White Paper 2010/2011

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February 2011

Abstract. **This white paper summarises the R&D activities carried out during 2010 and those planned for 2011. It also reports on the results of the ongoing validation programme of the WINDIE™ CFD software in terms of wind resource assessment. Validation efforts have mainly taken the shape of cross-predictions between measurement data, whereby WINDIE™ results are synthesised with one measured wind series and transported to another mast's position. The resulting 'virtual' data series can then be compared with measurements at the target station. This assessment is carried out in all WINDIE™ studies, which are usually conducted prior to wind farm construction. In some cases, when WINDIE™ is used after the wind farm has been in operation, the opportunity may arise to compare WINDIE™ AEP estimates with wind farm SCADA data.**

1. Introduction

WINDIE™ is a computational fluid dynamics (CFD) code developed by a team of researchers from the Instituto Superior de Engenharia do Porto (ISEP, www.isep.ipp.pt). This team, lead by Prof. Fernando Aristides Castro, has over 15 years experience in the field of CFD modelling of atmospheric flows applied to the wind industry.

WINDIE™ is a non-linear model that solves the Reynolds-averaged Navier-Stokes equations (RaNS), on terrain-following meshes. It is specially suited to capture complex phenomena such as flow separation, turbulence induced by complex topography, thermal effects, large flow deviations and shear, as well as other flow features such as those induced by neighbouring forested areas.

Over the past 6 months, WINDIE™ has been used to study wind farms totalling over 250 MW of installed capacity, spread over 4 countries.

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2. Standing Out from the Pack

WINDIE™ CFD code contains a number of features that make it stand out from other wind engineering packages. This is a list of these features.

Better Results :: Growing Validation Track Record

WINDIE™, in its first year of activity as a fully-fledged wind engineering tool has come up against several real cases of considerable complexity. It has consistently outperformed WAsP in cross-predictions of mean wind speeds and in predictions of wind farm production and wind energy patterns compared with actual wind farm data. The number of cases is still small but the track record is rapidly mounting and track record reports will be published regularly with comparisons between WAsP, WINDIE™ and other codes, when available.

Coupling with Mesoscale Data

The use of mesoscale results as boundary conditions to WINDIE™ has been shown to improve results by bringing more realistic boundary conditions to the CFD computational domains. This procedure also brings with it the possibility of including more physics in the WINDIE™ simulations, though more research is required at this stage.

Modelling Thermal and Coriolis Effects

WINDIE™, in contrast with most tools on the market, can also solve the temperature field and include its effects (in terms of buoyancy and turbulence production/destruction) in the flow field. Coriolis effects are also included in the WINDIE™ formulation.

Forest Canopy Model :: Concept & Detail

WINDIE™ has, to our knowledge, the forest canopy model which has been more extensively validated with real data (Lopes da Costa (2006)). It describes the vertical shape of the trees in terms of its leaf area density and it has detailed interpolation techniques to model small or complexly shaped tree patches.

Turbulence Modelling Portfolio

WINDIE™ contains no less than 5 turbulence models in its portfolio. These models can help confirm site assessment results or help investigate phenomena that a single model may not capture. In essence, it presents the user with more possibilities of investigating what is going on at a given site.

Versatility

WINDIE™ is a growing entity, constantly developed by its authors. This makes it versatile and better equipped to meet the needs of each client.

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Interaction with other Wind Engineering Tools

With further and further use in wind engineering projects, the abilities of WINDIE™ to interact with other common wind engineering tools (WAsP, WAT, WindFarmer, OpenWind, etc.) has grown immensely over the past year. This is expected to continue as new advantages are seen in providing outputs to other specialised software or receiving inputs from other sources.

3. R&D Activities 2010

Progress in Resource Assessment Studies

Until recently, the use of CFD codes in the wind industry had been almost exclusively focussed on Site Assessment studies, with production estimates and resource being carried out with traditional linear models. It is our belief that this need not be so, and that one can take advantage of the more accurate modelling afforded by CFD to also improve the quality of wind resource estimates. Towards that end, WINDIE™ has suffered major developments over the past year to be able to deliver accurate resource assessment studies. The synthesis procedure, in particular, brought a fundamental change in the way the results of a set of simulations performed for a particular site were used to obtain data at layout positions or over the entire site. The other improvements introduced aimed at better interaction between WINDIE™ and other tools used in the wind industry.

