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A stochastic economic viability analysis of residential wind power generation in Brazil

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ABSTRACT

This study evaluates the stochastic economic viability of residential wind power generation in Brazil. Three scenarios representing different regions from Brazil were considered: high, low, and intermediate wind speed. For each scenario, 10,000 simulations were conducted using the Monte Carlo Simulation (MCS)[1] method to obtain possible Net Present Values (NPV) for a project. The sensitivity analysis revealed that wind speed and investment are essential for the viability of this type of project. For the evaluated scenarios, the results show that the investment in residential wind power generation has a low feasibility probability. The high, low, and intermediate wind speed scenarios produce feasibility results of 22.04%, 1.51%, and 15.06%, respectively. This result infers that it is essential to subsidize this technology and decrease the uncertainty of price fluctuations in order to leverage the residential wind power generation. The National Agency of Electrical Energy's (ANEEL) initiative to encourage installation of residential microgenerators is the first step to disseminate and consolidate clean energy generation technologies. Additional policies must be adopted in order to reduce the risk assumed by investors in residential wind power generation in Brazil.

1. Introduction

Fossil fuels dominate the worldwide energy matrix [1]. However, the impact of fossil fuel consumption and possible environmental damage must be decreased [2]. Consequently, several countries are moving toward sustainability and energy efficiency. According to data from the International Energy Agency (IEA) [3], worldwide energy production up to 2014 constituted 67% fossil fuels, 11% nuclear, and 22% renewable energy. Furthermore, hydroelectric energy accounted for 16% of the total worldwide energy matrix; this constituted 74% of the total energy from renewable sources. Faced with this challenge, renewable energy sources (RES) have been receiving greater attention from national governments [2,4].

Renewable energy refers to forms of energy that occur in nature and are continuously produced due to the energy absorbed from the sun, which, from the humanity perspective, has infinite duration. Many types of energy fit this definition, such as those coming directly from the sun (such as photovoltaic energy), wind, biomass, and water movement in general (tides, waves, and so on).

Since electric energy is the principal energy vector available today, mechanisms that take advantage of clean energy generation sources must be developed. Regarding the use of clean energy in a residential context, several studies in the literature have presented new technologies for heating and generation of energy, capable of replacing conventional technologies [5–8].

Carbon dioxide emissions from the process of electric energy generation are expected to increase until 2030, owing to the strong dependence on coal as an energy source in many developed and developing countries. Considering this situation, it is necessary for countries to shift to energy generation with low carbon emission. RES are capable of making an important contribution toward this objective [9–11].

Lipp [12] states that many countries have begun to commit to goals for RES utilization, which has contributed to a significant increase in the installed capacity of renewable energy, as observed in Fig. 1.

However, renewable energy sources face several technical and economic barriers to their development. Thus, suitable measures are

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[1] MCS: Monte Carlo Simulation; NPV: Net Present Value; ANEEL: National Agency of Electrical Energy; IEA: International Energy Agency; RES: Renewable Energy Sources; AEP: Annual Energy Production; WACC: Weighted Average Cost of Capital; CAPM: Capital Asset Pricing Model; CAS: Constant Amortization System.

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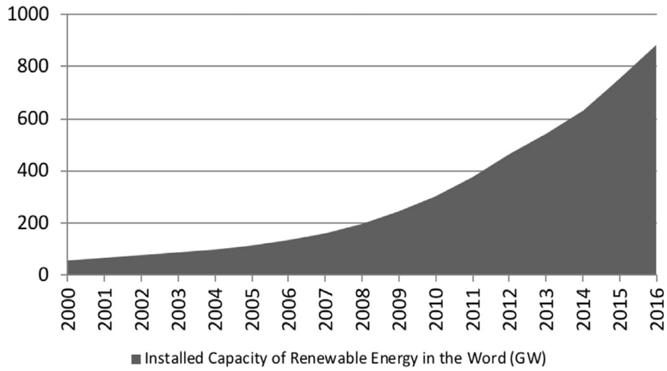


Fig. 1. Installed capacity of renewable energy in the world. Source: Adapted from IRENA [13].

needed to promote fund raising for research and development of the technology in the sector. These technologies will lead to new energy generation and improved consumption habits, by consequently encouraging a learning-by-using approach, which leads to a reduction of generation cost [14].

One of the strategies adopted in most countries to realize the objective of expanding the use of renewable energy is the introduction of decentralized technologies such as small-scale infrastructure to generate wind and solar energy, which are changing the characteristics and structures for energy supply [15,16]. This small-scale renewable energy production is known as microgeneration [17]. According to Bayod-Rújula [18], some benefits associated with microgeneration are as follows: it avoids transmission blockages; a capital-intensive energy infrastructure can be substituted by resources focused on the microgeneration; and local production (on-site production) reduces transmission losses.

The diffusion of microgeneration technology has a positive appeal based on the demonstration of energy savings and cost reduction. Walters and Walsh [17] emphasized that consumers will have a financial benefit, such as a reduced electric bill or positive return on investment through more sophisticated calculations. However, Sauter and Watson [19] observed that small-scale buyers of renewable energy generation technology do not use rigorous economic evaluation methods to make their decisions regarding equipment acquisition.

This study aims to present a stochastic model of investment analysis in wind power microgeneration, which considers all the uncertainties inherent to the variables related to this type of investment. Furthermore, the study analyzes the uncertainties of wind speed behavior in three different regions of Brazil.

