Influence of topographic maps on Energy Production Assessments

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The accuracy of Energy Production Assessments (EPA) strongly depends on the input data. With this paper we focus on how the topographic maps can affect WAsP predictions. Wind energy is quickly developing in countries without full map coverage or the desired map resolution. It will be shown that the use of accurate maps can prevent large errors on the results. Despite the recognised importance of the map quality, few studies on the subject can be found in the literature and they typically focus on a limited amount of sites only.

The sites are grouped in three classes: flat terrain, complex terrain without forestry and complex with forestry. Final EPAs in Italy are based on regional CTR or IGM maps and are considered the reference scenarios ("reference maps") for the investigation, whilst the results obtained with low-resolution satellite maps deviate from the reference. The wind speed frequency distributions which are used for the investigation range from strongly unidirectional to those without any prevailing wind directions.

Reference maps have been clipped within a larger area covered by satellite maps. In many cases the wind speeds are shown to change only if e.g. the SRTM satellite maps are closer than four kilometres from the proposed wind farm in all directions, but the result is also strongly correlated to the complexity of the terrain. The wind speed differences are low, albeit not negligible, provided that a reference map is used at the turbine and mast locations.

INTRODUCTION

Albeit the best practice approach in energy production assessments involves detailed inputs to be utilised, it is acknowledged that high resolution topographical data suitable for wind energy applications are not readily available in all countries. Therefore low resolution satellite based digital height contour maps can be a valuable alternative as these data are freely available and cover almost 80 % of the total Earth landmass. However, their use for wind flow modelling may represent a source of error in any energy production assessment especially on complex and mountainous terrain.

In the present work, we have investigated the effects of low resolution satellite maps in terms of bias and statistical scatter introduced into the predicted wind speeds. A number of Italian wind farm sites in simple terrain, complex terrain without forestry and complex terrain with forestry has been selected to perform the study based on both high resolution and satellite based low resolution height contour maps.

INPUT DATA

The topographical data available for the investigations were either 1:25,000 maps from the Italian military institution IGM (Istituto Geografico Militare) or higher resolution CTR (Carta Tecnica Regionale) maps which are typically 1:10,000 or 1:5,000 from local authorities. According to best practice methodology, these maps extend for approximately 10 km from the wind farm layout. For confidentiality reasons, the locations of the sites will not be disclosed.

IGM topographical data are available either as digital height contour maps with contour lines every 25 m and higher resolution lines when required to characterize the terrain features or as Digital Terrain Model (DTM) with a horizontal grid resolution of 20 m. CTR map resolution differs in each Region of Italy depending on the local regulation; these topographical data are usually available as digital height contour maps with contour lines every 10 m up to 5 m. These datasets are the reference topographical inputs in the investigation and they represent the necessary requirement for performing final and bankable energy production assessments of wind farms in Italy.

Publicly available digital terrain and elevation models include maps derived from satellite data; the most common source of such data is the National Aeronautics and Space Administration (NASA) Shuttle Radar Topographic Mission (SRTM) which was flown on board the Space Shuttle Endeavour in February 2000 to obtain a near-global elevation dataset. The mission covered 80 % of the total Earth landmass between the latitudes 60° North and 56° South. The technology was based on the Interferometric Synthetic Aperture Radar (InSAR), i.e. a measurement technique based on the principle of interferometry [1] [2]. It can be expected [3] that the InSAR signal is reflected with various scatters associated with leaves, branches and stems. As a result, the surface height detected by the InSAR instruments in presence of vegetation is higher than the actual terrain elevation, with a gap mainly depending on the height and density of the vegetation. Following the mission, the SRTM dataset was processed by the NASA Jet Propulsion Laboratory (JPL) and made available to the public with a horizontal spacing of 3 arc seconds, corresponding to approximately 90 m of east-west resolution and approximately 70 m north-south resolution. Higher resolution grid data are instead available for the United States. For the purpose of this work, we have used the Global Mapper Software [4] to generate at each site a digital height contour map featuring contour lines every 10 m from the downloaded SRTM based datasets. By this method, we have obtained for each site a map based on satellite data with the same extension and limits of the corresponding reference map. For this study, version 4 of the SRTM based datasets has been used.

We aim to validate the study for a generic wind farm site, which may include open and forested areas for turbines as well as for masts. In addition, steep slopes are a common feature of all complex sites. Therefore the wind speeds values obtained for random locations within the maps are not selected accordingly to steep slopes or terrain topography features, but instead they remain within an appropriate distance form the mast. Examples of topographical maps for flat and complex terrain respectively are shown in Figure 1. As part of this work, 29 different wind farm sites in Italy have been identified and grouped into three categories:

- simple sites, as from the definition of the IEC [5]
- complex sites without forestry
- complex sites with forestry

Complex sites with forestry are mainly characterised by scattered patches of trees rather than by a dense canopy over the entire territory. An example is shown in Figure 2.