Synthesis Procedure

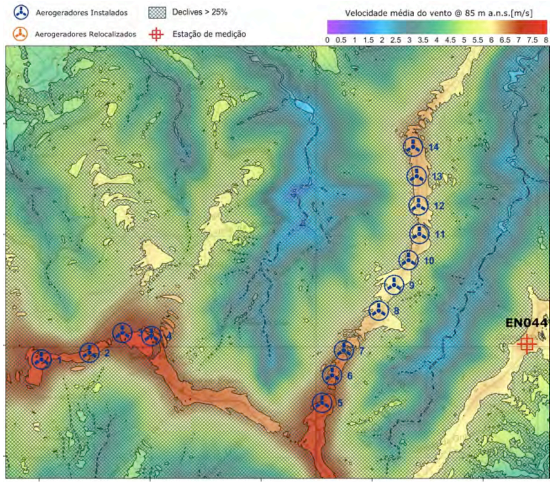
The synthesis procedure uses a set of stationary WINDIE™ results covering the whole wind rose (12 3D wind fields, for example) as a transfer matrix for the measured data. The procedure consists in feeding each wind measurement collected at a reference measuring station to the transfer matrix and obtaining a corresponding simultaneous estimate of the wind conditions at any spatial point in the computational domain. This leads to 'virtual data series' (or 'synthetic data series') at any layout position or WRG grid point, from which Weibull parameters and production estimates can be derived. All quantities are transported: wind speed, wind direction and the standard deviation of the wind speed.

Calculation of Weibull Parameters

From synthetic wind data, a more advanced algorithm for the calculation of the Weibull function was developed. The algorithm calculates shape and scale factors according to the methods of 'Standard Deviation', 'Energy Pattern Factor', 'Maximum Likelihood', 'Least Squares' and 'Method of Moments', selecting as the final Weibull function the solution which provides the best fit to the data series.

RSF Output

From the synthetic data series produced at layout positions, Weibull parameters are derived for the whole data and for each sector, to produce a RSF (WAsP Resource Data) file which can be fed into other software, notably WindFarmer orOpenWind, to obtain wind farm production estimates. (http://www.wasp.dk/support/FAQ/WebHelp/FileFormatofRSFG.htm)



WRG Output

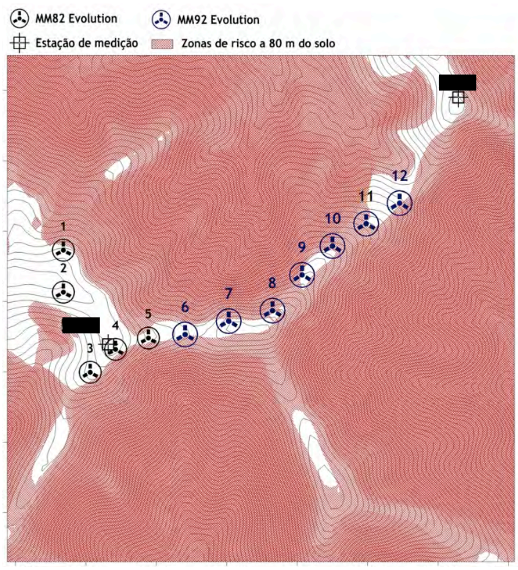
WINDIE™ can now produce WRG (Wind Resource Grid) files by producing synthetic data series at each point in a WRG, and then deriving all data that comprises a WRG file. (http://www.wasp.dk/support/FAQ/WebHelp/FileFormatofWRG.htm). The WINDIE-WRG utility also produces SURFER compatible GRD files of the global Weibull parameters, average power density, average wind speed and terrain elevation at the WRG grid positions.

