WIND FARM PERFORMANCE ASSESSMENT UNDER DIFFERENT WAKE MODELS: A CASE STUDY IN COMPLEX TERRAIN

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ABSTRACT
The focus of this paper is a wind farm located in Calabria (Italy). The objective is to implement a support tool (a simulator) to be used for carrying out specific analyses in order to test system performance in terms of energy production under different wake models. After the modeling phase, the simulation model has been validated. Three different wake models are introduced to evaluate system power loss due to near and far wake effects in complex terrain.

Keywords: wind farm Modeling & Simulation, wake models, wind farm performance analysis, complex terrain

1. INTRODUCTION

According to Shakoor *et al.* (2016), during the last decade energy production from non-conventional resources (wind, solar, biogas, etc.) have registered an outstanding increase due to the forthcoming sale of all conventional stocks.

In particular, wind energy has had a growth of 27% in the last five years for a total installed capacity of about 230 GW at the end of 2011 with an overall turnover of 50 billion Euro (Grassi *et al.* 2014). In addition, the Global Wind Energy Council Report in 2012 stated that wind energy has become the most rapidly rising source of energy in the world, having a steep increase in development from 2009.

Energy from wind is generally obtained through wind farms (WFs), which consist of hundreds of turbines (WTGs). A WTG aims at extracting the kinetic energy from wind, converting it into mechanical energy at the rotor axis and then into electrical energy (Vermer *et al.* 2003; Shakoor *et al.* 2015). During the first phase (when WTG extracts energy from wind), the rotation of wind turbine rotor cause a reduction of the wind speed behind it and swirls the air flow, i.e. the Wake Effect (WE) of a wind turbine: the area behind the wind turbine is characterized by a modified wind flow both in terms of mean velocity and turbulence intensity. A wind speed decrease causes a reduction of the WF energy production while a turbulence intensity increase produces dynamic mechanical loadings on downwind WTGs (which are said to be *shadowed* by the turbine generating the wake), see Gonzalez-Longatt *et al.* (2012).

As a consequence, wake effects evaluation plays an important role in the WF design in order to maximize the energy production and WTGs lifetime (Kiranoudis and Maroulis 1997). In order to describe WEs, several models have been developed which can be classified in:

- *analytical/explicit* or *kinematic* wake models: these are the earliest and use self-similar velocity profiles determined semi-empirically; they evaluate the velocity in a wake through a set of analytical expressions and are based on the conservation of mass and empirical relations of wake decay, which are mainly used for micro-siting and WF output predictions, see Lissaman (1979), Jensen (1983) and Voutsinas *et al.* (1990);
- *computational/implicit* wake models: developed as alternatives to the explicit models, these are based on approximations of either the Navier-Stokes or vorticity transport equations, see Zervos *et al.* (1988); Smith and Taylor (1991); Crasto and Gravdahl (2008).

According to Kozmar *et al.* (2016), several studies on WEs of wind turbines at the flat terrain and open sea have been carried out. However, little is known about WEs in *complex terrain*, see Yang *et al.* (2015).

In particular, the contribution proposed by authors aims at extending research knowledge on this topic. The main objective of this paper is to present a simulation model used as support tool for carrying out specific analyses for testing wind farm performance in terms of energy production under three different wake models in a complex terrain environment. Simulation model development, validation and preliminary analysis are presented. It is worth mentioning that Simulation has been extensively used in many sectors for complex systems design, decision support and training, from Industry to Logistics, from Defense to Environmental Sustainability (e.g. Longo, 2012-a; Longo 2012-b; Bruzzone et al. 2011). More recently Modeling & Simulation based approaches, have been also used to support design of sustainable energy production systems (Perez et al. 2015). The paper is organized as follows: Section 2 reports a description of the existing wind farm; Section 3 presents the simulation model as well as validation results while Section 4 describes the preliminary analysis and simulation results. Finally, Conclusions summarize critical issues and main results of the study.

2. THE WIND FARM

As before mentioned, the wind farm considered in this research work is located in Calabria, south part of Italy, in a complex terrain which rises from sea level to a maximum altitude of 340 m.

In particular, terrain complexity is due to the succession of hills and increasing slope areas, i.e. *complex orography*, with trees of variable height, low greenery and cultivated plots of land, i.e. *complex roughness*, as reported in Figure 1.

