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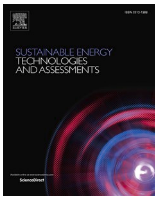

Original article

Wind energy investments facing uncertainties in the Brazilian electricity spot market: A real options approach

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ABSTRACT

This study proposes a Real Options approach to investigate the economic feasibility of a wind power plant investment with the option of abandoning along the project life cycle. This novel approach considers uncertainties representation concerning electricity sales revenue in the spot market, and the uncertainty represented by the settlements of energy trading differences. Our results show that when considering these uncertainties, the abandonment option adds 30.3% to the value of the project, and the chance of not abandoning it until the end of the useful life is equal to 70.9%.

Introduction

Renewable energy sources (RES) for electricity generation provides a variety of benefits for electric power systems and society. Among these benefits, the most critical are the reduction of greenhouse gas emissions and the low operational and maintenance (O&M) costs over the project lifetime cycle [1]. Moreover, RES are indispensable to supply electrical power systems to achieve sustainable development goals.

Even though investments in RES are capital intensive, such processes have been supported in the past through incentive policies in different countries, which has contributed to the worldwide growth of RES electricity generation [2–4]. Although for remote off-grid systems, investments in RES has always been technically viable and an economic alternative [5–7], the RES on-grid systems investments became more competitive nowadays, due to the reduction in technology prices and efficiency improvements. This can be observed in recent deployment plans, for example, in the United States, 64% of the total 24 GW of new generation investments were destined to RES in 2019 [8]. The correct representation of RES capital and operational cost trajectories are fundamental for long-term energy planning studies [9].

In this context, wind power is a RES generation that increased the contribution to electricity generation over time [10–11]. In Brazil, for example, wind power has grown significantly regarding the participation in the electricity matrix [2,12–13], growing from 602 MW in 2009 to 14,401 MW in 2019 [14].

Historically, Brazil has experienced a hydro-dominant electricity matrix, where hydro resources corresponded to approximately 85% of the available electricity supply [15]. However, events such as the blackouts between 2001 and 2002 and, more recently, a drought in 2015, which affected mainly states in the South and the Southeast regions of the country, have motivated the diversification of the electricity portfolio and the use of other RES [16,17].

The first incentive policy directed to the wind power sector in Brazil appeared between 2001 and 2002 [18]. The first actions were based on programs related to feed-in tariffs mechanisms, and it was named as the Emergency Wind Energy Program (PROEÓLICA), whose objective was to promote an alternative model for economic, social, and environmental development based on wind power [19]. However, PROEÓLICA

Abbreviations: RES, Renewable energy sources; NPV, Net Present Value; RO, Real Options theory; MCS, Monte Carlo Simulation; PG, Physical guarantee; WACC, Weighted Average Cost of Capital; MEP, Monthly estimated energy production.

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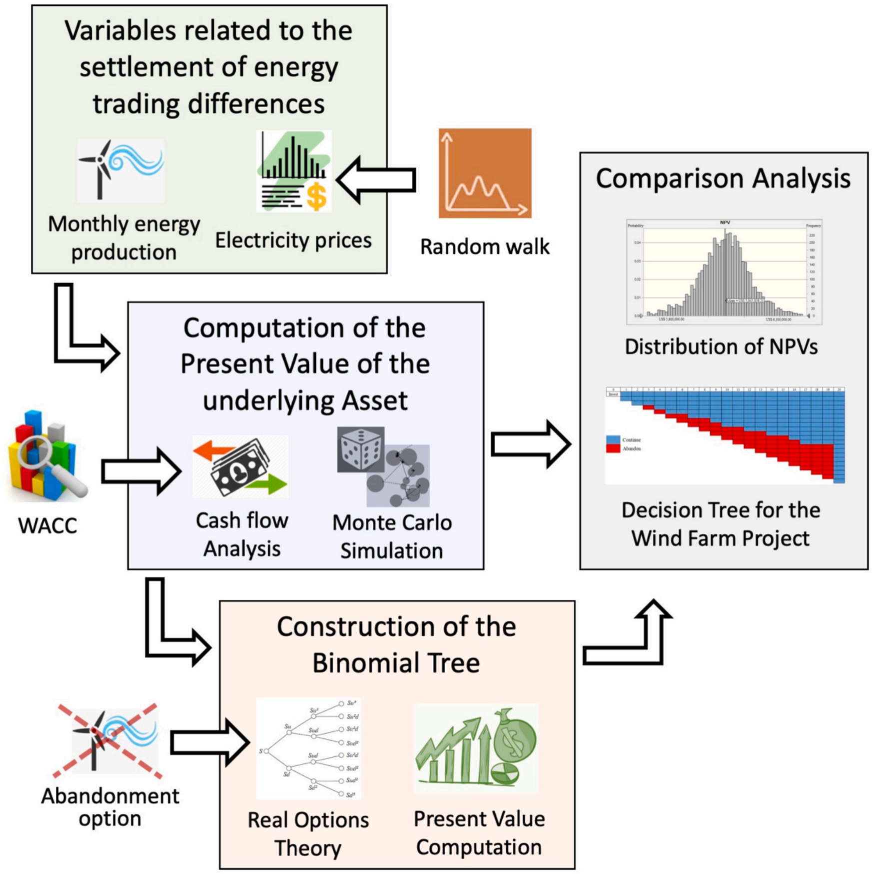

Fig. 1. The proposed framework for Wind Power Investment Analysis.

was closed in 2002, when wind power was included in the Alternative Sources Incentive Program (PROINFA). The PROINFA was developed to promote a regulatory structure for RES power investments, and it also supported the electricity generated by small hydro plants and biomass [20,21].

Since the PROINFA creation, wind energy has grown in the Brazilian electricity matrix [2]. In 2009, when the first long-term auction directed to promote wind energy participation occurred, wind power revealed strong competitiveness and started to increase the share in the Brazilian electricity generation [22].

More recently, wind farms started to be traded in the Brazilian spot market. Until February 2019, wind farms in the spot market represented approximately 17.5% of the total wind power capacity installed. The work presented in [23] explains that in the Brazilian electricity spot market, bilateral contracts are flexible and negotiated between wind power producers and energy buyers. These direct negotiated and flexible contracts allowed investors to have better opportunities to trade electricity, making the investments more economically attractive.

In the Brazilian electricity market, the entire demand of both the plants contracted in auctions and the spot market (from captive and free consumers) have to be 100% covered by electricity trading contracts (settled either in the regulated or free-market) [24]. As the settlement of generation differences is also priced at the spot price, it can be considered that spot price corresponds to an important uncertainty source so that the projects present a value negotiated in the spot market.

Due to the hydro-dominant characteristics of the Brazilian power system, the spot price values reach low levels in periods with abundant rainfall. However, during periods of drought, thermal plants with high marginal operating costs can be dispatched, increasing the spot prices. In some cases, jumps in spot prices may occur, causing an increase in the prices established in bilateral contracts as well as in the settlement value associated with the energy trading differences.

However, investors and governments show a substantial interest in increasing the negotiation of wind and other RES in the spot market. Investment analysis and decision-making related to RES generation projects devoted to selling energy in the spot market are complex. These investments are irreversible, and there are underlying characteristics such as uncertainty in resource quality, technology prices, spot prices, macroeconomic factors (e.g., exchange rate and commodity prices), and policies that differentiate them from other types of investments [25,26].

