Lecture Notes in Networks and Systems 379

Manuel Ignacio Ayala Chauvin
Miguel Botto-Tobar
Angela Díaz Cadena
Sergio Montes León *Editors*

Sustainability, Energy and City

Proceedings of CSECity'21

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Preface

The 1st Congress in Sustainability, Energy and City (CSECity'21) was held at Universidad Tecnológica Indoamérica, in Ambato—Ecuador during June 28–29, 2021, and it will be organized and supported by GDEON. CSECity'21 will bring together experts in sustainability, urbanism, energy and industry. This multidisciplinary group of researchers will allow the transfer of knowledge between academic institutions, raise research and analyze how intermediate cities and industries are likely to change and adapt in the coming months and years in a sustainable way. Presenting high-quality, peer-reviewed papers, the book discusses the following topics:

- Energy sustainability
- Information and knowledge management
- Information technologies.
- Innovation, technology and society
- Software and systems modeling
- Software systems, architectures, applications and tools
- Sustainable energy and the city

CSECity'21 received 142 submissions written in English by 710 authors coming from 15 different countries. All these papers were peer-reviewed by the CSECity'21 Program Committee consisting of 107 high-quality researchers. To assure a high-quality and thoughtful review process, we assigned each paper at least three reviewers. Based on the peer reviews, 17 full papers were accepted, resulting in an 12% acceptance rate, which was within our goal of less than 40%.

We would like to express our sincere gratitude to the invited speakers for their inspirational talks, to the authors for submitting their work to this conference and the reviewers for sharing their experience during the selection process.

June 2021

Ignacio Ayala Chauvin
Miguel Botto- Tobar
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Contents

Statistical Analysis of Villonaco Wind Farm Annual Energy Production

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Abstract. The Villonaco Wind Farm is located between coordinates 693030 E 9558392 N and 693526 E 9556476 N in the province of Loja in southern Ecuador. It is the first wind farm in continental Ecuador, with a capacity of 16.5 MW and a location of roughly 2720 m above sea level in rugged terrain, which is especially relevant compared to others wind farms in the global context. This paper presents a statistical analysis of the Annual Energy Production of the Villonaco Wind Farm in the period from 2014 to 2018. In this analysis, actual wind speed and active power values were used, outliers and missing data were identified, and a new methodology was used to complete the missing data. With the complete dataset, an analysis of variance was performed to compare the means of the annual energy production. The results obtained in this study show an error of ±4% compared to the information available on the website of the Agency for Regulation and Control of Energy and Non-Renewable Natural Resources of Ecuador.

Keywords: Statistical analysis · Annual Energy Production · Villonaco Wind Farm

1 Introduction

Global warming has prompted scientists to look for new energy sources, and renewable natural resources are being promoted as a viable alternative to traditional energy generation from fossil waste fuels.

Among renewable energy sources, wind energy has demonstrated outstanding characteristics that have attracted the attention of the scientific community. With an average annual growth rate of 30% over the last two decades, the wind energy has been dubbed “the world's fastest-growing renewable energy source” [1].

In this context, the wind industry has experienced in recent years a dizzying growth worldwide, as stated by the Global Wind Energy Council (GWEC) in its latest annual report published, which shows that the installed wind power in the world at the end of 2017 reached 546.38 GW, and by the end of 2019 it will increase to approximately 651 GW [2].

For wind farm investors and operators, it is of great importance to know precisely what the energy yield of the wind farm is. In this respect, it is important to mention that

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the Annual Energy Production (AEP) of a wind farm is influenced by a variety of factors, including the availability of wind resources, the number and capacity of wind turbines installed, and the structure and design of the wind farm, among others [3].

This paper presents a statistical analysis of the Annual Energy Production of the Villonaco Wind Farm (VWF) for the period from 2014 to 2018. Descriptive and inferential statistical techniques were used for the data processing, and the MATLAB toolbox Statistics and Machine Learning was used for the analysis of variance.

The structure of this document is as follows: the second section of this article is dedicated to the materials and methods used in the research, the methodological procedure to complement the missing data (*NaN*) is described here, in the third section the results obtained are presented and discussed, and finally, in the fourth section the conclusions are presented.