The wind farm on this complex terrain is made up by 27 WTGs located at different altitudes: the base of the lowest turbine is located at 280 m above sea level while the highest is at about 340 m. The remaining WTGs are arranged within the altitude range.

All the three blades WTGS have a rated power of 2.0 MW: 17 of them are mod. *Vestas V90* with a rotor diameter of 90 m and a hub height of 80 m; the others 10 are mod. *Repower MM92* with a rotor diameter of 92.5 m and a hub height of 80 m.

Table 1 reports for each WTG its longitude and latitude in UTM-WGS 84 coordinate system, altitude above sea level and model.

Table 1: WTGs of the on-shore wind farm

WTG	***Long. East***	***Latitude North***	***Alt. (m)***	***Mod.***
WTG1	627232	4304548	337.5	*Vestas V90*
WTG2	626763	4304481	319.8	“ ”
WTG3	626308	4304660	337.5	“ ”
WTG4	625986	4305421	334.3	“ ”
WTG5	625550	4304266	307.7	“ ”
WTG6	625571	4303990	310.0	“ ”
WTG7	626221	4303380	324.9	“ ”
WTG8	626079	4303841	321.3	“ ”
WTG9	625913	4303353	314.8	“ ”
WTG10	626033	4303598	286.9	“ ”
WTG11	626900	4302881	339.1	“ ”
WTG12	626233	4303064	325.4	“ ”
WTG13	627238	4302928	336.3	“ ”
WTG14	627290	4303239	339.6	“ ”
WTG15	627287	4303418	324.4	“ ”
WTG16	626799	4303117	318.5	“ ”
WTG17	627041	4303548	323.8	“ ”
WTG18	626195	4304791	340.8	*REpower MM92*
WTG19	625904	4305054	336.1	“ ”
WTG20	625750	4304662	318.8	“ ”
WTG21	625297	4304561	311.4	“ ”
WTG22	625160	4304067	309.6	“ ”
WTG23	625524	4303778	309.0	“ ”
WTG24	625395	4303330	309.0	“ ”
WTG25	625685	4303140	304.0	“ ”
WTG26	625451	4302881	285.0	“ ”
WTG27	624982	4303112	289.0	“ ”

Figure 1: Wind Farm terrain complexity

3. THE SIMULATION MODEL

According to authors experience, simulation is the most effective tool for designing and analyzing systems behavior under internal/external changes, see Curcio and Longo (2009) and Longo et al. (2012).

In fact, the simulation model presented in this research work aims at reproducing system performance in terms of energy production under three different *analytical/explicit* or *kinematic* wake models, i.e. Jensen, Larsen, Ishihara.

The software tools adopted for the simulation model implementation and climatology data analysis are:

- *Minitab 14.0*, *WindRosePro3*, *MS Excel* for probability plots, Weibull distribution parameters and wind roses from available climatology data;
- *WindSim Express 7.0* in the pre-processing step for digital terrain model (DTM) definition, WF layout (including WTGs technical specifications), masts with climatology data;
- *WindSim 7.0* as a post-processor for average wind speed at each WTG estimation, wake effects, full load hours evaluation, wind farm power assessment.

3.1. Wake models description

Three different *analytical/explicit* or *kinematic* wake models are investigated in this research work: Jensen, Larsen and Ishihara.

Table 2 lists all the factors considered in each wake model while the following subsections describe more in detail each wake model.

Table 2: Wake models parameters

Parameter	*Jensen*	*Larsen*	*Ishihara*
Incoming wind speed	•	•	•
Downstream distance from the WTG	•	•	•
Radial distance from the WTG		•	•
Rotor diameter	•	•	•
Hub height		•	
Turbulence intensity		•	•

3.1.1. Jensen wake model

The analytical wake model developed by N.O. Jensen is one of the oldest analytical wake models.

According to N.O Jensen, the wake behind the wind turbine has a linear expansion and the velocity deficit is only dependent on the distance downstream from the turbine.

