Mendonça AKS & Bornia AC (2020). Electric power generation in wind farms with pumping kites: levelized cost of energy and sensitivity analysis. ***Research, Society and Development***, 9(7): 1-21. e666974528.

Geração de energia elétrica em parques eólicos com aerofólios cabeados: Custo nivelado de energia e análise de sensibilidade

Electric power generation in wind farms with pumping kites: levelized cost of energy and sensitivity analysis

Generación de electricidad en parques eólicos con perfiles cableados: costo de energía nivelado y análisis de sensibilidad

Recebido: 14/05/2020 | Revisado: 20/05/2020 | Aceito: 24/05/2020 | Publicado: 01/06/2020

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Resumo

Esta pesquisa tem o objetivo de analisar o custo nivelado de energia (LCOE) de parques eólicos com aerofólios cabeados. Para isto, foi considerando as características técnicas do sistema, a localização de operação, os investimentos necessários e as características do mercado brasileiro, para analisar o custo nivelado de energia de três cenários de parques eólicos: Parque eólico clássico, Parque eólico com aerofólios cabeados operando no modo *Pumping Kite* e um parque híbrido com as duas configurações de parque estudado. A pesquisa faz uso do método de LCOE. Os resultados indicam que a tecnologia com aerofólios cabeados requerem menos investimentos e que os parques eólicos com esta tecnologia podem gerar mais energia que um parque eólico clássico de mesma potência nominal, uma vez que os aerofólios cabeados podem explorar ventos de alta altitude, onde são mais frequentes e fortes. Os resultados também indicam que parques eólicos com aerofólios cabeados não são apenas economicamente viáveis, mas produzem energia a um custo nivelado, bem abaixo dos valores atualmente praticados para a venda de energia no mercado interno.

Palavras-chave: Custo nivelado de energia; Energia eólica; Energia eólica com aerofólios cabeados; Energia eólica em alta altitude.

Abstract

This research aims to analyze the levelized level energy cost of energy (LCOE) of wind farms with tethered airfoils. For this, it was considering the technical characteristics of the system, the location of operation, the necessary investments and the characteristics of the Brazilian market, to analyze the levelized cost of energy of three wind farm scenarios: Classic wind farm, Wind farm with tethered airfoils operating in Pumping Kite mode and a hybrid park with the two park configurations studied. The research makes use of the LCOE method. The results indicate that the technology with wired airfoils requires less investment and that wind farms with this technology can generate more energy than a classic wind farm of the same nominal power, since the wired airfoils can exploit high altitude winds, where they are more frequent and strong. The results also indicate that wind farms with wired airfoils are not only economically viable, but produce energy at a level cost, well below the values currently practiced for the sale of energy in the domestic market.

Keywords: Levelized cost of energy; Wind energy; Wind energy with tethered airfoils; High altitude wind energy.

Resumen

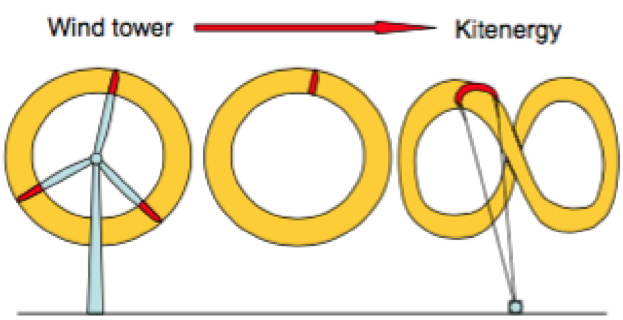
Esta investigación tiene como objetivo analizar el nivel de costo de energía (LCOE) de los parques eólicos con perfiles de cable. Para esto, se consideraron las características técnicas del sistema, la ubicación de la operación, las inversiones necesarias y las características del mercado brasileño, para analizar el nivel de costo de energía de tres escenarios de parques eólicos: parque eólico clásico, parque eólico con aviación con cable en funcionamiento en modo Pumping Kite y un parque híbrido con las dos configuraciones de parque estudiadas. La investigación hace uso del método LCOE. Los resultados indican que la tecnología con perfiles con cable requiere menos inversión y que los parques eólicos con esta tecnología pueden generar más energía que un parque eólico clásico de la misma potencia nominal, ya que los perfiles con cable pueden explotar vientos de gran altitud, donde están más frecuente y fuerte. Los resultados también indican que los parques eólicos con perfiles de cable no solo son económicamente viables, sino que producen energía a un nivel de costo, muy por debajo de los valores practicados actualmente para la venta de energía en el mercado interno.