2 Material and Methods

For this study, wind speed and active power data are available from the VWF, which have been provided by the public company (GENSUR-EP) to the authors of this study using a confidentiality agreement. In order to complete the missing values, the authors propose a methodology based on the following criteria:

i) *Spatial interpolation*

The procedure is based on the method called *Inverse distance weighting*, which is an approach that uses a linear weighted average of data from known points to approximate a value at an unknown place [4].

The reference anemometric station with the required data should be as close as possible to the study site (wind turbine with missing data). The method applies to a site with similar physical-geographical characteristics and is calculated by the following equation:

$$z(x) = \sum_{i=1}^{n} (\lambda_i \cdot z_i) \tag{1}$$

where:

$z(x)$ is the value of the wind speed at the point to be interpolated
z_i is the value of the wind speed at the known point i
λ_i is the weight of station i
n is the number of stations considered

ii) *Time interpolation*

It consists of finding the average wind speed value employing Eq. 2, using the available wind speed data of the immediate next years in the same time window.

$$\overline{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{2}$$

where:

$\overline{x}$ is the mean wind speed value
x_i is the value of the wind speed for the known station i

Missing wind speed data can be replaced based on the above-mentioned criteria by applying the flowchart of Fig. 1.

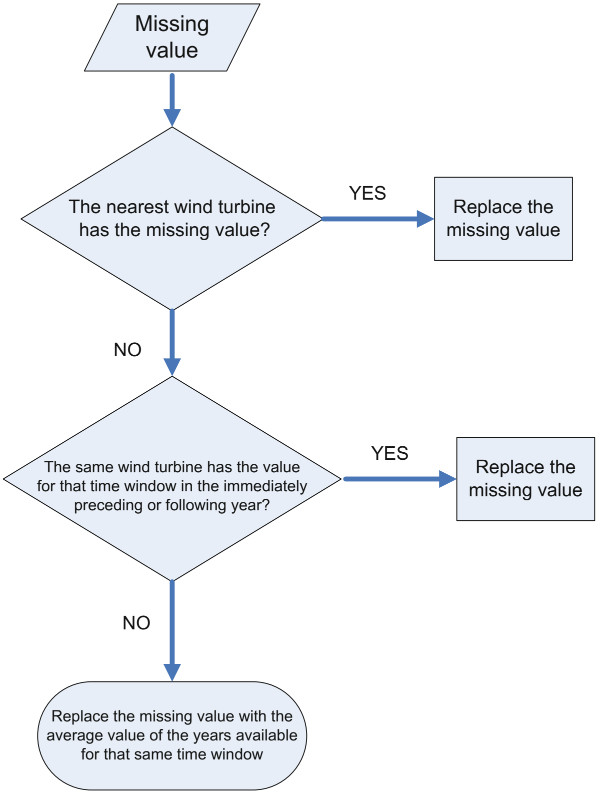


Fig. 1. Flow chart for filling in missing data.

2.1 Study Area

Since 2013, nine hydroelectric power plants have been built and commissioned in Ecuador, to change the country's energy matrix and achieve energy sovereignty. The hydroelectric power plants are: Coca Codo Sinclair, Delsitanisagua, Minas San Francisco, Manduriacu, Mazar Dudas, Quijos, Sopladora and Toachi Pilatón, which represent an installed capacity of 2589.5 MW, and the Villonaco Wind Farm [5].

The VWF started its operations in 2013 and is located in a mountainous area of the province of Loja in the southern region of Ecuador, between UTM coordinates 693030 E and 9556476 N. (Fig. 2). The VWF has an installed capacity of 16.5 MW, is located in the mountainous region of complex orography at 2720 m.a.s.l., in an area with average annual wind speeds of more than 10.5 m/s [6].

The VWF is composed of 11 wind turbines of 1.5 MW nominal unit power, GOLDWIND, type GW70, class "S", equipped with *Direct Drive technology* and a permanent magnet synchronous generator [7].

Fig. 2. Panoramic view of *Villonaco Wind Farm* [8].

The Electric Public Company Corporation of Ecuador (CELEC-EP), is the entity in charge of the operation of the VWF through their business unit called GENSUR-EP [8].

