RESEARCH TREATISE

M.Sc. Statistics and Data Science 2024-2026

"Wind speed analysis for renewable energy at Indian airports using Weibull and Truncated Weibull Distributions"

Group – 14

Roll No.	**Name**	**SAP ID**
A018	*Aayushi Fariya*	*86062400043*
A019	*Jainam Gada*	*86062400025*
A064	*Drishti Shah*	*86062400034*
A065	*Payal Shah*	*86062400040*
A074	*Harshita Warang*	*86062400031*

Project Supervisor

Dr. Pradnya Khandeparkar
Chairperson M.Sc(Statistics & Data Science)

NILKAMAL SCHOOL OF MATHEMATICS, APPLIED STATISTICS AND ANALYTICS,
SVKM'S NARSEE MONJEE INSTITUTE OF MANAGEMENT STUDIES (DEEMED-TO-BE-UNIVERSITY)

V.L. MEHTA RD, VILE PARLE (WEST), MUMBAI – 400056

ACKNOWLEDGEMENT

We extend our heartfelt gratitude to Our Mentor, **Dr. Pradnya Khandeparkar**, for her invaluable guidance, unwavering support, and profound insights throughout the journey of crafting this project. Her Expertise, Mentorship and in depth knowledge about the Statistical concepts have been instrumental in shaping our ideas and refining our work.

We would like to express our sincere gratitude to everyone who contributed to the completion of this project. Active participation, enormous thoughts, criticisms, suggestions and guidance of people helped us to complete it efficiently.

Lastly, we acknowledge the contributions of all the authors, researchers, and practitioners whose work served as a foundation for our project. The project has truly broadened our horizons and we have learnt much more than we ever imagined.

ABSTRACT

The report evaluates the potential for generating renewable energy at Indian airports by harnessing wind energy in hybrid mode with solar power.Utilizing wind speed data, the study employs quantitative methodologies to assess the viability of wind energy in the aviation sector.It focuses on airports near coastal or open plains, having more favorable wind conditions.The Weibull distribution is known to be the best fit for wind speed data.However, Wind speed below a specific truncation point is unable to generate the energy and the Wind speed above a specific truncation point damages the turbine. Using Truncated Weibull Distributions, the study assesses wind speed patterns at selected airports to estimate potential energy output. This analysis includes a case study on various Airports, demonstrating the feasibility of wind energy with Savonius Vertical Axis Wind Turbines (VAWT) as an efficient supplement to solar power in helping Indian airports achieve carbon neutrality goals.Among the airports the energy output of the Porbandar Airport is the most ,of around 86.3064 kWh.

Keywords: Wind speed, Airports, Weibull Distribution, Lower-Upper Truncated Weibull distribution,Mean energy density

INTRODUCTION

In recent years , the global energy domain is experiencing a sudden change transforming from the most used fossil fuels to underrated but an effective way to produce energy i.e renewable energy sources . Among the renewable energy (RE) sources, solar energy comes out to be the most proficient and an effective way of producing energy using the sun's abundant and inexhaustible power.

India is a major developing country, and is actively working towards reducing its carbon footprint and thus thriving to become carbon-neutral in the coming decades. As announced during the COP26 summit, India has pledged to achieve net-zero carbon emissions by 2070. To meet the energy demand of India various natural and renewable sources are explored according to their potentials. As in India the aviation sector is growing rapidly in the past decade and there is much more potential for growth, thus one of the factors for growth can be focusing towards the total energy consumed by airports to function properly, various natural and renewable sources of energy are used according to their availability. As the number of airports and number of passengers both are increasing, reducing the carbon emissions would be beneficial.

Solar energy is preferred and contributes significantly as a renewable energy source at airports due to its low installation cost and abundant sunlight, but due its limitations, solar energy is not a consistent energy source. Along with Solar energy, Wind energy can be considered as a great contributor of the energy generation from renewable sources. Airports located near coastal areas, such as those near oceans or in flat open plains, are more suitable for wind energy generation.

In light of these limitations, wind energy sources come out as a good alternative for generating energy. Wind power is one of the fastest-growing renewable energy sources worldwide, characterized by its ability to generate electricity consistently, particularly in locations with favorable wind conditions. Wind energy comes out as a continuous source of providing energy as it can be generated day and night, making it more effective. The installation of wind turbines can not only provide a constant energy source but also contributes to the reduction of greenhouse gas emissions, and helps meet our global sustainability goals.

The only challenge it faces is that it must be placed carefully to avoid interfering with radar, navigation equipment, or flight paths. The height of wind turbines can pose a challenge in areas near runways or aircraft. So, with proper execution and placement of the wind turbine and without intervening the runaway path, For example , in Mumbai airport , Vertical Axis wind Turbine(VAWT) model is used to generate electricity which doesn't even occupy huge space and is placed in such a way that it doesn’t intervene the runaway path . Thus ,Wind energy at airports can boost the renewable energy generation at airports and can turn out as an asset. Not concluding that , wind energy is better than solar energy or vice-versa, but through proper planning and execution of installing wind turbines at the airports, we can achieve our goal of becoming carbon-neutral sooner. Wind speed (WS) is a crucial factor in modeling wind energy. WS below a certain threshold typically cannot generate energy, while WS exceeding an upper limit can potentially damage wind turbines[1].In statistics, a truncated distribution is defined as a conditional distribution that results from restricting the domain of the statistical distribution .Hence ,truncated distributions are used in cases where occurrences are limited to the values which lie above or below the given threshold value or within a specific range. If occurrences are limited to values which lie below a given threshold , the upper (right) truncated distribution arises[2].