The Net Present Value (NPV) is a commonly used financial criterion to evaluate RES investments. However, in circumstances where flexibility is present in the project, the NPV disregards the value created by options and underestimates opportunities and, consequently, the real project value [27–29]. To overcome this limitation, the literature has been using Real Options theory (RO) as a method capable of evaluating the generation of RES projects in the face of uncertainty and irreversibility. In such circumstances, RO evaluates investments considering that decision-makers have the option of postponing their decision on irreversible investments [25].

RO theory to evaluate wind power investments has been modestly addressed in the literature. From the few available references, most applications are concentrated in exploring the European electricity markets, where RES are already well established. For example, in [30], the investment value of small wind turbines to be deployed in the Nordic region and uncertainties related to selling electricity to the market is evaluated.

The study presented in [31] shows the flexibility value provided by the option of abandoning, postponing, or expanding wind farms in Europe. In [32], the study analyzes a decision to invest in a wind farm in Europe regarding a feed-in tariff and tradable green certificates policy. In [33], six case studies considering the waiting and abandonment options for wind farms in the Spanish scenario is presented. In [34], the authors determine the value of the abandonment option for a wind farm during the development phase as a function of energy prices in Denmark. In [35], they compare the wind farm value, taking into account real options considering different regulatory environments in three European countries.

Only a few references are available considering RO in the context of other regions. In [36], options value for hybrid generation plants (wind-diesel) in Japan are evaluated; and the work presented in [37] investigates the expansion option at different scales for a wind farm concerning the uncertainty in the United States. About the Brazilian context, the work presented in [23] highlights the A-5 long-term energy auctions, where the authors evaluate an option that can provide a possibility to trade wind electricity in the spot market to investors before the initial contract agreement date. In [38], it is emphasized that most RO research refers to external or exogenous uncertainties, and the authors also point out that there are endogenous uncertainties that affect only specific types of projects, and they should not be neglected.

The main contribution of this study is to present a structure for a robust analysis of investment feasibility in RES generation projects that can be used to support decision-making. In this novel approach, a deterministic analysis is complemented by a risk analysis by employing Monte Carlo Simulation (MCS) and the incorporation of the value of managerial flexibility, using RO theory, provided by uncertainties associated with spot prices.

In this case, the uncertainty of electricity sales revenue represents an uncertainty to the RES project, and another uncertainty is related to the calculation of the settlements of energy trading differences. A mean-reverting process with jumps is used to predict the spot prices, bringing the real characteristics of this variable. The approach is then applied to evaluate the abandonment option to a wind farm project in the Brazilian electricity spot market. To do so, the volatility of the project's market value is represented by the spot market price volatility, and the present value of the project is calculated from a cash flow analysis considering the estimated generation differences.

Materials and methods

The proposed method to estimate the Present Value (PV) of a wind farm, considering that three steps construct an option of abandonment. The first step is directed to calculate the variables related to the settlement of the energy trading differences. In this case, monthly energy production values are initially estimated, and then a random walk representing the behavior of monthly electricity spot prices is constructed.

The second step structures and computes the PV of the underlying asset, considering the settlement of the energy trading differences. The PV of the underlying asset is estimated by using the cash flow method associated with the value created for the company [39]. Thus, the PV of the wind farm project is calculated using the Monte Carlo Simulation (MCS), which generates random walks of the monthly electricity spot prices.

The third and final step involves the construction of the binomial tree model that is used to compute the value of the asset considering the abandonment option. In this step, we also devise comparisons of the wind farm project PV, discounted by a risk-free rate, with and without considering the abandonment option. The flowchart illustrated in Fig. 1 represents the three steps considered to construct the proposed approach for RES investment analysis considering options.

Wind energy generation

Wind power has intra-temporal variability concerning available resources. This characteristic affects the skills of forecasting models designed to predict wind energy generation. However, forecast accuracy is key for energy trading and planning [40]. Wind formation occurs from the circulation of air layers in the atmosphere [41], where the main factors that influence the circulation of the air layer (at both global and local scale) are the solar radiation and the Earth rotation. Because of this reason, wind speeds and directions have well-defined yearly and seasonal trends.

The wind is transformed into electricity using a turbine that captures part of kinetic energy when wind passes through the area covered by the turbine rotor. The wind power is obtained as a function of the cubic wind speed [42,43], as indicated in Eq. (1).

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

where: P is the wind power in (W); ρ is the air density (kg/m^3); A_r is the area encompassed by the rotor (m^2); v is the average wind speed (m/s); C_P is an aerodynamic coefficient of rotor power (unitless); η is the efficiency of the turbine/generator set and electricity transmission losses (%).

The wind electricity can be calculated by the product between the wind power estimated by Eq.1 and operating hours of the wind farm turbines. Considering 8760 h of operation during a year, and Eq. (2) can compute losses due to unavailability and technical issues in the Brazilian transmission system, equal to 3% and 4%, respectively [44], the annual wind electricity amount.

$$E_{pw} = \frac{8760 \times 0.93}{2}\rho A_r v^3 C_p \eta \tag{2}$$

where: E_{pw} is the wind electricity (MWh).

For wind electricity conversion, it is important to analyze the vertical wind behavior in the surface boundary layer, where wind turbines are usually located. In this sense, the roughness length (z_0) is the average height of the soil protrusions, responsible for the frictional force that opposes the movement of the air mass, resulting in a reduction of the wind velocity near the surface of the soil [45]. Therefore, it is possible to infer that by the influence of the viscosity of the air in contact with the ground, it gives rise to a wind profile, whose speed varies with the height. To determine the wind speed at another height, it is possible to use the logarithmic wind speed behavior, as indicated by Eq. (3):

$$\frac{v_1}{v_2} = \frac{ln\left(\frac{h_1}{z_0}\right)}{ln\left(\frac{h_2}{z_0}\right)} \tag{3}$$

where: h_1 is soil height at point 1 (m); h_2 is soil height at point 2 (m); v_1 is wind speed at point 1 (m/s); v_2 is wind speed at point 2 (m/s); z_0 is roughness length at the site (m).

Another detail is the fact that the wind turbine C_p varies according to the wind speed. Using the data from each C_p of a wind turbine for each wind speed, it is possible to construct a model that estimates the wind turbine C_p as in [42]. The wake effect is also a technical aspect that occurs when the wind passes through a turbine and goes towards a second turbine located behind. When this occurs, there is a reduction in wind speed and an increase in turbulence from the first to the second turbine [46]. However, in this study, a real wind farm was not analyzed, and commercial software was not used for wind farm modeling. Wind electricity was estimated using a model developed in *MS Excel*® worksheet, using *Crystal Ball*® to implement MCS to estimate the input for investment analysis. Therefore, for this case, the turbulences caused by eventual wake effects were not considered. Nonetheless, for practical implications, it is recommended to use advanced tools to assess the impact of this phenomenon.