Progress in Site Assessment Studies

Site Assessment, being the primary use for CFD in the wind industry, also endured some transformations over the last year, although namely in the output of results. The synthesis procedure brought about the concept of transporting measured turbulence to anywhere in the domain via a transfer matrix, and incorporating an empirical relationship which makes this transport depend on the ratio of wind speeds at the measuring point and the target location. As such, a 'synthetic turbulence time series' can now be obtained, yielding curves of TI vs Vh at any point in the domain.

Characteristic Turbulence

Apart from the transport of individual measurements, WINDIE™ utilities can, alternatively, transport a Dir/Vh matrix of measured turbulence values, onto which the standard deviation can previously be added to obtain a matrix of characteristic turbulence. The synthesis procedure now transports this characteristic turbulence to any layout position to obtain estimates of characteristic turbulence anywhere in the domain. This procedure assumes that the standard deviation of turbulence varies with velocity in a similar way to the turbulence itself, which is a sounder approach than adding the same standard deviation at all positions, as previously carried out with other CFD tools.



GRD Output

The latest improvement in Site Assessment studies has been the production of GRD files of the nefarious wind characteristics which can impair wind turbine functioning.
In a procedure similar to the generation of WRGs, WINDIE™ now yields, through its WINDIE-SA-GRD utility, grids of maximum and minimum flow inclination, average shear factor, mean wind velocity and characteristic turbulence at 15 m/s. This allows the definition of exclusion zones over a studied site, helping in the layout definition. Furthermore, these GRDs can be fed into other software, e.g. OpenWind, for automatic optimisation of the layout.

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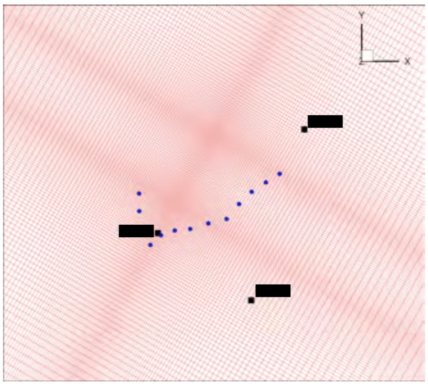
Automated Calculation of 50-year V_{ref}

An algorithm for the calculation of these velocities based on a minimisation of the standard deviation of the wind velocity, whilst preserving a minimum number of samples has been concluded following Mann's method of independent storms.

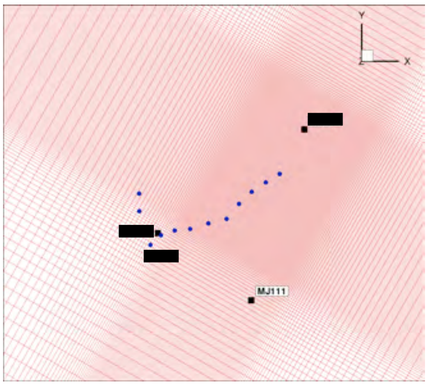
Other Improvements

Multi-refined meshes



In order to better cope with large wind farms over which is hard to maintain high resolutions without employing a massive number of grid points, an initial code was implemented to allow mesh attraction to various points simultaneously. Improvements in this area are still needed and will be added over 2011.

Meshes with High-Resolution Areas



An alternative mesh type was also included in WINDIE™ portfolio this year, whereby the user can define an area of regular high resolution from the edges of which the mesh expands to the domain boundaries. This code is more stable and easy to use than the existing others but tends to require a higher number of grid points.

Planned Improvements for 2011

2010 has marked the consolidation of WINDIE™ as a new wind engineering code, having been applied to a variety of projects throughout the world. In 2011, a number of other features will be added to further improve the quality of the results, the interaction with other wind industry tools, and the optimisation of a number of procedures to improve productivity.

Improvement in the Calculation of V_{ref} in Site Assessment

Several other methods, besides Mann's, will be added to WINDIE™. A GRD file of V_{ref} values will be added to the output to complete the maps of risk areas and bring it fully in line with the normative requirements of IEC 61400-1 ed.2.

