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

Daniel Agnese Ramos[1], Vanessa Gonçalves Guedes[1], Angelo Alberto Mustto Cabrera[1]

1 Departamento de Tecnologias Especiais/

Diretoria de Pesquisa, Desenvolvimento e Inovação

CEPEL – Centro de Pesquisas de Energia Elétrica

Av. Horário Macedo 354, 21941-911, Ilha do Fundão, Brazil

daniel.agnese@poli.ufrj.br , vanessag@cepel.br , mustto@cepel.br

ABSTRACT

In this article, our studies will be concentrated on improvements in the calculations using the CFD-based software WindSim. For testing this methodology a site was chosen in an inner area of Ceará, Brazil. In order to implement improvements, we use the technique of Nesting, and then we make comparisons with the results of a simulation that is not using the cited technique. The Nesting technique consists in performing a simulation in a larger area with reduced horizontal resolution, in this article denominated "Large Scale" step. Then, the results of this step are used in the Nesting step as initial boundary condition. The results of P50 capacity factor and P50 net production of the two steps show differences larger than 18%, emphasizing the importance of applying techniques to reduce uncertainties.

Key-words: *Wind Power Production, Site Assessment, CFD-Based Model, Wind Flow*

1 INTRODUCTION

The increasing demand for electricity is still a very present problem today and it is a source of inspiration for numerous engineering studies. In recent decades the use of renewable resources has gradually became possible and more frequent, regarding their generation and integration into the electrical system, and resources such as solar radiation and energy of winds represent, nowadays, a significant portion of production of energy in certain countries - among which stand out Denmark, Portugal, Ireland, Spain and others. Wind energy represents approximately 6% of the Brazilian energetic matrix and the main States leading the wind energy production are Rio

Grande do Norte, Bahia, Rio Grande do Sul and Ceará, covering over 90% of the total production in the country [1].

In the Brazilian energy exploration scene, the use of wind power comes to be an even more interesting option because of its complementarity with the main source of energy in the Brazilian energetic matrix, hydroelectric plants, and the promising potential of wind resources in certain regions of the country. To take advantage of such a source is necessary to ensure that the quality of the wind regime is really satisfactory in the area to be explored, and it is necessary to implement a detailed study in order to corroborate it. In this area, new methodologies are being used, like CFD-based wind production calculations and mesoscale/micro-scale coupled methodologies. Both of them bring promises of improvements in the results of the flow in the site of interest.

In this article, our studies will be concentrated on improvements in the calculations using the CFD-based software WindSim. In order to implement improvements, we use the technique of Nesting, and then we compare the results with a calculation that is not using the cited technique. This methodology consists in performing a simulation in a larger area with reduced horizontal resolution, in this article denominated “Large Scale” step. In this step, the boundary conditions, in the boundaries of the simulation mesh, use the simplified logarithmic law, with geostrophic winds of 10 m/s at the height of the boundary layer of 500 m. The next step is the Nesting which consists of simulations using results of the wind speed of the previous step as initial boundary condition. That is, the boundary conditions do not use the simplified logarithmic law, but the wind speed data calculated in “Large Scale” step. Summarizing, the first step is performed in a larger area with less resolution, and the second step occurs in a smaller area with initial boundary condition previously calculated and refined horizontal mesh resolution, which leads to an improvement in the results.

2 METHODOLOGY

This study is performed in a site of complex topography located near the coast of Ceará, in the Brazilian Northeast. WindSim, a CFD-based software, is used for the calculation of the wind power electricity production. The input data of the flow simulations are the roughness, the topography and the wind data. The details of the input data are presented in the next sections.

2.1 Topography and Roughness

Accurate, high resolution topographic data are essential for the numerical wind flow modeling. A typical spatial resolution for modeling is 50 m. It is likewise important to employ land cover data that are both accurate and with high resolution [3].

In this article, the digital terrain model used has a resolution of 92.2 m and the roughness digital model has the resolution of 500 m, as shown in Figure 1.

