Further considerations on WAsP, OpenWind and WindSim comparison study: Atmospheric flow modelling over complex terrain and energy production estimate.

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ABSTRACT

This paper analyses Brazil’s most used wind assessment computational tools: WindSim, OpenWind and Wind Atlas Analysis and Application Program (WAsP). Each program produced a Wind Resource Grid (WRG) data base – through different methodologies – utilizing the same 5 anemometric towers, elevation grid and roughness map to generate it. The turbine layout was kept the same during all simulations and the net energy, wake loss and capacity factor were acquired for each WRG at different heights. A map with the turbine layout and the difference between WRG’s along with tables showing the program’s output is presented. A comparison was made with the acquired data, relative errors were obtained and program’s limitations were perceived for the studied area.

Keywords: *Wind Energy, Flow Modelling, CFD, Energy Production Estimate*

INTRODUCTION

The world’s ever growing energetic demand has become a constant topic of discussion within the scientific community and among enterprises and the general population. Its importance is easily perceived as one possibly finds it difficult to imagine modern life without electric energy.

In order to supply such high demand, different exploration methods were developed. Although hydroelectricity is still Brazil’s major primary energy source, the biggest relative increase in the installed power comes from wind energy, as shown in the Brazilian Electricity Regulatory Agency (ANEEL) quarterly reports [8].

As a result of multiple government initiatives such as the Alternative Energy Source Incentive Program (PROINFA), Energy Auctions and special credit conditions from the Brazilian Development Bank (BNDES), a total of 10.39 GW of power have already been installed and another 7.60 GW are in construction or still have to be constructed [9]. Along with the generation expansion, a considerable advance in computational capacity as well as the development of methods to map and measure variables like wind speed and direction, terrain elevation and roughness were observed.

There are two main computational methods for the wind resources calculation: the numerical implementation of simplified physics models and Computational Fluid Dynamics (CFD) turbulence models. The main programs that utilize the first of the two presented methods are Wind Atlas Analysis and Application Program (WAsP) (linear model [6]) and OpenWind (Mass Consistent Model [4, 5]). WAsP utilizes topography, roughness and obstacles to take the wind to a free-flow layer, and then it returns the free-flow wind value for a region close to the ground. As the model's name implies, WAsP doesn't take into account nonlinearities inherent to wind flows, thus affecting its results in complex terrain simulations. The OpenWind mass conservation model approach towards solving wind flows minimizes the difference between calculated and measured wind components. Both of these methods require less computational cost than the CFD's one. WindSim calculates the wind field through Reynolds Averaged Navier-Stokes (RANS) model, a momentum conservation calculation method.

In the current paper, a continuation of comparisons between the main commercial wind modelling tools used in Brazil [7] is made in order to evaluate the efficiency of those energy production estimate techniques.

METHODOLOGY

A preliminary data treatment is necessary in order to generate the required inputs for the mentioned computer programs. The long-term series of wind data is correlated with the measurements from anemometric towers via linear Measure Correlate Predict (MCP). Roughness and topography are also acquired and georeferenced.

This preliminary data analysis is crucial for the simulation, since it serves as a base for the programs to build upon. If the inputs are not reliable the results will not be coherent and will not do as data for future comparisons – this work wants to compare three models.

The first input data consists of topography information, digital terrain model and the location of the 5 anemometric towers used in the MCP correlation. Figure 1 shows a map containing the information ensemble.