Wind Turbine Manufacturers Requirements

We plan to make some modifications to include all parameters and outputs required by some wind turbine manufacturers site verification procedures. Most output required is already produced by WINDIE™ post-processing utilities. However,

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some quantities are still missing, such as directional shear over the swept area and velocity dependent curves of effective turbulence, to allow manufacturers to perform full turbine load studies. We plan to add these over the next few months.

Integration of Flow-following Wake Model

In collaboration with ISEP, the first half of 2011 will mark the inclusion of the first WINDIE™ wake model. The model will have the distinguishing characteristic in that the wakes will follow the surrounding flow patterns, which is of greater importance in complex terrain situations. The model is at the latter stages of development.

Multi-Mast Syntheses

Up to now, all syntheses have been carried out using one reference mast at a time, with some post-processing interpolation having been carried out in some projects to compute the mean wind speed at layout positions using more than one synthetic time series. In 2011, we will implement a fully-automated multi-mast synthesis procedure, whereby a single synthetic time series will be produced at a given point when two or more measured data series are supplied. This is expected to improve the results considerably, as the simultaneous influence of two or more met masts will be accounted for.

Fully Non-Orthogonal Meshes

To improve the flexibility of the mesh generation in WINDIE™, the use of fully non-orthogonal meshes will be added. This will require changes in the WINDIE™ code itself by addition of all the geometric terms that were previously discarded due to orthogonality. Additionally, a new mesh generation program will be required to solve the entailing Poisson equations.

Large Eddy Simulations

Although WINDIE™ is a RaNS model, work is underway by WINDIE™'s authors using large eddy simulations (LES) to improve turbulence parametrisations and the future wake model of WINDIE™.

4. Validation Track Record

WINDIE™ validation track record is growing every month with new cases in varied conditions. In all cases thus far WINDIE™ results are compared with measurements and with WAsP predictions. Whenever results are also available using a commercial wind engineering CFD tool, an additional comparison is performed.

The results of all cross-predictions are listed in the next table, followed by a summary of these results and a brief description of each site.

Cross-Predictions between WINDIE results and measured data for average wind speed

