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SOLUTIONS FOR WIND RESOURCE ESTIMATION ON DIFFERENT TERRAIN MODELS

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Abstract: *It is known that the growing need for energy has consequences that constitute major demands on the environmental conditions when the classical methods of obtaining are used. This is why this action to develop the capacity to produce energy from renewable sources must be Wind continued, among which wind power occupies a prominent place. Resource estimation is crucial for assessing the viability of wind energy projects. The accuracy of wind resource assessments depends heavily on the terrain over which the wind flows, as different terrains (flat, hill, mountain, coastal) affect wind behaviour in distinct ways. Solutions and methods for estimating wind resources across different terrain models can be developed by computational fluid dynamics (CFD) simulations intended for complex terrains (hill, mountain areas). CFD models simulate the flow of wind over various terrain features by solving the Navier-Stokes equations. The simulations account for the complex interactions between the wind and the terrain, including turbulence, vortex formation, and speed-up effects providing high accuracy for the complex terrains, modelling the local effects such as ridges, valleys, different obstacles and providing further detailed 3D wind flow data. Using numerical analysis methods for wind resource estimation over terrain is feasible, especially for preliminary analysis. It is performed meaningful analyses by processing and visualizing terrain preliminary data, being able to generate further wind profiles using empirical models, applying simple numerical methods in order to estimate wind flow over terrain, permitting the results visualization to gain insights into wind speed distribution and potential energy yield. The method for wind resource estimation depends heavily on the terrain complexity, the scale of the project, the available budget and the required accuracy. A numerical approach is presented in this paper necessary for analyzing the wind resource potential, involving a combination of mathematical models with advanced simulations in order to establish solutions function of terrain complexity type. Starting from specific wind velocity and roughness characteristic values for each terrain type, which can have impact on wind flow, by means of a numerical analysis method the mean wind velocity profile for different heights and terrain types is highlighted. The modelling method used is represented by the logarithmic wind profile method which uses the mathematical model to estimate the wind velocity values at different heights above the ground. This approach provides good estimation results for wind velocity profile over various terrain types.*

Keywords: *Wind resource, air pressure, energy production, terrain model, numerical analysis*

1. Introduction

Wind resource estimation on different terrains represents a critical aspect of planning and optimizing wind energy projects. The availability and characteristics of wind resources can vary significantly depending on the topography and surface features of a specific location.
Terrain influences wind patterns through factors such as elevation changes, surface roughness, and the presence of obstacles like forests or buildings, which affect wind speed, direction, and turbulence levels.
Flat terrain typically allows for more predictable and uniform wind flow, making it easier to estimate wind resources. However, complex terrains, such as mountainous areas, coastal regions, or urban environments, present additional challenges due to the variability in wind speed caused by topographical features. Wind speeds may accelerate over ridges, decelerate in valleys, and experience significant turbulence near abrupt changes in elevation. Similarly, coastal areas exhibit unique wind behaviours due to the interaction between land and sea, while forested and urban terrains introduce roughness elements that disrupt the wind flow.
Accurate wind resource estimation is essential for identifying suitable locations for wind farms, optimizing turbine placement and ensuring efficient energy production. The process involves a

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combination of meteorological data collection, computational modelling and the use of specialized software to simulate wind flow across different terrains. Understanding how various terrains influence wind patterns is a key in reducing uncertainty of wind assessments and maximizing the potential of wind energy as a sustainable power source.

2. Wind resource estimation across various terrain models

Estimating wind resources accurately across different terrain models is crucial for optimizing wind energy projects. The complexity of the terrain significantly influences wind flow patterns, requiring tailored approaches and methodologies.

Table 1: The main characteristics of terrain types

Crt. No.	Terrain type	Characteristics	Average wind velocity up to 100 m altitude (m/s)
1.	Flat	Plains - homogeneously gentle terrains	12.5
2.	Complex Terrain	Hills, Valleys, and Ridges	16
3.	Coastal Areas	Sea coast-Sand open space	13
4.	Forested Areas	Forest roughness	18
5.	Urban or Built-Up Areas	Flow separation, turbulence, wind channelling	19
6.	Mountainous Regions	High altitude, steep slopes, temperature gradients	21

For flat terrain the wind flow is generally uniform with fewer disturbances.
Complex terrain can significantly alter wind flow due to topographical features causing speed-ups, turbulence and flow separations.
Coastal terrains pose unique challenges due to land-sea interactions, which create complex wind patterns.
In case of forests significant roughness are created, altering wind speed and turbulence.
Wind estimation in urban environments is complicated by the presence of buildings, which cause flow separation, turbulence, and wind channelling.
Mountainous terrains experience complex wind behaviour due to high altitude, steep slopes, and temperature gradients.
Wind estimation models include some atmospheric stability corrections, as thermal stratification which can significantly affect wind flow, especially in mountainous and coastal areas.
All the specific methods used to establish a wind model help to reduce uncertainties in wind resource assessments, leading to more accurate estimations and better-informed decisions for wind energy projects [1-7].