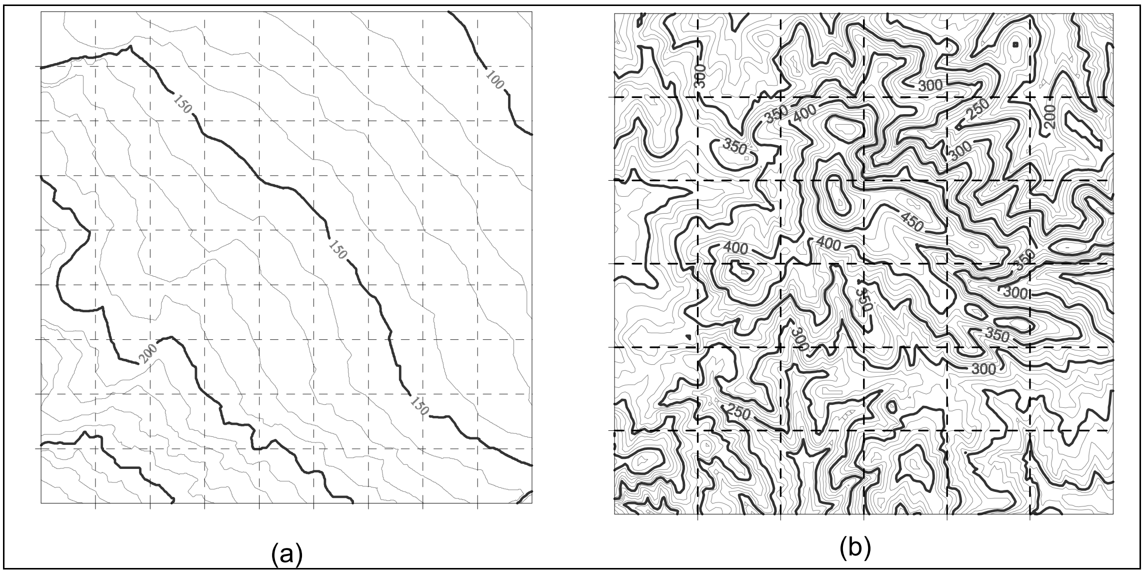

Figure 1: **Sample height contour map of simple (a) and complex (b) terrain with 10 m contour lines. Each grid interval corresponds to 1 km.**

Following this classification, 8 sites have been considered as simple, 12 as complex without forestry and 9 as complex with forestry, as it is summarised in Table 1. A total of 417 turbine locations have been identified. All locations have been investigated considering both a mono-directional and a multi-directional wind speed and direction frequency distributions, reported in Figure 3 at 80 m height, which can be considered representative of modern installations. No appreciable differences between the results have been observed, therefore suggesting that the actual shape of the wind rose has no influence. As a result, a total of 834 turbine locations have been included in the investigations as reported in Table 1.

Terrain Type	Number of sites	Number of turbine locations
Simple	8	124
Complex without forestry	12	169
Complex with forestry	9	124
	29	**417**