WINDIE™ VALIDATION TRACK RECORD

SITE ID	#	Reference Mast	Target Mast	Period	Type	MEASURED	WINDIE Calc	WINDIE Diff %	WAsP Calc	WAsP Diff %	COMMERCIAL CFD Calc	COMMERCIAL CFD Diff %	TERRAIN RIX ref	TERRAIN RIX target	TERRAIN DELTA RIX	FOREST
SITE 1	1	MAST1 15m agl	MAST1 30m agl	Nv04_Dc09	vertical	5.8	5.5	-5.2%	5.3	-8.3%	-	-	24.5%	24.5%	0.0%	Y
	2	MAST3 30m agl	MAST3 60m agl	Ja06_Dc09	vertical	7.0	6.7	-4.3%	6.8	-3.4%	-	-	15.3%	15.3%	0.0%	Y
	3	MAST1 30m agl	MAST3 60m agl	Ja06_Dc09	hor + vert	7.1	7.2	1.4%	6.3	-11.0%	-	-	24.5%	15.3%	-9.2%	Y
	4	MAST3 60m agl	MAST1 30m agl	Ja06_Dc09	hor + vert	6.0	6.0	0.0%	6.6	9.7%	-	-	15.3%	24.5%	9.2%	Y
	5	MAST4 40m agl	MAST4 60m agl	Mr07_Ag10	vertical	6.4	6.2	-3.1%	6.2	-3.4%	-	-	17.1%	17.1%	0.0%	Y
	6	MAST2 30m agl	MAST2 60m agl	Fb07_Dc09	vertical	6.4	6.5	1.6%	6.2	-3.8%	-	-	28.9%	28.9%	0.0%	Y
	7	MAST2 60m agl	MAST5 81m agl	My10_Ag10	hor + vert	6.8	6.8	0.0%	6.9	1.9%	-	-	28.9%	31.4%	2.5%	Y
	8	MAST5 81m agl	MAST2 60m agl	My10_Ag10	hor + vert	6.4	6.4	0.0%	6.5	1.3%	-	-	31.4%	28.9%	-2.5%	Y
SITE 2	9	MAST1 40m agl	MAST2 61m agl	Oc09_Jl10	hor + vert	7.9	8.5	8.1%	8.3	5.6%	8.5	8.0%	30.5%	25.7%	-4.8%	Y
	10	MAST2 61m agl	MAST1 40m agl	Oc09_Jl10	hor + vert	8.7	8.1	-7.0%	8.1	-7.8%	8.1	-7.0%	25.7%	30.5%	4.8%	Y
SITE 3	11	MAST1 30m agl	MAST1 50m agl	Nv07-My08+Jn10-Sp10	vert	6.6	6.6	0.0%	6.8	2.7%	6.7	2.0%	5.7%	5.7%	0.0%	Y
	12	MAST1 50m agl	MAST1 30m agl	Nv07-My08+Jn10-Sp10	vert	6.4	6.5	1.6%	6.1	-4.8%	6.3	-1.1%	5.7%	5.7%	0.0%	Y
SITE 4	13	MAST2 50m agl	MAST3 50m agl	Mr03-Ap05	hor	7.1	7.1	0.0%	7.2	1.4%	7.2	0.8%	0.1%	0.1%	0.0%	Y
	14	MAST2 50m agl	MAST1 42.5m agl	Mr03-Ag05	hor + vert	7.1	7.5	5.6%	7.3	2.1%	7.4	4.5%	0.1%	0.3%	0.2%	Y
	15	MAST3 50m agl	MAST2 50m agl	Mr03-Ap05	hor	7.4	7.5	1.4%	7.4	0.0%	7.4	0.3%	0.1%	0.1%	0.0%	Y
	16	MAST3 50m agl	MAST1 42.5m agl	Mr03-Ap05	hor + vert	7.4	7.7	4.1%	7.4	-0.3%	7.7	3.4%	0.1%	0.3%	0.2%	Y
	17	MAST1 42.5m agl	MAST2 50m agl	Mr03-Ag05	hor + vert	7.2	6.9	-4.2%	7.1	-1.8%	6.9	-4.2%	0.3%	0.1%	-0.2%	Y
	18	MAST1 42.5m agl	MAST3 50m agl	Mr03-Ap05	hor + vert	7.1	6.9	-2.8%	7.1	-0.1%	6.9	-2.4%	0.3%	0.1%	-0.2%	Y
SITE 5	19	MAST2 50m agl	MAST3 58m agl		hor + vert	5.4	4.9	-8.3%	5.0	0.9%	-	-	0.7%	1.5%	0.8%	Y
	20	MAST3 58m agl	MAST2 50m agl		hor + vert	5.3	5.8	9.8%	5.8	0.3%	-	-	1.5%	0.7%	-0.8%	Y
	21	MAST1 60m agl	MAST2 50m agl		hor + vert	5.3	5.4	1.4%	5.8	8.3%	-	-	1.9%	0.7%	-1.2%	Y
	22	MAST2 50m agl	MAST1 60m agl		hor + vert	5.4	5.2	-3.9%	5.0	-2.8%	-	-	0.7%	1.9%	1.2%	Y
	23	MAST1 60m agl	MAST3 58m agl		hor + vert	5.4	5.1	-6.0%	5.4	7.0%	-	-	1.9%	1.5%	-0.4%	Y
	24	MAST3 58m agl	MAST1 60m agl		hor + vert	5.4	5.7	5.7%	5.5	-3.4%	-	-	1.5%	1.9%	0.4%	Y
	25	SODAR3 100m agl	MAST3 58m agl		hor + vert	5.7	5.7	-0.0%	5.5	-3.7%	-	-	1.1%	1.5%	0.4%	Y
	26	MAST3 58m agl	SODAR3 100m agl		hor + vert	6.3	6.3	-1.1%	6.7	7.5%	-	-	1.5%	1.1%	-0.4%	Y
	27	SODAR3 120m agl	MAST3 58m agl		hor + vert	5.8	5.8	-0.0%	5.5	-4.7%	-	-	1.1%	1.5%	0.4%	Y
	28	MAST3 58m agl	SODAR3 120m agl		hor + vert	6.5	6.5	-0.9%	7.1	9.9%	-	-	1.5%	1.1%	-0.4%	Y
	29	SODAR1 80m agl	SODAR1 120m agl		vert	5.6	5.5	-1.8%	5.9	7.1%	-	-	1.9%	1.9%	0.0%	Y
	30	SODAR1 80m agl	SODAR1 100m agl		vert	5.5	5.4	-1.8%	5.6	3.5%	-	-	1.9%	1.9%	0.0%	Y
	31	SODAR1 80m agl	SODAR1 60m agl		vert	5.2	5.3	1.9%	5.1	-4.5%	-	-	1.9%	1.9%	0.0%	Y
	32	SODAR1 80m agl	SODAR1 50m agl		vert	5.1	5.2	2.0%	4.9	-6.3%	-	-	1.9%	1.9%	0.0%	Y
	33	SODAR1 80m agl	SODAR1 40m agl		vert	4.9	5.1	4.1%	4.7	-7.3%	-	-	1.9%	1.9%	0.0%	Y
	34	SODAR3 80m agl	SODAR3 120m agl		vert	6.5	6.5	0.0%	6.9	5.4%	-	-	1.1%	1.1%	0.0%	Y
	35	SODAR3 80m agl	SODAR3 100m agl		vert	6.4	6.4	0.0%	6.5	1.3%	-	-	1.1%	1.1%	0.0%	Y
	36	SODAR3 80m agl	SODAR3 60m agl		vert	5.9	5.9	0.0%	5.8	-2.0%	-	-	1.1%	1.1%	0.0%	Y
	37	SODAR3 80m agl	SODAR3 50m agl		vert	5.7	5.8	1.8%	5.5	-4.7%	-	-	1.1%	1.1%	0.0%	Y
	38	SODAR3 80m agl	SODAR3 40m agl		vert	5.5	5.6	1.8%	5.4	-4.3%	-	-	1.1%	1.1%	0.0%	Y

