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# A new statistical based energetic-economic methodology for wind turbine systems evaluation

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## Abstract

The present paper deals with the implementation of a new statistical based methodology for energetic and economic evaluation of wind turbine systems without using anemometric measurements for specific installation sites. In particular, the procedure aims at the evaluation of single small wind turbine, as well as small wind turbine fields. The choice of using small wind turbines is due to the impact of the wind velocity measurements from both the cost and the time-needed point of view.
Monte Carlo Method was used to study statistically the effects of wind velocity variability on wind turbines energy production and consequently on the economic performance of the system. Starting from the average wind velocity for the site, the type of the site (plain, hill, mountain, etc.), as well as the height of the turbine, the procedure analyses different wind velocity statistical distributions (based on Weibull distribution) to obtain energy production and then investment profitability.
In order to test the methodology a case study was analysed using both classical (using one year of wind velocity measurements) and new procedure (using only the average value of the wind velocity for the same installation site). On the basis of the results it is possible to state that the new methodology is able to determine the Net Present Value of the investment showing small differences between new and classical procedure.

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Wind turbine; Energetic-Economic evaluation; NPV; Monte Carlo Method; Weibull Distribution.

## 1. Introduction

The European Parliament gave its backing to the European Union climate change package. The package aims to ensure that the European Union will achieve its climate targets by 2020 [1]. According to the package, a 20%

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reduction in greenhouse gas emissions, a 20% improvement in energy efficiency, and a 20% share for renewable in the European Union energy mix should be achieved by 2020 [1].

Wind energy will play an important role to achieve the targets in the present energy scenario. Both home and industrial size wind turbines systems have the maturity to be considered economically effective.

During 2012, European Union countries installed 11,895 MW of wind power of the 12,744 MW installed all over the Europe. This represents a market growth in the EU of about 23% compared to 2011 installations. Of the 11,895 MW installed in the European Union, about 11,334 MW (95.3%) was onshore, and about 560 MW (4.7%) offshore [2].

Home size wind turbines market is new and in strong expansion [2]. Technologically, small wind turbines have reached high level of efficiency with low environmental impact. Unfortunately, to evaluate energy production it is necessary to measure wind velocity for at least a year. Wind measurements have a negative impact on the investment decision-making process.

Therefore, the present paper deals with the implementation of a new statistical based methodology for energetic and economic evaluation of wind turbine systems without using anemometric measurements for specific installation sites. Particularly, the presented methodology aims to choose the most suitable commercial wind turbine for a specific installation site. Monte Carlo Method [3, 4] was used to study statistically the effects of wind velocity variability on wind turbine energy production and consequently on the economic performance of the system. Starting from the average wind velocity registered in the installation site, the type of the site (plain, hill, mountain, etc.), as well as the height of the turbine, the procedure analyses different wind velocity statistical distributions (based on Weibull distribution [5]) to obtain energy production and then investment profitability of different wind turbines. Therefore, a wind turbine for the installation site is chosen on the basis of energetic and economic considerations.

The proposed method can be used in two ways: the design mode to choose the best wind turbine for a specific installation site; the evaluation mode to estimate energy performance and investment profitability.

**Nomenclature**

| | |
|---|---|
| NPV | Net Present Value |
| $F_k$ | Cash flow |
| j | Actual year |
| i | Discount rate |
| n | Total considered years |
| p.d.f. | Probability Density Function |
| k | Weibull shape factor |
| A | Weibull scaling factor |
| V | Wind velocity |
| $V_m$ | Site mean wind velocity |
| $E_e$ | Annual electric energy |
| N | Total hours in a year |

## 2. Background

### 2.1. Monte Carlo Method

To analyse systems of large dimensions [6], such as in this case, two main methodologies can be used. The first, the analytical methodology, is based on enumerating the situations that describe components of the whole system. Only critical cases based on study-specific criteria are considered. The second, the statistical methodology, is based on the Monte Carlo Simulation Method. This methodology deals with the total number of cases, which is very important in the case of wind turbine energy production because every single wind probability density function may be the correct one.

