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Simulation of Wind Speed Distribution Through Spreadsheets

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Abstract

A simulator was developed using a spreadsheet to model wind energy distribution, providing an accessible platform for both students and researchers. This tool aims to demonstrate the application of statistical modelling in renewable energy, using the Weibull distribution with adjustable shape and scale parameters. The simulation includes a user-friendly interface with a single spin button, enabling users to calculate probability density function (PDF) values and generate histograms to visualize the simulated PDF. The methodology involved designing an intuitive, spreadsheet-based tool that facilitates hands-on learning and modelling of wind energy systems. The results show that the simulator accurately models wind energy distribution and can be adapted to simulate other physical systems, offering flexibility for a range of research applications. This tool is especially valuable for educational purposes, providing practical experience for novice learners and enabling more advanced research for experienced researchers. The study contributes to the field by offering an accessible and effective simulation tool for wind energy modelling, enhancing the learning and research experience.

Keywords: wind speed simulation, spreadsheets, weibull distribution.

INTRODUCTION

Renewable technologies are increasingly considered clean sources of energy that contribute to sustainability, reduce adverse environmental effects, and generate minimal secondary waste (Hussain, Arif & Aslam, 2017). As global economic and societal needs evolve, optimal use of renewable energy sources like wind, solar, and hydro can mitigate the negative environmental impacts caused by fossil fuels, such as coal, oil, and natural gas. Non-renewable energy sources are associated with higher carbon emissions and financial inefficiency when compared to renewable energy alternatives (Fareed & Pata, 2022; Shrestha et al., 2022). A key driver of climate change is the overconsumption of fossil fuels, which contribute significantly to carbon dioxide emissions, with the energy sector being responsible for nearly 75% of all global CO2 emissions (Huang et al., 2023). Historically, following the Industrial Revolution, fossil fuels like coal and oil have been the primary energy sources. However, the limited potential of these resources and their environmental impact make renewable alternatives more essential for sustainable development. Renewable energy options like wind, solar, and hydropower are now actively being pursued to reduce carbon footprints and combat climate change.

Wind energy, as one of the most promising renewable sources, offers numerous applications, including powering windmills, water pumps, and boats. The growing focus on environmental sustainability has made clean energy generation increasingly important, and wind power, in particular, is becoming an attractive solution for meeting energy demands while reducing carbon emissions (Yang & Dong, 2024). Wind energy has proven to be an effective, sustainable, and economically viable energy source, and its role in meeting global energy needs continues to expand (Yang et al., 2023). Furthermore, scientific advancements in wind energy generation have led to the increased adoption of wind power, especially in offshore projects, which are contributing to diverse global energy portfolios (Nizamani et al., 2024).

In the field of wind energy research, many studies have focused on modelling and simulating wind data to predict power generation outcomes. The Weibull distribution, commonly used to model wind speed, plays a crucial role in wind power simulations (Usta, 2016; Kadhem et al., 2017; Sarkar et al., 2017). For example, a study by (Feijóo & Villanueva, 2016) used Weibull distribution to generate synthetic wind speed data for wind parks and utilized a Vector Auto-Regressive (VAR) model for cross-correlation analysis. Other simulation methods, such as those implemented in MATLAB, have been employed to assess wind energy potential at different locations, demonstrating the importance of accurate wind speed modelling for optimizing wind power generation (Zaheer et al., 2021).

While commercial simulation software such as MATLAB offers powerful tools for wind energy analysis, these packages are often costly. In contrast, MS-Excel, a widely available and affordable alternative, can be used for wind energy simulations, making it an accessible tool for both educational and practical purposes. MS-Excel's computational and statistical capabilities, along with its flexibility for automating tasks via scripting, present a unique opportunity for teaching physics and renewable energy concepts at various educational levels.