Palabras clave: Costa nivelada de energía; Energía eólica; Energía eólica con perfiles de cable; Energía eólica a gran altitud.

1. Introduction

Airborne Wind Energy (AWE) or High-Altitude Wind Energy (HAWE) is a renewable energy technology that uses flying devices that take advantage of the kinetic energy of the wind and are capable of being held in the air by means of aerodynamic forces or aerostatic forces (Archer & Caldeira, 2009). The airborne wind energy research field has attracted a great deal of interest in recent years (Cherubini, Papini, Vertechy, & Fontana, 2015; de Souza Mendonça & Bornia, 2020; Mendonça, 2017; Mendonça, Vaz, Lezana, Anacleto, & Paladini, 2017), stimulated mainly by the drastic reduction of materials and the extraction of energy from high-speed winds at higher altitudes than classic horizontal-axis wind turbines (Ahrens, Diehl, & Schmehl, 2013). The main advantages of this technology are the replacement of classic wind turbine towers by cables of variable length, and of the blades by aerofoil tethered like a balloon or wings similar to a paraglide, kite surf or plane (Diehl, 2013). This replacement allows the devices to operate at higher altitudes, where the winds are stronger and more stable, characterizing a higher energy potential. The airfoil is connected to the ground by one or more cables whose main role is to transfer the energy to the ground, whether mechanical, when the generator is in the ground, or electrical, when the generator is on board. Figure 1 presents the basic concept of AWE technology.

Figure 1. Comparison between the operating principles of classic wind energy technology and technology with tethered airfoils.



Source: (Fagiano, Milanese, & Piga, 2012).

Another advantage has to do with the reduction in project costs, especially in terms of transportation and installation, due to the absence of a tower that must withstand the torque caused by the operation of the turbine.

This research aims is to analyze of the levelized cost of energy (LCOE) in wind farms with tethered airfoils. For this, we continued our research in this area, expanding an earlier study, described in (De Lellis, Mendonça, Saraiva, Trofino, & Lezana, 2016).

2. Pumping Kite

The most studied configuration in energy generation through tethered airfoils is the Pumping Kite configuration. In this configuration, the airfoil is connected to the ground through a tether of variable length, wound around a spool, whose axis is connected to the generator. As the airfoil is dragged by the wind, the cable is unwound, causing the spool and generator to spin, thus generating energy.

In addition, in order to avoid torsion buildup on the tether, an " lying eight" type of trajectory (∞) is generally used. Note that a circular trajectory would also be possible if a swivel cable is used. The airfoil traverses this trajectory with a much higher speed than that of the wind, which allows to increase in a marked way the efficiency in the utilization of the energy of winds.

