Graphical interface for wind resource estimation in a region, case study: Cuatrocienegas, Coahuila de Zaragoza

Interfaz gráfica para la estimación del recurso eólico en una región, caso de estudio: Cuatrocienegas, Coahuila de Zaragoza

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Abstract

Mexico has an estimated wind potential of 70 GW, however, until 2022 only 7.3 GW were used. This is due, among other factors, to the lack of analysis of the wind resource in many of the country's regions, especially in those where the wind potential is not obvious. With the aim of promoting wind power throughout the country, a free application has been developed that analyzes the resource in detail in any region using the annual records of its wind speed and direction. To demonstrate its functionality, data from the year 2022 from Cuatrocienegas, Coahuila de Zaragoza were used, obtaining the average energy density per hour (MED) using two analytical methods and the Weibull probability distribution function (WPDF). The instantaneous power curve, the histogram of the occurrence of the wind and the wind rose that shows the predominant direction of the wind and its trend of change were also presented. In conclusion, the developed application provides the necessary information to evaluate the technical feasibility of installing horizontal axis wind turbines in the analyzed region.

Wind resource, WPFD, MED

Resumen

México tiene un potencial eólico estimado de 70 GW, sin embargo, hasta el año 2022 solo se aprovechaban 7.3 GW. Esto se debe entre otros factores, a la falta de análisis del recurso eólico en muchas de las regiones del país, especialmente en aquellas donde el potencial eólico no es evidente. Con el objetivo de impulsar el aprovechamiento eólico en todo el país, se ha desarrollado una aplicación gratuita que analiza detalladamente el recurso en cualquier región utilizando los registros anuales de su velocidad y dirección del viento. Para demostrar su funcionalidad, se utilizaron datos del año 2022 de Cuatrocienegas, Coahuila de Zaragoza, obteniendo la densidad de energía media por hora (DEM) mediante dos métodos analíticos y la función de distribución de probabilidad de Weibull (FDPW). También se presentaron la curva de potencia instantánea, el histograma de la ocurrencia del viento y la rosa de los vientos que muestra la dirección predominante del viento y su tendencia de cambio. En conclusión, la aplicación desarrollada proporciona la información necesaria para evaluar la factibilidad técnica de instalar aerogeneradores de eje horizontal en la región analizada.

Recurso eólico, FDPW, DEM

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I. Introduction

Electricity generation is the second largest human activity producing CO_2, SOx, NOx, CO, PM10 and PM2.5 in Mexico (SyD, 2019). Specifically, in 2019, electricity generation accounted for 17% of total CO_2 emissions in Mexico (Evalua, 2022). For this reason, this industry is one of the human activities that alter the greenhouse effect causing global warming (International Energy Agency, 2016a; IEA, 2016b; IEA, 2016c; REN21, 2016; IEAd, 2016). Although current electricity systems globally have been able to meet energy demand for the past 70 years, demand is soon expected to outstrip energy production (Farhangi, 2010).

In 2022, 73.9% of electricity production in Mexico will be from fossil fuel-based power plants. Combined cycle, conventional thermal, turbogas and coal-fired power plants accounted for 58.1%, 6.3%, 4.6% and 4.3% of this percentage, respectively. While the use of renewable energies such as hydro, wind, solar, nuclear, geothermal and biomass was limited to 10.7%, 6.1%, 4.9%, 3.2%, 1.3% and 0.03%, respectively (CIPP, 2023).

Since 2014, the distribution between the use of renewables and oil derivatives had not changed significantly. To address this problem, Mexico undertook a series of energy, political, economic and social reforms with the aim of enabling the significant introduction of renewable energy power generation systems (Cancino et al., 2011).

These reforms were cancelled, however, Mexico will comply with the commitments agreed in the 2015 Paris Convention, generating 35% of electricity from renewable energy by 2030 (Lopez, 2022).

In Mexico, electricity generation from renewable energy is mostly supported by hydropower and wind energy (CIPP, 2023; Murthy & Rahi, 2017).

Wind energy in Mexico is abundant, has a high energy density, its exploitation is viable and it is widely distributed in the territory, which makes it one of the best alternatives for electricity production (Pérez-Denicia *et al.*, 2017).

However, until 2021, only 7312 MW of the total wind potential, which has been estimated at around 70 GW (MEP, 2023), was being exploited in Mexico. By May 2022, only 15 of the 32 Mexican states will have partially harnessed their wind resources. The installed capacity in Oaxaca (2758 MW), Tamaulipas (1725 MW) and Nuevo León (793 MW) stands out, accounting for 72% of the total in the country (AMDEE, 2023). While states such as Yucatán, Veracruz and Coahuila de Zaragoza, which also have a substantial wind resource, do not have the same level of development (NREL, 2022).