All cross-prediction results comparing measured data with WINDIE™ and WAsP estimates.

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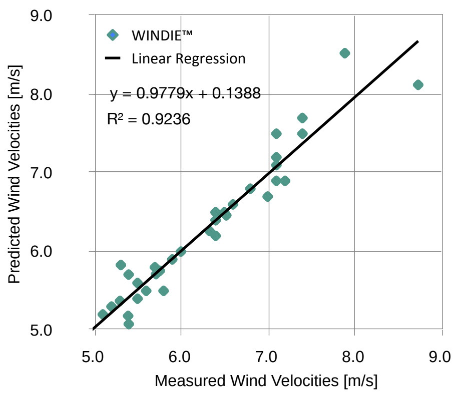
The following table summarises the results of all cross-predictions for the three models in terms of statistical parameters. It can be seen that WINDIE™ produces better results for all parameters. The correlation of WINDIE™ results is also shown.

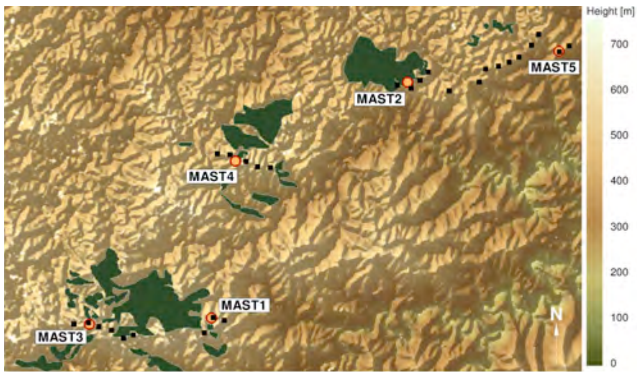
	WINDIE™ (5 sites)	WAsP (5 sites)	Other CFD (3 sites)
Average Diff	0.0%	-0.3%	0.4%
RMS	3.8%	7.6%	4.2%
STDEV	3.8%	5.1%	4.4%
R2	0.924	0.868	0.741
R	0.961	0.932	0.861