Real options evaluation using the binomial model

The traditional NPV method does not consider managerial flexibilities. Moreover, this method only represents a difference in net cash flow returns, discounted from the future periods related to the initial

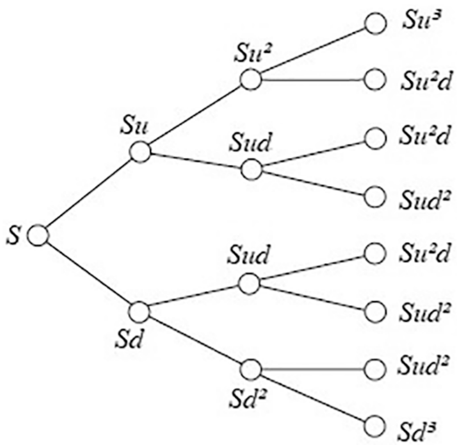

Fig. 2. Binomial tree for a three-stage decision problem.

investment, as indicated in Eq. (4).

$$NPV = \sum_{t=0}^{N} \frac{CF_t}{(1+\mu)^t} \tag{4}$$

where: t is the time; CF_t is the cash flow at period t; μ is the discount rate.

Through MCS, uncertainties related to NPV estimative can be incorporated. MCS is performed through numerous iterations, using the different values randomly selected for the uncertain parameters. In turn, RO is the application related to financial options evaluations to real projects analyzed [47,48].

The main purpose of RO is to identify and evaluate options that managers must adjust their investment decisions, given the uncertainties that are intrinsic to a problem [49]. Therefore, RO recognizes the managers' flexibility in modifying projects, intending to maximize profit and minimize risk in a dynamic environment [35].

The most popular and transparent RO method is the binomial model [50]. This model is based on a simple discrete-time option pricing model, approximating a continuous stochastic process [51]. The model assumes that an underlying asset (S) has a PV in period (t), and it can assume two values in the following period ($t + 1$). The value of the underlying asset is subject to variations, and it is multiplied by an upward (u) or a downward (d) factor in each period (Δt). The factors u and d are calculated from underlying asset volatility (σ) and the expiration period of the option (Δt).

The formulation for factors u and d is described in Eqs. (5) and (6), respectively:

$$u = exp^{\sigma\sqrt{\Delta t}} \tag{5}$$

$$d = \frac{1}{u} = exp^{-\sigma\sqrt{\Delta t}} \tag{6}$$

where: u is the upward multiplicative factor (up); σ is the volatility of the underlying asset; Δt is the option expiration time; d is the downward multiplicative factor (down).

At each period, the asset can only assume two alternatives (rise or fall), with probabilities p and 1-p, respectively. For the probability calculation, besides the values of σ, Δt, u, and d, a risk-free rate (r_f) is also used. However, since the binomial model is a discrete-time approach that approximates a continuous-time stochastic process, it is common to use a continuous-time risk-free rate (r_{fc}), calculated by ln $(1 + r_f)$. From these variables, it is possible to obtain the risk-neutral probability, whose calculation is presented in Eq. (7).

$$p = \frac{e^{r_{fc}t} - d}{u - d} \tag{7}$$

where: p is upward probability; r_{fc} is the risk-free rate.

After determining all parameters, an option value can be calculated from a binomial decision tree. The constructed binomial decision tree is then solved using stochastic dynamic programming, where the period analysis is divided into intervals, and the backward calculation technique is employed to define the best decision for each possible situation [52]. Fig. 2 shows a binomial tree for a simple three-stage decision problem.

The backward procedure starts from leaf nodes, determining at each node whether it is optimal to exercise the option (X) or not, and it proceeds backward in time until the node represented by the initial time ($t = 0$) is reached [52]. Eqs. (8) and (9) describe the calculations for the value of the option at each stage.

$$F_{(t)} = max\left[S_t - X; \frac{(pS_{u_{t+1}} + (1-p)S_{d_{t+1}})}{(1+r_c)}\right] \tag{8}$$

where: S_t is an underlying asset value at period t; X is an abandonment exercise value; $pS_{\mathrm{ut}+1}$ is an upward underlying asset value at $t + 1$; (1-p) $S_{\mathrm{dt}+1}$ is a downward underlying asset value at $t + 1$; r_c is the continuous risk-free rate.

If the expiration occurs in period t = T, the option value is defined by Eq. (9).

$$F_{(t)} = max[S_t - X; 0] \tag{9}$$

The application of the binomial model allows the incorporation of a flexibility value provided by an abandonment option for a wind farm, given the spot price volatility. The binomial model is suitable for this analysis since it employs only one source of uncertainty in the volatility calculation.

Mean-reverting process with jumps

Any variable that changes its value over time evolves in a way that is at least partially random and unpredictable following a stochastic process [53]. The probability law for variable x_t evolution defines a stochastic process so that the probability that the value x_t belongs to a specific interval ($a_t < x_t < b_t$) [48].

The random walk is a stochastic process characterized by a Markovian process, which is not influenced by past events due to the memoryless property. That is, in a random walk, a probability distribution of x_{t+1} depends only on x_t and not on what occurred before time t. In this respect, the most noticeable behavior for energy commodities is the mean-reverting process [54]. The mean-reverting process is a Markovian process, with random variation over time around a mean value. The simplest mean-reverting process is known as the Ornstein-Uhlenbeck (O-U) process [48].

As described in Eq. (10), the O-U mean-reverting process can be seen as a continuous-time version of the discrete-time Markov process, well-known in econometrics, like lag-one autoregressive [48].

$$x_t - x_{t-1} = x_{t-1}(e^{-\eta\Delta t} - 1) + \overline{x}(1 - e^{-\eta\Delta t}) + \varepsilon_t \tag{10}$$

where: x_t is a random variable; Δt is the discrete-time interval; $\overline{x}$ is the long-term average associated with stochastic variable; η is the mean-reverting speed (the rate at which the stochastic variable reverts to the mean in the long run); $\varepsilon_t\sim$ is the normal distribution $N\ (0,\sigma^2)$.

The variance associated with a random variable can be expressed using Eq. (11).

$$Var[x_t] = \frac{\sigma^2}{2\eta}(1 - e^{-2\eta\Delta t}) \tag{11}$$

To perform the parameter estimation related to the O-U process and the random walk simulation, it is more useful to describe a discrete version given by Eq. (11), as a regression described in Eq. (12) [48].

$$x_t = x_{t-1}e^{-\eta\Delta t} + \overline{x}\left[\left(\frac{\mu - r_{fc}}{\eta}\right)\right](1 - e^{-\eta\Delta t}) + \sigma\sqrt{\frac{(1 - exp(-2\eta\Delta t))}{(2\eta)}}N(0,1) + \sum_{i=1}^{J(\Delta t)}\phi_i \tag{12}$$

where: μ is the discount rate; $r_{fc}$is the continuous risk-free rate.

The regression equation that estimates the log-returns is represented by:

$$ln[x(t)] - ln[x(t-1)] = a + (b-1)ln[x(t-1)] + \varepsilon_t \tag{13}$$

where: *a* and *b* are the estimated coefficients of the regression equation.

Using the regression parameters, it is possible to estimate the O-U process parameters, as follows:

$$\eta = \frac{-ln(b)}{\Delta t} \tag{14}$$

$$\overline{x} = \frac{a}{(1-b)} \tag{15}$$

$$\sigma = \sigma_\varepsilon\sqrt{\frac{2\text{In}b}{(b^2-1)\Delta t}} \tag{16}$$

where: σ_ε is the standard error of the regression.

However, energy commodities have particular characteristics, such as difficulty to store and low elasticity since it is related to the needs of consumers, and the demand is not very sensitive to price changes [55]. Due to this fact, in some moments, electricity prices can experience jumps [54]. Therefore, the models of the mean-reverting process, despite capturing the characteristic of mean reversion of electricity spot prices, need to be complemented to consider the possibility of price jumps [56].