This problem is due, among other factors, to the lack of wind resource characterisation in many of the country's regions. Efforts for the detailed analysis of the wind resource in the country have focused on areas with obvious wind potential that allow the installation of high-power horizontal axis wind turbines. This has led to a lag in the exploitation of the wind resource in regions with little obvious potential (NREL, 2022). In order to contribute to the exploitation of the wind resource in the whole country, and especially in those regions with a non-obvious wind potential, this article shows a final graphical interface developed for a web application that allows a detailed analysis of the wind resource in any region.

This application will require wind speed and direction data for the area of interest recorded at a height of 10 metres, every 10 minutes, for at least one year. For the development of this application, Matlab software was used for data processing (back-end), while the C# .NET programming language was used for data capture and as a graphical interface (front-end), in conjunction with the tools provided by the Microsoft Visual Studio suite. The rest of the paper is organised as follows: Section II describes the three methodologies used to calculate the DEM, as well as the process of creating the polar graph that describes the predominant wind direction in the region of interest; Section III deals with the development of the web application used to calculate and display the elements described in the previous section; Section IV presents the results obtained from the analysis of the wind resource of the region taken as a case study to evaluate the functioning of the graphical interface . The work concludes with Section V.

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II. Methodologies used for wind resource assessment in any region

The wind energy potential can be estimated from an exact empirical method or by numerical methods that approximate the parameters of interest in the region. The former involves the analysis of the terrain topography and its roughness coefficient, the local temperature and pressure and the wind speed to obtain the mechanical wind power which in conjunction with its direction will determine the wind energy potential of the wind. The second involves the use of probability density functions (PDF) such as the Weibull to estimate the wind behaviour and thus the wind potential of the region.

2.1. Mean Energy Density Extracted from the Wind Obtained through the Root of the Mean Cubic Velocity (DEM_VRMC).

2.1.1. Instantaneous power of the free air stream.

The kinetic energy in air of mass m moving with velocity V, is (Patel, 2006):

$$Ec = \frac{1}{2}\, m\, V^2 \tag{1}$$

The power available in a free air stream is the flow of kinetic energy per unit time through the cross-sectional area of the wind turbine rotor blade (Patel, 2006):

$$Pa = \frac{EC}{t} = \frac{1}{2}\frac{m}{t}\, v^2 = \frac{1}{2} M v^2 = \frac{1}{2}\rho\, A\, v^3 \tag{2}$$

where P is the instantaneous mechanical power of the moving wind (w), M is the mass flow rate (Kg/s), ρ is the air density (Kg/m^3), A=πr^2 is the area swept by the rotor blades (m^2) and v is the air speed. (m/s).

2.1.2. Instantaneous Power in the Wind Harnessed by a Wind Turbine

The instantaneous power extracted by the rotor blades is obtained from the difference between the incoming wind v and the outgoing wind. vo (Wais, 2017):

$$P = \frac{1}{2} M(v^2 - vo^2) \tag{3}$$

Macroscopically, the wind speed is discontinuous from v to vo in the plane of the rotor blades, averaging approximately (v+vo)/2, thus:

$$M = \rho\, A\left(\frac{v+vo}{2}\right) \tag{4}$$

The instantaneous mechanical power extracted by the rotor, which drives the electrical generator, is therefore:

$$P = \frac{1}{2}\rho A \frac{\left[\frac{1}{2}(v+vo)\right]}{(v^2-vo^2)^{-1}} = \frac{1}{2}\rho A v^3 \left[\frac{\left(1+\frac{vo}{v}\right)\left[1-\left(\frac{vo}{v}\right)^2\right]}{2}\right] \tag{5}$$

$$P = \frac{1}{2}\rho\, A\, V^3 Cp \tag{6}$$

where Cp is the power coefficient and represents the fraction of the incoming wind power that is extracted by the rotor blades (Wais, 2017). In this article a value for Cp of 0.4 was assumed, which is typical for commercial wind turbines (THE WIND POWER, 2023).