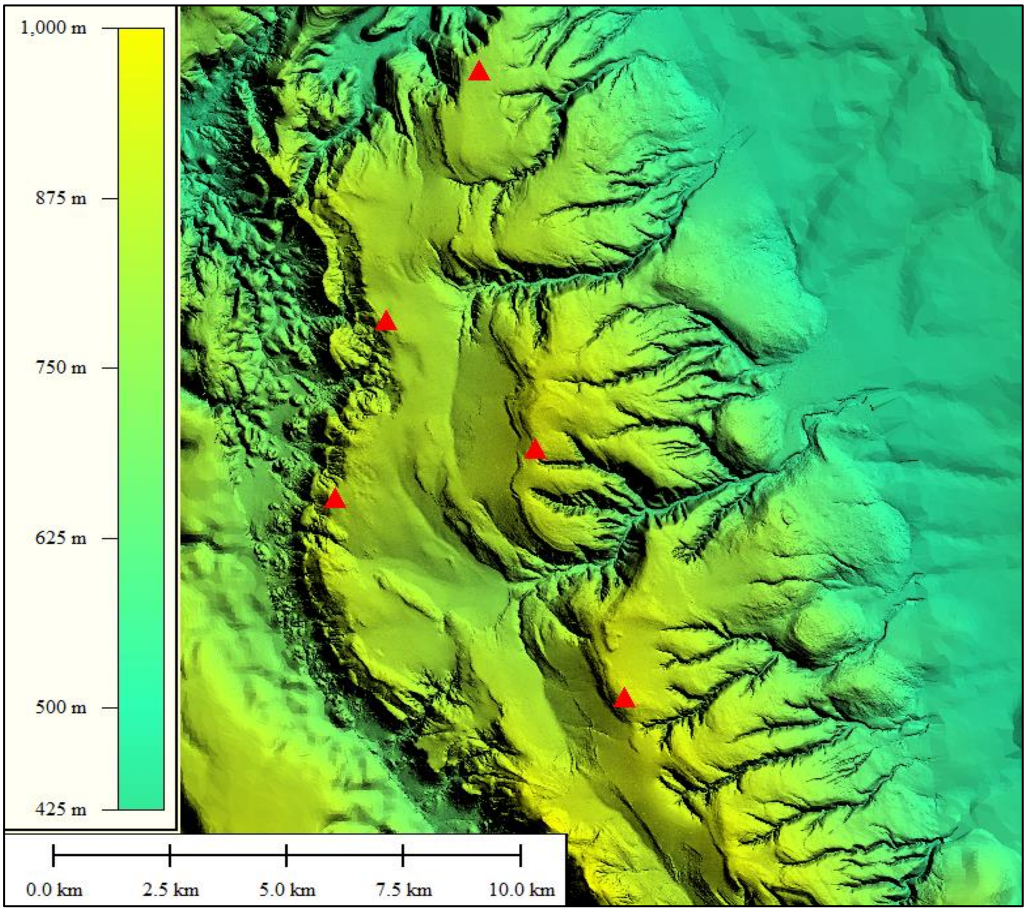

Figure 1 – Topography and anemometric towers.

Figure 1 data alone does not meet the requirements for the programs' calculations. The measured roughness of the area and the wind turbine power curve – provided by wind turbine manufactures – are amassed to other preliminary data, providing enough information to obtain the energy production prospection.

This assemblage is utilized as an intake to calculate wind resources in each computation tool. The resolution is kept the same – 100 m horizontally – for a fair comparison. It is also important to point out that the different models – mentioned in the introduction – demand different times to compute, proportional to their complexity. Even though WindSim's implemented methodology utilized a two-step simulation that benefits processing time and does not jeopardize the results [1], its simulation took much longer than the OpenWind and WAsP simulations to make the Wind Resource Grid (WRG).

After the WRG formation, 18 simulations – a combination of 2 different turbine types, 3 distinctive heights and 3 programs – were made. The turbine layout and the installed power were kept the same by preserving the number and location of georeferenced turbines for all simulations. The objective of these simulations was to compare each model output of energy production estimate with the exact same input for calculation.

WindSim (CFD)

The Navier-Stokes equation meets mechanical principles such as mass, linear and angular momentum and energy conservation. WindSim solves the Reynolds Averaged Navier-Stokes equation (RANS) – in which the instant velocity was replaced by a sum of average velocity and fluctuation –, through the two equation turbulence model based on the k- ε model and the numerical implementation of Finite Volumes – utilizing a nucleus made by the solver PHOENICS [2].

Initial and boundary conditions are inputted by the user so WindSim calculates a timed average solution. This model exports a probabilistic distribution of wind and turbulence as a WRG data base. RANS model can be seen below:

$$\frac{\partial U_i}{\partial x_i} = 0 \qquad (1)$$

$$U_i \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\upsilon\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_i}{\partial x_i}\right) - \left(\overline{u_i u_j}\right)\right) \qquad (2)$$

in which: U_i is the average velocity in i's direction; u_i is the velocity fluctuation in i's direction; x_i is the position component in i's direction; P is the pressure; ρ is the specific mass; and υ is the kinematic viscosity.