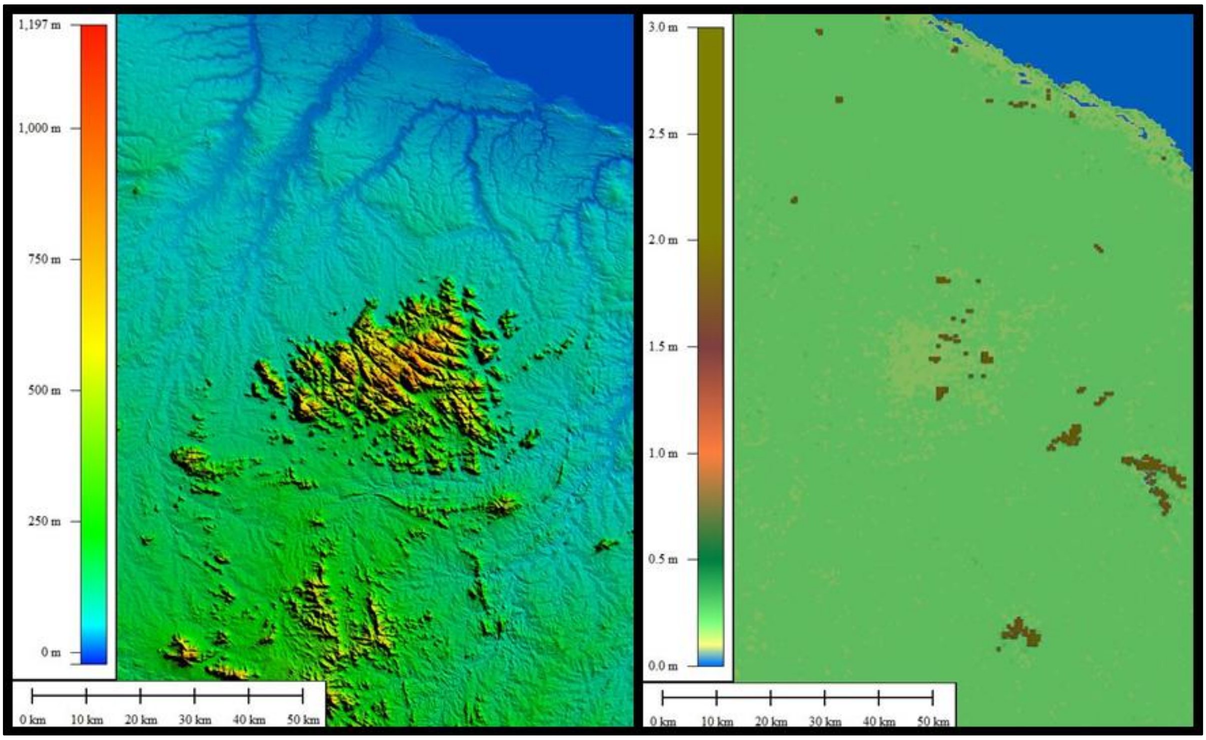


Figure 1 – Digital Terrain and Roughness Model.

2.2 Meteorological Wind Data

For the “Large Scale” step, considering that it is a large area, six MERRA historical reanalysis data series of fifteen years were used, for points distanced from each other approximately 70 km in the North-South direction and 50 km in the East-West direction. Also, in this step, wind measurement data of three meteorological towers were used. Histogram and wind rose of one of the meteorological towers are presented in Figure 2. The wind speed values are in the order of 8 m/s and the main direction of the wind is East. The positions of the MERRA historical reanalysis data series and of the three meteorological towers are shown in Figure 3.

