THE EFFECT OF PARNASSUS MOUNTAIN ON WIND FARM SITTING – AN EXPERIMENTAL AND A GIS-BASED INDUSTRIAL SYMBIOSIS STUDY TOWARDS SUSTAINABLE DEVELOPMENT

***G. Xydis** [a] **, E.A.Nanaki** [b]**, C.J.Koroneos** [c]*
[a]Intelligent Energy Systems Programme Risø DTU National Laboratory for Sustainable Energy
Frederiksborgvej 399, P.O. Box 49, 4000 Roskilde
E-mail: gexy@risoe.dtu.dk

[b] University of Western Macedonia, Department of Mechanical Engineering, Bakola and Sialvera,
50100 Kozani, Greece
E-mail: evananaki@gmail.com

[c]Laboratory of Heat Transfer and Environmental Engineering, P.O. Box 483,
Aristotle University Thessaloniki,
GR-54124, Thessaloniki, Greece
Email: koroneos@aix.meng.auth.gr

Abstract

The wind potential around mountain Parnassus in central Greece has been studied and an experimental analysis has been presented which could be used as a wind farm sitting selection tool aiming at maximization of the production output. Different wind sites within Fokida prefecture were studied based on field measurements around the large mountainous area of Central Greece. Understanding flow not only above mountains but also in the foothills and the wider area of mountains is of great importance for estimating energy yield in rough terrain. Forced air flow around mountainous masses was examined based on the wind velocity results in the wider area. In this paper, special focus was given also to the environmental constraints for achieving a green development strategy in the area.
Keywords: Wind Measurement, Air Flow, Mountainous terrain, Industrial Symbiosis

Introduction

Wind resource analyses in flat terrain are well established on the contrary to the applications in strictly mountainous terrain. Accurate wind resource measurements – using, usually, wind meteorological masts – are absolutely necessary for the exploitation of wind energy. However, wind farms in a mountainous area are not only difficult to be constructed for the utility but many times is even more difficult to complete field measurements for the needed period. Wind resources are rarely consistent and vary with time, season, terrain type, height above ground level and from year to year, and consequently it is needed to be thoroughly – especially in rough terrain – investigated prior to any exploitation [1]. Air flow above mountains, is very advantageous for wind farms with increased wind speed compared with the incoming flow. Hills and mountains suitable for wind farms tend to increase the wind speed because of the obstructions on the incoming wind and therefore are many times preferable as this way the power output is increased [2]. This effect is experimentally studied – in particular the forced air flow around – and not only over – significant mountainous masses was investigated. Greek terrain is mainly mountainous with ranges extending into the sea as peninsulas most of the times. In many cases for determining wind speed & profile different modelling techniques are used to correlate measurements from other sites of the same area using meteorological masts where possible and therefore often results are not trustworthy. However, some of these techniques at least mark out a method and in some cases new sites appropriate for wind farm installation are revealed. A draft literature review, the site experimental results, a GIS-based analysis and discussion follows in the next sections.

Literature Review

A large body of literature concerning wind resource assessment applications worldwide has been carried out over the past few decades. Not that many though deal with modelling and wind measurements exclusively in mountainous terrain. Literature includes studies concerning optimal wind farm sitting models based on the exergy analysis and the inversed distance weighting methodologies in Southern Greece [3], comparisons of wind velocity based on numerical weather prediction models over rough terrain [4], and outcomes of wind prediction in coastal mountains using WAsP tool [5]. It also includes studies about comparison of real and model wind speeds [6] or turbulence effects [7], and studies about the tunnel effect in wind speed [8 - 10]. According to the literature, there are also wind studies on modelling related to the evaluation of models designed for siting wind turbines in areas of mountainous terrain [11 - 12], critical evaluation of different correlation methods in wind resource assessment of an area using short term data correlated to long term data in a mountainous environment [13].