Theoretical Foundation:

The theoretical foundation of this research is based on existing literature regarding renewable energy technologies, with a focus on wind energy and its modelling through statistical and computational methods. Accurate wind speed modelling is critical for optimizing wind power generation, as it directly influences the performance and efficiency of wind turbines. Previous studies have emphasized the importance of tools like MATLAB and MS-Excel in simulating and teaching renewable energy concepts, particularly in the context of wind energy. The *Weibull distribution* is commonly used to model wind speeds due to its flexibility in representing wind conditions across different geographic areas. This distribution allows for the prediction of wind patterns, making it an essential tool for both research and practical applications in wind energy systems. Additionally, simulation techniques provide an effective way to predict power generation and enhance the understanding of renewable energy systems. This research draws on these key principles to develop an accessible simulation tool that can be used for educational purposes, offering an interactive platform for students and researchers to explore wind energy modeling.

Research Objectives:

In this study, the aim is to develop a teaching tool using a spreadsheet to simulate wind speed distributions. The Weibull distribution is employed to model wind speed characteristics, given its proven accuracy in capturing wind speed variability (Hellalbi & Bouabdallah, 2024; Patidar et al., 2022). The design strategy focuses on creating an interactive tool that enables users to simulate and visualize wind speed distributions based on empirical data. The key objectives of this study are:

1. To explore the role of MS-Excel spreadsheets in simulating wind energy data and its potential applications in educational settings.
2. To evaluate the effectiveness of MS-Excel as an affordable and accessible tool for teaching wind energy concepts in comparison to more expensive commercial software.
3. To analyze the potential of wind energy simulations for improving the

understanding of renewable energy systems among students and educators.

4. To assess the feasibility of using MS-Excel for wind energy simulations in real-world applications, including predicting wind energy generation for specific geographic locations.

Many educational institutions use software like Python, MATLAB, and MS Excel for teaching and employing simulation in teaching science disciplines, particularly mathematics and physics, and simulation is quickly becoming a necessary tool for instructors (Erol & Demir, 2024; Voda et al., 2024). Simulation typically takes the form of a simple computer program with a graphical user interface created to numerically and visually mimic the operation of a genuine physical system (Katoch, 2020). Therefore, using simulation to teach these subjects could partially replace the need for laboratories at the beginning of the course (Binek et al., 2018). Even though simulation cannot wholly replace an actual physical laboratory experiment, it still has several benefits, including the capacity to substitute for experimental kits that aren't readily available, easily accessible spreadsheet software, and discounts for multiple copies.

Spreadsheets can be employed in a variety of educational contexts (Gul & Tufail, 2024; Tufail & Gul, 2025). Compared to MATLAB, Excel is more straightforward for beginners to use and construct mathematical models. It aids teachers in developing engaging and more effective classroom demonstrations so students can quickly grasp mathematical ideas. Microsoft Excel is a program for processing large amounts of data. It is primarily helpful for accountants but also gives scientists and engineers access to a potent computational tool. With MS Office, Microsoft Excel is widely accessible and straightforward to use. Many spreadsheets can be created similarly to how they would be using pencil, paper, and a calculator once a few fundamental skills have been comprehended, but with more speed, accuracy, and flexibility (Bendre et al., 2019). Various functions in Microsoft Excel can be used for data analysis and display. The knowledge of worksheet elements, such as toolbars, the formula bar, sheet tabs, cells, and cell ranges, is the first step in understanding Excel spreadsheets.

A comparison between MATLAB and Excel is required to establish the contrasts in features, program construction, operation, and solution quality. MATLAB is a program for numerical analysis (Yang et al., 2020), whereas Excel is a kind of spreadsheet. MATLAB offers more practical and tailored tools for program creation and anticipated outcomes than Excel. As a result, MATLAB gives students a more robust computational tool to handle beam problems. Excel is the natural choice, as MATLAB is out of most students' price range due to its hefty acquisition costs. Excel is easily accessible because it is a part of the Microsoft Office suite. Excel outperforms MATLAB in terms of programming complexity. Calculation using an Excel spreadsheet is more straightforward and intuitive than MATLAB. Excel has a user-friendly design, several tools, and various functions. Although Visual Basic provides a feature for it, the user is not required to go deeply into the code. Excel provides a valuable system called a Macro that presents all computations and outcomes in a single worksheet, even without Visual Basic. Input data files and results display can be integrated into the worksheet without creating a user interface, like in MATLAB. Because each phase is independent, it is simple to identify bugs.