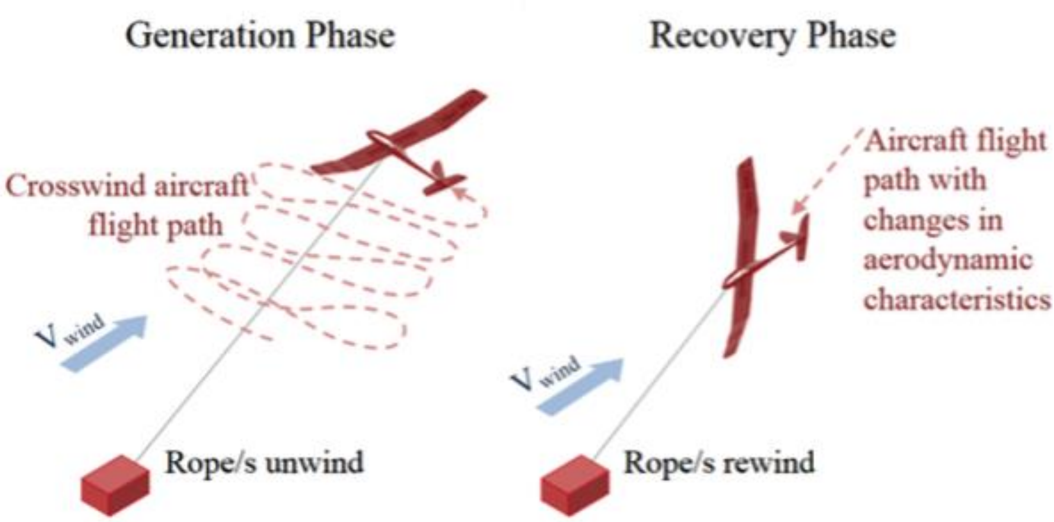
When the maximum cable length is reached, the power generation is interrupted, the airfoil is reconfigured to reduce the cable traction as much as possible and the airfoil is collected using a small part of the generated energy.

As soon as the airfoil is brought to the starting point (initial cable length), the airfoil is reconfigured again to increase the cable traction and the generation phase is restarted. The energy produced in the generation phase minus the energy spent in the recovery phase is the energy that the Pumping Kite system can effectively supply.

This airfoil traction and retraction cycle is known as a pumping kite operation. The interest in the Pumping Kite system is probably due to its concept, with a simple generation electromechanical structure, with only one airfoil to move the structure.

In addition, the cost of a Pumping Kite system is attractive when compared to other configurations, such as carousel or multiple airfoils. This makes it easier and less costly to build research prototypes for this technology. Figure 2 shows a system operating in the sustain mode in the pumping kite configuration.

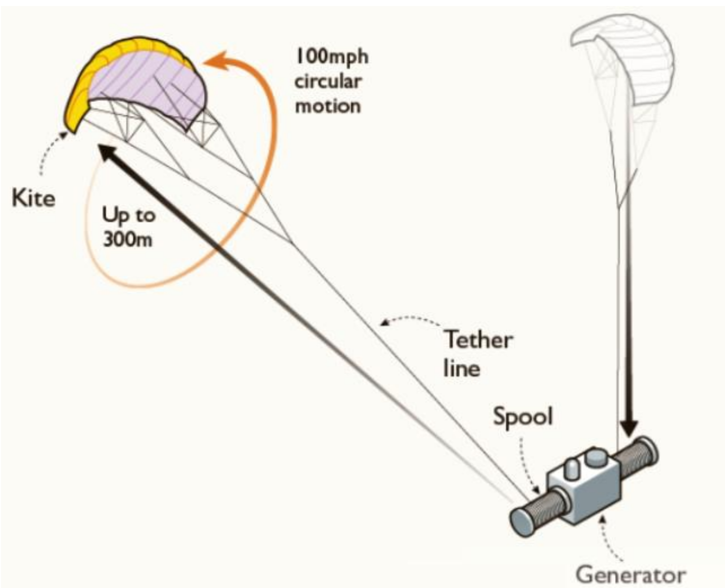
Figure 2. Lift mode with fixed base.



Source: From (Cherubini et al., 2015).

Figure 3 shows a schematic with a generating unit connected to two spools by means of clutches operating in pumping kite mode. While one airfoil is in the generation phase, the other is in the retraction phase, which can generate energy continuously.

Figure 3. Pumping kite concept with two complementary mode airfoils for continuous energy generation.