The Monte Carlo class of algorithms are based on repeated random sampling to compute the results [6] and tend to be used when it is unfeasible to compute an exact result with a deterministic algorithm. These methods are especially useful for simulating systems with many-coupled degrees of freedom and when phenomena present significant input uncertainty. In the Monte Carlo Method, solutions are considered as parameters of a hypothetical population, a sample of which can be constructed using a random sequence of numbers, and from which statistical estimates of the parameter can be obtained [6].

### *2.2. Net Present Value*

The Net Present Value (NPV) method [7] is one of the main methods for determining the cost-effectiveness of an investment. The NPV method is based on two main parameters: the discount rate and the cash flow.

The NPV method is a decision-making tool giving a concrete answer to situations such as "do or not to make the investment?" or "which investment do?" In the first case, actual NPV is compared to an appropriate reference NPV. In the second case, NPV method allows you to make a comparison between the value NPV of the investment “A” and NPV of investment “B”, then going to compare them and choose the investment with the value greater NPV.

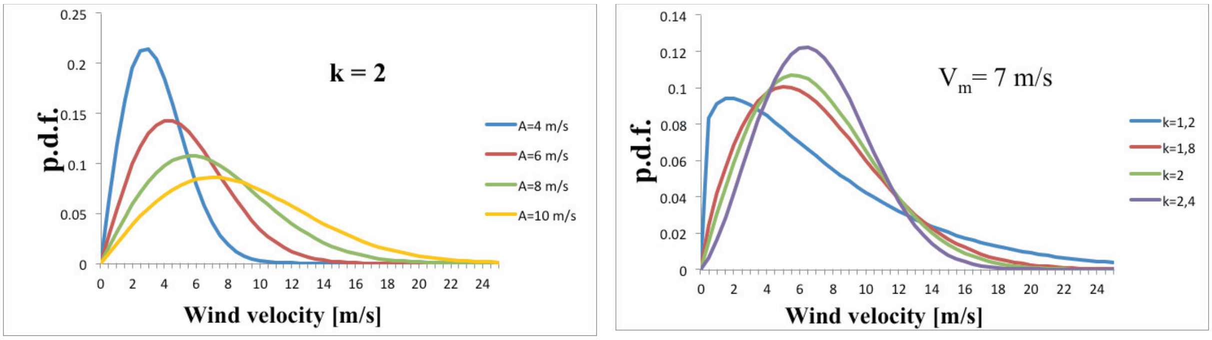
### *2.3. Wind model*

The wind conditions of a specific installation site can be summarized using a wind curve. This one shows the frequency distribution of wind velocity. Thus, for each wind velocity returns the percentage of time that the considered wind velocity occurs in a year. Since the anemometers, most commonly used to record the wind data, measure in probabilistic terms, it is possible to consider a probability density function (p.d.f.) [5, 8]. The probability density function for a specific site is normally determined from measured wind data.

Moreover, it is possible to approximate the p.d.f. using a Weibull distribution [5] with two parameters: the scaling factor “A” and shape factor “k”.

The scaling factor “A” has the physical dimensions of a velocity, and is closely related to the average velocity of the site. This factor represents the most likely wind velocity. Higher it is, more likely and quickly higher wind velocities become. Scaling factor, shape factor and mean wind velocity are interconnected [5].

Fig. 1 shows the influence of both scaling (Fig. 1(a)) and shape (Fig. 1(b)) factors on the Weibull distribution. Both influence are reported for fixed shape factor and fixed mean wind velocity.



a b

Fig. 1. (a) Influence of shape factor on Weibull distribution; (b) Influence of scaling factor on Weibull distribution.

The advantage of using a Weibull distribution, instead of measured data, it is strongly related to its analytical type, which makes it easier to use especially for estimating the producible electricity from wind power.

On the contrary, the use of Weibull distribution leads to drawbacks due to the process of idealization: it can return information that is not always in line with the physical reality. In addition, the parameters "A" and "k" are not so immediate to be determined from experimental data.