The wake increase is described by the following equation:

$$D_{wake} = D(1 + 2ks) \quad (1)$$

while velocity deficit u_{def} due to wake effects is defined as follows:

$$u_{def} = U_{\infty}\left[\frac{1-\sqrt{1-C_T}}{(1+2ks)^2}\right] \quad (2)$$

where:

- D: rotor diameter (m);
- D_{wake}: wake diameter (m);
- k: *wake decaying constant* (it represents how the wake breaks down by specifying the growth of the wake width per unit length in the downstream direction);
- s: normalized downstream distance (with respect to the rotor diameter) from the turbine;
- U_{∞}: undisturbed wind speed (m/s);
- C_T: thrust coefficient.

3.1.2. Larsen wake model

Larsen wake model is based on Prandtl turbulent boundary layer equations.

The wake flow is assumed to be incompressible, stationary and asymmetric. The wake increase is described by the following equation:

$$D_{wake} = 2\left(\frac{35}{2\pi}\right)^{\frac{1}{5}}(3c_1^2)^{\frac{1}{5}}[C_T A(x + x_0]^{\frac{1}{3}} \quad (3)$$

while velocity deficit u_{def} due to wake effects is:

$$u_{def} = -\frac{U_{\infty}}{9}[C_T A(x + x_0)^{-2}]^{\frac{1}{3}}\left\{r^{\frac{3}{2}}[3c_1^2 C_T A(x + x_0)]^{\frac{-1}{2}} - \left(\frac{35}{2\pi}\right)^{\frac{3}{10}}(3c_1^2)^{\frac{-1}{5}}\right\}^2 \quad (4)$$

where:

- r: radial distance from the turbine (m);
- x: downstream distance from the turbine (m);
- A: rotor swept area (m^2);
- x_0: constant that denotes the turbine's position with respect to the applied coordinate system;
- c_1: constant representing the non-dimensional mixing length (related to Prandtl mixing length).

3.1.3. Ishihara wake model

In this model turbulence effects on the wake from both the ambient turbulence and the mechanical generated turbulence are considered.

The wake increase is described by the following equation:

$$D_{wake} = \frac{k_1 C_T^{\frac{1}{4}}}{0.833} D^{\left(1-\frac{p}{2}\right)} x^{\frac{p}{2}} \quad (5)$$

The velocity profile of Ishihara model is assumed to have a Gaussian profile and the velocity deficit is given by:

$$u_{def} = \frac{\sqrt{C_T}}{32} U_{\infty}\left(\frac{1.666}{k_1}\right)^2\left(\frac{x}{D}\right)^{-p} exp\left(-\frac{r^2}{D_{wake}^2}\right) \quad (6)$$

with

$$p = k_2(I_a + I_w) \quad (7)$$

where I_a and I_w are respectively the ambient turbulence and the turbine-generated turbulence while $k_1 = 0.27$ and $k_2 = 6$.

3.2. Wind data analysis

Before simulation model implementation, wind data of two different on-site masts, i.e. MAST1 and MAST2, have been analyzed.

Table 2 shows for each MAST its longitude and latitude in UTM-WGS 84 coordinate system and height.

Each mast consists of 5 wind anemometers at different heights, a pressure detector and a thermometer. Two years of wind speed, wind direction and temperature data are available for each mast. In the following pages, the data will be analyzed and filtered by using Minitab 14.0, WindRosePro3, MS Excel in order to evaluate for each wind anemometer:

- prevailing wind directions, see Figure 2-3;
- main wind speed statistics and percentage distribution for different wind speed classes, see Figure 4;

- Weibull distribution plots and parameters as reported in Figure 5.

Table 2: On site masts

MAST	*Long. East*	*Latitude North*	*Alt. (m)*
MAST1	626938	4304099	50
MAST2	625829	4304814	66