Wind energy is available globally, but power generation is dependent on wind velocity.Only if the wind turbine rotates at a specified speed , it will generate efficient power. To access the potential of wind energy , data needs to be analyzed properly. Appropriate statistical analysis helps in evaluating wind resources which is essential for generation of wind energy. Generally the wind power density function gives insights about mean wind power. Talking about wind energy, Weibull distribution (WD) is a well known and most widely-used distribution to estimate wind energy potential as this distribution is easily computable.[1]

MOTIVATION

One of the booming industries at present is “Sustainable Energy ”. With the increase in energy demand and a pressing need to cut down on Carbon footprints, the transition from fossil fuels to renewable energy is a global task at the moment . India’s commitment to achieve net zero carbon emission motivated us to explore the innovative renewable sectors especially with rapidly expanding industries such as aviation. Airports in India consume vast amounts of energy to work efficiently . Given the much favorable conditions at coastal and open plain airports gave us a thought of exploring the wind energy potential at selective airports located in these areas ,as wind energy is also a promising energy source .Inspired by successful cases like the Vertical Axis Wind Turbine(VAWT) at Mumbai Airport, we saw a potential in investigating wind energy’s viability at airports. Investing in wind energy at airports isn’t just about sustainability—it also boosts the economy. This research aims to understand how harnessing wind power could contribute to carbon-neutral operations and align with India's sustainability goals and make India become net zero carbon contributor to the world.

LITERATURE REVIEW

Aviation is a rapidly growing industry that has contributed to global environmental degradation.AAI has set a plan to switch from fossil fuel-based electricity to green electricity and achieve 100% energy through RE in all airports . AAI aims to achieve net zero emissions by 2050 to contribute to GoI's goal of achieving net zero emissions by 2070 [5].Amongst most emerging renewable energies such as solar wind and hydropower, wind energy is currently the most widespread on earth with a total power availability estimated between 300,000 and 870,000 GW [10].There is a lack of studies that evaluate the potential and performance of solar and wind farms in meeting airport demand in terms of energy, economic, and ecological parameters[4].During the pre-pandemic year of 2019-2020, 22% of all electricity consumed by Indian airports was from solar.[6]

Wind speed (WS) is the most important factor for modelling wind energy. WSs below a lower truncation point are usually not able to generate energy. Conversely, WSs higher than the upper truncation point may damage wind turbines[1]From several studies, it is known that Weibull is the most widely-used distribution to estimate wind energy potential because of its flexibility and easy computation . However, it should be noted that the Weibull distribution is unable to model all the wind structures encountered in nature. For this reason, in recent years, in order to model wind speed data more smoothly, the use of a variety of statistical distributions has been proposed in a large number of studies.[2]

The monthly wind data analysis helps us to estimate the power output for each month so that optimal usage of the wind power plant can be done. This mostly helps where there is a hybrid wind-solar power plant. As mentioned earlier for a hybrid wind-solar power plant, this type of analysis helps to make the optimum use of the plant by properly distributing the loading from each source. It can be said that the maximum wind speeds were observed during the monsoon season when the solar power plant is not able to generate enough power due to the rains and cloudy weather. The minimum wind speeds were observed during the winter and summer season.[3] Energy-saving potential analysis and audits can improve efficiency and reduce costs across industries, including aviation. In addition, advancements in energy storage technologies, such as mechanical, chemical, and hybrid systems, are vital for stabilizing renewable energy like solar and wind, ensuring a reliable power supply and better energy management.[4]

OBJECTIVES

1. To evaluate the capability of Weibull Distribution and Truncated Weibull Distribution in modeling wind speeds at selected Indian airports.

2. To explore the potential of Indian airports in generating energy from wind turbines.

3. To estimate the potential power output by integrating wind speed distribution with power density calculations.

4. To assess the feasibility of using Savonius - Vertical Axis Wind Turbine (VAWT) at Indian airports by identifying where deployment of wind turbines will be beneficial.

DATA PREPROCESSING

This study employs a quantitative approach, utilizing wind speed data from the IEM which maintains an ever growing archive of automated airport weather observations from around the world.

The methodology for analyzing wind speed at Indian airports to assess their potential for energy generation includes:

1. DATA COLLECTION:

The data is collected from IOWA state university which contains an archive of weather observations at an airport. A more generic term used for it is METAR (Meteorological Aerodrome Report) which is a brief report in the form of an alphanumeric code which provides detailed meteorological information about a specific airport at a time.

The data contains the following variables:

station, valid, tmpf, dwpf, relh, dect, sknt, p01i, alti, mslp, vsby, gust, skyc1, skyc2, skyc3, skyc4skyl1, skyl2, skyl3, skyl4, wxcodes, feel, ice acceleration 1hr, ice acceleration 3hr, ice acceleration 6hr, peak wind gust, peak wind drct, peak wind time, metar.

The wind speed data (in knots) cover a significant time frame at the above given 11 airports from (2014-2024) to account for seasonal variations.

SELECTION OF AIRPORTS

To assess wind energy potential, we will focus on a diverse array of coastal airports across India. The selected airports include:

1)VAPR (Porbandar Airport)

2)VARK (Rajkot Airport)

3)VASD (Shirdi Airport)

4)VECC (Netaji Subhash Chandra Bose International Airport) (Kolkata)

5)VOCB (Coimbatore International Airport)

6)VOCL (Kozhikode International Airport)(Calicut)

7)VOMD (Madurai Airport)

8)VOML (Mangalore International Airport)

9)VOMM (Chennai International Airport)

10)VOTK (Tuticorin Airport)

11)VOTR (Tiruchirapalli International Airport)

Table 1

Geographical Coordinates of Airports

Station	Longitude	Latitude
Rajkot	70.7795	22.3092
Mangalore	74.8898	12.962
Chennai	80.1805	12.9944
Calicut	75.9553	11.1368
Kolkata	88.4467	22.6547
Tuticorin	78.7097	10.7654
Porbandar	69.6572	21.6487
Coimbatore	77.0434	11.03
Tiruchirapalli	78.0262	8.7223
Madurai	78.0934	9.8345
Shirdi	74.3789	19.6886

2.DATA PARAMETERS:

The following variables from the data were considered for further analysis:

(i)valid: timestamp of the observation in the format ‘MM-DD-YY HH:MM’.