Table 1: **Classification of the sites**

Figure 2: **Example of site with forestry**

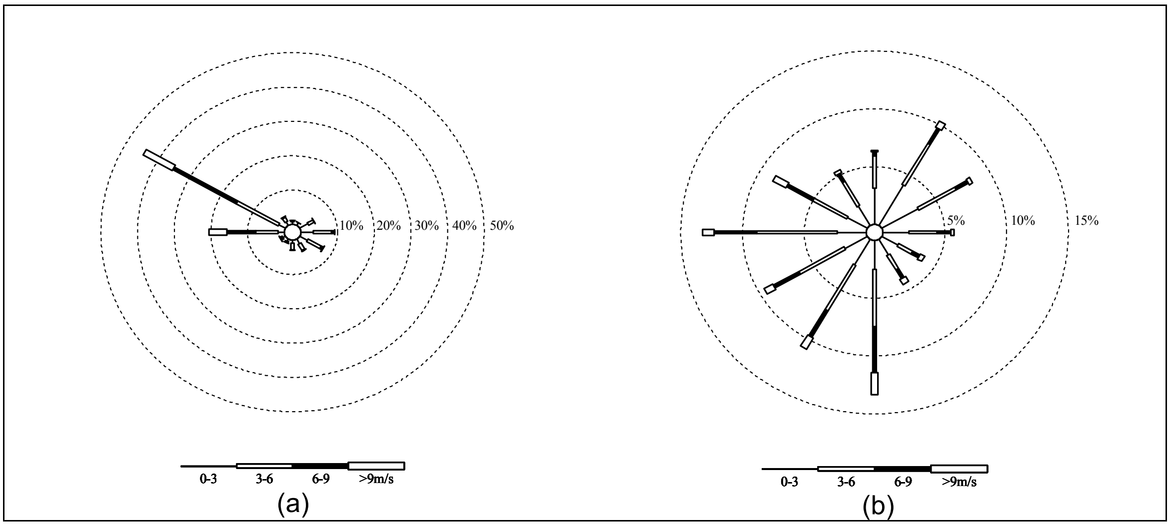

Figure 3: Wind speed and direction frequency distributions used in the calculations

The absolute site elevations range from sea level to approximately 1,500 m altitude, whilst the turbine locations are from 165 m below up to 154 m above the mast to include turbines with better and worse exposure. As regarding the distance from the mast, 78 % of the considered turbine locations are within 2 km from the mast, while 90 % are within 4 km. No roughness values have been included in order to investigate the effects of the forestry on the topography of the satellite based maps.

METHODOLOGY

The wind flow model used for the calculations is the Wind Atlas Analysis and Application Program (WAsP) [6], which implements the so-called BZ flow model [7]. The wind flow model has been initiated from a single mast (initiation mast) which is considered sufficiently representative of the turbine locations for a final energy assessment to be performed [8]. It is noted that the accuracy of WAsP in complex terrain, which has been the subject of several studies in the past [9] [10], is not considered in this work. For this purpose, the wind flow model simulations were performed at each site with both the reference and the SRTM based digital height contour maps as input topographical data, by inserting the almost mono-directional and the multi-directional wind speed and direction frequency distributions.

We have also investigated the effect of clipping the reference map and using it in combination with SRTM data on 9 sites (2 in simple terrain, 3 in complex terrain without forestry and 4 in complex terrain with forestry). The reference maps have been increasingly cropped and the removed area replaced by SRTM maps.

RESULTS AND DISCUSSION

The results are presented as the ratios of the wind speeds at the turbine locations calculated with the SRTM maps over the wind speeds calculated with the reference maps. These are referred to as ratios R. In order to ensure that each bin has a significant number of observations, we have used a 0.01 binning step for the discrete probability and cumulative distributions.

The results are presented in Figures 4, 5 and 6. The mean and standard deviations derived for the ratios R in each of the three cases of simple terrain, complex terrain without forestry and complex terrain with forestry are shown in Table 2.

Terrain Type	Mean of wind speed ratio	Standard Deviation of wind speed ratio
Simple	1.000	0.006
Complex without forestry	1.008	0.015
Complex with forestry	0.995	0.014

Table 2: Mean and standard deviations of the distributions

The normal function has been considered for fitting the discrete distributions based on the values reported in Table 2, which are based on the actual observations. In Figure 7 the frequency distributions obtained in simple terrain, complex terrain and complex terrain with forestry are plotted together for comparison.