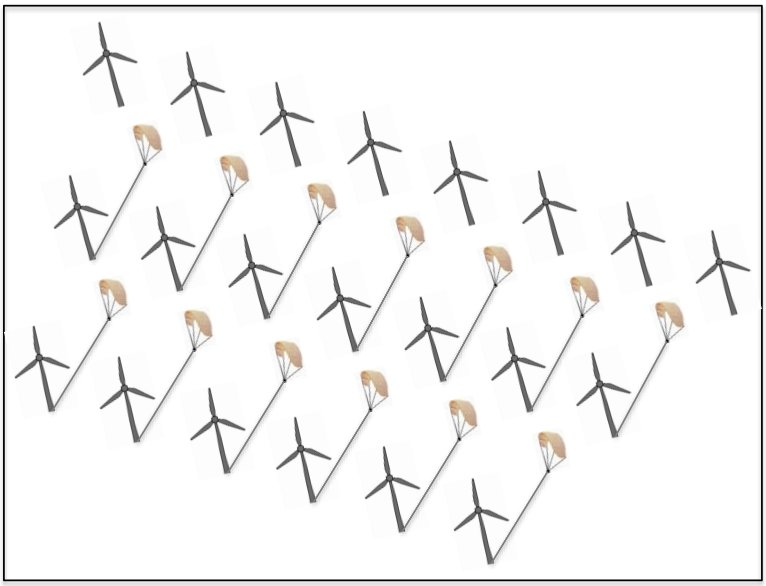
Source: From (Webster, 2017).

The main variants of this configuration are related to the type of airfoil used. They may vary, e.g., in the number of airfoils (single or multiple), number of tethers reaching the ground, their rigidity (rigid or flexible), and the location of the generators in this case is always on the ground. As shown, the Pumping Kite configuration can be implemented with the use of Multiple Airfoils fixed on the same connection tether with the ground unit.

3. Economic Analysis

The objective of the economic analysis is to estimate under realistic conditions the cost of energy production in three scenarios of wind farms: (scenario A) classical wind turbine farm, (B) hybrid farm with two types of wind turbines, WTs (Wind Turbines) and PKs (Pumping Kites), and (C) wind turbines farm with tethered airfoils in Pumping Kite mode. Scenario A includes the existing wind farm called Dunas de Paracuru located in Fortaleza - CE with 21 units of WTs. The wind farm consists of 3 lines perpendicular to the predominant wind direction, with 6, 7 and 8 WT units as shown in Figure 4.

Figure 4. Wind farm integrated with wind turbine and pumping kite.



Source: Authors.

In order to remain with the same land area of 150 ha, in scenario B a PK unit was placed downstream of each WT of the first and second lines, resulting in an increase of 13 PKs. In scenario C, the 21 WTs of scenario A were replaced by PKs, these two scenarios being hypothetical. Table 1 presents some characteristics of the investigated wind farm scenarios.

Table 1. Investigated wind farm scenarios.

Characteristic	A	B	C
Location	**Fortaleza**		
Wind speed [m/s]	7.5		
2 MW geration units	21 WTs	21 WTs +13 PKs	21 Pks
Installed capacity (Calisti & Creemwood)	42	68	42
Capacity factor [%]	31.36	36.77	45.52
Annual energy generation [MWh]	115.363,7	219.031,6	167.463,6
Annual equivalent time in hours	2.746,8	3.221,1	3.987,2
Sale price of wind energy in Brazilian market	65.48 EUR/MWh		

Source: (De Lellis et al., 2016).

The analysis developed in this article makes use of the initial investment estimate of a PK unit presented in (De Lellis et al., 2016). The authors divided a PK unit into 14 groups of components, taking as assumption in Group 1, the airfoil is assumed to be a flexible and lightweight semi-rigid carbon fiber wing. In Group 2 (airfoil control unit), there was an extrapolated cost estimate from existing prototypes. Group 3 (takeoff and landing system) uses a land-based lifting mast whose cost estimate was based on sailing vessel prices. In Group 4 (tether), it is made of dyneema with average price in the retail market. In Group 5 (winch spool), it is assumed to be made of aluminum and Group 6 (tether handling system) is responsible for the winding of the tether around the spool. In Group 7 (winch bearings), it is assumed that the cost depends on the square root of the total tether traction. In Group 8 (yaw movement), the same system cost used in a WT is adopted. In (cover and structure ground station) Group 9, it is assumed that cheaper alternatives to WTs will be taken, given the absence of restrictions of weight and height in the case of PK. In Group 10 (gearbox and generator), the gearbox is avoided by using a low speed generator, and the cost of the generator is interpolated given the prices of the generators on the market for different speeds. In Group 11 (power electronics), it is assumed to cost 50% of the value of a WT, due to the absence of a tower. Group 12 (hydraulic and refrigeration systems) are assumed to have the costs similar to those of a WT, which are linearly dependent on the rated power Pnom = 2 MW. In Group 13 (control and monitoring system), the costs are assumed to correspond to those of an offshore WT, due to the challenges of the introduction of AWE technology in the market, and Group 14 (electrical interface of the PK), the cost associated with a WT is assumed to be around 86 EUR/kW, as it involves the electronic connection network (power). More information on the groups of components of a PK unit can be found in (De Lellis et al., 2016). The estimate of the cost of transport and assembly of a PK system is reduced due to the reduction of materials and the execution of its assembly being on the ground. Table 2 presents the initial investment estimate for a PK unit.