List of Validation Sites

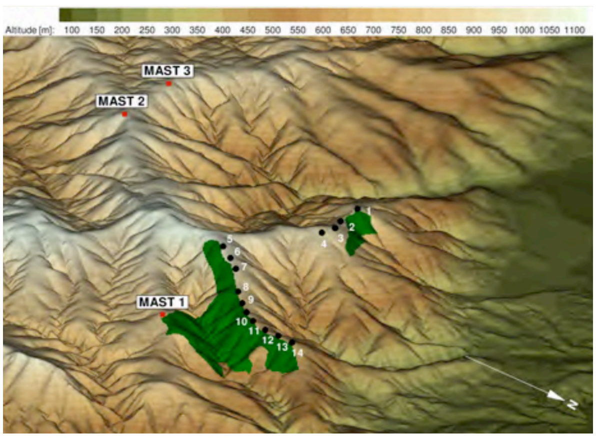
Site 1. Southern Portugal

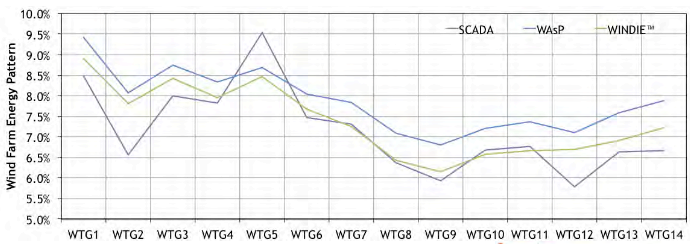
Site 1 consists of three wind farm clusters that were modelled in three different sets of simulations, so that they could, in fact, be considered separate wind farms. **Forested areas** were present in all three regions. Cross-predictions were carried out between pairs of met masts in the same farm cluster. For the central area, only vertical cross-predictions were performed for Mast 4.



Site 2. Central Portugal

Site 2 is in complex terrain with some wooded areas present. Numerical predictions are further complicated by the fact that the **reference mast is located in a different ridge**, situated approximately 1.3 km from the nearest turbine.
This case was studied using WINDIE™ after the wind farm was in operation and an additional **comparison between predicted and actual wind farm production** was carried out. Agreement was very good for the wind turbines along the ridge parallel to that were the reference mast (MAST1) was installed, despite the presence of the forested valley. WINDIE™ results were less accurate for the other turbines.





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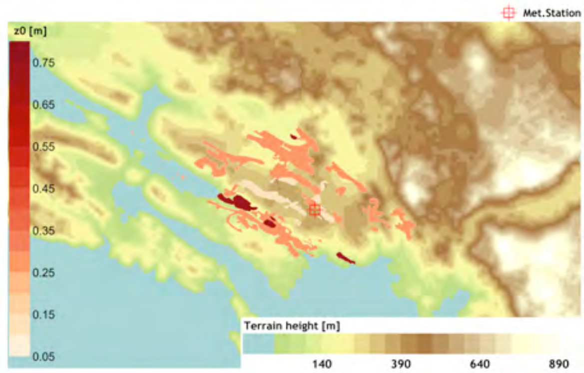
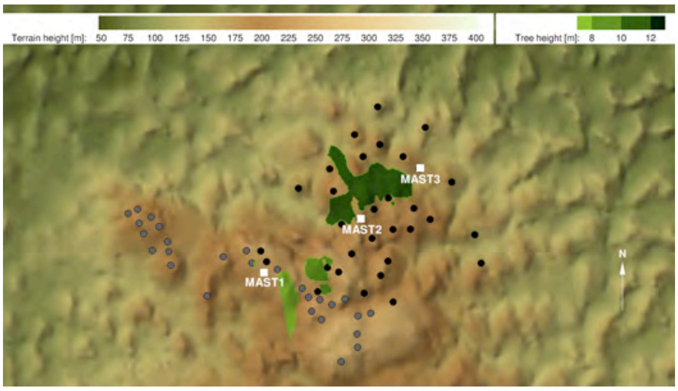
Site 3. Croatia