In this aspect, it is valid to include their possibility in the mean-reverting process, and this approach is described by Eq. (17).

$$x_t = x_{t-1}e^{-\eta\Delta t} + \bar{x}\,\_\left[\left(\frac{\mu - r_{fc}}{\eta}\right)\right](1 - e^{-\eta\Delta t}) + \sigma\sqrt{\frac{(1 - exp(-2\eta\Delta t))}{(2\eta)}}N(0,1) + \sum_{i=1}^{J(\Delta t)}\phi_i \tag{17}$$

where: *N*(0,1) is a random number drawn from a standard normal distribution; $\sum_{i=1}^{J(\Delta t)}\phi_i$are the jumps represented by the sum of the probability of upward and downward jumps.

The Poisson process fits well to model the discontinued portion of mean reversion with jumps. Therefore, the jumps can be represented by a discrete stochastic process. The event is a jump of size *k*, which may be random or deterministic. We define here λ to be an average arrival rate of an event during a dimensionless interval *dt*. The probability of this event is λ*dt,* and the non-occurrence probability is 1- λ*dt.* Thus, the Poisson process *q* can be represented by its probability of occurrence, such as:

$$dq = \begin{cases} 0, \text{ with probability } 1 - \lambda dt \\ \phi - 1, \text{ with probability } \lambda dt \end{cases} \tag{18}$$

In the present study, the upward jumps possibility included a mean-reverting process associated with the Brazilian electricity spot prices. Although not common, electricity price jumps have already occurred on several occasions in Brazil (e.g., in 2014 due to a drought period), causing significant reductions in the reservoirs levels of hydroelectric plants, which affected the energy supply and increased electricity prices.

Abandonment option

Over the wind farm lifetime, due to the oscillation of electricity spot prices, the project market value may increase or decrease. Depending on the circumstances, it may be more advantageous for the producer to sell the wind turbines and the rest of the wind farm infrastructure at market value, that depreciates exponentially in each period at 5% and 20%, respectively [44], except in the last year when the operating period ends.

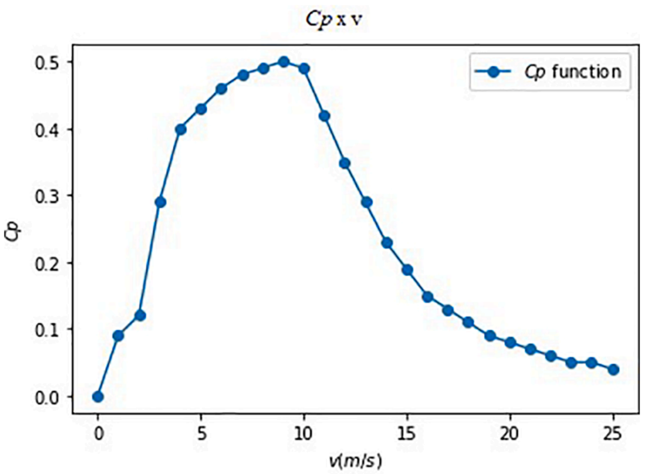

Fig. 3. C_p function in relation to *v*.

In the case of project abandonment, it can be considered that the producer can sell the wind turbines. Therefore, if at the end of each period, the project is worth below the market value of the turbines, the investor may exercise the abandonment option. In the case analyzed, it is considered that at the end of each year, the producer can choose between continuing the operation of the wind farm or exercising the abandonment option.

The abandonment option can prove to be very valuable for companies in many areas. As an example, a pharmaceutical industry that is developing a particular drug, there is a natural uncertainty during the development process, the behavior of the demand, the success of the test phases, and the regulatory approval. During this period, the manager may review the evolution of research and development and choose to abandon it in case of an unfavorable scenario [52].

Case study

In the present study, it considered a wind farm project to be installed in the Caetité region, in the state of Bahia, which already houses wind power generation projects. The PV of the wind farm project, with the option of abandonment in the Brazilian electricity spot market, is calculated from the binomial model, and, after discounting the investments, the additional managerial flexibility is calculated. The procedures for calculating and model applying were performed using mathematical models developed in *MS Excel*® and *Crystal Ball*®.

Data and assumptions

For the proposed model application, we analyzed a case study referring to a hypothetical wind farm. To this case, it was considered that a wind farm with 16 MW of power, being composed of 8 turbines of 2 MW and 138 m of height. Turbines are from the E82 model produced by Enercon, which has consolidated manufacturing in the Brazilian wind sector. However, the proposed model can be extended to wind farms with different power sizes and different turbine models, this being a case study only to validate the proposed approach.

The average site air density (ρ) is 1.225 (kg/m^2), and to calculate the C_p, we use a cubic regression, and its estimation is presented in Eq. (19). Here, we considered C_p values of the 2 MW wind turbine with a swept area equivalent to 5,281 m^2 [57] for 25 different wind speeds, which can be observed in Fig. 3.

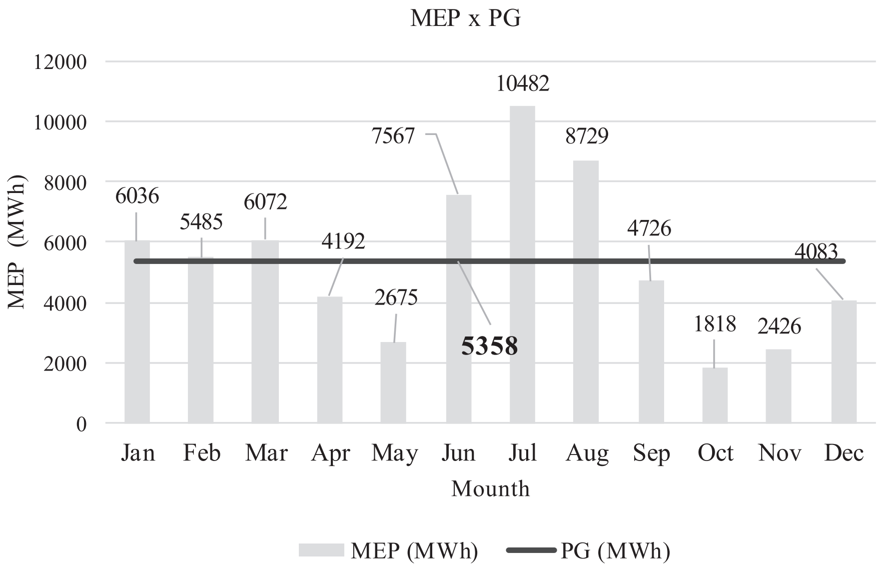

Fig. 4. Comparison of MEP in relation to PG.

$$C_p = -0.07248v^3 + 0.1599v^2 - 0.01403v + 0.000316 \tag{19}$$

The monthly wind speeds were collected from measurements made by NASA at the height of 10 m from the coordinates of the Caetité region (14° 40′) are considered as well [58]. It is worth mentioning that the wind speeds are corrected to the height of 138 m using Eq. (3). After this correction, it is possible to estimate the monthly average energy production of the wind farm. From Fig. 4, it can be observed that the monthly estimated energy production (MEP) can vary above or below the monthly PG, which causes the producer to have to settle the energy trading differences using the electricity spot prices.