For this purpose, Monte Carlo Simulation (MCS) is used as a tool to perform the stochastic Net Present Value (NPV) analysis of the investment in microgeneration in each region, and finally, relevant hypotheses are tested to find whether the means of NPV have a significant statistical difference between the regions.

This paper is organized as follows: Section 2 discusses the policies for generation of renewable energy; Section 3 deals with the calculation of energy production by wind generators; Section 4 explains the analysis of economic feasibility; Section 5 presents the methodology proposed; Section 6 presents the results and discussions; and finally, Section 7 concludes the study.

2. Policies for generation of renewable energy

Wong et al. [20] state that policies promoting renewable energy encourage investors to provide clean energy to final consumers, and consequently create a sustainable development model. However, Walters and Walsh [17] state that concern about the environment is not enough to attract an investor to invest in this type of energy generation: financial incentives must be introduced. Furthermore, strategies may vary according to a country's economic, social, and territorial conditions [21].

Regarding these policies, Ragwitz et al. [22] consider that dynamic efficiency is an essential criterion to evaluate the success of RES adoption. Dynamic efficiency is understood as the capacity of a mechanism related to the generation of renewable energy to facilitate continuous advancement of technology and cost reduction. Appropriate incentive policies contribute to technological maturity in addition to acquiring the society's support to establish a sustainable consumption model. Through these factors, it becomes possible to pursue cost reduction for the generation of renewable energy and to achieve the goal of carbon emission reduction.

Mir-Artigues and Del Río [23] mention that these policies can be divided into two groups: long-term and short-term policies. Examples of long-term policies are as follows: (i) Feed-in tariffs: based on a fixed tariff by kWh or MWh generated, with an obligation of energy purchase by distributors or consumers already established; (ii) Quotas with green certificates: an obligation is established for energy consumption from renewable sources, with the demand being supplied by more efficient producers that receive certificates, creating an additional profit for green electricity generation projects; and (iii) Auctions: the government holds contests for renewable energy producers within a pre-established pricing limit or a maximum generation capacity. Today, this mechanism is most commonly used in Brazil, in which the producers offering energy at low prices are considered to supply energy to the interconnected national system [21,24,25].

Among the short-term complementary policies, Ayoub and Yuji [21] emphasize the following main strategies: direct subsidies for investment in the renewable energy project, fiscal incentives such as rebates or tax exemptions, in addition to a special financing line for green electricity generation projects, with lower interest rates than those in the market and long periods for amortization.

According to Bertoldi et al. [26], the most suitable way to reduce greenhouse gas emission, decrease energy dependence on fossil fuels, and fulfill the increasing demand for energy is to improve energy efficiency through technological improvements or create changes in the energy consumption standard. The energy savings obtained with these measures makes it possible to preserve scarce natural resources, since it gives access to the same goods and services with less consumption. In this sense, in order to reach the desired energy efficiency, energy generation by the consumer has become an alternative in many countries.

Bayod-Rújula [18] observes the trend of increasing liberalization of energy networks in many countries. This liberalization is characterized by open access to transmission networks and distribution to accommodate sources of distributed energy. The author describes a change in the control of energy flow from traditional energy systems with large companies and centralized services to a more liberalized system. In this case, very small amounts of energy are produced by small and numerous module conversion units that are often located next to the final usage point.

The liberalization of the electricity market creates a context in which electricity generation by individuals is possible. Because restriction by the central electric system controller is no longer necessary, small-scale generators can proactively generate their own energy supply and sell excess energy back to the system [17].

According to Yamamoto [27], electric energy generation has become attractive to many families. This can be partly attributed to the technological evolution that has helped in reducing the cost of renewable energy generation, such as solar and wind power. Moreover, several programs in many countries are motivating families to install residential systems to generate solar energy and wind power. The electricity produced in the residence can be sold for a favorable price through establishment of programs based on premium tariffs known worldwide as feed-in tariffs, systems for net metering, and purchase and sale of liquid energy.

Since the 2000s, Brazil has introduced different incentive strategies directed at RES, which has directly benefited the wind sector [28]. Among them, a recent net metering policy created in 2012 is microgeneration, which can benefit investors interested in producing small-scale wind power.

The National Agency of Electrical Energy (ANEEL) [29], the Brazilian agency that regulates the electricity sector in the country, introduced a net metering system with the objective of motivating small-scale RES energy generation. This mechanism is applicable to small-scale clean generation systems (up to 1 MW). Through this mechanism, the final consumer (a residence, business, or industry) was allowed to be an energy generator that utilizes energy sources based on hydraulic, solar, wind power, or biomass.

Net metering is an incentive mechanism for RES use, which allows the consumer unit to sell the excess energy that it produces. In this system, when there is excess production, the electric energy is injected into the network, which serves as an electricity storage [30,31]. For cases in which the consumption is larger than production, the unit is authorized to use the electricity supplied by the network. The energy produced and injected into the network is deducted from the amount of electricity consumed in the form of electrical energy credits (in kWh) rather than monetary units [30].

Considering the savings on electricity expenses that arise from the generated credits as income for the individual who invests in electric microgeneration, it is possible to apply a robust tool for the economic feasibility analysis of this type of project. As suggested in the literature, there are various risks associated with electric energy microgeneration projects [15,32,33]. Thus, a stochastic approach is needed to better analyze the feasibility of the process. For this purpose, the current study uses the MCS method.