As mentioned before, WindSim uses the k-ε model and the closure problem is treated by the Boussinesq Hypothesis (equation 3) and by two differential equations artificially created to enclosure viscosity dimension.

$$\left(\overline{u_i u_j}\right) = -\upsilon_T\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) + \frac{2}{3}\delta_{ij} k \qquad (3)$$

in which: υ_T is a dimensional proportionality constant called turbulent viscosity (equation 4); k is the turbulent kinetic energy; and δ_{ij} is a second order tensor called Kronecker Delta.

$$\upsilon_t = C_\mu \frac{k^2}{\varepsilon} \tag{4}$$

Following equations (5 - 6) show those two aforementioned differential equations.

$$\frac{\partial}{\partial x_i}(U_i k) = \frac{\partial}{\partial x_i}\left(\frac{\upsilon_t}{\sigma_k}\frac{\partial k}{\partial x_i}\right) + P_k - \varepsilon \tag{5}$$

$$\frac{\partial}{\partial x_i}(U_i \varepsilon) = \frac{\partial}{\partial x_i}\left(\frac{\upsilon_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_i}\right) + C_{\varepsilon 1}\frac{\varepsilon}{k}P_k - C_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{6}$$

in which: P_k is the turbulent kinetic energy production term (equation 7); and C_μ, σ_k, σ_ε, $C_{\varepsilon 1}$ and $C_{\varepsilon 2}$ are constants *a priori* parameterised.

$$P_k = \upsilon_t \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j} \tag{7}$$

OpenWind

OpenWind utilizes a Mass Consistent Model [4, 5] that solves the velocity field of an atmospheric flow. The model aims for a vector $U=\big(u(x,y,z),v(x,y,z),w(x,y,z)\big)$, which minimizes the functional J defined as:

$$J = \iiint_V \left[\alpha_1(u-u_0)^2+\alpha_2(v-v_0)^2+\alpha_3(w-w_0)^2\right]dxdydz \tag{8}$$

Restricted to:

$$G = \frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{9}$$

in which: $U_0=\big(u_0(x,y,z),v_0(x,y,z),w_0(x,y,z)\big)$ is the measured velocity field.

The above process utilizes a mathematical approach to solve the velocity field without the need to use transport equations, such as Navier-Stokes equations. It returns a suitable result and furthermore, it requires minor computational effort.

WAsP

WAsP utilizes a linear model of the Navier-Stokes equations [6]. It is built on simplified equations solutions, where nonlinear effects are not taken into consideration. Thus, obtaining fast and less precise results for average flows.

RESULTS

In what follows, simulation results and discussions will be presented. As mentioned before, the layout and installed power were kept the same in order to better compare the 3 programs.

The differences between WindSim's CFD model and the 2 WRG's velocities calculated through simplified methods are shown in Figure 2.