2.1.3. Root Mean Cubic Velocity

The monthly wind speed varies around ±30% to±35% above the average wind speed at a typical location during the year (Patel, 2006). Therefore, the wind speed used to determine the power density in (6) should be (Pishgar-Komleh *et al.*, 2014):

$$V_{rmc} = \left(\frac{1}{n}\sum_{i=1}^{n} vi^3\right)^{\frac{1}{3}} \tag{7}$$

Finally, the average energy density extracted from the wind (DEMV) will be obtained in a period that will depend on the quantity and frequency with which the measurements have been made (Patel, 2006):

$$\frac{E}{A} = \frac{1}{2}\rho\, {V_{rmc}}^3 Cp \tag{8}$$

2.2. Mean Extracted Wind Power Density from the Weibull Density Probability Density Function (DEM_FDPW)

2.2.1. Weibull PDF

The PDF indicates the probable frequency at which the specified velocity will occur in the study region. The Weibull PDF is given by (Murthy, 2017; Patel, 2006; Ozat & Celiktas, 2016; Wo *et al.*, 2011):

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^{k}} \quad (9)$$

where v is the wind speed (m/s), k>0 is the shape factor (dimensionless) and c>0 is the scale factor (m/s).

2.2.2. Weibull Cumulative Distribution Function

The cumulative distribution function is the accumulation of relative frequency of each wind speed interval, it is defined by (Murthy, 2017; Patel, 2006; Ozat & Celiktas, 2016; Wo *et al.*, 2011):

$$F(v) = \int_0^v f(v)dv = 1 - e^{-\left(\frac{v}{c}\right)^{k}} \quad (10)$$

2.2.3. Estimation of the Parameters of the Weibull PDF

There are at least 15 methods to estimate the c and k parameters of the Weibull PDF. In this paper only the four most common methods will be presented: Justus standard deviation, MDEJ (Justus *et al.*, 1977), Lysen standard deviation, MDEL (Lysen, 1983), simplified moments, MMS (Azad *et al.*, 2014), and probability weighted moments, MMPP (Usta, 2016). Table 1 summarises the equations used in each method to estimate by the parameters c and k.

	Shape Parameter (k)	Scale Parameter (c)
MDEL	$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086}$ (11)	$c = \frac{\bar{v}}{\left(0.568 + \frac{0.433}{K}\right)}$ (15)
MDEJ		$c = \frac{\bar{v}}{\Gamma\left(1+\frac{1}{k}\right)}$ (16)
MMS	$k = \left(\frac{0.9874\,\bar{v}}{\sigma}\right)^{1.0983}$ (12)	
MMPP	$k = \frac{\ln(2)}{\ln(\bar{C})}$ (13) $\bar{C} = \frac{\bar{v}}{\frac{2}{n(n-1)}\sum_{i=1}^{n} v_i(n-1)}$ (14)	

Table 1 Equations for determining the parameters of the Weibull WDF for the four methods used

2.2.4. Characteristic Wind Speed Values Using the Weibull WTPF

Knowing the Weibull parameters, the root mean cubic velocity, the mean cubic velocity, the most probable wind speed and the highest wind speed can be calculated from equations 17, 18, 19 and 20, respectively. (Justus, 1977; Akdag & Guler, 2015; Christofferson & Gilette, 1987).

$$V_{rmc} = \int_0^{Vmax} v * f(v)\, dv \quad (17)$$

$$V_{rmc}^3 = \int_0^{Vmax} v^3 * f(v)\, dv \quad (18)$$

$$V_{mp} = c\left(1 - \frac{1}{k}\right)^{\frac{1}{k}} \quad (19)$$

$$V_{max} = c\left(1 - \frac{2}{k}\right)^{\frac{1}{k}} \quad (20)$$

2.2.5. Energy Density with the Weibull PDF

Substituting equation 18 into equation 8, the following equation is obtained:

2.3. Average Extracted Power Density from Wind Obtained by Instantaneous Power

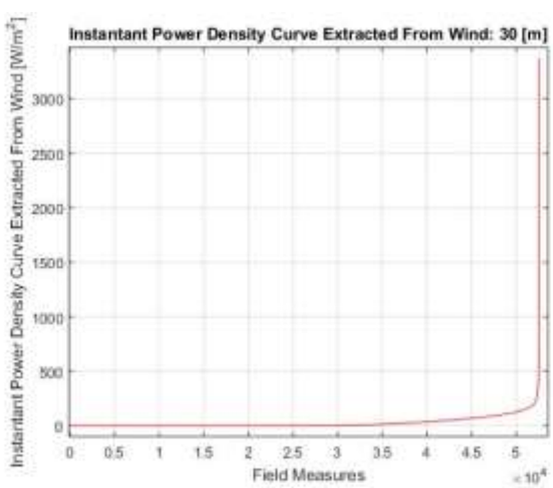
Curve Integration (DEM_IPI).