3. Energy production calculation for wind power generators

Wind is apparently unpredictable. It comes from the continuous circulation of layers of air in the atmosphere. The main mechanisms are the action of solar radiation and the Earth's rotation. The uneven heating of the terrestrial surface can be emphasized among the mechanisms of wind formation. This occurs at a global as well as local scale. Because of this, wind speeds and directions have well-defined seasonal and daily trends within their stochastic character [34].

The wind can vary significantly within an interval of hours or days; however, in statistical terms, it will tend to have a predominant daily regimen, governed by local (microscale) and regional (mesoscale) influences. In monthly or yearly intervals, wind regimens are remarkably regular with a well-defined seasonal regimen. Throughout decades, in general, annual average speeds vary less than 10% of the long-term average [34].

Many studies in the literature base their statistical analyses for wind characteristics and energy potential on the supposition that the Weibull distribution is a suitable approximation for wind speed [32,35,36]. This is because of the easy estimation of the distribution parameters to approximate the empirical distribution of wind observations [35]. Furthermore, Weibull distribution has the best adherence to the most varied cases of wind regimens [37]. The probability density function of a Weibull distribution with two parameters is given by Eq. (1), as proposed by Justus et al. [38]:

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

where v represents the wind speed (m/s); k denotes the shape parameter; and C represents the scale parameter (m/s). Larger values of k indicate higher wind stability with fewer occurrences of extreme values [37].

A wind power turbine captures part of the wind's kinetic energy, which passes through the area encompassed by the rotor and is transformed into electrical energy. Electric power in watts is a cubic function of wind speed (v) given by Eq. (2) [39]:

$$P = \frac{1}{2}\rho A_r v^3 C_P \eta \tag{2}$$

where ρ represents the air density; A_r stands for the area encompassed by the rotor ($\pi D^2/4$, where D is the rotor diameter); C_P represents the aerodynamic coefficient of rotor power; and η denotes the efficiency of the generator-mechanical set and electric transmissions.

In line with Amarante [39], the following values were considered for the current study: $\rho = 1.225\ \text{kg/m}^3$; $D = 3.72$ m; and $\eta = 0.98$. According to Custódio [40], the C_P for a wind power turbine varies with the wind speed. From this premise, this study used regression calculated based on wind speed and the C_P value provided by the wind generator manufacturer. Eq. (3) presents the function obtained, which is a good adjustment ($R^2_{adj} = 90.5\%$), based on Hair Jr. et al. [41]:

$$C_P = -0,08114 + 0,1771v - 0,01539v^2 + 0,00034v^3 \tag{3}$$

Amarante et al. [37] mention that it is generally possible to accurately estimate the annual production of a wind power turbine, considering two Weibull distribution factors, k and C, plus the air average density. Thus, the Annual Energy Production (AEP) for a wind power turbine can be calculated by integrating power curves and the frequency of wind speed, according to Eq. (4):

$$AEP = 8,76\text{x} \int_{v_{\min}}^{v_{\max}} P(v) f(v) dv \quad (\text{kWh}) \tag{4}$$

4. Economic feasibility analysis

The feasibility analysis for decentralized renewable energy projects, including residential microgeneration of wind power energy, is made up of a sequence of different measures to identify, evaluate, and allocate project risks. According to Arnold and Yildiz [15], the objective of this procedure is to focus on factors that could impact a project's cash flow, in order to analyze—both quantitatively and qualitatively—the possible effects of an adverse event on the project's earnings, and consequently its feasibility. This type of analysis provides insights into the risk that small wind power projects for energy generation would not offer financial benefits to the investor.

Even though there are several methods to evaluate a project's financial feasibility, most studies in the literature focusing on the evaluation of feasibility for projects related to renewable energy generation use the NPV method [8,15–17,30,32,33,42–44]. In relation to other clean energy systems for residential purposes, some authors [5–7] perform the economic analysis from the NPV and other methods that use the discount rate. In addition, according to Johnson [45], the NPV is easy to understand, convincing, and practical, even to those involved in the project but have little knowledge about investment analysis. The NPV for time 0 is given by Eq. (5):

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} \tag{5}$$

where r represents the discount rate; t denotes the time in years; and CF_t stands for the liquid cash flow in year t.

Arnold and Yildiz [15] state that an NPV equal to zero indicates that the investor completely recovers the invested capital plus an appropriate interest rate. On the other hand, a negative NPV implies that the investment did not generate enough funds to compensate the opportunity costs. Projects with positive NPV generate funds above the expected average profitability. The authors argue that the discount rate r has a significant influence on NPV and serves as an indicator for the opportunity cost.

The different risk factors for the revenue derived from investment in wind power projects will be considered as random variables [32]. The deterministic method assumes that the input values for the cash flow are constant and does not consider the possibility of them varying over the life of the project. In the case analyzed, the input data for the cash flow are derived from variables such as the discount rate, the energy price charged by the distributor, and the cost of the initial investments in the microgeneration. Thus, there are uncertainties in all the analyzed variables, which may increase the investment risks of the project. These risks can only be analyzed through the stochastic method [8]. Therefore, the MCS method will be employed to calculate NPV, as proposed by Arnold and Yildiz [15].