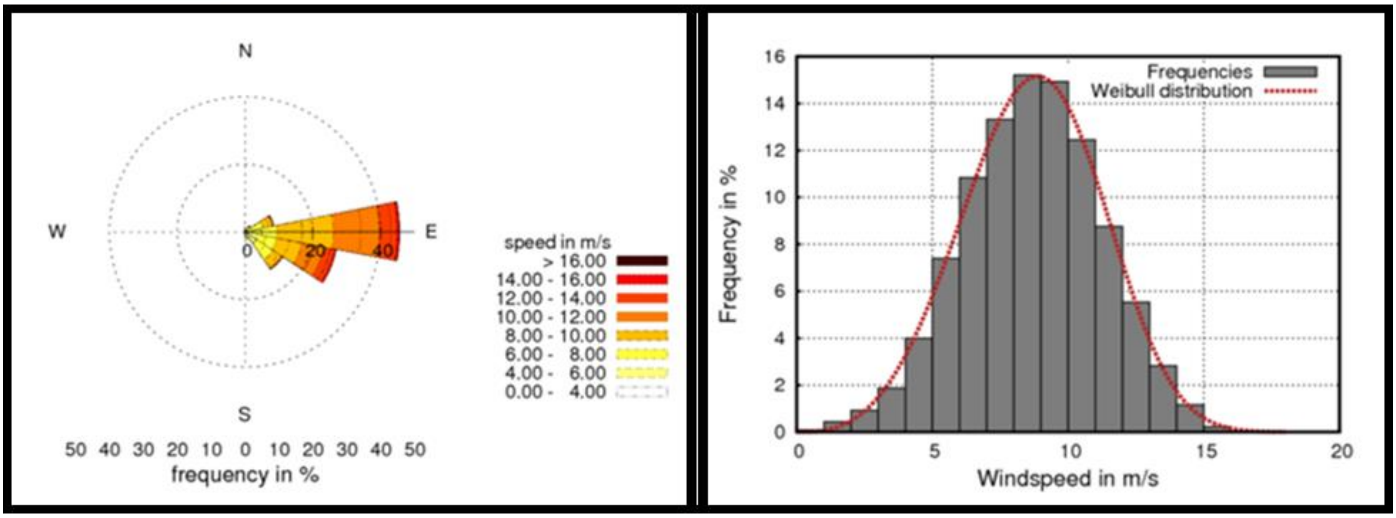


Figure 2 – Histogram of Wind Speeds Frequency and Wind Rose of One Meteorological Tower Used in the "Large Scale" Step.