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Table 2. Estimate of initial investment for a PK unit.

Item		Cost [EUR]
group of components	1 - Flexible Airfoil	258.9k
	2 - Kite control/steering unit(airborne)	87.5k
	3 - Take-off and landing system (with mast)	70.8
	4 - Tether	58.1 k
	5 - Winch spool	25.7 k
	6 - Tether handling system	94.5 k
	7 - Winch bearings	1.8 k
	8 - Yaw movement	64.9 k
	9 - Ground station (cover and structure)	45.4 k
	10 - Electric generator	156.4 k
	11 - Power electronics (winch control)	197.4 k
	12 - Hydraulic and refrigeration systems	23.9 k
	13 - Control and monitoring system	50.2 k
	14 - Electrical interface	171 k
	TOTAL	1, 306.4 k
Transport and assembly		49.3 k

Source: (De Lellis et al., 2016).

In Table 3, the total investment for each investigated wind farm scenario is presented.

Table 3. Total investment for the scenarios.

Category	Investment – Scenario [EUR]		
	A	B	C
69 kV Transmission line	60.3	97.6	60.3
Civil works wind farm	9, 474.4	15, 339.5	9, 474.4
Road access	99.7	99.7	99.7
Substation construction	2, 445.4	3, 959.2	2, 445.4
Engineering and consulting	698.7	1, 131.2	698.7
Implementation of the wind farm	1, 479.7	2, 395.7	1, 479.7
Generation Units	27, 261.2	44, 244.6	27, 434.6
Archaeological services	35.8	35.8	35.8
Juridical services	38.8 k	62.8 k	38.8
Transport and assembly	17, 496.9	18, 137.8	1, 035.3
Intermediate voltage transmission line (EPC)	1, 462.8	2, 368.3	1, 462.8
69 kV Transmission line (EPC)	1, 746.2	2, 827.1	1, 746.2
TOTAL	62, 303.4	90, 702.9	46, 015.1

Source: (De Lellis et al., 2016).

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3.1. Methodology

The economic feasibility of the proposed scenarios is analyzed by estimating the Levelized Cost of Energy (LCOE). The LCOE is an equilibrium value that a power producer would need to obtain per megawatt hour (MWh) as sales revenue to justify an investment in a given power generation facility (Reichelstein & Yorston, 2013). The eighth edition of the report entitled Projected Costs of Generating Electricity, developed by the International Energy Agency (IEA), the Nuclear Energy Agency (NEA) and the Organization for Economic Co-operation and Development (OECD), examines in detail the levelized cost of energy for all major generation technologies. In the 2005 edition, the levelized cost of energy is defined as a calculation of energy generation costs related to the supplied liquid energy (OECD, 2005). In the 2010 and 2015 editions, the levelized cost of energy is based on a weighted average cost approach that incorporates the cost discount to its current values, defined as a discounted cash flow (DCF) method (OECD, 2010, 2015).

Short, Packey and Holt (1995), provide in the Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies an LCOE method, which includes Total Life Cycle Cost after Tax (TLCC), and recommend the use of LCOE as an ideal tool to classify comparative energy systems for investment decisions.