Regarding speeding-up only few studies have been made so far. Lubitz and White investigated the phenomenon not only in a tunnel but also in the field [14], while Pellegrini and Bodstein revealed what happens just over low hills [15]. Lemelin *et al.* [16] and Miller and Davenport [17] made some simple calculations regarding wind profile from flow over hills or complex terrain. Although, these studies have been implemented over the past years of intensive research in the field of wind energy, there is no an experimental study showing that there could be a “one-side tunnel effect” or in other words forced air flow around – not over – significant mountainous masses. Significant amount of literature is related to complex terrains, correlation tools and flow over complex terrain but almost no research is related to wind assessment and strictly mountainous terrains and the possibility of sitting wind farms on those “alternative” areas. To fill the gap related to wind speed, and wind farm evaluation methodology, under this “speed-up” phenomenon of forced air flow around mountainous masses and flow in the wider area, in this paper an experimental study has been carried out.

Site Experimental Results

As a part of this research paper, a case study was carried out on wind characteristics for mountainous Central Greece. Wind profile measurements were carried out for specific periods using initially four (4) different meteorological masts for the speed-up effect and six (6) more for the explication of the results in the wider area. Wind speed intensity and wind direction as well as other characteristics have been observed for the ten (10) meteorological towers in the area in total. Vector Hellenic Windfarms S.A.

operates a certified laboratory (Laboratory of Wind Measurements) from Hellenic Accreditation System S.A. (E.SY.D.) in Greece and the meteorological stations were under the laboratory's supervision. Figure 1 shows – facing North and Northeast – in a 3D viewing image the exact place of the first measuring mast ("Z" wind mast).

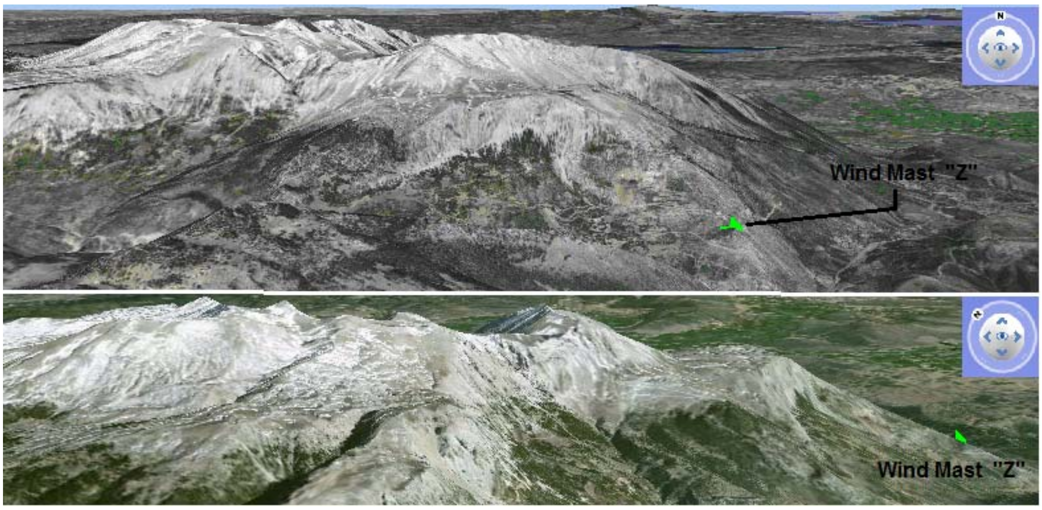

***Fig. 1**: Location of "Z" mast installed*

It is quite obvious that mast "Z" is located in the foothills of a large mountainous mass (the mountain of Parnassus – elevation: 2,457 m.). Also, wind mast "K" is also installed on the foothills of the mountain 2.25 km away from the first mast. On the north-eastern side of the mountain, there are two more wind masts installed (mast "M1" and mast "F") measuring for at least a year each (the distances among sites are shown on figure 2).