This gives a probabilistic model with a range of possible values for each parameter and consecutive reproduction of an efficient number of random scenarios. The synthesis of all iterations generates a range of possible results [46]. Since an economically attractive project in this study has an NPV > *0*, at a certain *r*, the probability of feasibility is given by Eq. (6):

$$P_{NPV>0}(x_1 \ldots x_n;\, r) = \int_0^{+\infty} pdf\,(N\widetilde{P}V)\,dN\widetilde{P}V \tag{6}$$

where $P_{NPV>0}$ represents the accumulated probability of positive NPVs in the project; $pdf\,(N\widetilde{P}V)$ stands for the probability density function (pdf) of NPVs in the project ($N\widetilde{P}V$); and x_i represents the project's random variables.

The *r* of the residential wind power microgeneration project will be equivalent to the Weighted Average Cost of Capital (WACC). According to Ertürk [33], the WACC is obtained through the following calculation in Eq. (7).

$$WACC = k_d D(1-\tau) + k_e E \tag{7}$$

where k_d represents the cost of debt; *D* denotes the weight of debt applied to the investment (%); τ stands for the income tax; k_e represents the cost of equity; and *E* denotes the weight of equity in the investment (%).

In the current study, which deals with residential microgeneration, Eq. (7) was modified in order to eliminate the influence of the discount regarding income tax, creating Eq. (8).

$$WACC = k_d D + k_e E \tag{8}$$

Following Ertürk [33], Eq. (9) was used to calculate the cost of debt:

$$k_d = R_f + pRisk + R_B \tag{9}$$

where k_d represents the cost of debt; R_f stands for the risk-free rate; *pRisk* denotes the debt risk premium; and R_B represents the country's risk premium.

For the calculation of cost of equity, the Capital Asset Pricing Model (CAPM), which was originally presented by Sharpe [47], was employed, adding the country risk premium similar to that adopted by Ertürk [33]. Eq. (10) presents the CAPM model for the current study:

$$k_e = R_f + \beta(R_M - R_f) + R_B \tag{10}$$

where R_f represents the risk-free rate; β denotes the leveraged beta (equity beta) and measures the project risk in regards to the market; R_M stands for the expected market return; and R_B represents Brazil's risk premium.

The leveraged β was calculated from the unleveraged β for the renewable energy sector, which is given in the sector beta table by Damodaran [48]; the value is 0.70. The procedure to obtain the leveraged beta is presented in Eq. (11) [49]:

$$\beta_{leveraged} = \beta_{unleveraged}(1 + D/E)(1-\tau) \tag{11}$$

where *D* represents the weight of debt capital applied to the investment (%); *E* denotes the weight of equity in the investment (%); and τ represents the income tax.

Since the current study deals with residential microgeneration, Eq. (11) was modified in order to eliminate the influence of the discount due to income tax, as was done for WACC. Eq. (12) presents the calculation for leveraged β in the current study:

$$\beta_{leveraged} = \beta_{unleveraged}(1 + D/E) \tag{12}$$

Regarding R_f, based on the US Treasury bond, a value of 3.17% was adopted, as presented by Ertürk [33]. Concerning R_B and *pRisk*, the adopted values were those indicated in the ANEEL technical note [50], as follows: R_B = 2.62% and *pRisk* = 3.37%. Finally, R_M was calculated through the sum of the market risk premium (7.56%) presented by ANEEL [50] and the R_f (3.17%), resulting in R_M = 10.73%.

If the proportion of *D* equal to 50% and that of *E* equal to 50% are considered, then k_d = 9.16%; k_e = 16.37%. Considering the North American inflation rate as 2.41% [50], the deflated costs of debt and equity are respectively k_d = 6.59% and k_e = 13.64%. In this situation, the WACC would be 10.11%. Similar to Ertürk [33], the expected inflation in the US is used, because all costs and electricity tariffs are calculated in US dollar.

5. Materials and methods

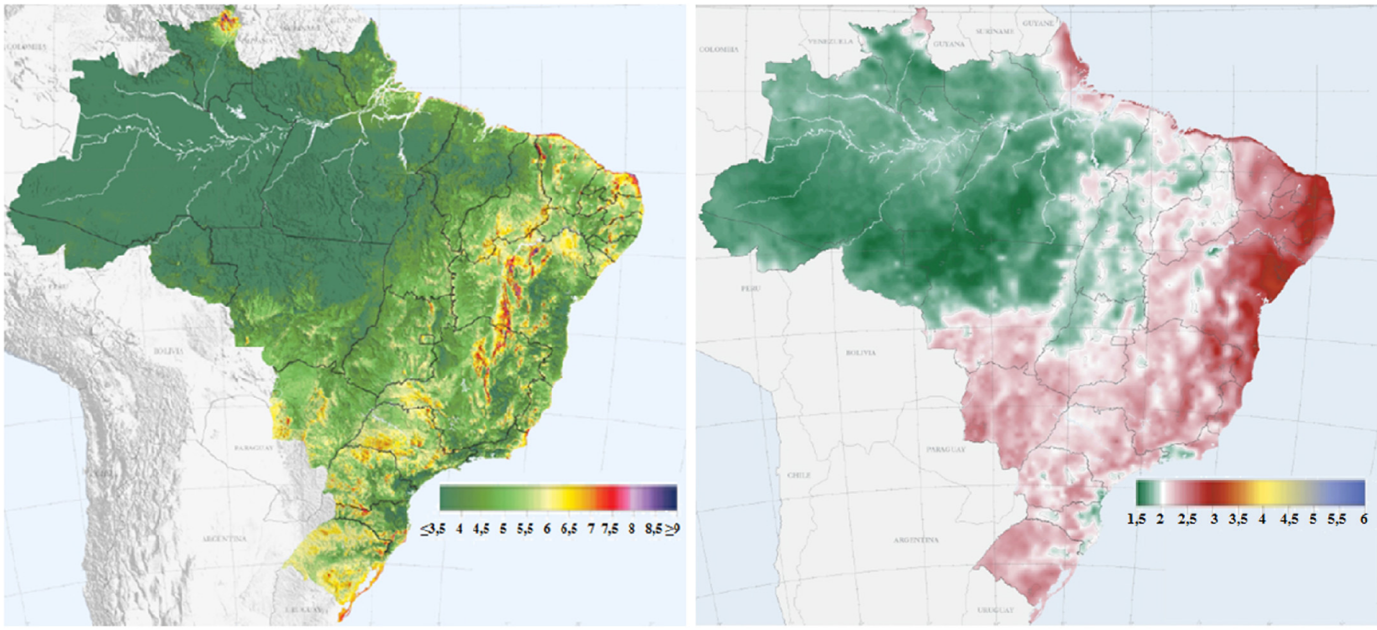
The method employed in this study is characterized as modeling and simulation, since cash flows will be modeled for a residential wind power generation project for different periods considering various financial premises. The MCS, which includes the uncertainty involved in the existing project variables, was used to generate 10,000 simulations for the NPV of the project being analyzed.