It is important to highlight that, in this study, the expected wind speed value for each month from 35 years of data was considered for MEP estimation. In this case, the uncertainties were not considered, as the months where there is a production deficit could be offset by the months of production surplus. In turn, the spot price is a market variable in which an increase or jump may not be offset at another time of the year, and with this, it can have a more significant impact on PV results. However, it is of great value that future studies consider new approaches that include investigating the impact of wind speed uncertainty.

The net cash flow that the project can generate for the producer is calculated from the financial assumptions of a wind farm during the project's 20-year life. The cash flow amounts correspond to the gross revenue formed by the PG multiplied by the energy sale price plus potential increases or reductions that occurred due to the settlement of the differences. Concerning the cash outflows, there are payments of PIS/Cofins taxes, sectoral specific taxes, O&M costs, administrative and insurance expenses, income, and social tax. PV of cash flow was subsequently discounted by the amount of the investment to calculate the NPV.

The investment and sale price representing the fixed portion of the revenue were estimated based on the average investment values, and the electricity prices exercised in the market by CCEE in 2016 [59]. We considered the 2016 data because it is the initial investment that is made two years before starting the operations (2018) since a wind farm takes about two years to build. The sectoral specific charges refer to the Transmission System Use Tariffs (TUST), the ANEEL tax, and the ONS/CCEE tax. The amounts used to calculate these charges and the other taxes and charges are listed in Table A1, in Appendix A, along with other project information.

The amount coming from the annual settlement of the differences is represented by the sum of each monthly spot price multiplied by the difference between the MEP and the PG in one year. The mean-reverting process with jumps is used to calculate the MEP. To do so, the monthly electricity spot price data for the period from May 2003 to March 2018 were collected, and then a linear regression in Eq. (20) was performed of the log-returns of the electricity spot prices with the logarithms of the electricity spot prices from period *t*-1.

$$ln[x(t)] - ln[x(t-1)] = \underbrace{0.407}_{a} - \underbrace{0.0886}_{b-1} ln[x(t-1)] + \varepsilon_t \tag{20}$$

From the parameters *a, b,* and σ_ε obtained in the regression and considering the interval of one period ($\Delta t = 1$), the parameters of the mean-reverting process η, $\bar{x}$, and σ, were calculated according to Eqs. (14)–(16) respectively. An electricity price jump is considered as a price above three standard deviations of the average price of the collected series and an upward jump frequency (λ) of 6.98% is obtained, with a normal probability distribution $N \sim (169.02; 25.52)$.

The discount rate (μ) is obtained from the Weighted Average Cost of Capital (WACC) method, described in Eq. (21) [60,61]:

$$\mathrm{WACC} = \mathrm{k_d D}(1-\tau) + \mathrm{k_e E} \tag{21}$$

where: k_d is the cost of debt; *D* is the weight of debt in the project investment (%); τ is the income tax; k_e is the cost of equity; *E* is the weight of equity in the project investment (%).

The WACC is deflated by inflation, as recommended by ANEEL (2016a). In the calculation of k_d for electric sector investor companies is applied [60,62]. This approach is based on the sum of the risk-free rate with the credit risk premium and the country risk premium. This calculation is presented in Eq. (22):

Table 1
Parameters used to calculate the discount rate.

Parameters	Values	Sources
D	63.55%	[63]
E	36.45%	[63]
r_f	2.73%	[64]
r_c	3.37%	[62]
r_b	2.62%	[62]
r_m	13.20%	[62]
β	1.14	[63]
k_d	11.63%	Eq. (22)
k_e	17.29%	Eq. (23)
Inflation	2.41%	[62]
μ	11.18%	Eq. (21)
μ deflated	8.56%	Calculated

Table 2
Parameters related to the mean-reverting process with jumps.

Parameters	Values
η	0.093
$\bar{x}$	4.59
σ	29.57%
μ	11.03%
$r_{fc} = \ln(1 + r_f)$	2.69%
j_m	169.02
σ_j	24.52

$$k_d = r_f + r_c + r_b \tag{22}$$

where: r_f is the risk-free rate; r_c is the debt risk premium; r_b is the country risk premium.

To calculate k_e, the Capital Asset Pricing Model (CAPM), was added to the country risk premium. This is a model widely used in the literature [42,62]. The calculation is presented in Eq. (23).

$$k_e = r_f + \beta \times \left(r_m - r_f\right) + r_b \tag{23}$$

where: r_m is the market risk premium; β is beta, which measures the risk of the project in relation to the market.

The risk-free rate is determined from the average of the United States government bond yields between October 2016 and September 2017. Table 1 shows all the parameters to calculate the discount rate.

Monte Carlo Simulation applied to compute the wind farm project value

After all the financial assumptions are defined, the mean-reverting process with jumps for electricity spot prices is modeled, and the net cash flow of the project for the 20 years of useful life is constructed to calculate the settlement value of the differences. Thus, from the discounted cash flow over 20 years using the discount rate without inflation, indicated in Table 1, it is possible to estimate the PV of the underlying asset.

To estimate the NPV without the managerial flexibility, which corresponds to the PV minus the investment cost, 5,000 scenarios for the NPV of the project cash flow are simulated. In this simulation, uncertainty is incorporated into the possible paths of the stochastic mean-reverting process with jumps, as described in Eq. (12). Consequently, it is possible to estimate the value of the project, considering different scenarios for the settlement of the differences. Table 2 shows the calculated parameters to model the mean-reverting process with electricity spot price jumps.

The wind farm expected PV is US$ 21.25 and, as can be seen in Fig. 5. The expected NPV is US$ 5.95 million, with a minimum and maximum value equal to US$ 5.39 million and US$ 6.58 million, respectively. In this way, the value of the underlying asset equivalent to the average NPV of the wind farm is considered. The positive NPV shows that the producer should consider the investment in the project. Therefore, the next step will analyze if the existence of the abandonment option, over the 20 years of project life, will add value to the asset.

Result of the investment analysis from the real options analysis

Finally, through the binomial model, the PV of the wind farm is analyzed, considering management flexibility based on the abandonment option. Therefore, during the 20 years of project life, it is analyzed whether, at the end of each year ($\Delta t = 1$), the producer continues to keep the project in operation or leaves the project, negotiating the wind turbines in the market. Eq. (24) is used to calculate the value of the asset in each period, which can be optimized through the possibility of exercising the abandonment option.

$$F_t = max(E_{PV_t}; V_{AO_t}) \tag{24}$$

Table 3
Amount redeemed when exercising the abandonment option.