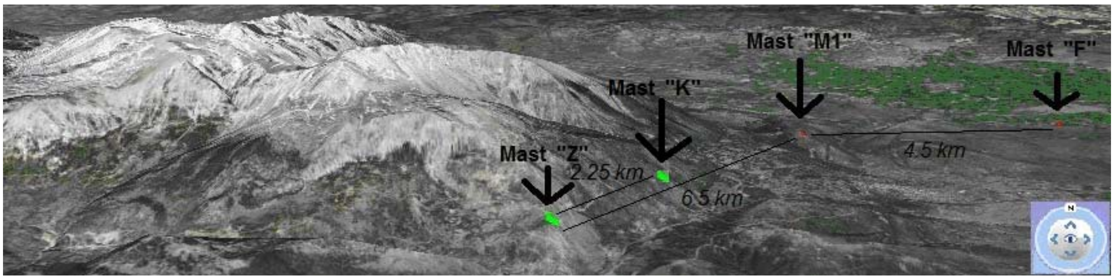

***Fig. 2:** Installed Masts "M1", "F" and "K" in the area and distances from mast "Z".*

Site coordinates, average velocity, period of measurement, height above ground level and turbulence at 10 m are shown on Table 1. It is rather clear that as height a.g.l. increases and as the distance from the mountain of Parnassus is reduced the average wind speed is increased. The software for wind data analysis & correlation WindRose [18] and WAsP software (Wind Atlas Analysis and Application Program) [19] were used for elaborating all the measurements and produce estimates of wind speed at various distances from the measuring meteorological masts.

Site / Code	Latitude (°)	Longitude (°)	Mean speed $(m \cdot s^{-1})$	Period of data analysis	Height (m.a.g.l.)	Av. Turbulence Intensity (at 10m.)
Z	38.48472	22.678333	7.3 at 10 m.	3 Feb '07 – 5 Aug '07	886	13.2 %
K	38.50194	22.694444	6.7 at 10 m.	14 Apr '08 – 14 Apr '09	815	14.1 %
M1	38.53861	22.721389	4.6 at 30 m.	7 Jul '08 – 15 Jun '09	570	14.4 %
F	38.55361	22.775556	4.2 at 20 m.	4 Oct '07 – 24 Sept '08	372	12.1 %

***Table 1**: Main measured characteristics of the four (4) initial sites*

A significant observation though has to do with the main and secondary directions of the wind roses. While in mast "M1" and in mast "F" the main directions seem to be N-NW in masts "Z" and "K" seem to have turned into NE.

