compete with WindSim, when energy production is examined. In diagram 3 the relative errors in energy yield per sector are presented for WindSim and Exponent Law (supposing the use of measurements at 30m.a.g.l. in both cases). Important to notice is that the overall relative error in Energy Yield at 65m for WindSim was **5.5%** and for Exponent Law was **8%**.

7. Conclusion - Possible Error Inducing Factors & Interpretation

Looking at the results in the previous chapter, it is obvious that even for a fine and carefully set up CFD model, errors in vertical profile estimation occur. The possible sources of errors can only be assumed taking into account bibliography and experience [7]:

- Uncertainty in roughness height estimation. This is the most difficult task in resource modelling, because there is neither a standardised way to estimate it nor a simple scientific method to measure it exactly. [5], [6]
- Uncertainty due to nesting technique. This technique imposes artificial boundary conditions in side walls of the micro-model that could affect the results. [4]
- Thermal effects in our case do not seem to add significant error, because in NNE direction, the dominant wind direction, the thermal stratification seems to be neutral. Only for S directions this could be a case, because the sea lies to the south.
- Uncertainty due to DTM in our case seems to be very small except for measurements at 10m.a.g.l., whereas even a rock 3m tall or a single fence could disturb significantly the wind flow at that height and that’s why we obtain so high errors at lower heights.

As far as WAsP modelling and results is concerned, a noticeable 0,1 m/s discrepancy which is visible (vertical profile diagram) between 30m predicted average wind speed and actual measurements is mainly due to the inavoidable Weibull fitting. This is normal for the analysis-apply procedure followed by WAsP, an issue met by all similar studies-references. In particular, large deviations in sectorwise mean wind speed self-prediction occur, due to:

- neighbouring sectors with big differencies in weibull distribution
- sectors with too few wind speed bins
- weibull fitting during analysis and apply modelling steps
- really complex micro and meso scale topography on the study area (tunneling effects) which seem to exceed WAsP modelling limits

This phenomenon practically renders the sectorwise WAsP predictions for each height useless and without scientific interest. Their presentation therefore on the polar diagram is purelly informational, as WAsP proved not really the suitable instrument for such comparisons (sectorwise vertical profile predictions).

8. Recommendations

Based on the study's results and prediction errors interpretation, we can also conclude to some recommendations towards members of the wind energy community.

8.1. For future research, studies and code developers.

For future validation studies it is emphasised by the authors the need for:

- Higher measurements either from tall masts either from a combination of mast and calibrated LIDAR measurements. The 10m.a.g.l. should not be examined at all in the future researches.

- Coupling of temperature equations with WindSim model has already been accomplished. But yet there must be a validation with common wind-speed and air temperature measurements at many heights.

8.2. For wind park developers, owners and financing sources

CFD wind resource modelling with one at least and tall enough mast is the one-way practice for adequate final installation planning of a modern wind energy project. It could save initial capitals and financial resources by reducing the risks in estimating the wind energy yield. In addition it can track problematic sectors with negative or extreme wind-shear that can cause problems to the operation of a WT.

9. Credits

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