The logic and calculations are created, processed, and visualized during the code design phase. Additionally, GUI design is used to complement the code. It is the most well-known type of user interface (UI) due to its simplicity. The capacity of human cognition is highly associated with the ability to visualize. GUI makes use of this relationship to give users the ability to control programs via buttons and toolbars. One of the most important aspects to consider while creating a GUI is usability, which evaluates the UI's accessibility, effectiveness, and visual appeal (Rahmadi & Sudaryanto, 2020).

METHODS

Research design:

The research design follows several steps: first, conceptualizing the tool's functionality and refining its visual design. The interface is built in Excel, ensuring it is user-friendly and intuitive.

The method of moments is incorporated to compute the essential shape (k) and scale parameters (c) of the Weibull distribution, chosen for its simplicity and effectiveness in estimating these parameters. The probability density function for the Weibull distribution is defined as:

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

Where:
$v \geq 0$; and it indicates wind speed
k is the shape parameter
c is the scale parameter

The concept of the Weibull distribution is not new; it dates to 1939 when Swedish engineer Wallodi Weibull first introduced it. However, his work gained significant recognition in 1951 when he presented seven case studies to the American Society of Mechanical Engineers, demonstrating the distribution's practical applications. Initially, Weibull distribution was developed for modelling material life data and estimating failure rates in mechanical systems. Due to its flexibility in characterizing diverse patterns of behaviours, such as the variability in wind speed—it was later adopted for wind speed modelling. Its capacity to effectively represent a wide range of wind conditions, from light breezes to strong gusts, has made it particularly valuable in wind energy research and meteorological studies.

The two parameters k and c---in Weibull distribution---are frequently used to model wind speed distribution, and there is are variety of statistical tools available for their determination (Khan et al., 2015). The corresponding cumulative distribution function for the Weibull distribution is given in Eq. (2):

$$F(v) = 1 - e^{-\left(\frac{v}{c}\right)^k} \quad (2)$$

With the help of the method of moments, we compute two essential statistical measures that are the mean ($\bar{v}$) and variance (σ^2). We use these parameters to compute the shape parameter (k) with the help of the following formula, Eq. (3).

$$\left(\frac{\sigma}{\bar{v}}\right)^2 - \left[c\,\frac{\left\{\Gamma\left(1+\frac{2}{k}\right) - \left(\Gamma\left(1+\frac{1}{k}\right)\right)^2\right\}}{\Gamma\left(1+\frac{1}{k}\right)}\right]^2 = 0 \quad (3)$$

Here Γ denotes the Gamma function. Eq. (4) yields the scale parameter c.

$$c = \frac{\bar{v}}{\Gamma\left(1+\frac{1}{k}\right)} \quad (4)$$

These computations are crucial for accurately modelling wind speed. The use of Weibull distribution in this research aims to provide students and researchers with a hands-on understanding of statistical modelling in climatology, particularly within the context of wind energy. This tool will help bridge the gap between theory and practical application, allowing users to better grasp the implications of statistical modelling for wind energy assessment.

Data collection:

In this study, we selected two distinct locations in Pakistan: Lahore and Karachi, to investigate the wind speed characteristics at these different geographical sites. The dataset---for this study---is used from *The World Bank Group*'s website. The complete details of the data source are available in the following link:

World Bank Group - Organizations - ENERGYDATA.INFO

After downloading the data from the above link, we generated the frequency distribution for the wind speeds at each location. This process involved grouping the wind speed values into equally spaced intervals (or bins) and counting the number of occurrences within each interval. These frequencies were then used to compute the corresponding probabilities for each wind speed value. The resulting frequency distribution was essential for calculating the average wind speed and variance, which are key parameters in estimating the Weibull distribution parameters.