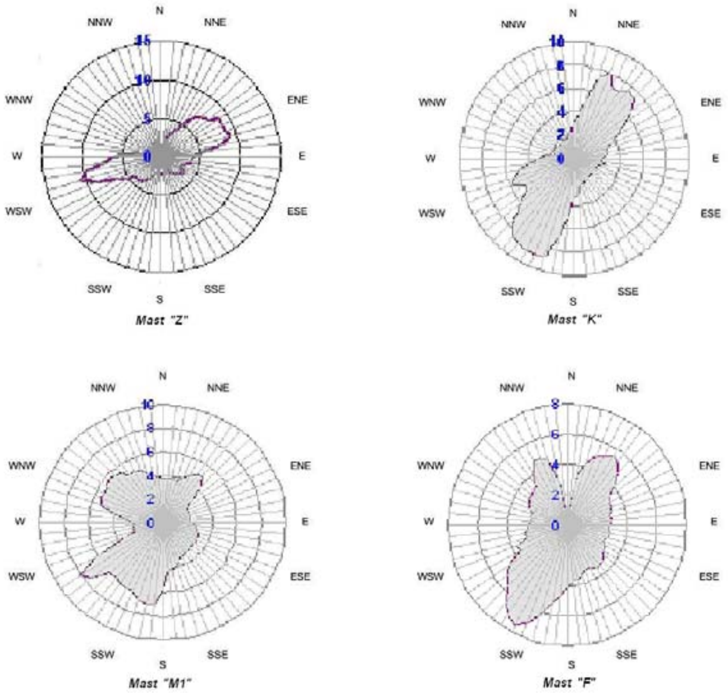

***Fig. 3**: Wind Directions of "Z", "K", "M1", and "F" wind masts.*

It is obvious that the distances among the sites are not that significant for the wind to be expected to have changed substantially. A physical obstacle – as a mountain is – could have caused that. What also should be noticed based on the exact sitting of the "K" and "Z" masts (Fig. 1, 2) is that "K" mast is notably more "open" to north winds and therefore sustains some of the characteristics of the other two masts ("F" and "M1"). "Z" mast however, is located in the SE side of the mountain and therefore it is not so easy to be accessible from direct north winds. The obstacle of mountain forces the flow to change route and "fold" the mountain speeding-up and of course changing direction. That explains the direction results in Fig. 3 and the speed results (Table 1). The positive effect – in the meaning of wind speed – of the mountain of Parnassus in the wider area (distance < 10 km) is not only limited to the foothills of the mountain. A number of other masts (Fig. 4, Tab. 2) installed in the wider area (mainly on the south of the mountain) prove that.

Site / Code	Latitude (°)	Longitude (°)	Mean speed ($m \cdot s^{-1}$)	Period of data analysis	Height (m.a.g.l.)	Av. Turbulence Intensity (at 10m.)
K2	38.38833	22.681111	6.43 at 30 m.	29 Feb '08 – 1 Mar '09	627	10.5 %
S	38.41361	22.675278	7.87 at 10 m.	28 Feb '08 –28 Aug '08	609	12.5 %
KR	38.41639	22.653611	6.45 at 10 m.	22 Jun '07 – 22 Jun '08	540	13.5 %
GP	38.41750	22.643611	6.09 at 30 m.	26 Mar '08 – 4 Dec '08	523	12.7 %
P1	38.39666	22.637500	5.93 at 30 m.	14 Jan '08 – 10 Dec '08	419	15.3%
P2	38.39750	22.625278	5.61 at 20 m.	23 Mar '08 – 9 Dec '08	477	15.2%

Table 2: *Main measured characteristics of other six (6) sites in the wider area*

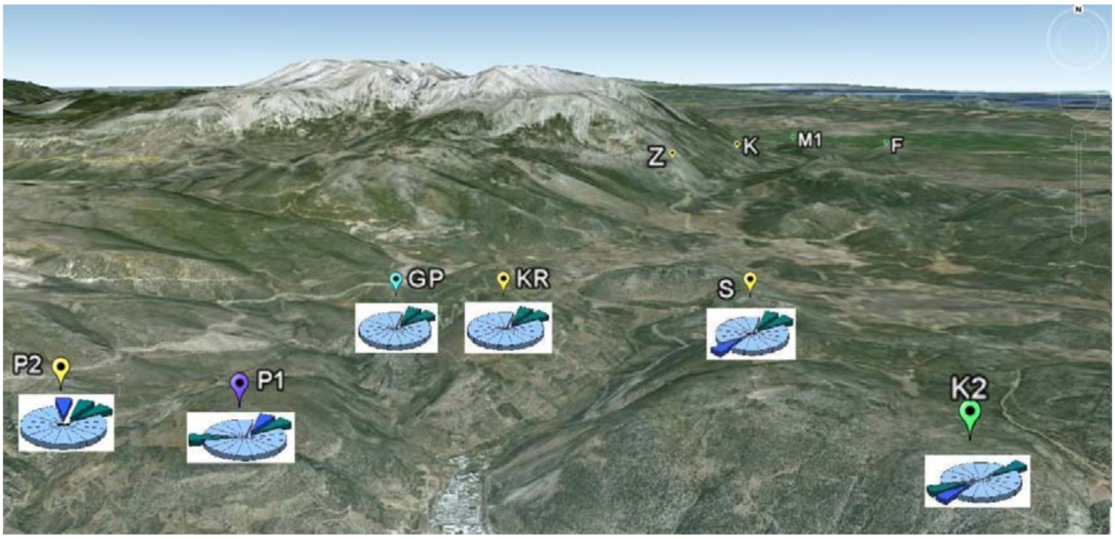

Fig. 4: *A number of other masts installed in the wider area*

The wind velocity results are impressive. For all six (6) masts wind speed varies from 5.61 – 7.87 m/s but doesn't fall bellow 5.61 m/s. That ensures in most cases the viability of possible wind projects. However, it is clearly observed that even 100 – 150 m. of difference in altitude among e.g. the first two sites on Table 2 ("K2" and "S") and the last two ("P1" and "P2") play a role on the average wind speed meaning that the wind speed is notably higher in cases where the hill where the mast is installed is higher as well.