(ii)sknt: Wind speed in knots recorded at 6 m of height

(iii)lat: Latitude of the airport

(iv)lon:Longitude of the airport

station	valid	lon	lat	elevation	tmpf	dwpf	relh	drct	sknt
VOMM	01-01-2014 00:40	80.1805	12.9944	16	73.4	68	83.21	360	3
VOMM	01-01-2014 01:10	80.1805	12.9944	16	71.6	66.2	83.09	350	3
VOMM	01-01-2014 01:40	80.1805	12.9944	16	71.6	68	88.43	0	0
VOMM	01-01-2014 02:10	80.1805	12.9944	16	71.6	68	88.43	320	2
VOMM	01-01-2014 02:40	80.1805	12.9944	16	75.2	69.8	83.32	0	0
VOMM	01-01-2014 03:10	80.1805	12.9944	16	77	69.8	78.48	30	3
VOMM	01-01-2014 04:40	80.1805	12.9944	16	80.6	68	65.54	20	11
VOMM	01-01-2014 05:10	80.1805	12.9944	16	80.6	66.2	61.58	50	9
VOMM	01-01-2014 05:40	80.1805	12.9944	16	80.6	68	65.54	40	10
VOMM	01-01-2014 06:10	80.1805	12.9944	16	82.4	69.8	65.74	60	11
VOMM	01-01-2014 06:40	80.1805	12.9944	16	82.4	69.8	65.74	50	10
VOMM	01-01-2014 07:10	80.1805	12.9944	16	82.4	69.8	65.74	70	8
VOMM	01-01-2014 07:40	80.1805	12.9944	16	82.4	68	61.81	50	8
VOMM	01-01-2014 08:10	80.1805	12.9944	16	80.6	68	65.54	60	8
VOMM	01-01-2014 08:40	80.1805	12.9944	16	82.4	69.8	65.74	70	11
VOMM	01-01-2014 09:10	80.1805	12.9944	16	84.2	69.8	62.03	60	12
VOMM	01-01-2014 09:40	80.1805	12.9944	16	82.4	68	61.81	70	8
VOMM	01-01-2014 10:10	80.1805	12.9944	16	78.8	69.8	73.95	40	10
VOMM	01-01-2014 10:40	80.1805	12.9944	16	78.8	68	69.52	60	10
VOMM	01-01-2014 11:10	80.1805	12.9944	16	78.8	68	69.52	50	8
VOMM	01-01-2014 11:40	80.1805	12.9944	16	78.8	69.8	73.95	10	6

Dataset preview

3.DATA CLEANING:

1. Time frame

The time period of the data collected for different airports roughly lies between 2014 to 2024. For better analysis , We considered the range 2017-2023 (7 years) for all airports ,i.e the common time interval available for all the airports was considered.

2. Data conversion

The wind speed data was recorded in knots. But for our analysis we converted it in meters/second (m/s). 1 knot=0.51444 m/s is the conversion for changing the data from knots to m/s.

While selecting airports for wind energy generation a key criterion is ensuring that the average wind speed exceeds 3 m/s, as this threshold is generally considered favourable for energy generation. Based on this criterion, out of the 13 airports considered , we have shortlisted only 5 airports based on the overall average of the wind speed.

Table 2

Average wind speed at airports

Station	Average WS (m/s)
Mangalore	2.173423011
Rajkot	**3.549560711**
Madurai	2.5724052
Coimbatore	**3.20580923**
Baroda	2.108448734
Kolkata	2.5489
Calicut	2.1083
Tuticorin	**3.23649**
Chennai	**3.17605**
Porbandar	**4.15798**
Shirdi	2.945