3. Mathematical model for wind flow potential on different terrain types

In order to establish a start point for modelling the wind flow action the fluid dynamics momentum equation is considered, in a simplified form where the wind action is affected by some factors like pressure gradients, terrain roughness, Coriolis force, or turbulence, that can be modified in accord with the terrain type:

$$\frac{\partial u}{\partial t}+\left(u\cdot\nabla\right)\cdot u=-\frac{1}{\rho}\cdot\nabla p+\nu\cdot\nabla^{2}u+F_{C}+F_{r} \tag{1}$$

For flat terrain the wind velocity profile can be generated as a function of height *(z)* at which is considered the *u(z)* velocity and a constant *(k)* as Karman constant (0.4), using a logarithmic wind profile:

$$u(z)=\frac{u_n}{k}\ln\left(\frac{z}{z_0}\right) \tag{2}$$

For complex terrains, hills, valleys and ridges the wind flow rate is significantly affected from the initial uniform pattern due to topography influence:

$$u(z)=u_f(z)\cdot c_t \tag{3}$$

where:

$u(z)$ -wind velocity at height z;

$u_f(z)$ -wind velocity for flat terrain;

c_t - terrain factor dependent on topographic features.

For complex terrains, the Navier-Stokes equations are able to provide an accurate solution by using specific CFD models. This approach considers the non-linear effects from turbulence, flow separation and surface roughness:

$$\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\nu\frac{\partial^2 u_i}{\partial x_j^2}+F_i \tag{4}$$

where:

u_i -velocity components;

x_i -spatial coordinates;

F_i -external forces.

In order to model the wind resources across larger regions with complex terrain features (coastal areas or mountain ranges), meso-scale atmospheric models are used that simulate large-scale wind patterns, while micro-scale models (CFD or linear models) refine the estimates at the local scale. The approach involves for meso-scale the modelling and solving the governing equations for atmospheric flow in order to capture regional wind patterns and meteorological phenomena. Further, for micro-scale modelling the local terrain features, roughness, and obstacles are considered to refine wind velocity predictions [8-10].

If the terrain contains gentle slopes or hills, the velocity can be approximated using simplified models, as an approach is represented by Jackson and Hunt's linear velocity model, which estimates the increase in wind velocity:

$$\Delta u=u_0\cdot\frac{h}{L} \tag{5}$$

where:

u_0 -undisturbed wind velocity;

h - hill height;

L - hill characteristic length scale.

Regarding the turbulences an important parameter is represented by the turbulence intensity on complex terrain models especially being modelled based on wind velocity standard deviation *(*σ_u*)*, and mean wind velocity *(*u*)* as follows:

$$I = \frac{\sigma_u}{u} \tag{6}$$

4. Numerical approach analysis for wind resource potential on different terrain types

Numerical approach to analyze wind resource potential involves the combination of mathematical models with advanced simulations to account for terrain complexity.
Based on the gathered wind velocity values and direction data from meteorological stations combined with collected terrain data, such as elevation, land use and roughness characteristics, which influence wind flow, using a numerical analysis method is computed the mean wind velocity profile for different heights and terrain types.
The main modelling method used is represented by the logarithmic wind profile method which uses the mathematical model to estimate the wind velocity values at different heights above the ground. This approach provides good estimation results for wind velocity profile over various terrain types. However, this method does not account for complex interactions, such as turbulence and localized effects due to topography [11-13]. Considering the principal terrain types parameters shown in table 2 and based on a different roughness heights characteristic for each terrain type according with their proper surface parameters (case 1 and case2), the wind velocity profile is calculated using the logarithmic wind profile method for each terrain type.
The results are presented in figure 1 and 2, showing the wind velocities for the considered terrain types according the two cases configurations regarding the roughness values.

Table 2: Terrain types parameters for analysis

Crt. No.	**Terrain type**	**Average wind velocity up to 100 m altitude (m/s)**	**Roughness values (m)**	
			Case 1	Case 2
1.	Flat	12.5	0.01	0.02
2.	Complex Terrain	16	0.5	0.6
3.	Coastal Areas	13	0.05	0.06
4.	Forested Areas	18	0.3	0.4
5.	Urban or Built-Up Areas	19	1.5	1.6
6.	Mountainous Regions	21	1.8	2

Based on the obtained results it can be observed that for the flat terrain where the low roughness values are encountered higher wind velocity values are registered near the ground and further this model is adopted also for the coastal areas. For the complex terrain type the roughness value is moderate due to the uneven surface distribution with higher velocity values, the forest areas present a higher roughness because of the trees presence and also an ascendant velocity trend especially beyond a height limit and finally the higher values registered by the urban and mountainous areas due to the high roughness from buildings and rocky mountain surfaces.