2.2 Description of the SCADA Data Used

Most modern wind turbines record more than 200 variables in 5 to 10 min intervals using their SCADA system (Supervisory Control and Data Acquisition), which generates a wealth of historical data [9].

According to [10], the SCADA system records some monitoring variables related to the parameters: wind, energy conversion and temperature.

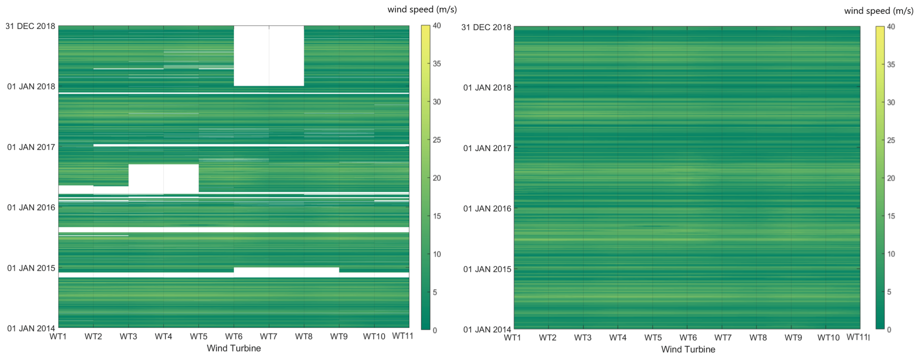
The data used in this study were obtained from the VWF SCADA system and correspond to the wind speed and active power variables recorded during the years 2014–2018 with a sampling frequency of 10 min. Table 1 shows the structure of the dataset used for wind turbine 1.

Table 1. The data format used in the study.

Data	Time	Wind speed (m/s)	Power active (kW)
01–01-2014	00:00	3.78	33.72
01–01-2014	00:10	3.13	15.59
01–01-2014	00:20	4.12	51.24
…	…	…	…
12–31-2018	23:50	16.38	1562.32

2.3 Data Analysis

Since not all speed data were available, the algorithm described in the Materials and Methods section was used to fill in the missing data. Figure 3 (a) shows a colour map indicating the missing wind speed data blocks, both for each wind turbine and for the data collection period. On the other hand, Fig. 3 (b) shows the wind speed colour map with the complete samples of the data set. The missing data represent 9.91% of the total data set.



(a) (b)

Fig. 3. Matrix of wind speed data at each wind turbine versus data collection period: (a) unfilled data, (b) filled data.

The most important factor in the power generated by a wind turbine is wind speed [11]. The theoretical wind power that can be extracted is stated by Eq. 3.

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot Cp(\lambda, \beta) \cdot v^3 \tag{3}$$

where:

P is theoretical wind power
ρ is air density
A is the area of the wind turbine rotor
$Cp(\lambda, \beta)$ is the power coefficient, indicates the efficiency of a turbine capturing the wind energy; and
v is the wind speed

From the valid data and using Eq. 3, the model shown in Fig. 4 was obtained, whose coefficient of determination $R^2 = 0.9958$ indicates that the model to obtain the dependent variable (power of each wind turbine) is mostly explained by the independent variability of wind speed, as shown in Fig. 5.

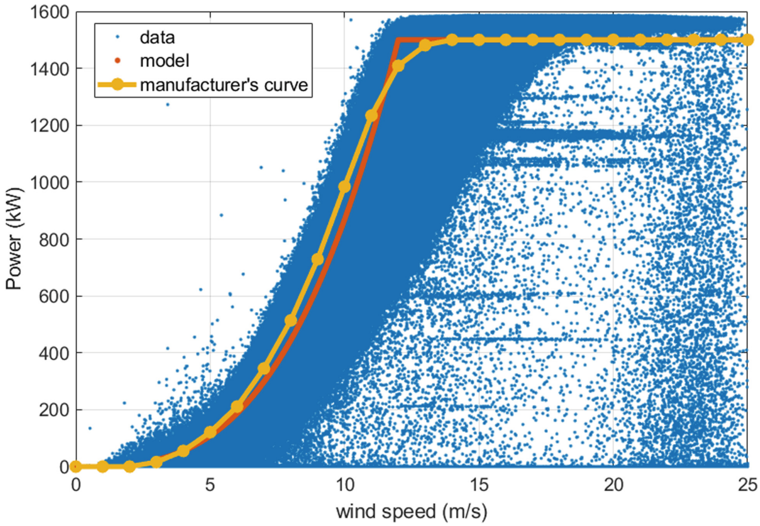


Fig. 4. Wind speed vs. wind power (blue dots). Raw data (10 min data) was obtained from the eleven wind turbines, from 01 January 2014 to 31 December 2018. The model obtained (red line) and the manufacture's curve (yellow dash and dot line) are compared.