Among the variables that influence cash flow, the residential electricity tariff (B1) and its interaction with the distribution probability of wind speed are fundamental to calculate energy savings obtained by installing the wind power generator. In order to obtain data on the electricity tariff paid by the residential consumer, tariffs charged were collected up to May 2016 from 40 electric energy distribution companies that work in different regions of the country. These tariffs are determined by the regulatory agency, ANEEL. The data collected were used to compose the parameters of a triangular distribution for the electricity tariff, in which 0.16438 and 0.11487 are the largest and smallest values found respectively, and 0.13137 is the mode of the values collected; the annual tariff readjustment is set as 2.3%, in line with Holdermann et al. [30].

The financing obtained for the acquisition of the wind power generator was considered to be equivalent to the cost of debt (k_d). Inflation was deducted from the price mentioned previously, since the investment analysis is conducted without considering the inflation throughout the periods. The amortization system chosen for this type of financing was the Constant Amortization System (CAS). For the simulation in this study, the capital structure is assumed to vary from 0% to 100% of the weight of debt, considering that the investor has free will to either use or not use the project funding. The deadline for debt period payment is also considered as a variable in MCS. A uniform distribution with a minimum of 5 years and a maximum of 25 years is considered for this parameter. These values were obtained from Rocha et al. [8] and are consistent with the housing funding practices involving sustainable technologies in the Brazilian market.

The investment considered involves the purchase of a wind power generator with a capacity of 2.4 kW, diameter of 3.72 m, and designed for a lifetime of more than 20 years without maintenance, which is easily found on the market. In relation to the life cycle of the mini wind turbines, a triangular distribution was defined based on the lifetime of the main mini wind turbines found on the market, with 20 years being the shortest and most probable lifetime and the maximum lifetime being 25 years.

The investment value is another variable involved in the project feasibility analysis. An uncertainty is incorporated into the cost corresponding to the wind power generator. To estimate the investment values, we consulted the main manufacturers involved in the commercialization of mini wind turbines in the Brazilian market, using the lowest, the highest, and the mean values, as the most probable value of the distribution. Thus, a triangular distribution was adopted with



(a) Average annual wind speed (m/s) (b) Weibull shape factor-annual average

Fig. 2. Wind speed and Weibull distribution parameters. Source: Amarante et al. [37].

values of US$15,000.00, US$20,000.00, and US$25,000.00, compatible with prices for this type of wind power generator on the market, considering the costs for structural modifications to the installation of equipment.

As mentioned previously, turbine power is a cubic function of wind speed. This variable is fundamental to determine the power of generated energy, and consequently, the energy savings obtained by the investor. The uncertainty regarding the wind speed variable is also incorporated. The Weibull distribution was employed for this purpose with different values for the scale parameter (C) and shape factor (k). Amarante et al. [37] presented the values of average annual wind speed and Weibull shape factor for different regions in Brazil, as shown in Fig. 2.

Based on Fig. 2, three regions were defined with different behaviors for the statistical distribution of wind speed: (1) a region with high wind speed in the northeast with the Weibull distribution parameters of $\bar{v} = 7$ and $k = 3$; (2) a region with low wind speed in the Amazon with the Weibull distribution parameters of $\bar{v} = 3.5$ and $k = 1.7$; and (3) a region with intermediate wind speed in the rest of the country with Weibull distribution parameters of $\bar{v} = 6$ and $k = 2.3$. Now using the parameters $\bar{v}$ and k, the Weibull parameter C can be found by calculating Eq. (13) [51]:

$$C = \frac{\bar{v}}{\Gamma\left(1 + \frac{1}{k}\right)} \tag{13}$$

where C represents the scale parameter; $\bar{v}$ denotes the average wind speed; Γ stands for the gamma function; and k represents the shape factor.