Periods	Recovered values [US$ millions]
1	14.424
2	13.121
3	12.474
4	11.842
5	11.249
6	10.687
7	10.153
8	9.645
9	9.163
10	8.705
11	8.269
12	7.856
13	7.463
14	7.090
15	6.735
16	6.399
17	6.079
18	5.775
19	5.486
20	0.000

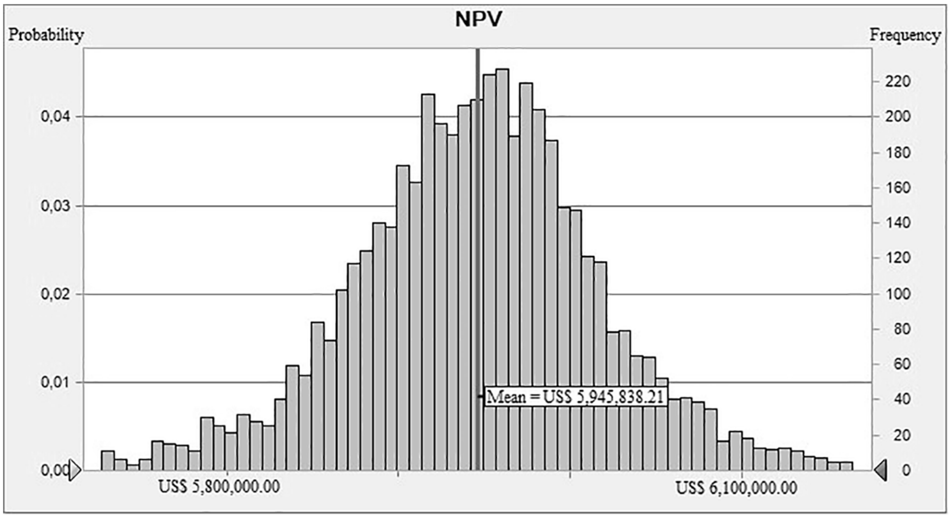

Fig. 5. Distribution of predicted NPV values considering 5000 Monte Carlo runs.

Table 4
Values of the parameters of the mean-reverting process with jumps.

Parameters	Values
u	1.344
d	0.744
p	0.473
$1\text{-}p$	0.527

Table 5
Wind farm NPV with and without managerial flexibility.

With abandonment option	No abandonment option	% Variation
US$ 7.747 million	US$ 5.946 million	30.29%

Table A1
Parameters considered to perform the NPV analysis.

Parameters	Values	Sources
Investment	US$ 956,466.81 per MW	[59]
Project life	20 years	[44]
Energy selling price	US$ 41.20	[59]
Physical Warranty	64,290.82 MWh	Eq. (1)
Leasing	1% of investment	[44]
O&M Cost	2% of investment	[44]
TUST	US$ 1,145.00 per MW	[44]
CCEE rate	US$ 17.5 per kWh	[42]
NOS rate	US$ 117.5 per MW	[42]
ANEEL rate	US$ 639.06 per MW	[42]
Administrative and insurance expenses	0.3% of investment	[44]
Social contribution	9% over 12% of gross revenue	[42]
Income tax	25% over 8% of gross revenue	[42]

where: E_{PVt} is the expected present value of the asset at time t; V_{AOt} is the value of the abandonment option at time t.

For the amount redeemed with the sale of wind turbines, the amount invested is considered to decrease exponentially at each period, except in the last period when the abandonment option does not exist (value 0). Table 3 shows the value recovered by the producer in each year, in case of exercising the abandonment option.

It is important to highlight that, to compare the value of the project with and without the abandonment option, the risk-neutral probability is calculated for the scenarios of rise and fall of the asset value. Therefore, in this stage, the PV of the project with and without the abandonment option is calculated, discounting the future values by the continuous risk-free rate (r_{fc}). Table 4 lists the parameters u, d, and p calculated from Eqs. (5)–(7), respectively. The values of σ and r_{fc} used in the calculations are the same as those obtained for modeling the mean-reverting process with spot price jumps.

In this way, it is possible to construct a binomial tree with twenty stages, with the PV of the asset at date zero equal to US$ 21.249 million. Therefore, after constructing the binomial tree and its respective parameters, the NPV of the project is calculated, discounted by r_{fc}, with and without the abandonment option. Table 5 shows the comparison of the results and the percentage increase created by adding the managerial flexibility.

It can be observed from the results that the abandonment option increases the NPV of the wind farm by 30.29%. Thus, although in the electricity spot market the project does not have the guarantee of a long-term contract, the managerial flexibility is greater and should not be underestimated in the evaluation of this type of investment. It is important to note that the abandonment option protects the investor from significant project value losses in a certain way, especially in cases of consecutive scenarios representing reductions in the overall project value.

The wind potential of the northeast region is greater during the dry season, which characterizes the complementarity of this source with hydroelectric energy, as previously shown by [65–67]. This factor reinforces the relevance of spot price volatility in the investment assessment in this wind farm since, besides being the spot market price, the source of wind energy can complement hydroelectric energy, the most representative source in the formation of spot electricity prices in the country during periods of low rainfall.

Still, regarding the volatility, it is necessary to emphasize the high sensitivity that it has for the value of the option. If it were underestimated at the 20% threshold, the option would add 16.2% of value to the project, and if it were overestimated to 40%, the option would increase the value of the project by 52.1%.

In the decision tree illustrated in Appendix B, it is possible to observe that the abandonment option would be exercised in 67 scenarios of the binomial tree. In comparison, in the remaining 163 scenarios, the producer would continue to operate the project. The predominance of non-exercise scenarios of the abandonment option reveals that in the region analyzed, the excellent wind potential provides an expected value of cash flows capable of guaranteeing project operation in most scenarios.

Conclusions

The main objective of this study was to evaluate the impact of the abandonment option in the NPV of a wind farm, considering the circumstances of electricity trading, with the presence of the settlement of

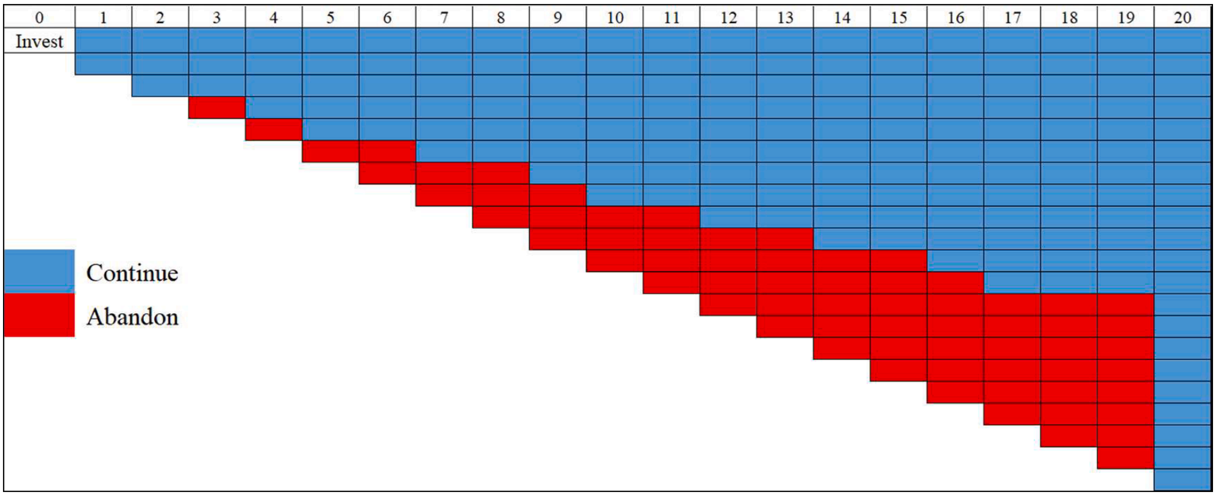

Fig. B1.

differences in the Brazilian spot market. A mean-reverting process with spot price jumps was considering in the analysis to represent the behavior of the parameter better. To do so, it was necessary to estimate the difference between the MEP and the PG of the plant and to model the stochastic process related to electricity spot prices. The high volatility of the spot prices reveals that the wind power producer selling electricity in the spot market faces many uncertainties. The possibility of jumps in prices, although rare, can also cause a high difference value to be settled in the short-term market, affecting the average market value of the asset. In this context, the abandonment option becomes valuable managerial flexibility, and, in a way, it protects the producer in the event of consecutive downward scenarios affecting the value of the asset.