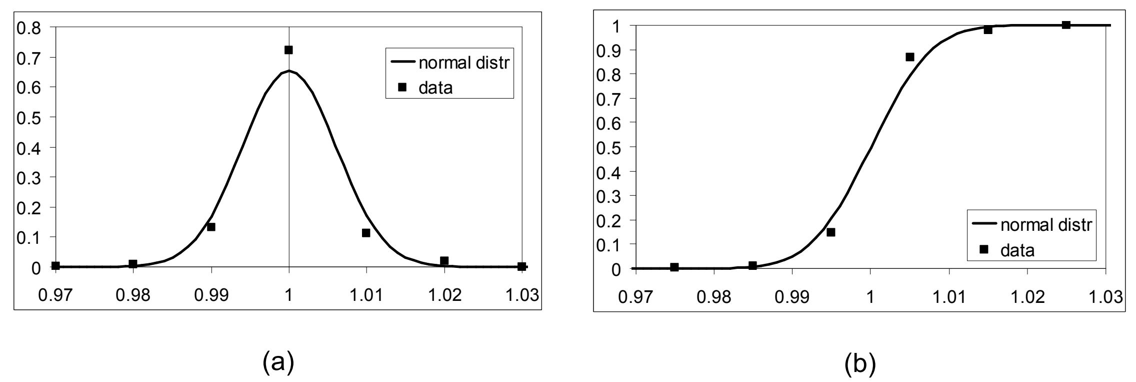

Figure 4: PDF (a) and CDF (b) of the ratios R in simple terrain

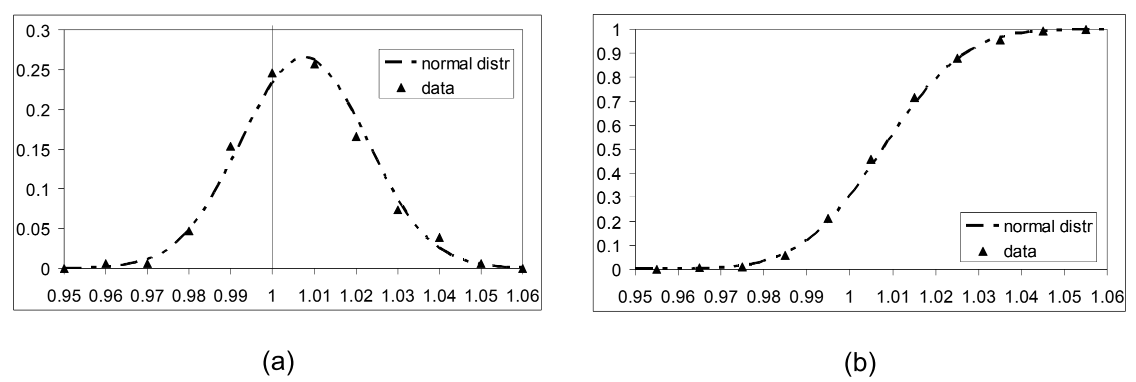

Figure 5: PDF (a) and CDF (b) of the ratios R in complex terrain without forestry

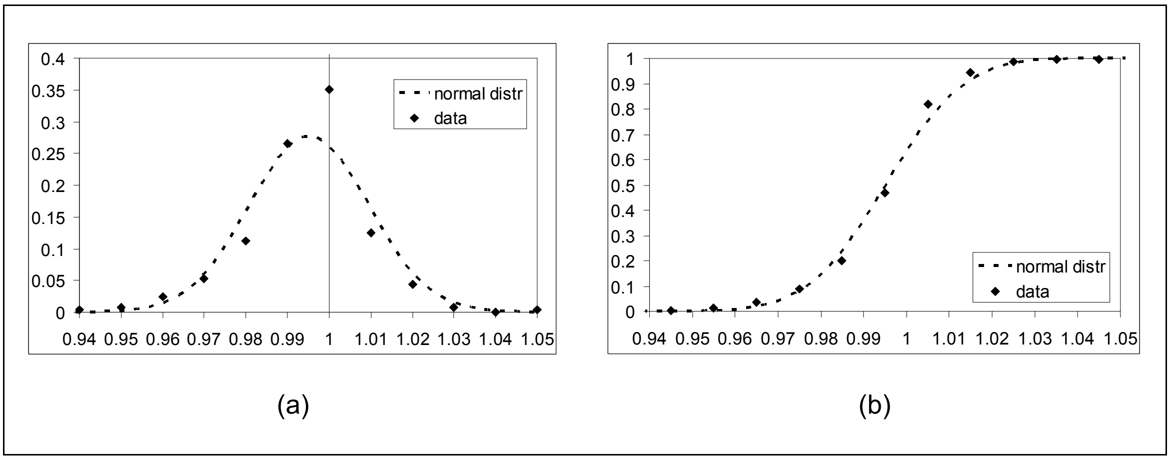

Figure 6: **PDF (a) and CDF (b) of the ratios R in complex terrain with forestry**