According to Islam et al. [51], using the Stirling approximation, the gamma function of (x) can be given by Eq. (14), where x is an exponential random variable greater than zero; and u is the time interval in which the given event occurs:

$$\Gamma(x) = \int_0^{+\infty} e^{-u} u^{x-1} du \tag{14}$$

The values of C are found using Eqs. (13) and (14). These values are 7.839, 3.924, and 6.772 for regions 1, 2, and 3, respectively.

Amarante et al. [34] show the values of $\bar{v}$ and k for a 50 m height. However, since the current study focuses on residential generation, it assumes that energy would be produced at a height of 20 m. Wind behavior changes with height, which results in changes of form and scale factors of Weibull distribution. Thus, these parameters are determined by Eqs. (15) and (17) [40].

$$C_2 = C_1\left(\frac{h_2}{h_1}\right)^n \tag{15}$$

$$n = \frac{0.37 - 0.088\cdot \ln(C_1)}{1 - 0.088\cdot \ln\left(\frac{h_1}{10}\right)} \tag{16}$$

$$k_2 = k_1\left(\frac{1 - 0.088\cdot \ln\left(\frac{h_1}{10}\right)}{1 - 0.088\cdot \ln\left(\frac{h_2}{10}\right)}\right) \tag{17}$$

where h_1 represents the reference height (m); h_2 denotes the desired height to estimate the parameters of Weibull (m); c_1 represents the scale factor in h_1; c_2 denotes the scale factor in h_2; k_1 stands for the form factor at height h_1; k_2 represents the form factor at height h_2; and n denotes the exponent of Eq. (15).

Using Eqs. (15) and (16), the presented values were adjusted for a height of 20 m. These values are 6.408, 3.005, and 5.460 for regions 1, 2, and 3, respectively. Using Eq. (17), the k values are 2.742, 1.554, and 2.102, for regions 1, 2, and 3, respectively.

Based on the definition of these regions, three different scenarios were created for the project feasibility analysis.

Considering the information stated, some parameters in MCS are assumed as fixed, some are probabilistic, and some are calculated using other parameters. The suppositions about the parameters are shown in Table 1.

Finally, it is worth mentioning that the software Crystal Ball® was employed to perform the MCS. The NPV value was determined for prevision, which will indicate whether the investment is feasible or not. Using the MCS, it was possible to verify the probability that the NPV would be positive, that is, the chance of project feasibility.

6. Results and discussion

After preparation of the project cash flow throughout the equipment

Table 1
Probability distribution and definition of parameters for input variables.

Parameter	Distribution	Minimum	Maximum	More Probable
Investment (US$)	Triangular	15,000.00	25,000.00	20,000.00
Equipment life cycle (years)	Triangular	20	25	20
Energy price (US $/kWh)	Triangular	0.11487	0.16438	0.13137
Annual electric price adjustment (%)	Fixed			
Wind speed (m/s)	Weibull			
Annual energy production (kWh)	Calculated			
Payment deadline (years)	Uniform	5	25	
Weight of debt (%)	Uniform	0	100	
Weight of equity (%)	Calculated			
Cost of debt (%)	Calculated			
Cost of equity (%)	Calculated			
WACC (%)	Calculated			

life cycle, 10,000 simulations were conducted for the NPV, considering the probability distributions for the variables shown in Table 1.

Fig. 3 shows that the feasibility probability for the wind microgeneration project varied significantly among the regions. Scenario 1 (high wind speed) produced a feasibility result of 22.04%; Scenario 2 (low wind speed) produced a result of 1.51%; and Scenario 3 (intermediate wind speed) produced a result of 15.06%. These results indicate that investment in residential wind power generation has a low feasibility probability, even for Scenario 1, in which the best parameters for wind speed distribution were considered. Holdermann et al. [30] also found low feasibility indices when analyzing the project for residential and commercial solar energy generation in Brazil.

It can be observed that the country has regions in which wind speed favors this type of generation. Nevertheless, complementary policies, especially financial policies, are necessary to strengthen ANEEL's initiative to motivate small-scale RES generation.

Considering NPV values, the averages of US$ −6900.13, US$ −16,151.70, and US$ −9630.87 were obtained for scenarios 1, 2, and 3, respectively. The average annual energy production was 7843.71 kWh, 1303.88 kWh, and 5863.72 kWh for the three scenarios, respectively. Table 2 shows the descriptive statistics for NPV distributions that were generated in each scenario.

In order to compare the mean values between different scenarios and identify the presence of statistically significant differences between one NPV mean and the others, ANOVA was used, and the results are presented in Table 3.

The results of ANOVA reveal a statistically significant difference between the means of NPV in the regions. Thus, as demonstrated by Aquila et al. [52] it is possible to infer that the wind potential between different regions of Brazil are very distinct with specific characteristics in each location.

Regarding the sensitivity analysis, in Scenario 1, the most impactful variable in the NPV was the wind speed. Except in Scenario 1, which has the highest average wind speed, it is noted that the most impactful variable was investment. From this result, it can be inferred that policies to reduce the cost of technology for wind power generation, such as tax exemption for the supply chain sector, are important. Fig. 4 shows the tornado graph for the scenarios analyzed.