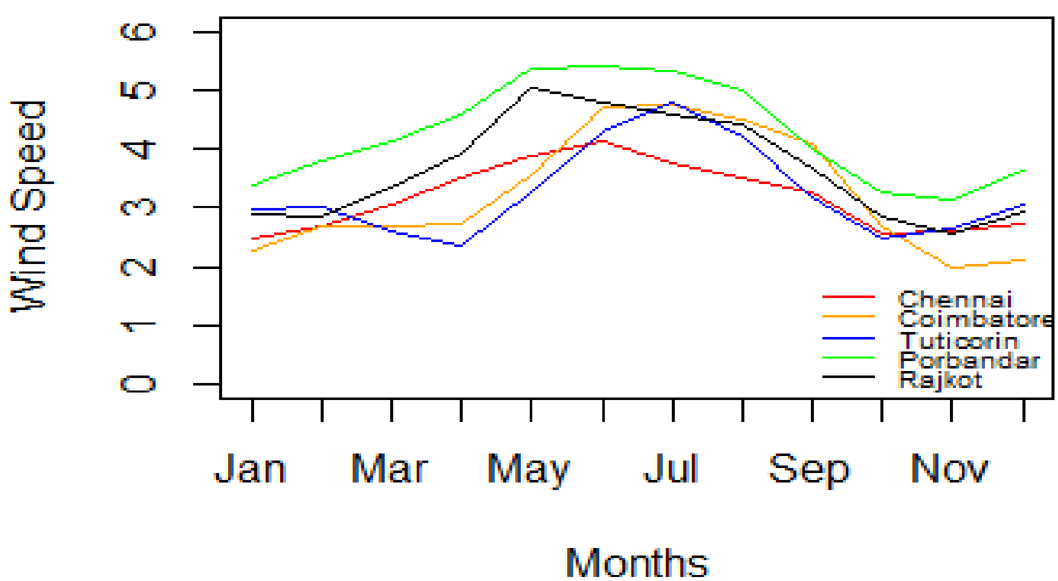

Fig.1 Monthly Average wind speed

Above figure shows the monthly average WS at selected 5 airports. This figure indicates that Porbandar has the highest WS compared with other stations. Moreover, this figure indicates that between June and September , all the stations had more WS than those in other months. Our decision to analyze wind energy potential specifically during the above months is justified by the minimal solar energy production during these months. By leveraging the high wind speeds associated with the above months we can basically fill the energy gap which is left by solar energy and thus leads to a more authentic and sustainable energy supply. Therefore the analysis is focused on months from June to september.

In our analysis we encountered several challenges during the data cleaning process. In our dataset the records were collected at every 30 minutes time interval. However, we noticed that some airports had gaps in their data with the observations recorded at intervals of about 1 hour gap, 2 hours gap,5 hours gap etc instead of expected 30 minutes. This inconsistency posed a challenge for our analysis as it could lead to inaccurate assessment of wind energy potential.

To address this issue we implemented a systematic approach to clean and standardize the data i.e, we considered the daily average data which contained only 1 value for a particular day.This method not only helped us fill in the gaps caused by missing 30-minute records but also provided a clearer picture of the wind energy potential at each airport over time. By ensuring that our dataset was standardized, we laid a strong foundation for further analysis and modeling of wind energy resources in our study.

3. Handling of missing values

After considering the daily average of WS, out of the 5 airports shortlisted, Porbandar and Rajkot airports still consisted of some missing values . In order to have standardized data we estimated the missing values using the ARIMA model.

After the process of Data cleaning, the final dataset consisted of all daily averaged values of wind speed for the months from June to september.

Based on the final dataset of 5 airports , skewness which is a statistical measure which indicates the asymmetry of the data, was used to check whether the model has a positive skewness or negative skewness as positive skewness implies that the model fits the data well and vice versa . Based on the skewness values above , Coimbatore and Chennai airports were eliminated for further analysis .

Table 3

Skewness of wind speed data

	Skewness
Porbandar	0.9733672
Rajkot	0.3337658
Chennai	-0.256781
Coimbatore	0.2217431
Tuticorin	-0.2000694

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METHODOLOGY

1. ARIMA MODEL

ARIMA stands for Autoregressive Integrated Moving Average , a technique for forecasting possible future values in time series.It combines the concepts of autoregressive modeling(AR) and moving average (MA) models.

$$Y_t = c + \phi_1 y_{dt-1} + \phi_p y_{dt-p} + \ldots + \theta_1 e_{t-1} + \theta_q e_{t-q} + e_t$$

The autoregression (p) process tests the data for its level of stationarity. If the data being used is stationary, it can simplify the forecasting process. If the data being used is non-stationary it will need to be differenced (d). Overall, initial analysis of the data prepares it for forecasting by
determining the parameters (p, d, and q), which are then applied to develop a forecast.
An ARIMA model can be understood by outlining each of its components as follows:
• Autoregression (AR): Refers to a model that shows a changing variable that regresses on its own lagged, or prior, values.
• Integrated (I): Represents the differencing of raw observations to allow for the time series to become stationary, i.e., data values are replaced by the difference between the data values and the previous values.
• Moving average (MA): Incorporates the dependency between an observation and a residual error from a moving average model applied to lagged observations.

The use of ARIMA model is made to estimate the missing values because the wind speed data generally tends to have seasonal variation in it , thus making the estimates more accurate and help get rid of the missing values in the data.

First, the missing values were filled temporarily using linear interpolation to create a complete dataset which is potential for ARIMA modeling.It is a statistical approach that uses past observations and seasonal patterns to make predictions.The auto.arima()function is used to find the best-fitting ARIMA model for our time series from its own , considering seasonal variations. After fitting the model, Forecasts were generated for the missing points in the original data. These forecasted values replaced the missing values ,providing a complete dataset that ticks the trends and seasonality of the wind speed data.

2. **Maximum likelihood Estimation (MLE)**

Our research aims at fitting weibull and truncated weibull distribution for the given wind speed data . MLE , Method of moments, least squares are some of the methods of estimating the parameters of the distribution .Research shows that the maximum likelihood method provides the best estimates as compared to other methods . Hence to obtain the estimated parameters of the respective distribution , the MLE method is used.

Maximum Likelihood Estimation is a statistical method used to find the best values for the parameters of interest of a model based on observed data. Essentially, it helps to determine which parameter values make the data most likely to occur. By creating a likelihood function which gives an overview about how probable the observed data is for different parameter values, MLE provides the values that maximize this likelihood.

Weibull Distribution

The Weibull probability density function(pdf) is expressed as,

$$f(x;c,k) = \frac{kx^{k-1}\ e^{-\left(\frac{x}{c}\right)^{k}}}{c^{k}} \qquad ; x \geq 0$$

Where,
f(x) is the probability of wind speed
‘k’ is the shape parameter
‘c’ is the scale parameter (in m/s).