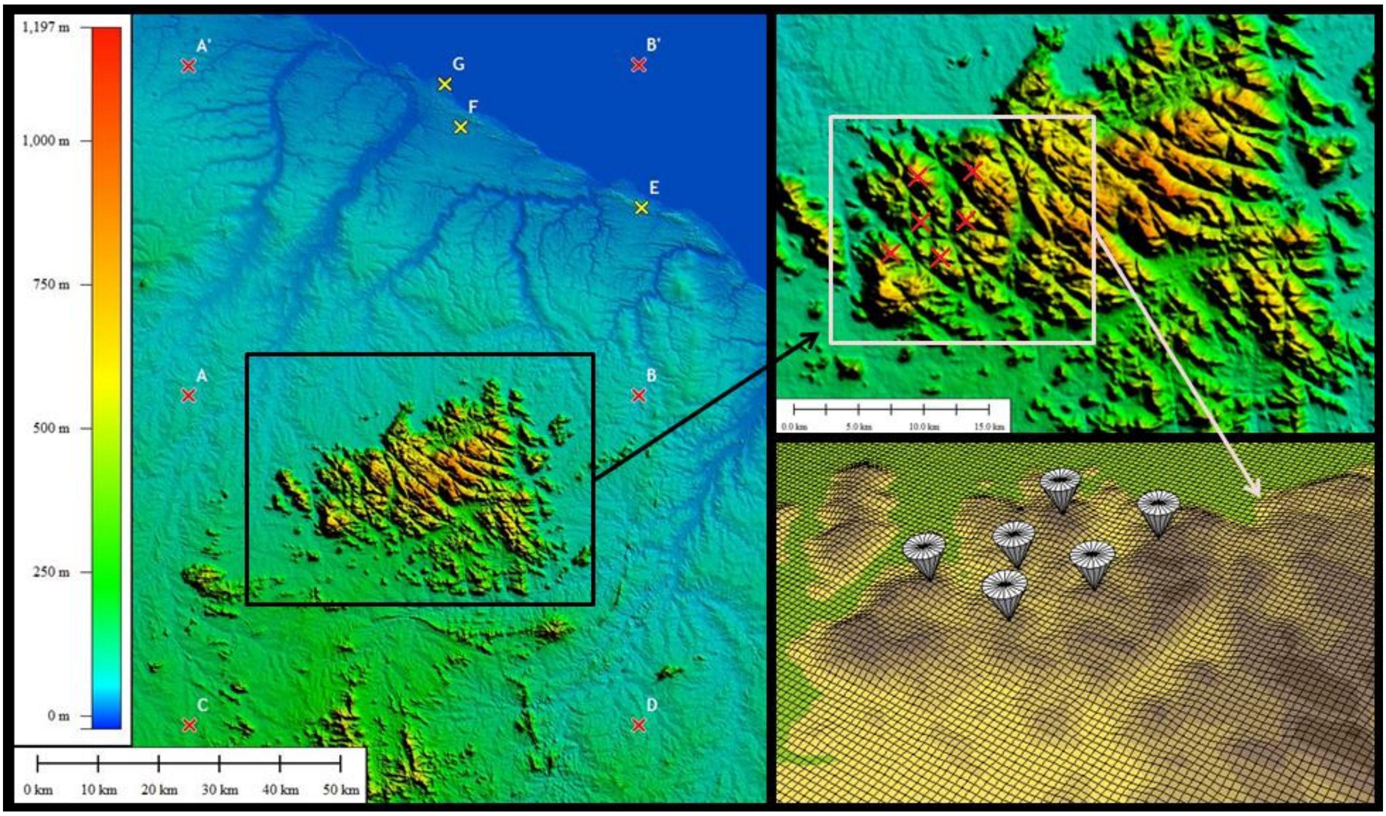


Figure 3 – Area of the "Large Scale" Step and Position of MERRA Points and Meteorological Towers. In Detail, Position of the Six Meteorological Towers for the Nesting Step.

For the next step, the Nesting step, six meteorological towers distanced 2 km from each other are used to define the wind regime at the region of the complex terrain of interest, according to [2]. Their positions are shown in detail in Figure 3 and their parameters are presented in Table 1.

Table 1 Meteorological Towers Parameters at 100 m at the Period of 01/01/1999 to 12/30/2014

Meteorological Tower	k	A	Average Speed
Tower 1	3.78	9.00	8.08
Tower 2	3.82	8.85	7.95
Tower 3	3.69	8.59	7.74
Tower 4	3.61	9.02	8.12
Tower 5	3.65	8.65	7.78
Tower 6	3.54	8.78	7.91

2.3 Micro-scale Modeling – WindSim

The micro-scale wind flow modeling is performed using the CFD-based software WindSim. It is an applicative used for energy production calculation and optimization of wind farms. That is, the WindSim performs the flow calculation using an Eulerian formulation that requires grid generation for the solution of the Navier-Stokes equation at all points of the fluid region by methods such as finite volumes or elements.

The Navier-Stokes equation is given by:

$$\rho(\partial_t \boldsymbol{u} + \boldsymbol{u} \cdot \nabla \boldsymbol{u}) = -\nabla p + 2\rho(\boldsymbol{u} \times \boldsymbol{\Omega}) + \mu \nabla^2 \boldsymbol{u} - \boldsymbol{f}_g \quad (1)$$

where ρ is the density, $\boldsymbol{u}$ is the velocity vector, t is time, $\boldsymbol{\Omega}$ is the Earth rotation, μ is the dynamic viscosity and $\boldsymbol{f}_g$ is the gravitational force.

After the statistical treatment of the meteorological data, the treatment of the geographical information and the generation of 3D terrain file concerning the region to be studied in WindSim and the calculation of flow field, then the energy production of the wind farm is performed. It was carried out sector simulations – 16 sectors evenly spaced – of the flow of the region of interest. The CFD step of the methodology applied by WindSim uses as input data the geostrophic winds – winds of 10 m/s at the height of the boundary layer of 500 m.

2.4 First Stage Simulation – The "Large Scale"

A first step of the simulations was defined as "Large Scale" and it was held due to the large extent of the area to be processed (approximately 15,927 km^2) and the resulting low resolution used for meshing (approximately 2 km) is due to hardware limitations. The large size of the area to have the flow simulated with WindSim is due to the need of studying the downstream and upstream flow behaviour of the mountainous region, which is the interest area for a wind plant project because of its high wind speeds. This evaluation of the downstream and upstream flow in relation to the interest area will reduce the impact of the generated uncertainty on the border of the study area in the region where the project will be located - West of the mountain.