Data Analysis:

Successful computation of the Weibull distribution's parameters---k and c---we are ready to model the Weibull distribution using Eq. (1). We developed a graphical user interface in an Excel spreadsheet incorporating the spin button for the simulation of the Weibull probability density function (PDF). Figure 1 gives the flowchart of the simulation process. This strategy allows us to model the wind speed distribution with the dynamical adjustment of the wind speed values. For a clearer understanding, we summarize the whole simulation in the following steps:

(i) ***Frequency distribution***: Generation of frequency distribution with the observed data (wind speed in our case)

(ii) ***Mean and variance computation***: Determination of the arithmetic mean and variance of wind speed.

(iii) ***Parameter estimation***: A Series of Parameters for the Weibull distribution is estimated along the flow of each iteration. Error is minimized in each iteration.

(iv) ***Convergence check/Stopping criteria***: The pre-set threshold value is 0.001. If the error is less than this value, the iteration will stop.

(v) ***Graphical results***: At the end of iteration, i.e., after convergence, the Weibull pdf is generated along with the histogram of the observed values of wind speed.

RESULTS AND DISCUSSION

Results:

This study developed an Excel-based graphical user interface (GUI) to simulate wind speed distributions using the Weibull probability density function. The tool allows users to input raw wind speed data, automatically compute frequency distributions, and iteratively adjust Weibull parameters for optimal fit. Figure 2(a–b) displays a screenshot of the simulator interface. The yellow-highlighted column shows the frequency distribution, while the green cells convert these frequencies into normalized probabilities. Column D contains the calculated Weibull values, based on the shape parameter k (cell E1) and the scale parameter c (cell F1). A spin button in cell E3 enables dynamic control over the value of k, with the corresponding value of c updated via Equation (4).

The simulator also calculates a stopping criterion (cell G1) based on Equation (3), the mean absolute error (MAE) between observed and modelled values is displayed in the cell H1, and the coefficient of determination is displayed in the cell I1. A histogram of observed wind speeds and a Weibull distribution curve are simultaneously generated to provide a visual representation of model performance.

Simulations were conducted using wind speed data from two locations: Lahore and Karachi. Each station had a dedicated sheet for raw data entry and simulation output. The optimal parameters and performance metrics for each location are summarized in Table 1.

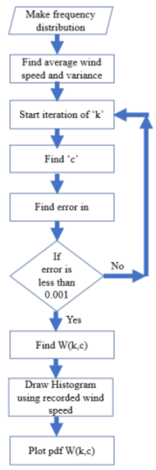

Figure 1. Flow chart of the simulation of wind distribution

To evaluate the goodness-of-fit of the Weibull model, a Chi-square test was applied. The critical value for the Chi-square distribution is 21.03 with degrees of freedom is 12. The calculated Chi-square values-cells K1 for each city-were below the critical value at the 0.05 significance level, indicating that the Weibull distribution provides a statistically acceptable fit for the observed wind data in both cities.

Discussion:

The primary objective of this study was to evaluate the effectiveness of the Weibull distribution in modelling wind speed and to develop a user-friendly simulation platform. The results affirm that the Weibull distribution accurately represents wind speed data across both locations, as evidenced by the low MAE values and high R^2 values, which reflect strong agreement between observed and modelled distributions.

A comparative analysis between Lahore and Karachi reveals regional variation in the Weibull parameters. Lahore's higher shape parameter k suggests a more concentrated distribution of wind speeds around the mean, while Karachi's lower k indicates a wider spread, potentially due to its coastal location and more variable wind patterns. These findings are consistent with earlier studies, such as those by Pobočíková et al. (2017) and Drobinski et al. (2015), which highlight the influence of geography and climate on wind speed behaviour.