The corresponding cumulative distribution function (cdf) of the Weibull distribution is the integration of the pdfs , and it is given as follows,

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

The likelihood function corresponding to WD is given as follows:

$$L(k,c) = \prod_{i=1}^{n}\left(\frac{k}{c^{k}}\ {x_i}^{k-1}\right) e^{-\sum_{1}^{n}\left(\frac{x}{c}\right)^{k}}$$

In order to find the MLE ,we differentiate the log of likelihood functions with its parameters which are to be estimated. This derivative is equated with 0 in order to find the maximum value of the likelihood function.
The equations obtained after differentiating the log likelihood equation of weibull distribution with respect to k and c and equating it with 0 are as follows

$$\frac{\partial lnL(k,c)}{\partial k} = \frac{n}{k} - nln(c) + \ln\left(\prod_{i=1}^{n} x_i\right) - \sum_{i=1`}^{n} \left(\frac{x_i}{c}\right)^k \ln\left(\frac{x_i}{c}\right) \quad = \ 0$$

$$\frac{\partial lnL(k,c)}{\partial c} = \frac{-nk}{c} + \frac{k}{c^{k+1}} \sum_{i=1}^{n} (xi)^k \quad = \quad 0$$

Lower-Upper Truncated Weibull distribution

A lower upper-truncated distribution is appropriate in scenarios where the values of a random variable are restricted by a minimal point and a maximal point , known as the truncation points. This means that if the random variable values lie between the interval [a, b], the lower upper-truncated distribution is suitable for use. Since wind speed measurements typically range from [a, b] as wind speeds lower than a point will fail to produce wind energy and wind speeds above a certain point will destroy the turbine , this type of distribution can effectively model wind speed data suitable for wind turbines. Therefore, a lower–upper truncated distribution can be applied to model WS data.The lower-upper truncated CDF of truncated weibull distribution is is defined as follows:

$$G(x) = \frac{F(x)}{F(b) - F(a)} \qquad a < x < b$$

Where F(x) is the distribution function of X.
Therefore the Cdf G(x) and pdf g(x) of lower upper truncated distribution is given as:

$$G(x) = \frac{1 - \ e^{-\left(\frac{x}{c}\right)^k}}{e^{-\left(\frac{a}{c}\right)^k} - e^{-\left(\frac{b}{c}\right)^k}} \qquad a < x < b$$

$$g(x) = \frac{\left(\frac{k}{c}\right)\left(\frac{x}{c}\right)^{k-1}\ e^{-\left(\frac{x}{c}\right)^{k}}}{e^{-\left(\frac{a}{c}\right)^{k}} - e^{-\left(\frac{b}{c}\right)^{k}}} \quad a < x < b$$

Where k and c are the shape and scale parameters respectively. Depending upon the geographical location and height , the lower truncation point ‘a’ is taken to be **3** and the upper truncation point ‘b’ is taken to be **10** for the further analysis.

The log likelihood function for lower upper truncated weibull distribution is given as

$$L(k,c) = \sum_{i=1}^{n}\left(\frac{1}{k} + \ln\left(\frac{x_i}{c}\right) - \frac{{x_i}^{k}\ln\left(\frac{x_i}{c}\right)}{c^{k}}\right) - n\,\frac{\left(\frac{a}{c}\right)^{k} ln\left(\frac{a}{c}\right) - \left(\frac{b}{c}\right)^{k} ln\left(\frac{b}{c}\right)}{e^{-\left(\frac{a}{c}\right)^{k}} - e^{-\left(\frac{b}{c}\right)^{k}}}$$

Differentiating the above likelihood with respect to k and c we obtain the estimates of the parameters of TWD

Table 4

Estimates of Parameters for Weibull Distribution

	June		July		August		September	
	Shape	**Scale**	**Shape**	**Scale**	**Shape**	**Scale**	**Shape**	**Scale**
Porbandar	3.23756	5.97977	3.11148	5.86485	4.23018	5.47275	2.82144	4.50262
Rajkot	3.58046	5.318712	3.993723	5.062364	4.219257	4.854098	4.122577	4.054815
Tuticorin	4.27672	4.73279	4.1135	5.25149	3.8481	4.65534	3.51998	3.55617

Table 5

Estimates of parameters for Truncated Weibull Distribution

	June		July		August		September	
	Shape	Scale	Shape	Scale	Shape	Scale	Shape	Scale
Porbandar	3.86963	5.700853	4.139823	5.580548	4.804637	5.456635	2.289947	4.01191
Rajkot	3.758616	5.40202	3.459922	4.862164	3.696253	4.681579	3.48879	3.854773
Tuticorin	4.28796	4.76342	3.98068	5.22826	3.15122	4.36407	2.831112	3.246579

The graphs given below gives a visualization of which distribution fits the wind speed data better. The graphs demonstrate the histogram, and the estimated WD and TWD for Porbandar airport. The TWD is a better fit for Porbandar as it exhibits a good fit to the peak of wind speed data. It can be seen from Fig. 1 that the probability of wind speed of 4–6 m/s is underestimated, using WD. On the other hand, TWD accurately describes an empirical distribution of wind speed data, particularly the peak and tail of wind speed data. Similarly,good performance of TWD is observed in Fig.2