As can be seen in Fig. 4, in the slope of the sigmoid curve, the model does not fully fit the curve guaranteed by the manufacturer, mainly because the curve guaranteed by the manufacturer (GOLDWIND) considers a standard air density of 1.22 kg/m^3 and the air density at the project location is 0.89 kg/m^3.

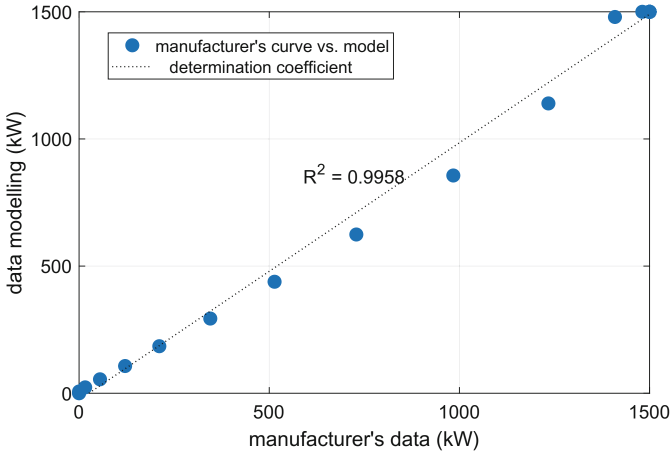


Fig. 5. Coefficient of determination when comparing the manufacturer's curve with the model presented in Eq. 3.

After obtaining 100% wind speed data, the model described in Eq. 3 was used to complete the power data and then calculate the annual energy produced by each wind turbine. Figure 6 shows the ordered pairs (wind speed, power) of each wind turbine after completing the data series.

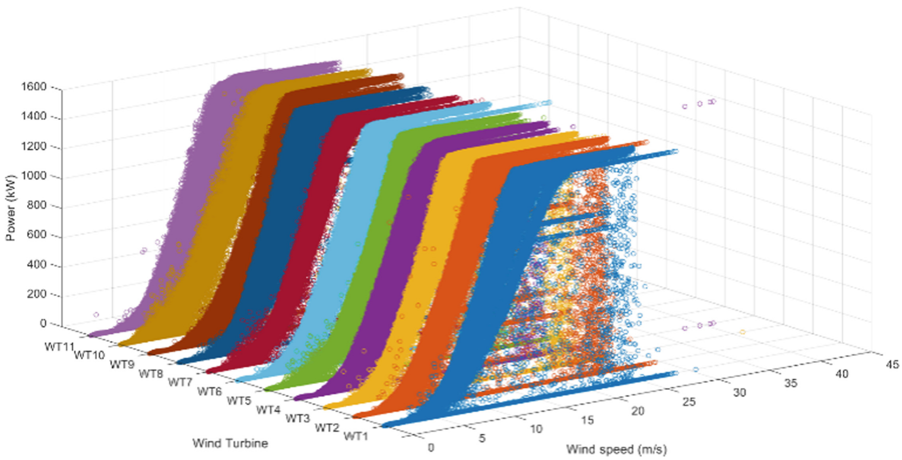


Fig. 6. Ordered pairs plot (wind speed vs. wind power) of each wind turbine.

2.4 Analysis of Variance (ANOVA) to Compare the Annual Average of Energy Production of the VWF

The statistical method of analysis used was "One-way analysis of variance". To perform this analysis the Matlab Toolbox called Statistics and Machine Learning was used. The purpose of this analysis is to determine whether the annual averages of energy production of each of the wind turbines of the VWF have a common average. In this case, the independent variable is each of the wind turbines and the response variable is the average annual energy production measured between 2014 and 2018.