In the analyzed case, it is noticed that the managerial flexibility provides the increase of value for the asset concerning the analysis without the abandonment option. It is also possible to highlight the wind potential of the region considered to install the wind farm, based on the scenarios verified in the decision tree. In 70.9% of the scenarios, it should be considered that the project must continue in operation, which is a consequence of the good market value provided by the wind potential of the region, which improves the asset value. Finally, it is important to highlight that the model developed and applied in this study can be replicated to evaluate projects inserted in a similar context involving the settlement of differences for electricity trading. However, to evaluate other types of options, the impact of other variables besides the electricity spot price should be analyzed, and the volatility and options considered from other methods should be evaluated in addition to those investigated here.

CRediT authorship contribution statement

G. Aquila: Conceptualization, Methodology, Formal analysis, Investigation, Software, Writing - original draft, Writing - review & editing, Visualization. **A.R. Queiroz:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **P.P. Balestrassi:** Resources, Data curation, Supervision, Funding acquisition, Supervision. **P. Rotella Junior:** Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **L.C.S. Rocha:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Visualization. **E.O. Pamplona:** Formal analysis, Funding acquisition, Supervision, Resources. **W.T. Nakamura:** Supervision, Methodology, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

The following table (Table A1) presents the main parameters considered in the NPV analysis to evaluate the asset value.

Appendix B

The following figure (Fig. B1) presents the decision tree for the wind project.

References

[1] Dovi VG, Friedler F, Huisingh D, Klemes JJ. Cleaner energy for sustainable future. J Cleaner Prod 2009;17:889–95.

[2] Aquila G, Pamplona EO, de Queiroz AR, Rotela JR, Nunes MF. An overview of incentive policies for the expansion of renewable energy generation in electricity power systems and the Brazilian experience. Renew Sustain Energy Rev 2017;70:1090–8.

[3] Abdomouleh Z, Alammari RAM, Gastli A. Review of policies encouraging energy integration & best practices. Renew Sustain Energy Rev 2015;45:246–62.

[4] Abolhosseini S, Heshmati A. The main support mechanisms to finance renewable energy development. Renew Sustain Energy Rev 2014;40:876–85.

[5] Romero A, Millar D, Carvalho M, Abrahão R. 100% renewable fueled mine. Energy 2020;205.

[6] Romero A, Carvalho M, Millar D. Optimal design and control of Wind-diesel hybrid energy systems for remote artic mines. J Energy Res Technol 2016;138.

[7] Carvalho M, Romero A, Shields G, Millar D. Optimal synthesis of energy supply systems for remote open pit mines. Appl Therm Eng 2014;64.

[8] EIA - U.S Energy Information Administration. New electric generating capacity in 2019 will come from renewables and natural gas, 2019. Available at: <https://www.eia.gov/todayinenergy/detail.php?id=37952> (accessed on July 25, 2020).

[9] Eshraghi H, de Queiroz AR, DeCarolis JF. US Energy-related greenhouse gas emissions in the absence of federal climate policy. Environ Sci Technol 2019;52(17):9595–604.

[10] Daim TU, Amer M, Brenden R. Technology Roadmapping for wind energy: case of the Pacific Northwest. J Cleaner Prod 2012;20:27–37.

[11] GWEC – Global Wind Energy Council. Globo Wind Report, 2017. 72p.

[12] Gonzalez MOA, Gonçalvez JS, Vasconcelos RM. Sustainable development: case study in the implementation of renewable energy in Brazil. J Cleaner Prod 2017;142:461–75.

[13] Silva NF, Rosa LP, Freitas MAV, Pereira MG. Wind energy in Brazil: from the power sector's expansion crisis model to the Favorable environment. Renew Sustain Energy Rev 2013;22:686–97.

[14] IRENA – International Renewable Energy Agency. Renewable Capacity Statistics 2019. Available online at:< https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Mar/IRENA_RE_Capacity_Statistics_2019.pdf> (accessed on July 25, 2020).

[15] Queiroz AR, Lima LMM, Lima JWM, Silva BC, Scianni LA. Climate change impacts in the energy supply of the Brazilian hydro-dominant power system. Renewable Energy 2016;99:379–89.

[16] Hunt JD, Stilpen D, Freitas MAV. A review of the causes, impacts and solutions for electricity supply crises in Brazil. Renew Sustain Energy Rev 2018;88:208–22.

[17] Bradshaw A. Regulatory change and innovation in Latin America: the case of renewable energy in Brazil. Utilities Policy 2017;49:156–64.

[18] Juárez AA, Araújo AM, Rohatgi JS, Filho ODQO. Development of the wind power in Brazil: political, social and technical issues. Renew Sustain Energy Rev 2014;39:828–34.

[19] Ruiz BJ, Rodriguez V, Bermann C. Analysis and perspective of the government programs to promote the renewable electricity generation in Brazil. Energy Policy 2007;35:2989–94.

[20] Dutra RM, Szklo AS. Incentive policies for promoting wind power production in Brazil: Scenarios for the Alternative Energy Sources Incentive Program (PROINFA) under the New Brazilian electric power sector regulation. Renewable Energy 2008;33:65–76.

[21] Costa CV, La Rovere E, Assmann E. Technological innovation policies to promote renewable energies: lessons from the European experience for the Brazilian case. Renew Sustain Energy Rev 2008;12:65–90.

[22] Rego EE, Ribeiro CO. Successful Brazilian experience for promoting wind energy generation. Electricity J 2018;31:13–7.

[23] Dalbem MC, Brandão LET, Gomes LL. Can the regulated market foster a free market for wind energy in Brazil? Energy Policy 2014;66:303–11.

[24] Mastropietro P, Batle C, Barroso LA, Rodilla P. Electricity auctions in South America: towards convergence of system adequacy on RES-E support. Renew Sustain Energy Rev 2014;40:375–85.

[25] Santos L, Soares I, Mendes C, Ferreira P. Real options versus traditional methods to assess renewable energy projects. Renewable Energy 2014;68:588–94.

[26] Fuss S, Szolgayová J, Khabarov N, Obersteiner M. Renewables and climate change mitigation: irreversible energy investment under uncertainty and portfolio effects. Energy Policy 2012;40:59–68.

[27] Pless J, Arent DJ, Logan J, Cochran J, Zinaman O. Quantifying the value of investing in distributed natural gas and renewable electricity system complements: applications of discounted cash flow and real options analysis with stochastic inputs. Energy Policy 2016;97:378–90.

[28] Fernandes G, Perobelli FFC, Brandão LET. A model for valuing new technologies under a pull new incentives environment. Renew Sustain Energy Rev 2016;59:482–93.

[29] Zhang M, Zhou D, Zhou P. A real option model for renewable energy policy evaluation with application to solar PV power generation in China. Renew Sustain Energy Rev 2014;40:944–55.

[30] Fleten SE, Maribu KM. Investment timing and capacity choice for small scale wind power under uncertainty. Series Energy Power Systems 2004:121–6.