Updating the roughness values for each terrain type the obtained results are presented as modification in wind velocity profile with a low increase in the inferior height, but with considerable increase at higher altitude (100 m).

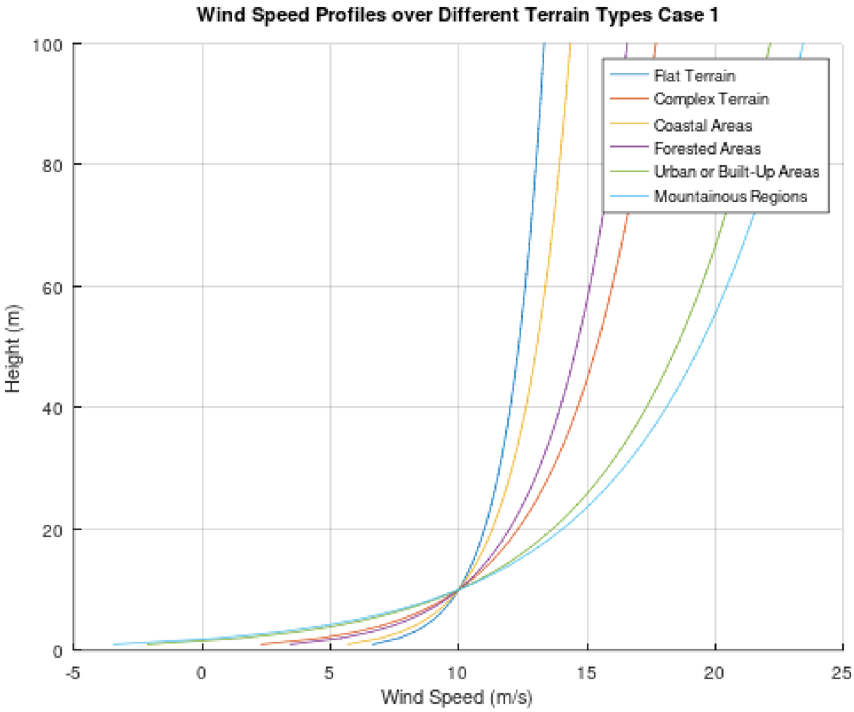


Fig. 1. Wind velocity profile on different terrain types (case 1)

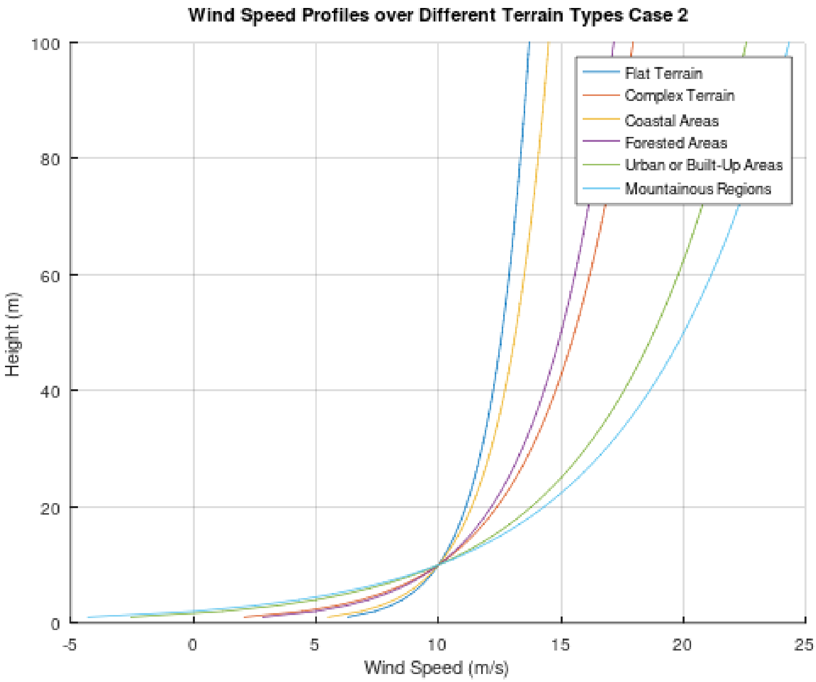
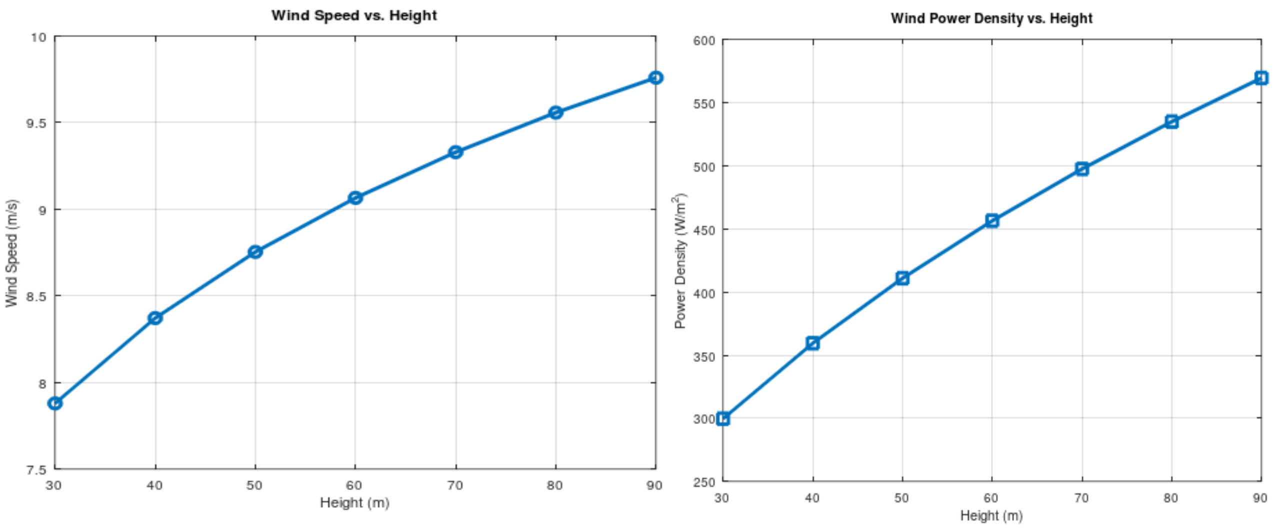