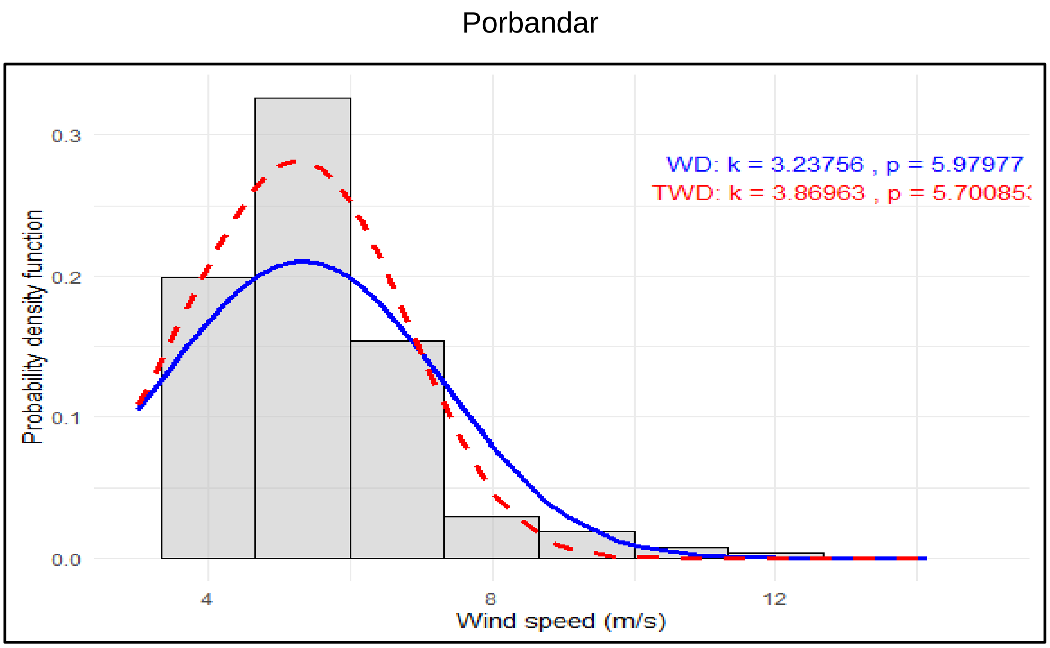

Fig.2 Histogram and PDF of WD and TWD for Porbandar Airport

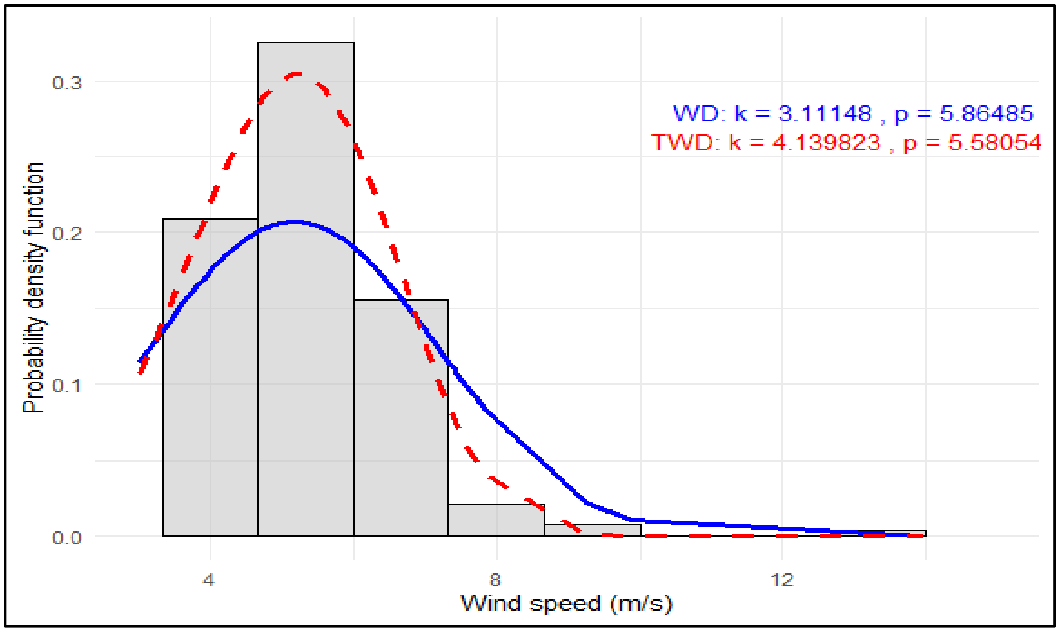

Fig.3 Histogram and PDF of WD and TWD for Porbandar Airport

3. Kolmogrov-Smirnov test (KS test)

KS test is used to verify whether a sample comes from a population with a particular distribution.

Hypothesis are as follows:

H0:The data follows the specific distribution.

H1: The data does not follow the specific distribution..

Test statistics for KS test is as follows,

$$D = \max(|F(x) - G(x)|)$$

where,

$F(x)$: Empirical CDF of hypothesized distribution.

$G(x)$: CDF of hypothesized distribution.

Criteria for Rejection:

p-value -In Kolmogrov Smirnov test, p value is often used to make a decision about whether to reject the null hypothesis.If the p-value is below chosen significance level, we reject the null hypothesis.

D-statistic-It is used to compare the CDF of sample data with the ecdf under null hypothesis. If the D-statistic is greater than critical value from KS distribution then you may reject the null hypothesis.

Table 6

KS test values

Months		Porbandar	Rajkot	Tuticorin
June	**WD**	0.13557	0.096958	0.35007
	TWD	0.082882	0.168655	0.16659
July	**WD**	0.16099	0.189031	0.24292
	TWD	0.087817	0.093568	0.11942
August	**WD**	0.045622	0.445622	0.0714
	TWD	0.037931	0.210622	0.30008
September	**WD**	0.277020	0.047362	0.0463
	TWD	0.047362	0.511893	1.18557

Table 6 shows that statistic D of truncated weibull distribution is less for all four months of the Porbandar Airport and most of the months of the Rajkot and Tuticorin Airport as compared to the weibull distribution. This infers that TWD fits better to the wind speed data as compared to WD for most of the stations.