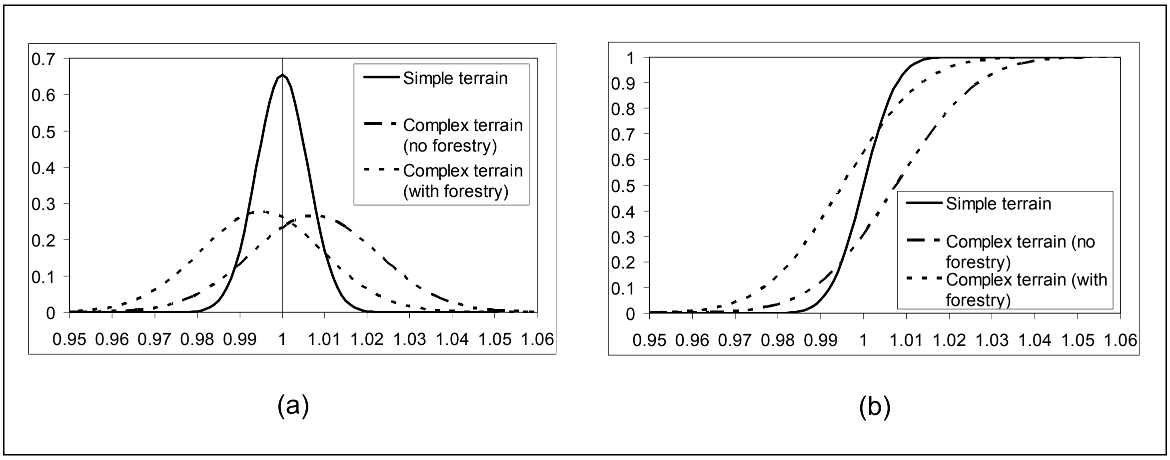

Figure 7: **Comparison of the PDF (a) and CDF (b) of the ratios R in simple terrain, complex terrain and complex terrain with forestry**

The normal Probability Density Functions (PDF) and Cumulative Density Functions (CDF) show good agreement with the discrete distributions. However, in Figures 4 and 6 a relevant number of ratios R equal to the unit can be observed. This result is somehow expected for the simple terrain case, where the terrain feature variations are relatively small and therefore the influence of different map sources have a limited effect on the WAsP outputs. As opposite, the high number of cases with R=1 for the complex terrains with forestry is remarkable, and in principle not anticipated. There may be different reasons for that; however no robust explanation has been identified to date. As expected, the influence of topographical input data on the wind speed predictions in simple terrain is small with a standard deviation less than 0.1 %. This deviation greatly increases at sites which feature complex terrain and can lead to significant deviations from the reference value. In this condition, the deviation obtained at complex sites with forestry is similar to that calculated at sites without forestry. However, the effect is not limited to a larger standard deviation. The results obtained suggest that wind speeds based on SRTM maps lead on average to an over-prediction of the mean wind speed at complex sites without forestry. In complex sites with forestry, on the contrary, the bias in the wind speed predictions appears to be negative, leading to an under-prediction of the mean wind speeds. It is noted that the same behaviour is obtained independently by the wind speed and direction frequency distribution or the roughness considered.

In June 2009, Version 1 of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) has been released by the Japan's Ministry of Economy, Trade and Industry (METI) in conjunction with NASA [11]. We understand that validation studies are currently being performed and at this stage the available datasets should be viewed as experimental or research grade [11]. A rough comparison of the elevations has been undertaken in this study and the results show that ASTER maps are characterized by an average lower elevation and an uncertainty significantly higher than the SRTM Version 4. For this reason the ASTER maps have not been included in the final investigations.

A further investigation involved the clipping of the maps for 9 sites with 106 turbine locations and two wind speed and direction frequency distributions. The total number of turbines is therefore 212. The outer area of the reference map has been replaced by the SRTM map at a decreasing distance from the layout border. The results are shown in Table 3.

Distance of the SRTM from the nearest turbine [km]	**0.5**	**1**	**2**	**3**	**4**	**5**	**6**
Turbines with a deviation from reference [%]	29.7	17.0	10.4	8.0	5.7	3.8	1.4
Mean absolute difference in wind speed compared to reference [%]	0.058	0.031	0.020	0.016	0.010	0.007	0.003
Maximum difference in wind speed compared to reference [%]	0.34	0.33	0.33	0.33	0.23	0.23	0.20

Table 3: **Results of the investigations on the required extension of reference maps**

If only an area extending as far as 1 km from the wind farm layout border is used, then 17 % of the wind speeds disagree with the reference; however, the difference in the predicted wind speed is lower than 0.33 %. As expected, when using reference maps with a larger extension, the percentage of deviation decreases. If the mean absolute difference is based only on the turbines which show a deviation from the reference, the value is approximately 0.2 % for all cases. It is noted that the 1.4 % of turbines which differ from the reference for a clipping at 6 km from the layout maintains the same value also for smaller clippings until the full reference map is restored.

CONCLUDING REMARKS

Based on the results, standard deviations of 0.6 %, 1.5 % and 1.4 % are obtained in simple terrain, complex terrain without forestry and complex terrain with forestry respectively. In complex terrain, the results suggest that SRTM based maps tend to introduce some bias into the wind speed predictions. These results are based on the principle that the mast location is representative of the turbine locations in terms of elevation and exposure. Where this “similarity principle” is not met, significantly different values have been obtained.

The results of the investigations on the clipping of the reference map suggest that acceptable levels of accuracy are achieved with a relatively limited extension of the high resolution map.

The statistical significance of the results must be increased by including additional sites in the analysis.

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