Fig. 2. Wind velocity profile on different terrain types (Case 2)

Based on the obtained results, it is possible to go further to establish the specific wind potential according to the height for the different land types. Considering that horizontal axis wind turbines of low installed power have the rotor positioned at heights between 90-120 m and even lower power vertical axis turbines that are used for residential applications have heights of up to 30 m, an analysis on the potential of wind action is carried out with emphasis on wind velocity function of height and further wind power density function on height values. The obtained results are presented in figure 3.



a) Wind velocity function of height values b) Wind power density function on height

Fig. 3. Wind power density and velocity profile on different heights

5. Conclusions

Wind potential varies significantly across different terrain models due to the influence of terrain features on wind speed, turbulence, and flow patterns. Understanding these variations is crucial for accurately assessing wind resources and optimizing wind energy projects. Here are some key conclusions regarding wind potential across various terrain types:
On flat, homogeneous terrain, wind flow is relatively uniform and the logarithmic wind profile method provides a good estimation of wind velocity distribution with height.
Wind potential is generally lower at ground level but increases predictably with height, so flat terrain is suitable for wind turbine installations, especially with taller towers to access the higher wind velocities.
In hilly areas, the topography causes wind speed-up on the windward side of hills and slow-down on the leeward side. The wind potential can be significantly higher in certain locations, like hilltops or ridge lines, compared to valleys.
Mountainous regions experience complex wind patterns with strong turbulence, flow separation, and localized wind accelerations due to steep slopes and valleys, while the potential can be high due to strong wind speed-ups in certain areas, but the variability and turbulence pose challenges for turbine installations and structural integrity.
Coastal terrains often experience steady, strong winds due to the lack of obstacles and proximity to open water. Sea breezes and topographic effects near cliffs or dunes can influence local wind patterns. The coastal regions typically have high wind potential, making them ideal for both onshore and offshore wind farms. The smoother terrain results in lower turbulence levels compared to inland mountainous areas.
Urban areas have high surface roughness due to buildings and other structures, leading to increased turbulence and variability in wind patterns. While wind speeds are generally lower at ground level, tall structures like skyscrapers can access higher winds.
Higher Roughness Length (forests, urban areas) leads to greater wind speed reduction near the surface and higher turbulence.

Lower Roughness Length (open plains, coastal areas) allows reaching higher wind velocities closer to the ground, improving wind turbine efficiency and reducing structural requirements.
The wind potential on different terrain models is shaped by a combination of factors such as surface roughness, topography and local climate conditions. While flat and coastal terrains provide more predictable wind profiles, hilly and mountainous areas can offer higher but more variable wind potential. Accurate wind resource assessment, using a combination of modelling techniques (logarithmic profiles, CFD, meso-scale/micro-scale coupling), is essential for optimizing turbine placement and maximizing energy yield across various terrains.

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