4. Akaike information criterion

The AIC is a statistical measure used for model selection and it is used for evaluating how well a model fits the data it was generated from.It is used to provide quantitative means to compare competing models based on their fit and complexity. The AIC is a way to balance the goodness of fit of a model with the simplicity of the model (to avoid overfitting).The distribution for which the value of AIC is low fits the data better.

The AIC criteria is defined as follows,

$$AIC = 2K - 2\ln(L)$$

Where,

K : Number of parameters in the distribution.

L : Likelihood Estimate of the distribution.

Table 7

AIC Values

Months		Porbandar	Rajkot	Tuticorin
June	**WD**	816.7752	762.9664	647.3534
	TWD	267.1575	270.6619	247.9952
July	**WD**	838.8677	716.2452	730.5155
	TWD	266.8567	367.6897	279.217
August	**WD**	732.5451	683.0825	699.2572
	TWD	214.3486	348.9718	458.3522
September	**WD**	771.0547	586.601	595.6214
	TWD	684.7644	415.5336	651.9296

Table 7 shows that AIC values for WD is greater than that of TWD for all the months except September of Tuticorin inferring that TWD fits better to the wind speed data as compared to WD for most of the stations.

5. MEAN ENERGY DENSITY:

The wind energy density is given by,

$P(\boldsymbol{\nu}) = 0.5*\rho*\nu^3$

where,

ρ : Air Density(Kg/m^3)

$\boldsymbol{\nu}$: Wind speed (m/s)

Since wind speed is changing we cannot just use a single value for $\boldsymbol{\nu}$. Instead we calculate mean energy density by integrating over probability distribution of wind speed which is Truncated Weibull distribution.

Mean energy density

The mean energy density can be calculated by integrating the wind energy density over the Truncated Weibull distribution,

$P_D = \int_0^{\infty} \mathrm{P}(\nu) \, . \, \mathrm{f}(\nu) \, \mathrm{d}\nu$

Substituting,

$$P_D = \int_0^{\infty} 0.5 * \rho * \boldsymbol{\nu}^3 \, . \, \frac{\left(\frac{k}{c}\right)\left(\frac{x}{c}\right)^{k-1} e^{-\left(\frac{x}{c}\right)^k}}{e^{-\left(\frac{a}{c}\right)^k} - e^{-\left(\frac{b}{c}\right)^k}} \mathrm{d}\boldsymbol{\nu}$$

Simplified formula for general mean energy density,

$P_D = 0.5 * \rho * c^3 * \Gamma(1 + \frac{3}{k})$ … (i)

where, Γ is a gamma function and

c and k are Truncated Weibull scale and shape parameters respectively.

Table 8

Wind Energy Density (W/m²)

Months	Porbandar	Rajkot	Tuticorin
June	127.18	86.81	59.02
July	121.75	73.05	81.12
August	91.40	63.80	57.23
September	57.50	37.33	26.07

CSMIA's VAWT & Solar PV hybrid (Solar Mill)

Chhatrapati Shivaji Maharaj International Airport (CSMIA) is India's first airport to launch a one-of-its-kind Vertical Axis Wind Turbine (VAWT) & Solar PV hybrid (Solar Mill) to explore the possibility of utilization of wind energy at the airport.They have deployed 10Kwp hybrid solar mill consisting of 2 Kwp turbo mill (3 Savonius type VAWT) and 8 Kwp solar PV modules, with an estimated minimum energy generation of 36 Kwh/day.WindStream Energy Technologies India Pvt Ltd has developed this novel and patented, first-of-its-kind, fully integrated, hybrid renewable energy product which harnesses solar and wind energy combined to generate electricity. CSMIA aims to replicate the project to increase the onsite renewable power generation in the coming years.[9]

Fig.4 Savonius VAWT installed at CSMIA

Savonius VAWT

A Savonius VAWT is a drag based VAWT with advantages of operational independence on direction of wind, simple design and stand alone behavior particularly suitable for small scale wind energy generation.They are designed to fit in compact spaces while operating quietly with its materials corrosion resistant for longevity making it suitable for installation at airports.

Equation (i) gives a general formula for mean energy density but for a more realistic estimate of power output of a specific turbine, consideration of the efficiency, Area swept by turbine blades and Time period is necessary.

For VAWT mean energy output is,

E_D = 0.5*ρ*A*c^3*$\Gamma(1+\frac{3}{k})$*η*T

where,

A is Area swept by turbine blades.

η is the efficiency.

T is the Time period.

Table 9

Expected Power Output for 1 VAWT for given airports

	PORBANDAR		RAJKOT		TUTICORIN	
Months	Mean Energy Density (kWh/m^2)	Mean Power Output (kWh)	Mean Energy Density (kWh/m^2)	Mean Power Output (kWh)	Mean Energy Density (kWh/m^2)	Mean Power Output (kWh)
June	119.87	86.3064	81.82	58.9104	55.62	40.0464
July	114.75	85.374	68.85	51.2244	76.46	56.88624
August	86.15	64.0956	60.13	44.73672	53.94	40.13136
September	54.19	39.0168	35.18	25.3296	24.57	17.6904

Mumbai Setup:

- The Mumbai system uses **3 Savonius-type VAWTs** which forms **1 unit** of a system with a **2 kWp** wind capacity and **8 kWp** of solar capacity.
- The system generates approximately **36 kWh/day** energy from the 2 kWp wind portion.