In this step, due to its large extent, three measured meteorological data and six reanalysis data were used for a better characterization of the wind regime of the total area. The position of the meteorological towers used are presented in Figure 3. The wind field was calculated at 120 m, defined in this article as WRG (wind resource grid) file, which is presented in Figure 5(a).

2.5 Second Stage Simulation – Nesting

After the first step of simulations (the "Large Scale"), a refined calculation of the flow with a resolution of 276 m, only in the mountainous region that encompasses the project area, is accomplished. Figure 4 illustrates the refined 3D terrain model of the processing area of the second step simulations.

The methodology of this second stage simulation is quite similar to the first, however, the boundary conditions, in the boundaries of the simulation mesh, do not use the simplified logarithmic law, but the wind speed data calculated in "Large-Scale" simulation, by performing then the coupling with the previous simulations cycle. To accomplish the simulations of this stage, the refined mesh simulation was also divided into 16 sectors evenly spaced and the condition of geostrophic winds, to a thickness of atmospheric boundary layer 500 m and intensity of 10 m/s, were used as input.

In this step, the meteorological data used were presented in Table 1. The meteorological towers are distant 2 km of each other, as recommended in IEA [2].

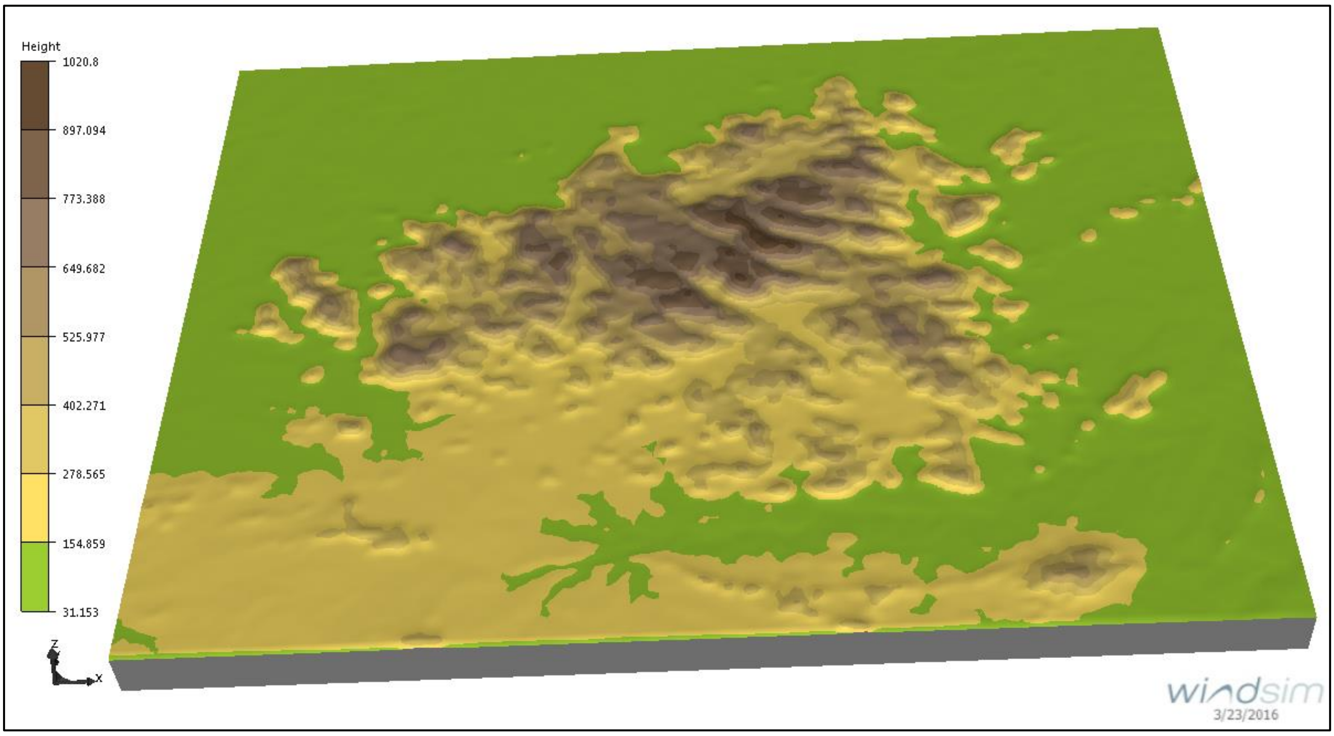


Figure 4 – Refined 3D Terrain Model.