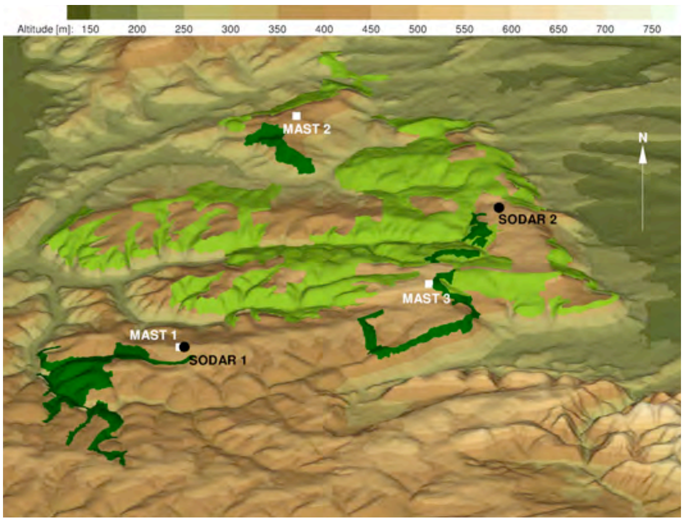
Site 3 is located near the coast and, although the site itself has little complexity, its immediate neighbourhood to the east has elevations of about 1000m and the vicinity of the sea to the southwest induces **thermal regimes** which complicate the analysis. Unfortunately, only one mast has a measurement period long enough to perform a comparison of vertical wind profiles. The site will be revisited once another station to the south collects sufficient data.





Site 4. Ireland

The site contains two densely packed wind farms, with wooded areas of different tree heights. Wake effects are prevalent for certain turbine positions. Slopes are gentle but small hills exist throughout. Cross-predictions were better between masts 2 & 3, than when using mast 1. Qualitatively all models had similar performances with some deviations in energy pattern from actual wind farm SCADA data.



Site 5. Bulgaria

Site 5 is located in heavily forested terrain in simple topography. Slopes are gentle and overall terrain height differences do not exceed 600m. The gentle terrain renders the effect of the forests on the flow all the more important. The site presented an excellent opportunity to assess model performance in terms of the wind profile and shear.

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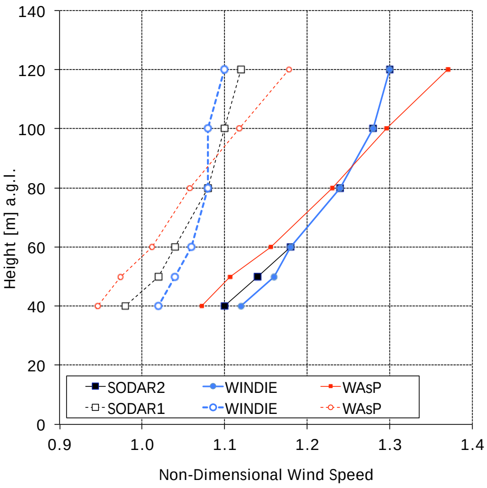
Two SODAR campaigns at Site 5 permitted the **validation of the vertical profiles** predicted by WINDIE™, at heights covering the rotor swept area. Numerical results at SODAR1 were similar in trend to the measurements and in better agreement than WAsP's. At SODAR2, WINDIE™ results were remarkably coincident with the measurements, as shown in the figure on the right.

(NB. wind speeds in the graph on the right were non-dimensionalised by a given velocity for confidentiality reasons)



Conclusion. **This white paper reported on the R&D activities carried out in 2010 in WINDIE™ and on the results obtained so far in WINDIE™'s validation programme. It focussed exclusively on resource assessment results. WINDIE™ results were show to be better than both WAsP and another CFD code used in the wind industry. The programme includes a total of 38 comparisons so far across 5 different sites in 4 different countries. WINDIE™ compared particularly favourably against SODAR data ranging from 40 to 120m above ground level. A future white paper will be published concerning WINDIE™'s performance in terms of site assessment quantities.**

Further Info.

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