### *2.4. Wind turbine energy production model*

In order to calculate wind turbine energy production, it is possible to integrate the product of wind turbine power curve *P*(V) and the probability density function *f*(V). Fig. 2 shows an example of wind turbine power curve. In particular, the wind turbine shown is the horizontal axis three blades (2.8 m diameter) Cydonia Eolo-600 with a nominal power of 600 W @ 10 m/s.

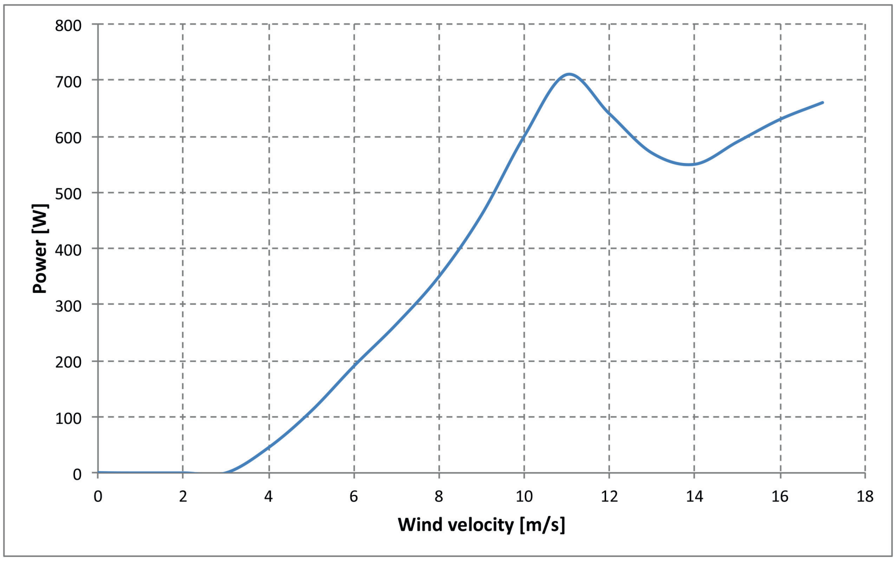


Fig. 2. Example of wind turbine power curve.

## 3. Methodology

The proposed methodology aims to the most suitable commercial wind turbine choice for a specific installation site. Economical aspects were the main choosing parameters. In this paragraph a description of the proposed methodology is given.

First of all, a database of commercial wind turbine technical and economical characteristics was implemented. About 50 horizontal and vertical axis wind turbines are in the database. The rated power range considered in this work is from 300 W to 20 kW. The choice of this range is related to two considerations. The first is an economical consideration: a 20 kW rated power wind turbine costs about 50,000.00 € [2] and to consider higher powers, up to 200 kW, have no appeal to small private investors. The second consideration regards the wind turbine dimensions and its strong environmental impact: higher the power, stronger is visual impact on the landscape. The database contains technical and economical information about considered wind turbines. In more details, the following information is stored:

1. Commercial name;
2. Numerical code;
3. Rated power;
4. Wind turbine type (horizontal or vertical axis);
5. Wind turbine cost;
6. Wind turbine installation height;
7. Cut-in wind velocity
8. Wind turbine power at cut-in wind velocity;
9. Nominal wind velocity;
10. Wind turbine power at nominal wind velocity;
11. Cut-off wind velocity;
12. Wind turbine power at cut-off wind velocity;
13. Wind turbine power versus wind velocity (power curve).

Secondly, the wind turbine database was divided into power classes to reduce calculation time. For each power class a “fictive” turbine is created. Each “fictive” wind turbine has the average parameters of all wind turbines in its class. The “fictive” wind turbine power curve has null values for any wind velocity less than the average cut-in and greater than the average cut-off. In the range average cut-in to average nominal wind velocity turbine power varies linearly between zeros to average nominal power. In the range average nominal wind velocity to average cut-off the power varies linearly between nominal power to average cut-off power. Fig. 3 shows an example of a 650 W “fictive” wind turbine power curve.