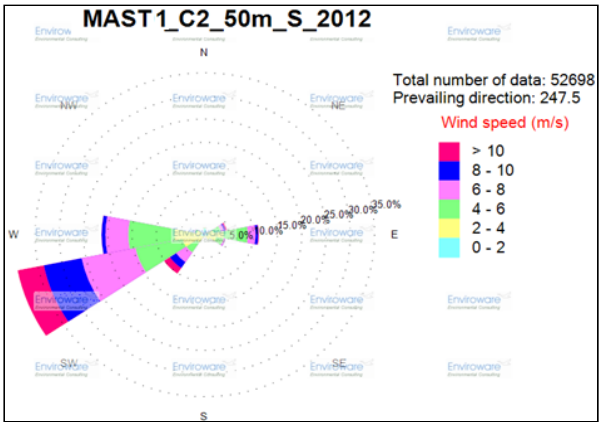

Figure 2: Prevailing wind direction for MAST1 at 50 m height

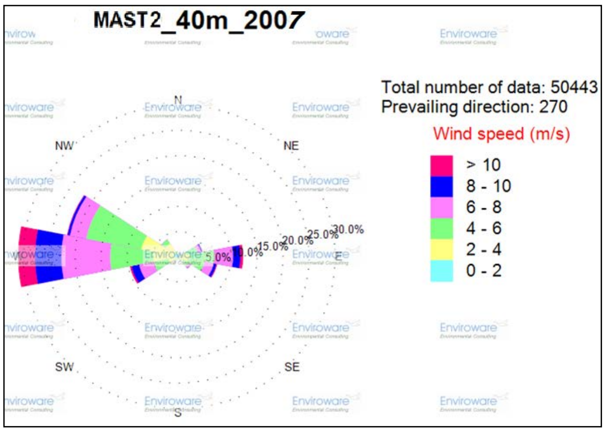

Figure 3: Prevailing wind direction for MAST2 at 40 m height

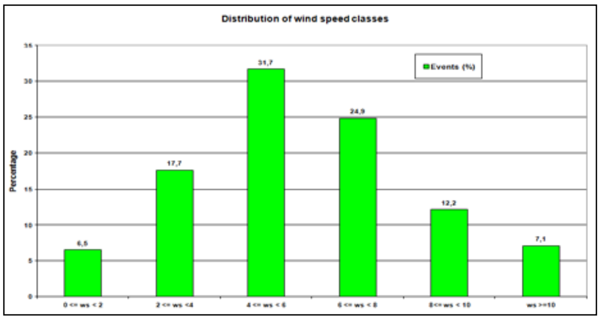

Figure 4: Distribution of wind speed classes for MAST2 at 40 m height

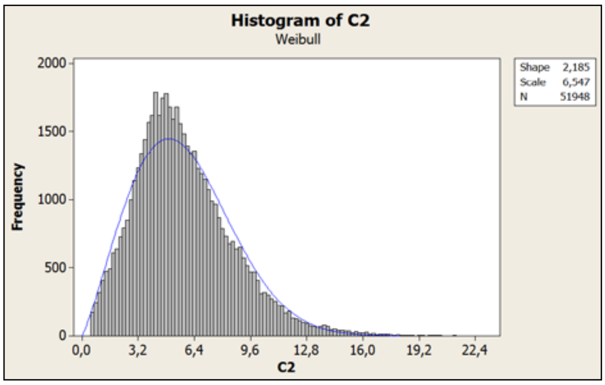

Figure 5: Weibull data distribution for MAST1 at 50 m height

Wind data analysis highlights that input data available for the simulation model are:

- MAST1: data from 01/01/2012 to 01/01/2013 registered at 50 m;
- MAST2: data from 01/01/2007 to 01/01/2008 registered at 40 m.

3.3. Digital Terrain Model (DTM)

As before mentioned, a digital terrain model has been generated through the software tool WindSim Express 7.0 by using the following on-line available resources:

- *ASTER GDEM v2 Worldwide Elevation Data (1 arc-second Resolution)* for elevation;
- *VCF Tree Cover Worldwide 2005 (500 m Resolution)* for roughness maps.

Table 3 reports DTM position, size and resolution in UTM-WGS 84 coordinate system while Figures 6 shows DTM elevation and roughness. Finally, in Figure 7 the WF layout (27 WTGs) including masts is represented.