When analyzing wind energy microgeneration in the UK, Walters and Walsh [17] found a significant influence of the wind power generator cost, energy production, and government incentive that is also referred to as capital grant. Results from this study are very close to those found in the current study. Regarding investment cost, in addition to the elevated cost for small-scale generation, there is a fluctuation in equipment prices due to the lack of maturity and the fact that there is

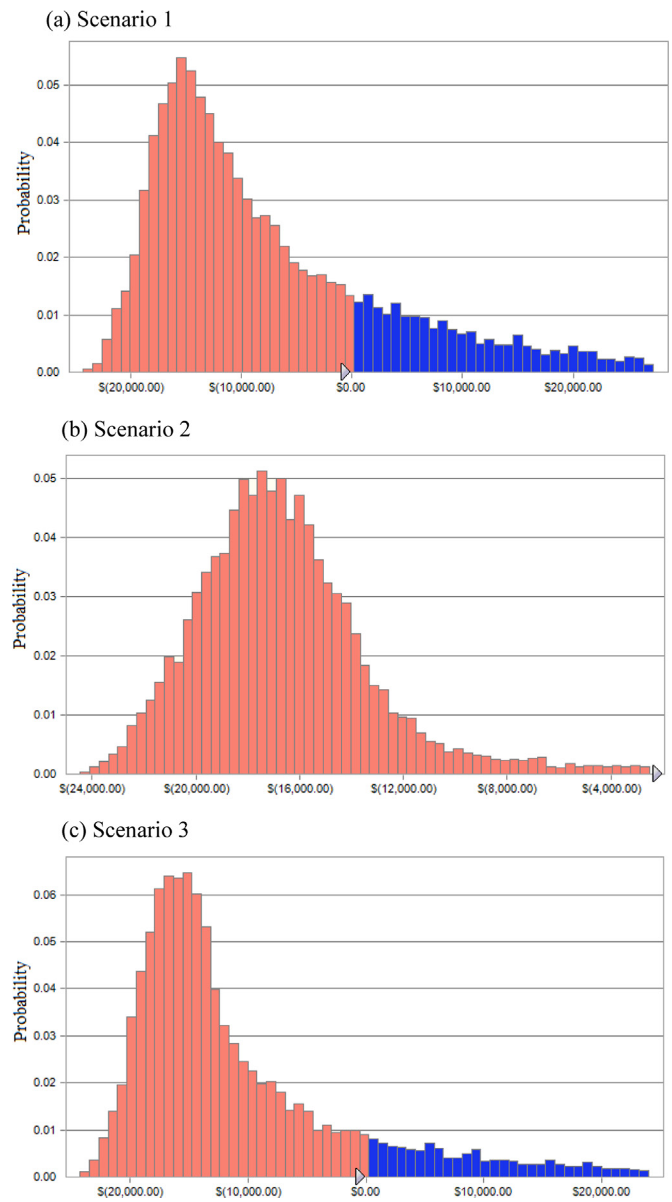


Fig. 3. Probability distribution for the NPV in each analyzed scenario.

Table 2
Descriptive statistics for NPV distribution in each scenario.

Characteristic	Scenario 1	Scenario 2	Scenario 3
Minimum	(US$ 24,296.69)	(US$ 24,453.70)	(US$ 24,221.01)
Average	(US$ 6900.13)	(US$ 16,151.70)	(US$ 9630.87)
Median	(US$ 10,826.11)	(US$ 16,920.01)	(US$ 13,835.57)
Maximum	US$ 58,881.89	US$ 39,584.30	US$ 68,879.92
Standard deviation	US$ 12,179.27	US$ 4869.58	US$ 11,992.97
Asymmetry	1.56	3.35	2.22
Kurtosis	5.68	23.17	9.04

Table 3
Results of ANOVA test comparing NPV mean in each scenario.

Scenario	P-value
Scenario 1 × Scenario 2	< **0.05**
Scenario 1 × Scenario 3	< **0.05**
Scenario 2 × Scenario 3	< **0.05**

Note: Values in bold represent statistical significance.