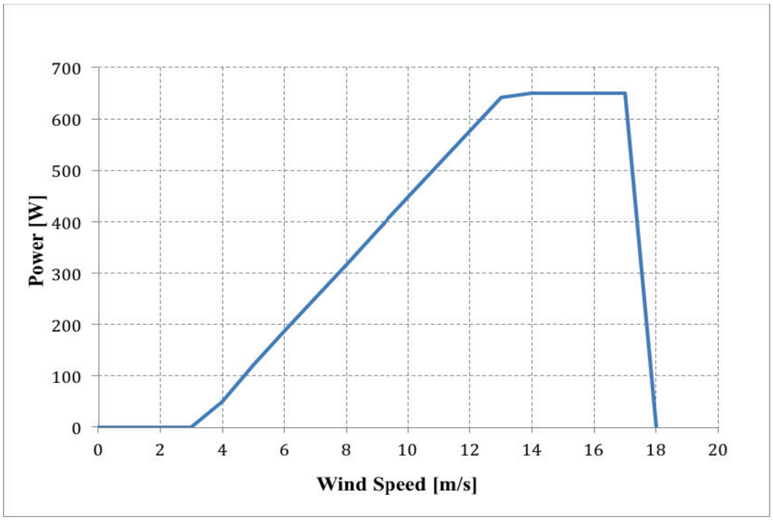


Fig. 3. Example of “fictive” wind turbine power curve.

Thirdly, a Monte Carlo simulation generates an established number (1,000 in the present work) of possible wind distributions starting form the average wind velocity and the considered site topological considerations (plane, hill, mountain, windy place, etc.). For each generated Weibull distribution a value of “k” and “A” are chosen randomly in the rages reported in Tab. 1 [5]. Thus, 1,000 possible wind probability density functions are generated using Eq. (1).

Table 1. Ranges of shape and scaling factors.

| Site type | Range of "k" | Range of "A" |
|---|---|---|
| Low-lying areas | 1.8 – 2.5 | 1.1 – 1.3 $V_m$ |
| Mountainous areas | 1.2 – 1.7 | |
| Windy areas | 2.5 – 3 | |
| Areas affected by trade winds and monsoons | 3 – 4 | |

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

Fourthly, annual energy production is calculated for each power class and for each Weibull distribution using Eq. (2).

$$E_e = N \int_0^\infty P(V)\, f(V)\, dV \quad (2)$$

where "N" is the total hours in a year.

Considering installation costs and cash flows from energy market, NPV is evaluated for all considered "fictive" turbines. Specific national grants can be introduced at this step. NPV can be calculated using Eq. (3).

$$NPV = \sum_{j=0}^{n} \frac{F_j}{(1+i)^j} \quad (3)$$

where "$F_j$" are the cash flows, "i" is the discount rate and "n" are the considered years. In the present work a temporal period of 20 years was considered. The cash flows can be determined as the difference between availability and outlay (see Eq. (4)).

$$F_j = D_j - I_j \quad (4)$$

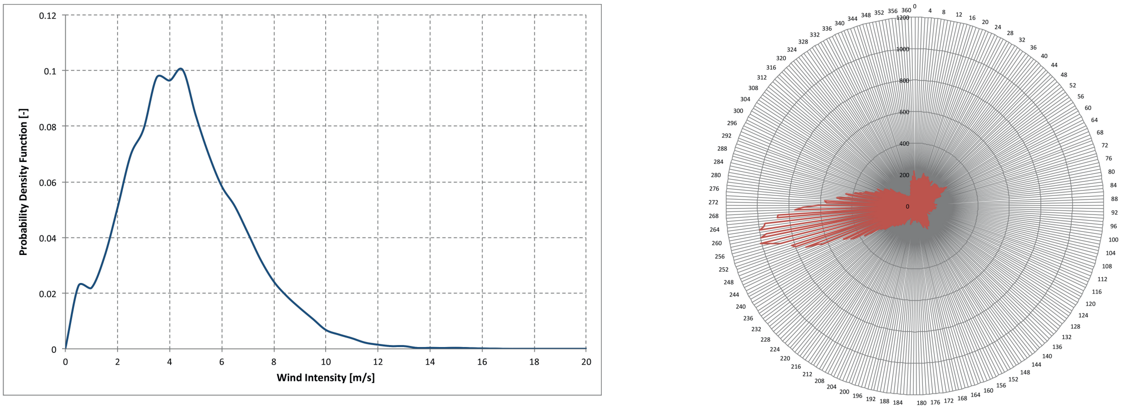
At the end of Monte Carlo method run, 1,000 NPV and annul produced energy values for each power class are stored. According to Monte Carlo Method average value tends to be close to the real one. NPV is used as decision maker about the power class. Thus, the power class that has the best NPV is selected.