In this study, ANOVA was used to test the hypothesis that all wind turbines' annual energy production (E_n) are equal, against the alternative hypothesis that at least one wind turbine has different averages than the others.

$$H_0 : \overline{E_1} = \overline{E_2} = \ldots = \overline{E_{11}} \tag{4}$$

The procedure performed in Matlab® is as follows:

i) *Entry of the data is shown in* Table 2.

```
>>energy =[ annual averages of wind turbines] ;
```

Table 2. Annual averages of wind turbines in MWh.

Year	WT1	WT2	WT3	WT4	WT5	WT6
2014	6390.69	7693.93	7777.51	7778.01	7681.31	7507.19
2015	8473.30	9108.61	9211.99	8895.64	8744.44	8931.09
2016	6804.02	7128.88	7395.43	7617.10	7306.70	7100.86
2017	6334.43	6719.87	6689.21	6677.17	6581.42	6621.41
2018	6898.92	7402.10	7295.40	7329.21	7231.50	7051.66
Year	WT7	WT8	WT9	WT10	WT11	
2014	7270.20	6976.40	7044.45	6455.15	5980.07	
2015	8375.47	8403.55	8513.77	7845.52	7613.24	
2016	6491.83	6623.28	6826.68	6303.51	5964.94	
2017	6198.72	6018.76	6056.70	5543.53	5214.57	
2018	6800.16	6495.85	6548.20	5994.21	5599.31	

ii) *Obtain the standard ANOVA table and the box plot of data per wind turbine.*

```
>> [ p,tbl,stats] = anova1(energy);
```

Table 3. ANOVA analysis results.

Source	*SS*	*df*	*MS*	*F*	*p-value*
Columns	1.37765e + 07	10	1377654.2	1.77	0.0944
Error	3.41861e + 07	44	776957.4		
Total	4.79627e + 07	54			

3 Results

According to Fig. 7 and the ANOVA (Table 3), the *p-value* = 0.1033 is obtained, which indicates that the counts of the annual averages of the different wind turbines are approximately equal. Therefore, the null hypothesis that all annual average energy production of the wind turbines are equal is accepted.

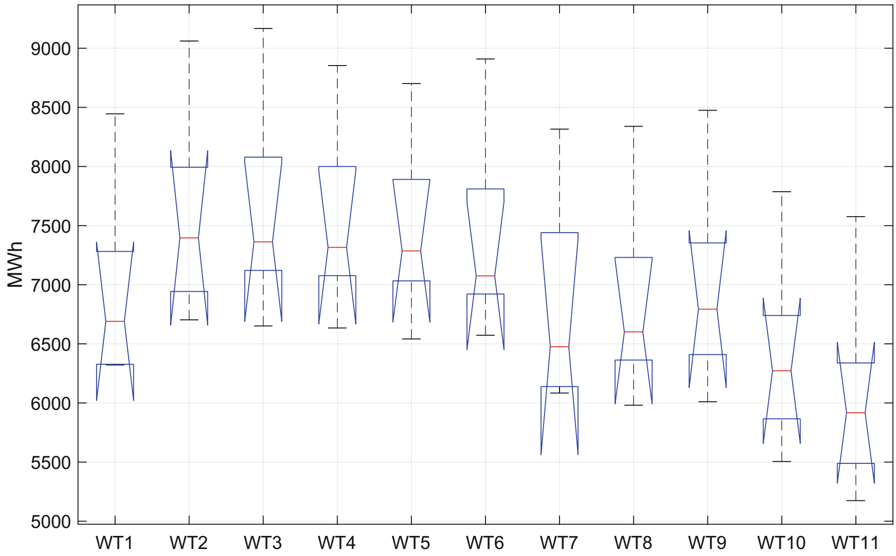


Fig. 7. Analysis of variance of the annual averages of each of the wind turbines.

Figure 8 illustrates that no wind turbine has averages significantly different from the rest. The coloured bars show the comparison interval for the average of each of the groups, and as can be seen, no bars overlap with each other. Therefore, all annual averages of energy production are not significantly different from each other.