The simulation also underscores the sensitivity of model accuracy to the shape parameter k. Minor adjustments to k led to noticeable changes in the fit quality, suggesting that accurate estimation of this parameter is crucial for reliable wind modelling. Future studies should consider incorporating environmental factors-such as topography, altitude, and seasonal variation-into the estimation of k and c to enhance model robustness.

From a practical perspective, the interactive GUI introduced in this study provides an accessible tool for wind energy researchers and planners. Its dynamic interface facilitates quick testing of parameter values and offers immediate visual feedback, making it especially useful for site-specific feasibility assessments in wind energy projects.

In theoretical terms, the successful application of the Weibull model in this context reinforces its status as a standard tool for wind resource assessment. Moreover, the GUI-based simulation approach represents a novel contribution to methodological practice, bridging the gap between statistical modelling and user-oriented design.

Table 1. Estimated Weibull Parameters and Error Metrics for Lahore and Karachi

Location	Shape parameter (k)	Scale parameter (c)	MAE	R^2	Chi-square
Lahore	4.04	8.85	0.0042	0.988	0.0128
Karachi	2.5	3.94	0.0185	0.982	0.0555

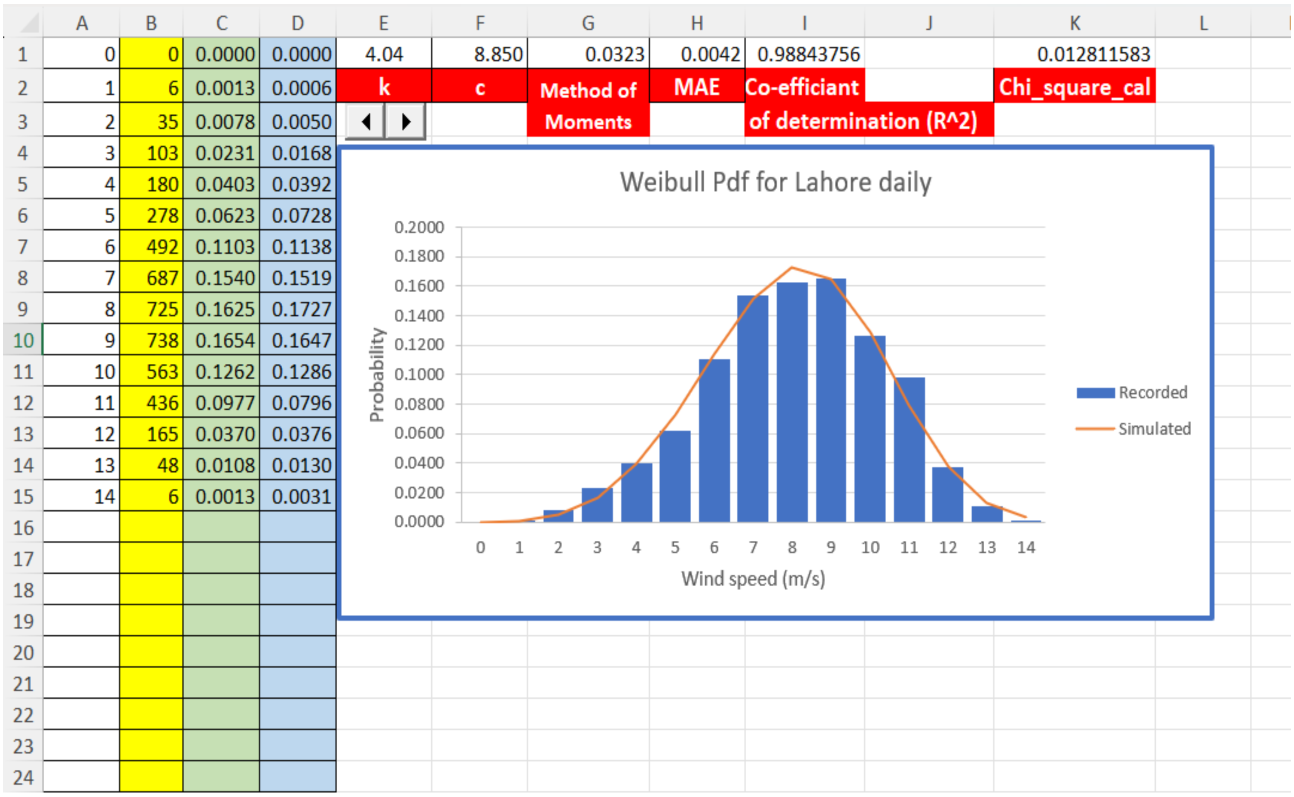

Figure 2(a). Screenshot of the PDF for Lahore

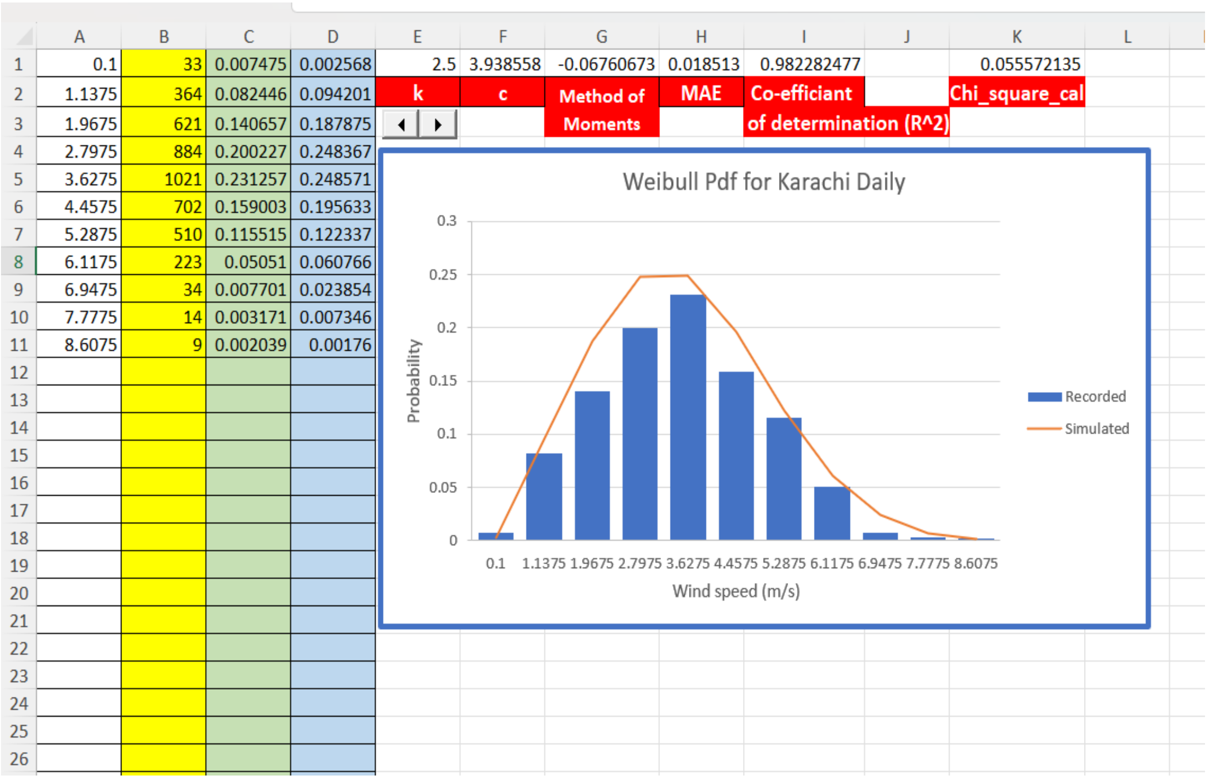

Figure 2(b). Screenshot of the PDF for Karachi

Supporting Data:

The following participants were contacted to evaluate the spreadsheet-based simulation tool. Their professional details and feedback are presented below:

1. Dr. Saima Gul
Assistant professor
NED University of Engineering & Technology
sagul@neduet.edu.pk
Comment: This is very interesting research. I have tested algorithms using various input values. The mathematical equations are correctly implemented, and the expected results are consistently obtained.