Industrial Symbiosis

The basic aim was to select different sites within the under examination area and estimate weather these sites were promising for wind farm development or not based on the existing constraints. In the wider area are located small villages and small cities and at the same time the interesting wind speed results make necessary the need for a symbiosis plan. A GIS-based methodology was used for the preliminary evaluation of the area prior to any investment. Taking into consideration planning constraints based on the Special Framework for Spatial Planning of Renewable Energy [20], and the Law 3851/2010 for accelerating the development of RES [21], as villages near the area, monasteries, archaeological sites, isolates buildings, Natura 2000 areas, Special Protected Areas (SPA), archaeological sites, important coasts and beaches, even roads, the necessary distances were kept and the available sites of possible wind development interest remained.

The area is of great archaeological interest as Delphi lie on the south-western spur of Mount Parnassus and is of great residential interest as the modern traditional villages of Delphi and Arachova are located in the western part of the prefecture of Viotia (close to the borders with the prefecture of Fokida) not mentioning all other small villages dispread in the wider area. Furthermore, over the last decades the touristic development is observed not only because of the slopes of Mount Parnassus (location of two major ski centres), but also because of a couple of beachfront villages. Therefore, there are a lot of constraints to be placed on a map and realize which are the sites available for exploitation. Based on the Special Framework for Spatial Planning of Renewable Energy [20], there are different safety distances that should be kept prior the final sitting of a wind farm. For instance, it's 1,500 m. from traditional villages (500 m. from every other village), at least 3,000 m. from important archaeological sites, 1,000 m. from organized touristic areas, 500 m. from excavating zones, 1.5·d from roads (class 3) and railways, where d equals the diameter of the proposed wind turbine.

All geographical constraints for the development of any industrial project (including wind farms) are shown on fig. 5. In a scaled 1:50,000 map are shown graphically all restrictions as residential zones, Sites of Community Interest (SCI), SPAs, traditional villages, archaeological sites etc.Based on the measurements in the area and model runs [19], an indicative wind map (Fig. 6) was produced describing the wind potential of the area and showing in one map the available/apropriate areas for wind farm development and at the same time the constraints. It's quite clear that from the remaining areas only few of them can be exploited based on the wind results. It's clear also that areas that were able to be exploited – as areas around masts K, Z – after the introduction of the new SPA sites are excluded.