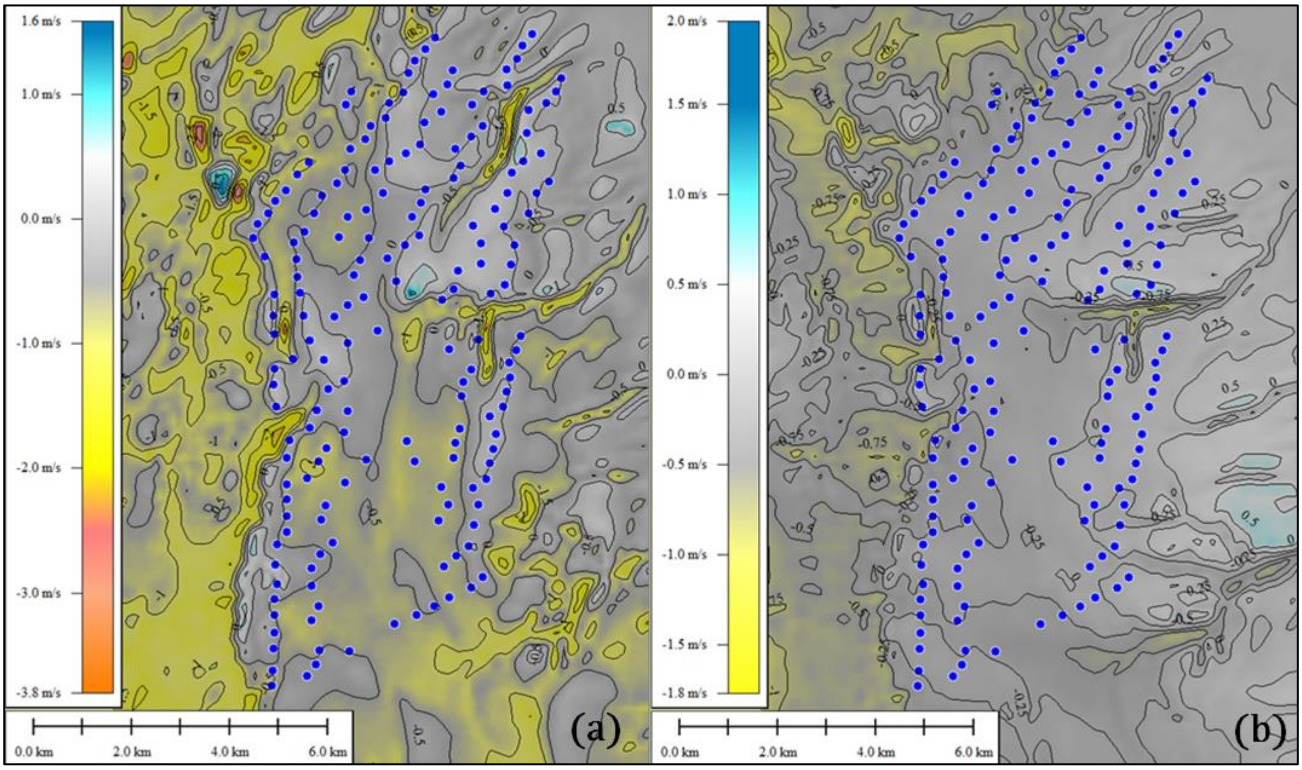

Figure 2 – Wind velocity difference map (WindSim – WasP [a] & WindSim – OpenWind [b])

The image on the left (a) shows the difference between results obtained with CFD modelling and Navier-Stokes equations' linear modelling. The negative numbers indicate how much the WAsP's model overestimates the velocity value compared to the WindSim's method. The disparity peaks show a 3.8 m/s difference – or approximately 47% – of the calculated average wind velocity via CFD in some regions with a more rugged orography. This shows the linear model's limitations for a complex terrain application.

The image on the right (b) shows the difference between results obtained with the CFD model and the Mass Consistent model. Negative results demonstrate how much OpenWind overestimated the wind velocity in relation to WindSim's results.

Once again, complex terrain regions showed the greatest differences, but in a smaller scale compared to WAsP's simulation.

Net Energy, Wake Losses and Capacity Factor at P50 were acquired for further comparisons. Table 1, Table 2 and Table 3 present results obtained respectively for 80 metres, 100 metres and 120 metres. Two generic 2.1 GW turbines – Turbine A and Turbine B – with rotor diameters (r_D) of 114 metres and 110 metres were used to simulate the desired layout to acquire the aforementioned data.

Table 1 WindSim, OpenWind and WAsP simulations at 80 metres

	Turbine A (r_D = 114 m)			**Turbine B** (r_D = 110 m)		
	Net Energy [GWh/yr]	**Wake Loss [%]**	**Capacity Factor [%]**	**Net Energy [GWh/yr]**	**Wake Loss [%]**	**Capacity Factor [%]**
WindSim	1,596.93	11.33	49.01	1,557.98	6.24	47.82
OpenWind	1,577.65	11.44	48.42	1,539.86	6.28	47.26
WAsP	1,852.06	9.68	56.84	1,808.55	5.38	55.51

Table 2 WindSim, OpenWind and WAsP simulations at 100 metres

	Turbine A (r_D = 114 m)			**Turbine B** (r_D = 110 m)		
	Net Energy [GWh/yr]	**Wake Loss [%]**	**Capacity Factor [%]**	**Net Energy [GWh/yr]**	**Wake Loss [%]**	**Capacity Factor [%]**
WindSim	1,706.26	10.58	52.37	1,676.43	5.16	51.45
OpenWind	1,729.08	10.37	53.07	1,699.14	5.04	52.15
WAsP	1,850.72	9.64	56.80	1,819.40	4.69	55.84

Table 3 WindSim, OpenWind and WAsP simulations at 120 metres

	Turbina A (r_D = 114 m)			**Turbina B** (r_D = 110 m)		
	Net Energy [GWh/]	**Wake Loss [%]**	**Capacity Factor [%]**	**Net Energy [GWh]**	**Wake Loss [%]**	**Capacity Factor [%]**
WindSim	1,811.44	9.85	55.59	1,789.05	4.30	54.91
OpenWind	1,941.87	8.88	59.60	1,918.18	3.88	58.87
WAsP	2,156.85	7.37	66.20	2,133.55	3.25	65.48

At 80 m OpenWind underestimated the capacity factor by 1.2%, resulting in a smaller net energy. The relative wake loss difference was less than 1% of WindSim's. WAsP overestimated the capacity factor by approximately 16%, thus resulting in a 255 GWh per year difference. The relative average wake loss difference was 14%.

At 100 m OpenWind's capacity factor is slightly overestimated by 0.7%, resulting in approximately 23 GWh per year of energy difference. The wake loss was underestimated by 2.3%. WAsP overestimated by 8.5% the net energy and capacity while it underestimated the wake loss by 9%.