2. Dr. Iqbal Tariq
Assistant professor
NED University of Engineering & Technology
aqbal@neduet.edu.pk
Comment: As a physicist, I find this to be very interesting research that effectively meets students' academic needs.

3. Dr. Fahim Raees
Assistant professor
NED University of Engineering & Technology
fahimned@neduet.edu.pk
Comment: As the Postgraduate Coordinator of Mathematical Sciences, I am pleased to provide very positive feedback on the developed spreadsheets. Both sheets are designed with clear and well-structured mathematical formulas, and their results align well with existing data.

4. Dr. Syed Tauqeer
Assistant professor
NED University of Engineering & Technology
stauqeer@neduet.edu.pk
Comment: The computations are well-defined and aligned with the theoretical framework of wind speed. The statistical data and its implementation in the spreadsheet effectively address students' needs, especially in contexts where distance learning is essential.

5. Dr. Ali Ashher Zaidi
Associate professor
Syed Babar Ali School of Science and Engineering, LUMS
ali.zaidi@lums.edu.pk
Comment: Both spreadsheets are clearly structured and contain appropriate formulations

with well-justified results. I have very positive feedback on these simulations of wind speed using the Weibull distribution for both cities.

6. Haris Ur Rehman
PhD Student
NED University of Engineering & Technology
haris.horani@cloud.neduet.edu.pk
Comment: These spreadsheets are an excellent contribution to the understanding of wind speed simulations for two major cities in Pakistan. This research is particularly useful in situations involving natural disasters, such as the recent COVID-19 outbreak.

7. Aamir
PhD Student and faculty member of
Muhammad Ali Jinnah University
aamiragain@yahoo.com
Comment: Very interesting simulation related to wind speed, and it fulfills the needs of distance learning students.

8. Maham Fahim
Student
NED University of Engineering & Technology
mahamfahim9@gmail.com
Comment: I have reviewed both spreadsheets, and they function correctly according to the given formulations.

9. Hafiz Kashif
Student
NED University of Engineering & Technology
eng.muhammadkashifaslam@gmail.com
Comment: I had the opportunity to review the implementation of data values in the spreadsheets for both cities, and I found it to be a valuable contribution to the pedagogical framework.

10.Sameer Khalid
Student
NED University of Engineering & Technology
mcmscm1941@gmail.com
Comment: From a student's point of view, I found these spreadsheets very helpful for understanding wind speed using the Weibull distribution.

CONCLUSION

In this study, we developed a two-part tool consisting of code for simulating wind speed distribution and a user-friendly graphical interface (GUI). The simulation employs the Weibull distribution, a common model for wind speed, allowing users to manipulate parameters via a single spin button. This simple yet powerful tool provides an intuitive way for students to explore and understand complex physical concepts. By adjusting the parameters, students can visualize how the Weibull distribution changes and apply this understanding to real-world phenomena such as wind energy.

Additionally, the simulation serves as a versatile educational resource. Students can use it to simulate a variety of physical scenarios, including projectile motion, by altering time parameters and studying how horizontal and vertical distances are affected. The inclusion of air drag effects in the simulation further enriches the learning experience, allowing students to gain a deeper understanding of dynamics in real-world conditions. For easy access to this tool and to further explore the possibilities, students and instructors can visit the following link:

https://docs.google.com/spreadsheets/d/1UCrdPuDzdQQjU0DndqUepHn3pJA47Yk9/edit?usp=sharing&ouid=102482519910110763707&rtpof=true&sd=true

This tool is particularly valuable for both instructors and students in educational settings. Instructors can integrate this simulation into their curricula to visually demonstrate abstract concepts, while students can use it as a hands-on learning tool to experiment with different variables and deepen their grasp of physics. We suggest that future iterations of this tool could expand to simulate additional physical systems, broadening its educational potential.

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