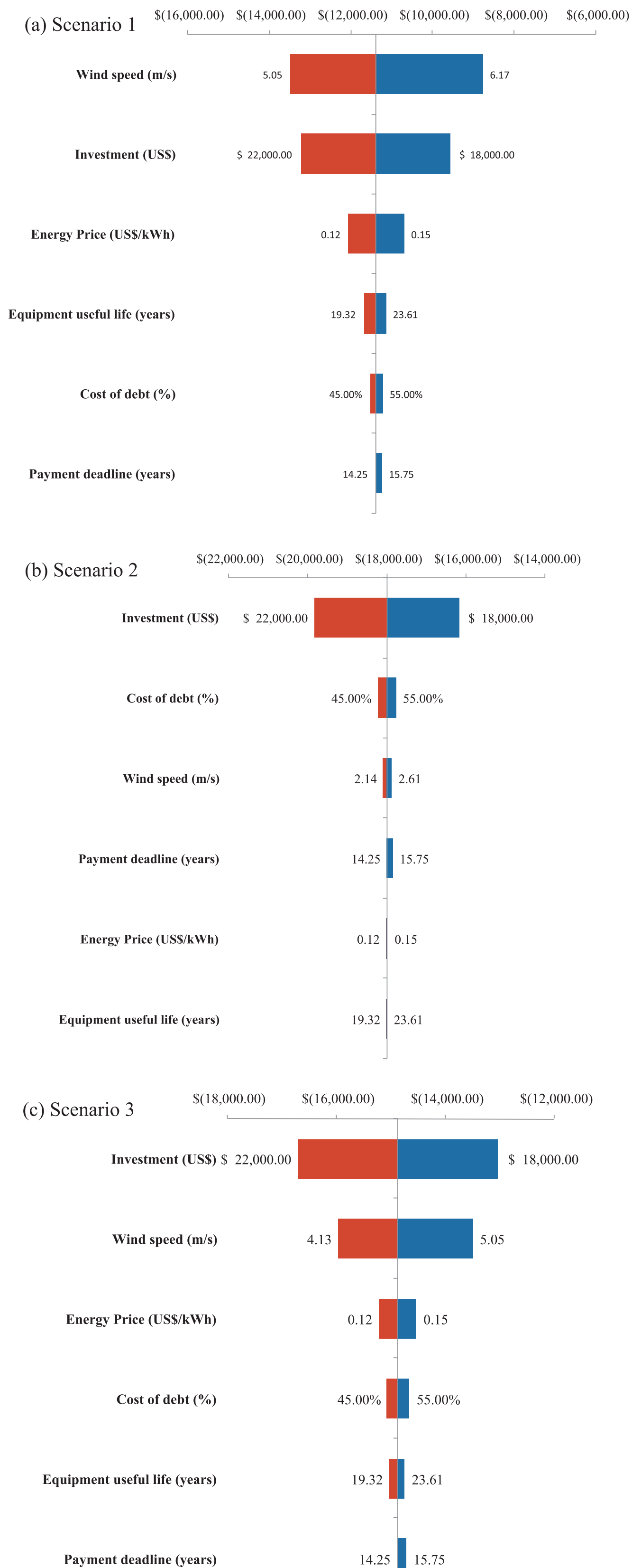


Fig. 4. Tornado chart for the sensitivity analysis results.

little dissemination of technology for small-scale generation. Thus, this technology must become less expensive and the uncertainty regarding price fluctuations must be decreased to leverage residential generation of wind power.

The results shown in the tornado chart reinforce the observation of Boomsma et al. [53], who claim that the cost of the initial investment is an important source of uncertainty for the renewable energy product. The authors attribute this to the fact that projects based on renewable energy are more capital intensive than conventional technologies. In the case of wind energy, the cost of the technology related to the wind turbines constitutes a significant portion of the investment value [54]. Thus, as Juárez et al. [55] argue, government involvement in creating tax incentives is important to support the growth of the wind industry in the country. In particular, the Brazilian government must consider a reduction of high import taxes, since the technology used in Brazil is manufactured by foreign companies established in the country [28].

It is also observed that in the region where wind speeds are lower, which is described in Scenario 2, other variables become more relevant, such as the percentage of weight of debt, which is directly linked to discount rate and the financing cost. In these circumstances, government support for expansion and implementation of this type of electric energy generation would be fundamental in order to minimize the investor's risk. Consumers interested in making this type of investment must pay very high interest rates to finance the equipment, which inhibits the use of domestic wind power generators. Thus, more adequate financial assistance for this type of investment is necessary to complement the policy adopted by ANEEL.

However, contrary arguments are also found in the literature. As defended by Walters and Walsh [17], if the production of renewable energy is always protected against market forces, it will never be forced to compete with lower cost alternatives, which will limit its technological development and efficiency, causing it to stagnate.

Finally, energy price significantly impacted the NPV in scenarios 1 and 3. The debt payment period and lifetime had little impact on the NPV for all the three scenarios analyzed within the amplitude used in this study.

7. Conclusions

The main purpose of this study was to present an investment analysis for those investing in micro generation technologies, which is capable of associating both the uncertainties related to the financial assumptions and wind speed behavior. That is, the analysis made in the study can capture the uncertainty of an environmental variable to measure the risks of investment in microgeneration of wind energy. The results of the study may also be useful in guiding regulators in the electricity sector and the wind energy market. Furthermore, the study developed mechanisms and incentive strategies to complement those already existing in the Brazilian wind energy market.

The highest probability of financial returns in the scenario with the highest average wind speed indicates that the wind potential of the region is critical to the feasibility of wind generation in residential context. However, the results of the sensitivity analysis for scenarios with low and intermediate average wind speed show the substantial importance of the value of investments so that technology becomes financially more attractive. This result infers that it is essential to subsidize this technology and decrease the uncertainty of price fluctuations in order to leverage residential wind power generation.

The sensitivity analysis for Scenario 2 showed that the weight of debt had a relevant impact on the NPV project results. Thus, lower interest rates for projects of this size can attract greater investment in residential wind power generation. With more advantageous funding, rather than inhibiting the dissemination of microgenerators, the demand for this technology would increase, thereby reducing the cost and encouraging frequent usage of residential wind power.

The low feasibility of projects indicates that appropriate policies are needed to propagate wind power microgeneration. A possible strategy could be the adoption of a feed-in-tariff system offering a specific payment baseline in each region for the kWh generated by the consumer. This type of strategy would enable the installation of microgenerators throughout the country, allowing manufacturers to offer their equipment in multiple locations. This would result in an increase in equipment production and create more jobs in the sector.

Even though the risks and uncertainties for an investor in this type of generation are not completely neutralized through the ANEEL initiative, the policy can be considered as the first step to promote the use of this technology. The countries that most benefit from green electricity generation are those that maintain, discuss, and improve their incentive programs for small- and large-scale generation projects.

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