[31] Méndez M, Goyanes A, Lamothe P. Real options valuation of a wind farm. Spain: Portugal & University of Santiago de Compostela; 2009.

[32] Scatasta S., Mennel T. Comparing feed-in tariffs and renewable obligation certificates -the case of wind farming. In: Paper Presented at the 13th Annual International Conference on Real Options at University of Minho, Portugal & University of Santiago de Compostela, Spain, 2009.

[33] Munoz J., Contreras J., Caamano J., Correia P. Risk assessment of wind power generation project investments based on real options. In: Proceedings of IEEE PowerTech. Romania, 2009.

[34] Frolund SG, Obling PE. Valuation Models for Wind Farms under Development. Copenhagen: Copenhagen Business School; 2010.

[35] Monjas-Barroso M, Balibrea-Iniesta J. Valuation of projects for power generation with renewable energy: a comparative study based on real regulatory options. Energy Policy 2013;55:335–52.

[36] Honda H, Goto M, Ono T. Real option approach on implementation of wind–diesel hybrid generators. In: Haasis H-D, Kopfer H, Schönberger J, editors. Operations Research Proceedings. Berlin Heidelberg: Springer; 2006. p. 519–24.

[37] Dykes K, Neufville RD. Real options for a wind farm in Wapakoneta, Ohio: incorporating uncertainty into economic feasibility studies for community wind. Paper Presented at the World Wind Energy Conference. 2008.

[38] Martínez-Ceseña EA, Mutale J, Rivas-Dávalos. Real options theory applied to electricity generation projects: a review. Renew Sustain Energy Rev 2013;19:573–81.

[39] Damodaran A. Avaliação de investimentos: ferramentas e técnicas para a determinação do valor de qualquer ativo. 5th ed. Rio de Janeiro: Qualitymark; 2003. p. 630.

[40] Okumus I, Dinler A. Current status of wind energy forecasting and a hybrid method for hourly predictions. Energy Convers Manage 2016;123:362–71.

[41] Rocha LCS, Aquila G, Rotela Junior P, Paiva AP, Pamplona EO, Balestrassi PP. A stochastic economic viability analysis of residential wind power generation in Brazil. Renew Sustain Rev 2018;90:412–9.

[42] Aquila G, Rocha LCS, Rotela Junior P, Pamplona EO, Queiroz AR, Paiva AP. Wind power generation: an impact analysis of incentive strategies for cleaner energy provision in Brazil. J Cleaner Prod 2016;137:1100–8.

[43] Lima LA, Filho CRB. Wind energy assessment and wind farm simulation in Triunfo – Pernambuco, Brazil. Renewable Energy 2010;35(12):2705–13.

[44] Aquila G, Rotela Jr P, Pamplona EO, Queiroz AR. Wind power feasibility analysis under uncertainty in the Brazilian electricity market. Energy Econ 2017;65:127–36.

[45] Bañuelos-Ruedas F, Angeles-Camacho C, Rios-Marcuello S. Analysis and validation of the methodology used in the extrapolation of wind speed data at different heights. Renew Sust Energ Rev. 2010;14:2383–91.

[46] Sun, H, Gao, X, Yang, H. A review of full-scale wind-field measurements of the wind-turbine wake effect and a measurement of the wake-interaction effect. Renewable & Sustainable Reviews, v. 132, 2020.

[47] Trigeorgis, L. Real Options: Managerial Flexibility and Strategy in Resource Allocation. MIT Press 427p., 1996.

[48] Dixit, A.K; Pindyck, R.S. Investment Under Uncertainty. Princeton University Press, Princeton, 468 p, 1994.

[49] Luehrman T. Investiment opportunities as real options: getting started on the numbers. Harvard Bus Rev 1998:51–67.

[50] Fonseca MN, Pamplona EO, Valerio VEM, Aquila G, Rocha LCS, Rotela Junior P. Oil price volatility: a real option valuation approach in an African oil field. J Petrol Sci Eng 2017;150:297–304.

[51] Cox JC, Ross SA, Rubinstein M. Option pricing: a simplified approach. J Financ Econ 1979;7(3):229–63.

[52] Mun, J. Real Options Analysis. .3ed Wiley Finance. 416 f .2016.

[53] Hull, J.C. Options, Futures, and Other Derivatives Securities. Prentice Hall, 7a ed., 2008.

[54] Deng S. Stochastic Models of Energy Commodity Prices and Their Applications: Mean-reversion with Jumps and Spikes. Berkeley: University of California Energy Institute; 2000.

[55] Guardia, E. C., Queiroz, A. R., & Lima, J. M. (2010, July). Estimation of electricity elasticity for demand rates and load curve in Brazil. In IEEE PES General Meeting (pp. 1-7). IEEE.

[56] Cartea A, Figueroa MG. Pricing in electricity markets: a mean reverting jump diffusion model with seasonality. Appl Math Finance 2005;12(4):313–35.

[57] The Wind Power: wind market intelligence. Manufactures and turbines: Enercon E82, 2020. Available at: <https://www.thewindpower.net/turbine_en_6_enercon_e82-2000.php> (accessed on July 27, 2020).

[58] Power Data Access Viewer – Prediction of worldwide energy resources. National Aeronautics and Space Administration. Available at: < https://power.larc.nasa.gov/data-access-viewer/>. (accessed on July 23, 2020).

[59] CCEE. Biblioteca virtual, 2020. Available at:< https://www.ccee.org.br/portal/faces/acesso_rapido_header_publico_nao_logado/biblioteca_virtual>. [In Portuguese] (accessed on July 27, 2020).

[60] Ertürk M. The evaluation of feed in tariff regulation of Turkey for onshore wind energy based on the economic analysis. Energy Policy 2012;45:359–67.

[61] UNFCCC – United Framework Convention on Climate Change. Guidelines on the Assessment of Investment Analysis, 2012.

[62] ANEEL – National Eletric Energy Agency. Technical Note 33 /2016–SGT/ANEEL, 2016. Available at: <http://www2.aneel.gov.br/aplicacoes/audiencia/arquivo/2016/005/documento/ntecnica_33_sgt_ap_caiua.pdf> [In Portuguese] (accessed on July 27, 2020).

[63] Damodaran A. Betas by sector (US). 2017. Available at: < http://people.stern.nyu.edu/adamodar/New_Home_Page/datafile/Betas.html > (accessed on July 23, 2020).

[64] USDT – United States Department of Treasury. Daily Treasury Long Term Data, 2017. Available at:< https://www.treasury.gov/resource-center/data-chart-center/interest-rates/Pages/TextView.aspx?data=longtermrate> (accessed on: July 23, 2020).

[65] Schmidt J, Cancella R, Pereira JRA. An optimal mix of solar PV, wind and hydro power for a low-carbon electricity supply in Brazil. Renewable Energy 2013;85:137–47.

[66] De Jong P, Sanchez A, Esquerre K, Kalid R, Torres E. Solar and wind energy production in relation to the electricity load curve and hydroelectricity in the northeast region of Brazil. Renewable and Sustainaible Energy Reviews 2013;23:526–35.

[67] Silva, S.R., de Queiroz, A.R., Lima, L.M. and Lima, J.W., 2014, July. Effects of wind penetration in the scheduling of a hydro-dominant power system. In 2014 IEEE PES General Meeting| Conference & Exposition (pp. 1-5). IEEE.