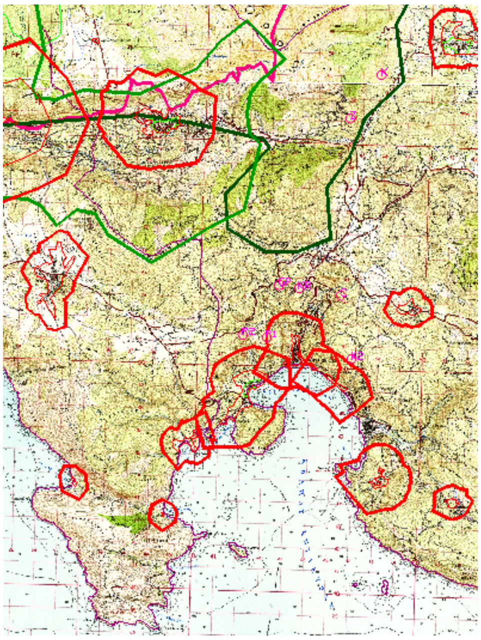

Fig. 5:*1:50,000 topographical map*

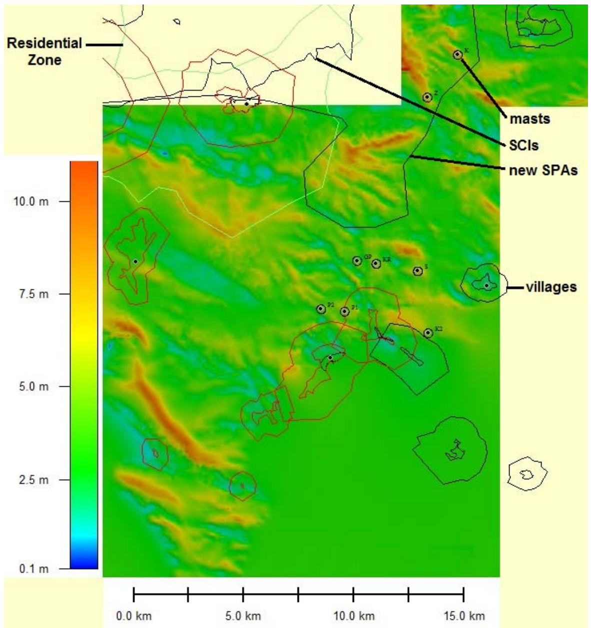

Fig. 6: *Wind Speed analysis map*

However, areas close to touristic villages are also affected, nevertheless there is still potential and space for development. Based on WAsP runs, windy sites of the area were determined and a much more accurate wind map than the one of the Center of Renewable Energy Laboratory wind map [22] was produced (fig. 6). Therefore, based on the findings, a sustainable development plan could be implemented and followed for the area for the wind farm growth plan covering not only environmental needs but also the grid needs of the area.

Discussion

The main idea behind this experimental study was to identify if and in what grade air flow speeds-up – not only above mountains – but also around them and of course what's happening with the flow after the speeding – up process. What was found from real life results is that the flow keeps its initial direction – not close to the mountain foothills though where perforce the direction is changing – but in the wider area.The whole area was extensively examined and reviewed with all the masts installed around it, it was found that the speed-up effect was met in the mountain's foothills and did not changed only the velocity of the wind but also the direction based on the sitting of the installed mast. In specific the mast was installed there as the area was considered possible wind farm development area. What's important additionally, is that in the first few km "away" from the mountain as the flow develops its route to the south, due to the existence of rough terrain with lots of hills the wind speed remains in "interesting" levels. Lastly, based on the industrial symbiosis study taking into account the environmental, archeological, and residential constraints and the results from the resultant wind map originated from software analysis the appropriate areas for wind farm development were "traced" in order the touristic, ecological and industrial growth to go along.

Acknowledgements

The preparation of this paper would not have been possible without the support of the Certified Laboratory of Wind Measurements of Vector Hellenic Windfarms S.A.. The used data array was made up of the average (1 value per second – 600 values in 10 min) and maximum 10-min wind speed values in the sites monitored by the laboratory of Wind Measurements of Vector – Hellenic Wind Farms S.A.

References

[1] J.R.Potts , SW Pierson, PP Mathisen , JR. Hamel, VC Babau, *Wind energy assessment of Western and Central Massachusetts*. AIAA-2001-0060, (2001).
[2] K. Røkenes, P.-A Krogstad, "Wind tunnel simulation of terrain effects on wind farm siting", *Wind Energy*, **12 -4** (2009) 391-410.
[3] G. Xydis, C. Koroneos, M. Loizidou, "Exergy analysis in a wind speed prognostic model as a wind farm sitting selection tool: A case study in Southern Greece", *Applied Energy*, **86** (2009) 2411–2420.
[4] S.J Mitchell, N Lanquaye-Opoku, H. Modzelewski, Y. Shen, R. Stull, P. Jackson, B. Murphy, J.-C. Ruel, "Comparison of wind speeds obtained using numerical weather prediction models and topographic exposure indices for predicting windthrow in mountainous terrain", *Forest Ecology and Management*, **254 -2** (2008)193-204
[5] E.Berge, F. Nyhammer, L. Tallhaug, Ø Jacobsen, "An evaluation of the WAsP model at a coastal mountainous site in Norway", *Wind Energy*, **9 /1-2** (2006), pp. 131-140.
[6]. S.J Reid &R. Turner, "Correlation of real and model wind speeds in different terrains", *Weather and Forecasting*, **16 -5** (2001) 620-627.