1. The instantaneous power density in the wind (IPD) is calculated from each of the 52560 wind speeds recorded by the automatic meteorological station (AMS) every 10 minutos durante al at least one year in the region of interest, as expressed in Equation 22.

$$DPI_i = \frac{1}{2}\rho\, {v_i}^3 Cp \quad (22)$$

where v_i is the ith wind speed recorded in the region.

2. The annual instantaneous power density curve for the region of interest is generated. An example of this power curve is shown in Figure 1.



Graph 1 Annual wind power density curve

3. The curve shown in graph 1 is numerically integrated with respect to time to obtain the total wind energy density for the year (DEVT):

$$DEVT = \left(\frac{1}{2}DPI_1 + \sum_{i=2}^{n-1} DPI_i + \frac{1}{2}DPI_n\right)T \quad (23)$$

4. Finally, by dividing the DEVT by the corresponding factor, the DEMV in a given period is obtained. Equation 24 determines the hourly DEVT from a sample of data recorded every minute for one year.

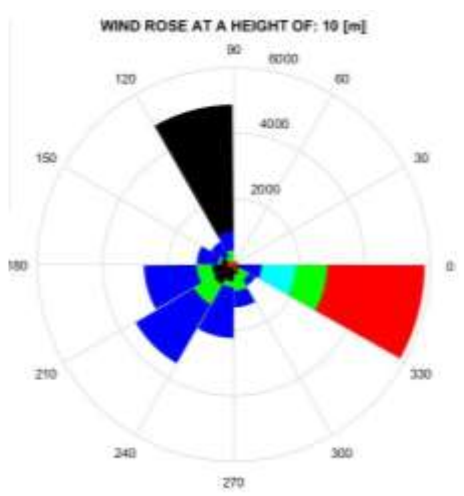
$$\frac{E}{A} = DEVT\left[\frac{W*año}{m^2}\right]\left[\frac{365\ dias}{1\ año}\right]\left[\frac{24\ h}{1\ día}\right] = \frac{DEVT}{8760}\left[\frac{w*h}{m^2}\right] \quad (24)$$

2.4. Wind Rose

It is a polar chart typically divided into 12 sectors representing ranges of wind directions.

$$\frac{E}{A} = \frac{1}{2}\rho\ Cp \int_0^{Vmax} v^3 * f(v)\ dv \quad (21)$$

Within these wind direction ranges, the annual frequency of 12 wind speed ranges is shown using colours. Sometimes, instead of frequency of occurrence, percentage of occurrence of each wind speed range is shown. An example of a wind rose is shown in figure 2.



Graph 2 Wind rose

Even if the wind in a region has a high average energy density, if the wind direction is not constant, it will not be suitable for the installation of wind turbines. This is because regions with a high turbulence rate (fluctuation in wind direction) cause wind turbines to be constantly rotating so that the swept area formed by the blades is oriented perpendicular to the wind.

III. Web Application

Web applications play a key role in the development of modern scientific applications. In this article, we explore the advantages of using a graphical interface created in C#.NET, an object-oriented programming language and development platform widely used in industry. C#.NET offers a robust development environment, design facilities and broad compatibility that make it an ideal choice for creating GUIs in scientific applications C#.NET provides in terms of performance, interoperability and access to scientific libraries, in the particular case of this article, for data analysis, C#. Net offers a library capable of interacting with the Matlab numerical calculation software. The final interface of the web application can be seen in Figure 3.

Graph 3 Developed graphical interface

The web application uses multiple methods developed in Matlab to calculate the wind DEM because it adapts to the available data that the user has for the region. The analytical methods based on the integration of the instantaneous power curve (DEM_IPI) and the mean cubic velocity (DEM_VRMC) are accurate, but require the recording of the velocities in the region every 10 minutes for a year, information that is not always available. While the methods based on the Weibull PDF are approximate numerical methods that in some cases require only a few data such as the average annual wind speed.

IV. Results

4.1. Region Analysed

The functionality of the graphical interface was tested using wind speed and direction data recorded every 10 minutes by the EMA Cuatrocienegas located in the state of Coahuila de Zaragoza (Latitude: 27.002, Longitude: -102.073) during the year 2022.