At 120 m OpenWind's capacity factor and net energy differed 7%, or 130 GWh per year, and its wake loss was 10% smaller. WAsP's simulation overestimated the net energy and capacity factor by 19%, a total of 345 GWh per year. WAsP underestimated the wake loss by 24%.

CONCLUSION

The capacity factor prospection is a vital step in any wind energy project. The more realistic the results, the better Return on Investment (ROI) and energy production estimate reliability will be – this last information is crucial considering Brazilian auctions.

WindSim's more robust method provided a better result, but adversely required more computational demand. Both simpler methods had some limitations on any complex terrains situation. As expected, these limitations became more evident at higher altitudes.

OpenWind was the least demanding software out of the three shown and produced reasonable results – within a range of 2.5% at 80 m and 100 m heights – when compared to WindSim. As expected, OpenWind exhibited worse results at 120 m height – due to its simplicity – with an overestimation of 130 GWh/yr – approximately 7% of WindSim's capacity factor – and the layout relative wake loss of 10%.

WAsP was the second most demanding software and its better return was at 100 m. It overestimated the capacity factor for all cases and unexpectedly outputted very similar results for different heights – 80 m and 100 m. WAsP presented a capacity factor discrepancy ranging from 8.5% at 100 m to 19% at 120 m. The wake loss also peaked at 24 % at 120 m.

In conclusion, this paper presented the importance of knowing how main wind modelling tools calculate the WRG data base over a complex terrain situation – this tricky situation tends to be more common as flat terrain projects become less available. Thus, it showed that for projects located over complex terrains it is strongly advisable to utilize robust programs to better evaluate the project.

REFERENCES

[1] Ramos, D.A., Guedes, V.G., Mustto, A.A., (2016), Development of a methodology to make improvements on a CFD-based model – use of nesting in a complex terrain in an inner area of Ceará, Brazil, Brazil Wind Power.

[2] N.D. Baltas, D.B. Spalding (1994) MIMD PHOENICS: Porting a Computational Fluid Dynamics Application to a Distributed Memory MIMD Computer. *EUROSIM Conference on Massively Parallel Processing Applications and Development*, Delft, The Netherlands, 715–725.

[3] Wallbank, T. (2008) WindSim Validation Study – CFD validation in Complex terrain(2008)

[4] Bilal, M., Birkelund, Y., Homola, M. e Virk, M.S. (2016) Wind over complex terrain – Microscale modelling with two types of mesoscale winds at Nygårdsfjell, *Renewable Energy*, Vol. 99(2016), pp. 647- 653.

[5] Brower, M., Zack, J. W., Bailey, B., Schwartz, M. N., and Elliot,t D. L. (2004) Mesoscale Modeling as a Tool for Wind Resource Assessment And Mapping, *14th Conference on Applied Climatology*.

[6] Jackson, P. S. and Hunt, J. C. R. (1975) Turbulent wind flow over a low hill. *Q. J. R. Meteorol. Soc.*, 101:929.

[7] Guedes, V.G., Ramos, D.A., Mustto, A.A. (2017) Comparação de cálculo de produção eólica utilizando WAsP, OpenWind e WindSim em terreno complexo na Bahia, Brasil, *SNTPEE*

[8] ANEEL's management information from the World Wide Web: http://www.aneel.gov.br/informacoes-gerenciais.

[9] ANEEL's Brazil's generation capacity from the World Wide Web: http://www2.aneel.gov.br/aplicacoes/capacidadebrasil/capacidadebrasil.cfm.

BIOGRAPHIES

Daniel A. Ramos – Born in the city of Rio de Janeiro on July 15th, 1993. He graduated in mechanical engineering at the Federal University of Rio de Janeiro in the middle of 2016, with emphasis in aerodynamics and numerical simulations of turbulent flows.

Eng. Daniel had internships in some energy companies, acquiring knowledge and experience in wind energy projects. Nowadays he is concluding his master's degree in Aerodynamics at PEM / COPPE-UFRJ (June 2017) and he is also fellow research at CEPEL with a few published articles related to wind energy applications.

Vanessa G. Guedes – Born in the city of Rio de Janeiro on October 31th. She graduated in mechanical engineering at the Federal University of Rio de Janeiro in 1995. Her master’s and doctor’s degrees at PEM / COPPE-UFRJ, were completed in 1996 and 2003, respectively, with specialization in aerodynamics and numerical simulations of turbulent flows.

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