Table 3: DTM size

	Min. (m)	*Max. (m)*	*Size (m)*	*Resol. (m)*
Easting (m)	620374	631950	11576	38.1
Northing (m)	4297892	4309469	11578	38.1

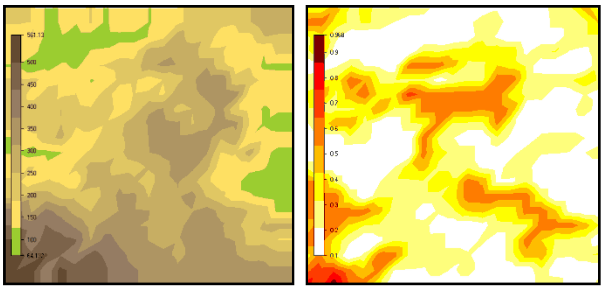

Figure 6: DTM elevation (left) and roughness (right)

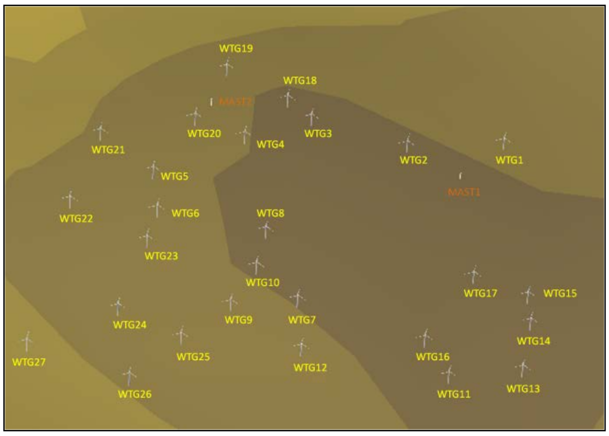

Figure 7: Wind Farm layout

4. SIMULATION MODEL VALIDATION

The digital terrain model is then introduced in the post-processor tool WindSim 7.0 in order to evaluate average wind speed at each WTG, wake effects, wind farm power assessment, full load hours.

Before carrying out specific analyses in order to test system performance in terms of energy production under different wake models, the simulation model was validated.

According to Balci (1998), validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended use of the model.

Data used for simulation model validation are wind farm annual energy production (AEP) from January 2011 to December 2015, see Table 4.

Table 4: Wind Farm real AEP (MWh)

	Real AEP
2011	97816,08
2012	110321,15
2013	109349,25
2014	102214,99
2015	98655,53
Av.	***103671,4***

The smallest estimated AEP given by the simulation model implemented is 111445 MWh/year which becomes 103643,85 MWh/year if a reduction of 7% related to technical losses (i.e. turbines internal/ external losses, machines availability, etc.) is considered.

Comparing the real AEP of the wind farm (which average value from 2011 to 2015 is 103671,4 MWh/year) with the simulated one (103643,85 MWh/year), they are quite similar. As a consequence, the simulation model implemented is an accurate representation of the real wind farm and wind input data chosen for each mast represent accurately the terrain and climatology complexity of the wind farm site.

5. SIMULATION RESULTS ANALYSIS

As before mentioned, the objective is of this research work is to implement a support tool (a simulator) to be used for carrying out specific analyses in order to test system performance in terms of energy production under different wake models. More in detail, three different scenarios corresponding to wake models considered, i.e. Jensen, Larsen, Ishihara, have been implemented; for each wake model wake losses, net AEP and full load hours have been monitored as system performance parameters.

In addition, according to Gonzalez-Longatt *et al.* (2012), the authors for evaluating the overall impact of wake effects on the output AEP of the wind farm, introduce a wake coefficient parameter (WCP) defined as follows:

$$WCP = \frac{Net\ AEP}{Gross\ AEP} \quad (8)$$

This parameter combines all the local wake effects at each WTG into a single measure of the overall wake effects of the wind farm.

Table 5 shows for each wind turbine generator its simulated Gross annual energy production (Gross AEP), i.e. not affected by wake effects, estimated in 124,483 GWh/year for the whole wind farm.

Table 5: Gross AEP (GWh/year)

WTG	***No Wake Model***
WTG1	4,123
WTG2	4,678
WTG3	4,813
WTG4	4,645
WTG5	4,438
WTG6	4,408
WTG7	4,463
WTG8	4,543
WTG9	4,278
WTG10	4,472
WTG11	4,794
WTG12	4,309
WTG13	5,024
WTG14	5,045
WTG15	4,962
WTG16	4,786
WTG17	4,81
WTG18	5,379
WTG19	4,749
WTG20	4,893
WTG21	4,419
WTG22	4,482
WTG23	4,736
WTG24	4,467
WTG25	4,461
WTG26	4,224
WTG27	4,082
Tot.	**124,483**

Tables 6 – 7 – 8 report respectively simulation results for each WTG related to wake losses (%), Net AEP (GWh/year), i.e. gross AEP with wake losses, and full load hours (hours) respectively for Jensen, Larsen and Ishihara wake models implemented.