Finally, within the selected power class the real wind turbine that has the power curve closest the "fictive" one is chosen. Therefore, a more precise NPV evaluation is carried out using the selected wind turbine only. Average (that tends to be the real one), minimum and maximum NPV values are calculated. Thus, a final decision is made about the investment on the basis of the results.

Some considerations can be made about NPV results interpretation. Three main cases can occur: negative values of average, minimum and maximum NPVs; positive values of all obtained NPVs; and positive values of average and maximum NPVs and negative value of minimum NPV. The investment with negative NPV is not profitable, while all positive NPV values lead to a profitable investment. In the third case investment risk should be considered. Higher the distance between minimum (negative) and average NPV values is, greater the risk.

## 4. Methodology validation

In order to validate the new methodology, a comparison with standard method to energetic-economic evaluation was carried out. The standard methodology is based on the wind velocity measurements on the installation site. Wind velocity and direction data (measurements every 10 min) were used in the standard methodology. The Probability Density Function of the wind intensity and wind direction frequency are shown in Fig. 4.



a

b

Fig. 4. (a) Wind Probability Density Function; (b) Wind direction frequency.

Using the new methodology, an energetic-economic evaluation of the wind system composed by a single wind turbine in an installation site plain with an average wind velocity of 5 m/s [5] was carried out. The presented methodology selected a 20 kW rated power wind turbine for the specific site. The same evaluation was carried out using standard procedure.

Annual Energy production and Net Present Value were calculated using both methodologies. The new methodology produce a statistically minimum, maximum and average values of both parameters. According to Monte Carlo Theory average values tend to be real. Tab. 2 shows the results after 1,000 Monte Carlo simulation iterations, as well as the average value errors respect to the real case values.

Table 2. Annual energy and NPV for real and simulated case, as well as errors.

| Description | Real Case | Simulated Case | | Error |
|---|---|---|---|---|
| | | Minimum | 44,746.83 | |
| Annual Energy [kWh/y] | 54,010.93 | Average | 54,432.85 | 0.78 % |
| | | Maximum | 64,118.88 | |
| | | Minimum | 64,598.16 | |
| Net Present Value [€] | 91,590.73 | Average | 92,820.09 | 1.34 % |
| | | Maximum | 121,042.00 | |

Observing the results reported in Tab. 2, it is well evident that the proposed methodology is able to evaluate with low errors both energy production and Net Present Value. On the basis of the presented results the methodology can be considered validated.

## 5. Conclusions

In the present paper, a new energetic and economic evaluation method of wind turbine investment was implemented and tested using measured data. The proposed method is based on Monte Carlo statistical method.

The new procedure is focused on small size wind turbine. This choice is related with the high impact on the investment of wind measurements cost. Therefore, the procedure does not need, to run, the wind measured data, but uses the average wind velocity and the typology of the installation site only.

Moreover, the proposed methodology was validated using experimental data. Thus, running both standard and new methodology an energetic and economic evaluation was carried out for a case study site. The results were compared.

On the basis of the presented results it is possible to state that the new methodology is validated due to the low errors on both annual energy estimation (error less than 1 %) and NPV calculation (error less than 2 %).

The goal of the proposed statistical method is related to the fact that it is not necessary to measure wind velocity for at least a year. Wind measurements have a big impact on the investment decision, especially in small size wind turbine systems. Therefore, avoiding the cost of wind measures in small size wind turbine could be the chance to increase small size wind turbines market.

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