3 RESULTS

In this section, the comparisons between the results of the two steps will be presented. Table 2 presents results of P50 capacity factor (P50CF), P50 net production (P50NP), array losses due to wake effects (ALW) and number of wind turbines for minimum efficiency of 45% and maximum wake loss of 10% in the selected area for three scenarios.

Table 2 Results of Energy Production and Capacity Factor using “Large Scale” and Nesting for Alstom ECO 122 2.7 Class 3A

Scenarios	Number of wind turbines	Installed power (MW)	Capacity factor at P50 (%)	Net production P50 (GWh/year)	Array losses due to wake effects (%)
Nesting’s WRG with Layout 1	94	253.8	45.16	1004.810	7.81
“Large Scale” WRG with Layout 1	94	253.8	54.54	1213.453	7.00
“Large Scale” WRG with Layout 2	128	345.6	53.23	1612.491	9.32

The first scenario, Nesting's WRG with Layout 1, consists in a layout of the position of the wind turbines optimized using the Nesting's WRG and the calculation of the energy prognostic using this same WRG.

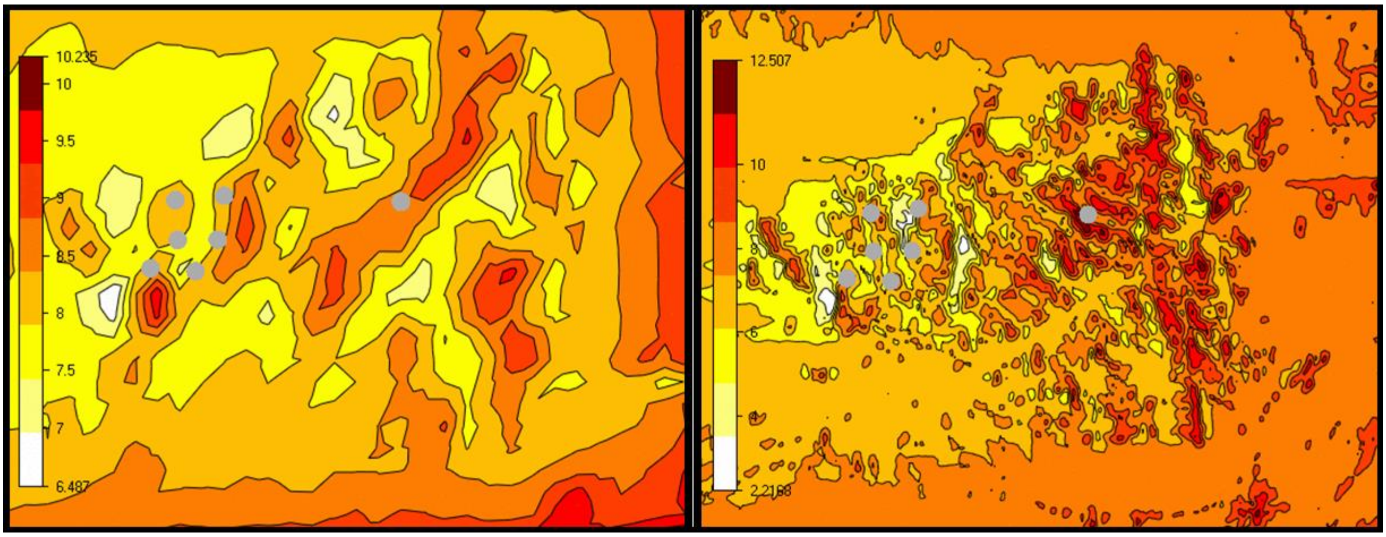
The second one, "Large Scale" WRG with Layout 1, is the presentation of the results for the wind turbines position layout optimized with the Nesting's WRG using the "Large Scale" WRG as the reference for the energy production estimate.

The third scenario is the calculation of the energy prognostic results with the "Large Scale" WRG and a layout optimization (Layout 2) using the "Large Scale" WRG. The chosen wind turbine is Alstom ECO 122 2.7 Class 3A because it is available for the market. The optimization was performed with the software Openwind due to the option of expansible layout, namely, the number of wind turbines can be increased to reach some criteria.