[7].R.T Nishiyama, A.J Bedard Jr., A.L. Kirschner, "Strong winds over mountains and infrasound: Possible applications for detecting regions related to aircraft turbulence reports", *International Geoscience and Remote Sensing Symposium (IGARSS)*, **2** (2002) 879-881.
[8]. H. Imamura, T. Tsumanuma, J. Kurokawa, H. Katsuchi, "Study on the wind measurements and performance evaluation of a WTGS in complex terrain (3rd report, influence of escarpment shapes)",

Nippon Kikai Gakkai Ronbunshu, *B Hen/Transactions of the Japan Society of Mechanical Engineers, Part B*, 70 -693 (2004) 1230-1236.
[9] C.G Li, Z.Q Chen, Z.T Zhang, J.C.K Cheung, "Wind tunnel modeling of flow over mountainous valley terrain", *Wind and Structures, An International Journal*, **13 -3** (2010) 275-292.
[10] J.-A Hertig, "Wind tunnel measurement of velocity profiles in complex terrain. Case of alpine regions", *Journal of Wind Engineering and Industrial Aerodynamic*, **28 /1-3** (1988) 105-115.
[11] A.Maurizi, J.M.L.M Palma, F.A Castro, "Numerical simulation of the atmospheric flow in a mountainous region of the North of Portugal", *Journal of Wind Engineering and Industrial Aerodynamics*, **74-76** (1998) 219-228.
[12] JC. Barnard, "An evaluation of three models designed for siting wind turbines in areas of complex terrain", *Sol Energy*, **46/5** (1991) 283–94.
[13] DA Bechrakis, JP Deane, EJ. McKeogh , "Wind resource assessment of an area using short term data correlated to a long term data set", *Sol Energy*, **76/6** (2006)725–32.
[14] W.D Lubitz, B.R White, "Wind-tunnel and field investigation of the effect of local wind direction on speed-up over hills", *Journal of Wind Engineering and Industrial Aerodynamics*, **95/8** (2007), 639-661.
[15] C.C.Pellegrini, G.C.R Bodstein, "The height of maximum speed-up in the Atmospheric boundary layer flow over low hills", *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, **26 /3 (**2004), 249-259.
[16] D.R Lemelin, D. Surry, A.G. Davenport, "Simple approximations for wind speed-up over hills", *Journal of Wind Engineering and Industrial Aerodynamics*, **28 /1-3** (1988) 117-127.
[17] C.A.Miller, A.G. Davenport, "Guidelines for the calculation of wind speed-ups in complex terrain", *Journal of Wind Engineering and Industrial Aerodynamics*, **74-76** (1998)189-197.
[18] WindRose – "A wind data analysis tool, User's Guide", *Centre for Renewable Energy Sources*, (2010), Available online: http://www.windrose.gr
[19] NG. Mortensen, L.Landsberg , I.Troen, El.Petersen, "Wind atlas analysis and application program (WAsP)", Roskilde, Denmark: Risø Nat. Labs; (1993) 126.
[20] Special Framework for Spatial Planning of Renewable Energy, Ministry of Environment, Energy and Climate Change, (2008), Available: http://www.minenv.gr/4/42/00/KYA.APE.January.2008.pdf
[21] Law 3851/2010, "Accelerating the development of Renewable Energy Sources to deal with climate change and other regulations addressing issues under the authority of the Ministry of Environment, Energy and Climate Change", Ministry of Environment, Energy and Climate Change, 2010, Available from: http://www.ypeka.gr/LinkClick.aspx?fileticket=qtiW90JJLYs%3D&tabid=37
[22] Centre for Renewable Energy Sources and Saving (CRES), Viotia prefecture wind map, Available from: http://www.cres.gr/kape/images/maps/img_pre2.htm