4.2. Average Wind Energy Density in Cuatrocienegas, Coahuila de Zaragoza

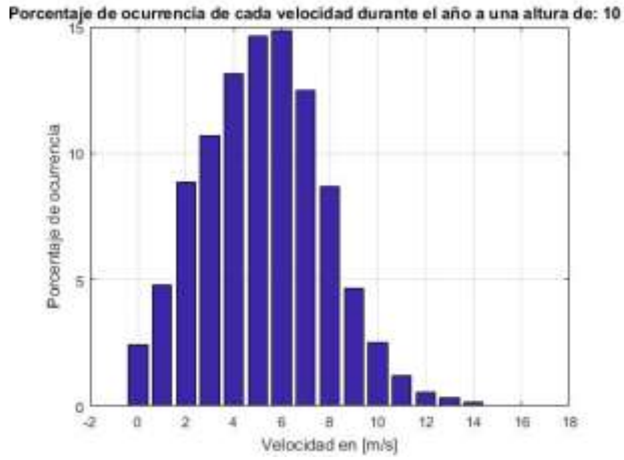
For the study region, the DEM obtained by the DEM_IPI and DEM_VRMC methods was 486.7 and 493.9 kWh, respectively. Where the DEM_IPI is considered the real value of the DEM and will be the reference to evaluate the accuracy of the other methods used in the GI. The MDEJ, MMS and MMPP methods presented an acceptable level of pressure with errors of 2.73%, 1.11% and 1.48%, respectively. On the other hand, MDEL presented an error of 57.4%. Table 2 summarises the above.

Method		Result [kWh/m^2]	Error [%]
DEM_IPI		486.7061	-
DEM_VRMC		493.8962	1.48
DEM_FDPW	MDEL	766.0859	57.4
	MDEJ	499.9966	2.73
	MMS	492.0928	1.11
	MMPP	493.8962	1.48

Table 2 Value of DEM obtained by various methods

4.3. Wind Behaviour

To determine the wind resource of a region it is not enough to determine the DEM, it is also necessary to analyse wind trends and wind direction. Graph 4 shows the percentage of occurrence of each wind speed, with speeds of 5 m/s and 6 m/s being the most frequent with 14.9% and 15% of the total recorded. From this graph it can also be deduced that the distribution of the frequency of occurrence of the speeds resembles a Gaussian bell, with most of the data concentrated in the centre of the curve and close to the value of the average speed.

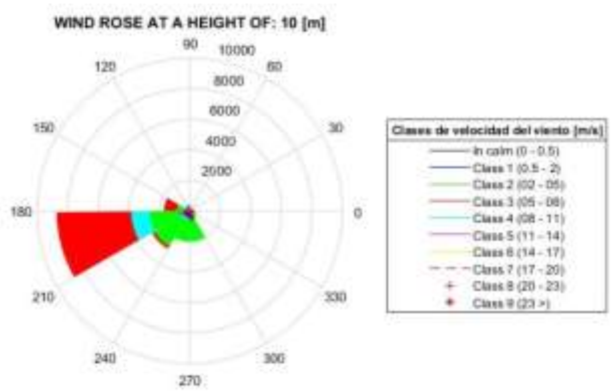


Graph 4 Percentage of annual occurrence of each wind speed

As mentioned in section 2.4, the wind rose allows to determine how stable the wind direction is throughout the year. Because even if the wind speed is high, if the wind speed is turbulent it will not be usable.

Low-power wind turbines tend to have a fixed orientation with their swept area perpendicular to the wind direction with the highest percentage of occurrence during the year. While medium and high power wind turbines, although they have a rotation system to follow the wind direction if the wind is very changeable, the wind turbine will consume much of the energy produced in this rotation making its operation deficient.

Graph 5 shows that wind speeds of 5 to 8 m/s (which have the highest frequency of occurrence) flow from the west throughout the year, as do wind speeds of 8 to 11 m/s.



Graph 5 Wind rose of the studied region

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Conclusions

According to the results obtained, it is possible to affirm that the application developed to determine the wind resource of a region of interest works correctly, offering the necessary information to determine the technical feasibility of the installation of a commercial wind turbine of any power.

The areas of opportunity to be covered are expected to add more methods for the estimation of the DEM from the Weibull FDP, the ability to extrapolate the results to different heights even without real measurements at those heights, the calculation of the instantaneous power from a specific and not approximate value for the air density, and the determination of the Weibull parameters with an acceptable accuracy when the frequency distribution of the wind speed is multimodal.

Finally, it is concluded that it is technically feasible to install a commercial wind turbine of low or medium power in the Cuatrociénegas region, whose typical start-up speed is 3 m/s.

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