The results in Table 2 show great differences in P50CF and P50NP for the Layout 1 considering Nesting's WRG (scenario 1) and "Large Scale" WRG (scenario 2). The capacity factor and the net production are smaller using the Nesting's WRG. The P50CF is reduced in almost 10%, meaning a reduction of the order of 210 GWh/year in the P50NP. It means that, for a given layout, if the nesting step is not performed (scenario 2), a less detailed wind field will be provided and, as a result of that, the separation and the recirculation of the flow will not be well described nor the turbulence intensity. As the wake model used is the Eddy Viscosity coupled with the Deep Array Methodology [4], the wind speed values of the input WRG are even more significant to the estimate of the array losses due to wake. Thus, it can be seen that the ALW of scenario 2 is 11% smaller than the one in scenario 1. The reason for the reduction of the ALW is that the input WRG of the first scenario is much more detailed, so it describes regions of low flow velocities due to recirculation zones inside valley regions that were not present in the input WRG of the second scenario.

Otherwise, if an optimization is performed using the "Large Scale's" WRG, the differences are even greater. With the restrictions of minimum efficiency of 45% and maximum wake loss of 10% – same restrictions applied to layout 1 –, the number of turbines increases from 94 to 128, that is an increase of 36%. The optimization reached greater values of P50 FC and ALW because the wind field calculated is less detailed, disregarding separation and recirculation of the flow, as pointed out above. Thus, it was possible to include more turbines and to keep a P50 FC similar to the one in scenario 2. As the number of turbines increased, the ALW increased about 33% in comparison to scenario 2.

The "Large Scale" and the Nesting wind fields are presented in Figure 5. By comparing the simulation results of the two simulations with different mesh refinements, it is clear that the simple fact of increasing the resolution of the mesh can dramatically change the results. A simple comparison between the range of the legend of the average speed of both WRGs is enough to substantiate the previous statement. While the WRG of the more refined mesh obtained by Nesting showed a range from 2.17 to 12.51 m/s, the simulation of the less refined WRG presented a range from 6.14 to 10.43 m/s.



(a) "Large Scale" (b) Nesting

Figure 5 – Velocity Field using "Large Scale" and Nesting.

4 CONCLUSION

In this article, our studies concentrated on studying improvements in the calculation of the energy prognostic using the CFD-based software WindSim for this purpose, we used the technique of Nesting to simulate the wind field and performed comparisons between the energy production results.

It is possible to see that, in this study, with a reduction of seven times the initial horizontal resolution, P50FC and P50NP reduce in approximately 18% for the same layout. And, making an optimization with a less detailed WRG produces an increase of 18% in the P50FC and 60% in the P50NP.

The larger the uncertainty in calculation, the higher the difference between P90 and P50. The lower the value of P90 relative to the P50, the lower the size of the loan, and a better equity return [5]. This fact justifies the study and analysis of other improvements of the simulation. Concerning WindSim, simulations considering the atmospheric stability should be tried. Concerning the input data, more refined topographic and roughness data should be used.

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BIOGRAPHIES

Daniel Agnese 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 a master student at PEM / COPPE-UFRJ and Cepel.

Vanessa Gonçalves Guedes – Born in the city of Rio de Janeiro on 31 October. 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.

Dr Guedes has worked in the wind energy sector over the past 13 years at Cepel - Electrical Energy Research Center. Her performance in the area consists of several projects for the Eletrobras System companies and publications and contributions for final course projects and master thesis for institutions such as IME, INPE and UFRJ.

Angelo Alberto Mustto Cabrera- – Born in Peru, he has Brazilian nationality. He has graduated in mechanical engineering at the Universidad Nacional Mayor de San Marcos, Lima, in 1994. His masters and doctor degrees at PEM / COPPE-UFRJ, were completed in 1998 and 2004, respectively, with specialization in aerodynamics and numerical simulations of turbulent flows.

Dr Mustto has worked in the wind energy sector over the past 13 years at Cepel - Electrical Energy Research Centre. His performance in the area consists of several projects for the Eletrobras System companies and academic publications.