Replicating the same setup at Porbandar airport, the estimated power output for the a month considering only wind turbine setup is:

Table 10

The estimated power output for the a month considering only wind turbine setup

Location	Wind Output for 1 VAWT/day	Wind Output for 3 VAWT/day	Monthly Wind Output
Mumbai	12 kWh/day	36 kWh/day	1,080 kWh
Porbandar	2.88 kWh/day	8.64 kWh/day	259.2 kWh

Table 11

The estimated power output for a month considering both wind turbine setup and solar setup for 1 unit of system

Location	**Wind Output for 3 VAWT/day**	**Solar Output (kWh/day)**	**Total Daily Output (Wind + Solar)**	**Monthly Output**
Mumbai	36 kWh/day	30-40 kWh/day	66-76 kWh/day	1,980 - 2,280 kWh
Porbandar	8.64 kWh/day	30-40 kWh/day	38.64 - 48.64 kWh/day	1,159.2 - 1,459.2 kWh

From table 11, the monthly energy output for Porbandar Airport is expected to be 1,159.2 - 1,459.2 kWh which can be used for the following application:

- Powering low-energy (Ground Support Equipment) GSE, EV charging stations, and administrative devices.
- Can be used for external lighting, runway lights, and energy-efficient LED systems.
- Serves as backup power for critical systems during outages
- Reduces electricity costs by offsetting grid power usage with renewable energy, contributing to long-term operational savings.

CONCLUSIONS

1. **Evaluation of Weibull and Truncated Weibull Distributions:**

Wind speed at Porbandar airport is better fitted by Truncated Weibull Distribution indicating the wind speed patterns are better captured in a specific range as extreme low or high wind speeds are less relevant for energy generation.

Wind speeds at Rajkot and Tuticorin airports fits the Truncated Weibull Distribution than Weibull distribution for only few months.

2. **Exploration of wind energy potential:**

Wind power density evaluations at Porbandar, Rajkot, and Tuticorin reveal that Porbandar has more potential power output due to the better fit of the TWD.This indicates that Porbandar may be more favorable for wind energy generation.The characteristic of Savonius VAWT makes it effective in regions where wind speeds are consistently within a moderate range, as seen in the data for Porbandar Airport.

Given that the truncated Weibull distribution (TWD) fits well for Porbandar Airport, it indicates that the wind speeds likely falls within the range where Savonius VAWT can operate smoothly..Based on the wind power density and the TWD fitting, the mean power output for Porbandar was estimated for a Savonius VAWT with a setup similar to that of Mumbai (3 Savonius VAWTs) which comes out to be 2.88 kWh/day from each VAWT that is 8.64 kWh/day from 3 VAWTs together.Thus the total expected power output at Porbandar Airport comes out to be 259.2 kWh for the month of June for a setup similar to that of Mumbai. This provides a data-driven recommendation for Porbandar Airport as a feasible location for wind energy projects using Savonius VAWTs.

LIMITATIONS

1. While the Weibull model seems like a better estimate of power output in this context, these results may not be generalized for different airports in India without taking into consideration further analysis approaches.

2. In addition to statistical considerations, factors like turbine selection and turbine placement needs to be considered.Factors that influence energy capture efficiency like turbine size, rotor diameter, height and optimal turbine type should be considered accordingly.Along with it, geographical factors like terrain, infrastructure of the region being studied and the potential environmental impacts should be assessed in detail at each location before selection of location for turbine deployment.

3. The two tests i.e. AIC and KS tests were only considered to draw conclusions regarding the best fit for the data but more tests can be considered for more accurate conclusions

FUTURE SCOPE

1. Since there are certain limitations of both Weibull and Truncated Weibull models, more distribution models such as Rayleigh, Gamma or Lognormal distributions should be explored to see if they provide a better fit for the wind speed data at different Indian airports.

2. Wind rose diagrams could help identify places with optimal turbine placement depending on the wind directions, wind intensity and potential seasonal changes which are important for maximizing energy production.

3. Considering the potential impact of climate change on wind speed is important. Along with it, long term trend analysis to understand the potential shifts in wind speed and direction should be explored more.

APPENDIX

1. ARIMA

```
library(forecast)
library(zoo)
wind_speed_data=Data
# Filling missing values temporarily with linear interpolation
wind_filled=na.approx(wind_speed_data)
wind_ts=ts(wind_filled, frequency = 30, start = c(2017, 1))
#Fitting ARIMA model
arima_model=auto.arima(wind_ts, seasonal = TRUE)  # Seasonal = TRUE for seasonal ARIMA
# Forecast missing values
fitted_values=fitted(arima_model)
# Replace missing values in the original series with the fitted ARIMA values
imputed_data=wind_speed_data
imputed_data[is.na(imputed_data)]=fitted_values[is.na(imputed_data)]
matrix(imputed_data,ncol=1)
```

2. Maximum Likelihood Estimator

```
wind_speed_data <-na.omit(data)
# Filtering the data between truncation points 3 and 10
truncated_data <- wind_speed_data[wind_speed_data >= 0 & wind_speed_data <= 10]

#log-likelihood function for the truncated Weibull distribution
trunc_weibull_loglik <- function(params) {
  shape <- params[1]
  scale <- params[2]
  p_a <- pweibull(0, shape = shape, scale = scale)
  p_b <- pweibull(10, shape = shape, scale = scale)
  log_lik <- sum(dweibull(truncated_data, shape = shape, scale = scale, log = TRUE) - log(p_b - p_a))
  return(-log_lik)
}

# Using optim function to estimate parameters
init_params <- c(shape =0.1, scale = 0.1)
fit <- optim(init_params, trunc_weibull_loglik)
```

3. KS Test

```
# Perform the KS test using your wind speed data for weibull and the truncated Weibull CDF
test <- ks.test(wind_speed, distribution_cdf)
```

4. AIC Test

```
AIC <- -2 * distr_log + 2 * no_of_parameters
```

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