Table 6: Wake losses (%)

WTG	*Jensen*	*Larsen*	*Ishihara*
WTG1	9,733	4,14	10,04
WTG2	9,583	4,263	9
WTG3	18,872	7,862	18,07
WTG4	17,743	6,374	17,38
WTG5	6,043	3,067	5,52
WTG6	11,92	4,912	12,29
WTG7	22,669	8,585	24,95
WTG8	10,969	4,682	11,38
WTG9	17,427	6,379	17,27
WTG10	9,386	4,213	8,39
WTG11	6,657	3,069	6,92
WTG12	13,787	5,467	13,64
WTG13	15,755	5,858	16,17
WTG14	8,349	3,744	8,16
WTG15	8,305	4,431	7,58
WTG16	11,661	4,831	10,92
WTG17	7,291	3,281	7,07
WTG18	12,111	5,583	10,93
WTG19	3,122	1,396	3,3
WTG20	12,451	4,799	12,58
WTG21	4,051	1,779	3,78
WTG22	4,42	1,785	4,66
WTG23	8,169	3,283	8,21
WTG24	8,92	3,476	8,47
WTG25	13,568	5,606	12,71
WTG26	5,521	2,571	4,72
WTG27	3,276	1,298	3,09
Av.	**10,435**	**4,323**	**10,266**

As showed in Table 6 and Figure 8, Jensen and Ishihara wake models estimate similar wake losses while Larsen model predicts the smallest ones.

According to Equation 3, Larsen wake model predicts a larger initial wake expansion than that evaluated by the other two models; in addition this model introduces all the climatology parameters at the WTG hub height.

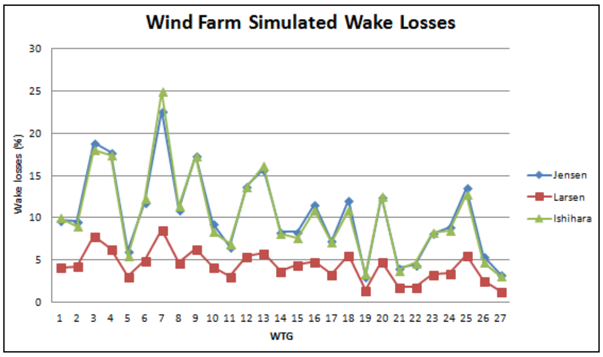

Figure 8: Wind Farm wake losses for each WTG

As a consequence, annual net AEP and full load hours reflect the same trend, see Tables 7 – 8 and Figures 9 – 10. In addition, wake coefficient parameters (WCP) for Jensen and Ishihara models are quite similar and smaller than Larsen, see Equations 9 – 10 – 11.

Table 7: Net AEP (GWh/year)

WTG	*Jensen*	*Larsen*	*Ishihara*
WTG1	3,722	3,953	3,709
WTG2	4,23	4,479	4,257
WTG3	3,905	4,435	3,943
WTG4	3,821	4,349	3,837
WTG5	4,17	4,302	4,193
WTG6	3,882	4,191	3,866
WTG7	3,452	4,08	3,349
WTG8	4,045	4,33	4,026
WTG9	3,533	4,005	3,539
WTG10	4,053	4,284	4,097
WTG11	4,475	4,647	4,461
WTG12	3,715	4,074	3,721
WTG13	4,232	4,729	4,211
WTG14	4,624	4,856	4,633
WTG15	4,55	4,742	4,586
WTG16	4,228	4,555	4,263
WTG17	4,459	4,652	4,469
WTG18	4,728	5,079	4,791
WTG19	4,601	4,683	4,592
WTG20	4,284	4,658	4,277
WTG21	4,24	4,34	4,252
WTG22	4,283	4,402	4,272
WTG23	4,349	4,581	4,347
WTG24	4,069	4,312	4,088
WTG25	3,856	4,211	3,894
WTG26	3,991	4,116	4,024
WTG27	3,948	4,029	3,955
Tot.	**111,445**	**119,074**	**111,663**

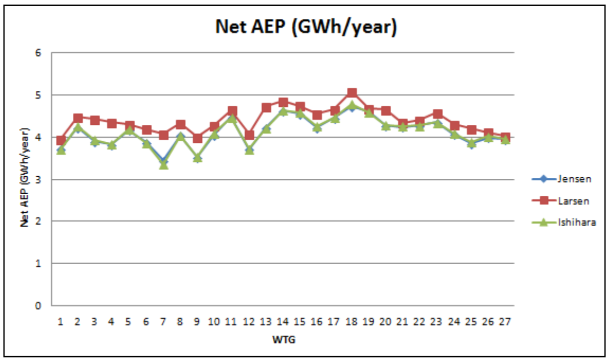

Figure 9: Wind Farm Net AEP for each WTG

$$WCP^{Jensen} = \frac{Net\ AEP^{Jensen}}{Gross\ AEP} = \frac{111{,}445}{124{,}483} = 0{,}895 \qquad (9)$$

$$WCP^{Larsen} = \frac{Net\ AEP^{Larsen}}{Gross\ AEP} = \frac{119{,}074}{124{,}483} = 0{,}95 \qquad (10)$$

$$WCP^{Ishihara} = \frac{Net\ AEP^{Ishihara}}{Gross\ AEP} = \frac{111{,}663}{124{,}483} = 0{,}897 \quad (11)$$

Table 8: Full load hours (hours)

WTG	*Jensen*	*Larsen*	*Ishihara*
WTG1	1860,95	1976,25	1854,6
WTG2	2114,85	2239,3	2128,6
WTG3	1952,35	2217,3	1971,6
WTG4	1910,55	2174,6	1918,9
WTG5	2084,95	2151	2096,5
WTG6	1941,25	2095,7	1933
WTG7	1725,8	2040,1	1674,9
WTG8	2022,3	2165,1	2013,1
WTG9	1766,4	2002,75	1769,8
WTG10	2026,3	2142	2048,6
WTG11	2237,25	2323,25	2230,9
WTG12	1857,55	2036,8	1860,7
WTG13	2116,15	2364,75	2105,7
WTG14	2311,95	2428,1	2316,7
WTG15	2275,1	2371,2	2293,2
WTG16	2114	2277,45	2131,8
WTG17	2229,65	2326,1	2234,9
WTG18	2306,24	2477,56	2337,2
WTG19	2244,43	2284,43	2240,3
WTG20	2089,61	2272,24	2086,6
WTG21	2068,29	2117,26	2074,1
WTG22	2089,46	2147,07	2084,3
WTG23	2121,51	2234,39	2120,6
WTG24	1984,82	2103,46	1994,6
WTG25	1880,87	2054,14	1899,5
WTG26	1946,82	2007,61	1963,4
WTG27	1925,90	1965,26	1929,6
Av.	**2044,64**	**2185**	**2048,65**

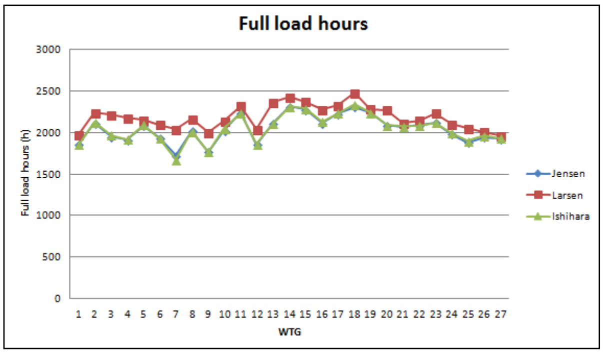

Figure 10: Wind Farm Full load hours for each WTG

6. CONCLUSIONS

This research work focuses on a wind farm located in Calabria (Italy) characterized by complex terrain.

A simulation model is implemented to test system performance in terms of energy production under three different wake models, i.e. Jensen, Larsen, Ishihara.

After the modeling phase, the simulator has been validated by using annual energy production data of the existing wind farm from January 2011 to December 2015.

Three different scenarios corresponding to wake models considered have been implemented; for each model wake losses, Net AEP, full load hours have been monitored as system performance parameters.

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