According to Short et al. (1995), the TLCC calculation is a key point of the LCOE estimates, being used to evaluate the differences in costs among alternative projects. The formula for calculating the total life cycle cost (TLCC) is presented in equation (1).

$$TLCC = Io - (T * PVDEP) + PVOM(1 - T)/(1 - T) \quad (1)$$

The total life cycle cost (TLCC) is referenced to the initial time (zero), the present values of the depreciation costs (PVDEP) and the operating and maintenance costs (PVOM) are subtracted annually from the initial investment costs (Fagiano et al., 2012). T represents the income tax rate, and (1-T) is used to reflect the value after taxes of the O & M costs annually.

One of the most common methods to estimate the LCOE of renewable energy technologies and widely used in the literature is presented in equation (2) (Díaz-Méndez et al., 2014; Malheiro, Castro, Lima, & Estanqueiro, 2015). The LCOE calculation is derived from the total life cycle cost (TLCC) formula.

The levelized cost of energy is calculated by making an additional treatment to the TLCC calculation of the project, starting to discount in the time period (one) and treating the cost of the investment as an overnight cost. Equation (2) presents the formula for calculating the LCOE:

$$LCOE = \frac{TLCC}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}} = \frac{\sum_{n=0}^{N} \frac{C_n}{(1+d)^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}} \qquad (2)$$

in which C_n is the total life cycle cost, Q_n is the amount of energy generated in the year, the discount rate appears in equation (2) to compensate for the value of money in time, and N is the period of analysis. To calculate the LCOE, one must first calculate the total life cycle cost (TLCC), which is the present value of the project costs throughout its life.

For technologies involving wind and solar projects, the depreciation of the Modified Accelerated Cost Recovery System (MACRS) with a five-year schedule is used. The asset should depreciate its capital costs with the following annual schedule: 33.33%, 44.45%, 14.81%, 7.41%, 11.52% and 5.76% over 6 years (Brealey, 2010).

The remaining task consists of calculating the discounted value of the annual energy production, the sum of these values is divided by the total life cycle cost. Equation (3) presents the formula for the calculation of the modified LCOE (Short et al., 1995).

$$LCOE = \frac{Io - (T * PVDEP) + PVOM * (1 - T)}{(1 - T) * \sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}} \qquad (3)$$

This research makes use of Equations 2 and 3 provided by (Short et al., 1995) to calculate the levelized cost of energy and to show how the parameters of the system and of the place of installation can affect the economy of a project. This method will be used as the basis for the development and analysis of the scenarios and for the sensitivity analysis of the project options.

3.2. Reference values

Using the formula for the levelized cost of energy presented above, the analysis was developed using a Discounted Cash Flow - DCF method. With this method, the levelized cost

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is discounted annually. The main entries used in the LCOE calculation are presented below:

- **C_I:** the installed cost of capital per scenario in EUR/MW is identified as the cost of developing the project.
- **P_i:** the installed power in MW corresponds to the capacity of electricity production annually. The installed power for the scenarios A = 42, B = 68 and C = 42.
- **Q_n:** is the amount of energy generated annually per investigated scenario. The result is given by multiplying the installed power in MW by the equivalent annual time in hours. As a result, we have scenarios A = 115,363.7, B = 219,207.8, C = 167,748.2.
- **PVOM:** the cost of operation and maintenance is associated with the continuity of operation of the project and constitutes a considerable part of the annual costs of a wind system. The operating and maintenance costs considered for analysis were 2% of the investment from 1 to 5 years, 4% of the investment from 6 to 10 years and 5% of investment from 11 to 20 years.
- **F_c:** capacity factor is the percentage of time a farm is in full operation. The analyzed scenarios were calculated considering the proportion between actual energy production over a period and the total generation capacity in this period. The capacity factor for the scenarios A = 31.36%, B = 36.77%, C = 45.59%.
- **w_d:** In order to calculate interest during the construction of the project, it is necessary to know the financing, the percentage of the debt and of the used equity. The debt, w_d, is the collection of funds through the Credit Line, which may be from BNDES or from other development bodies and agencies. The debt pattern for wind energy equipment is up to 80% of the invested capital.
- **w_e:** The equity, we, are the resources coming from the partners or shareholders of the project and is assumed to be 36.5%.
- **t_j:** For the interest rate, 3 levels (optimistic, realistic and pessimistic) were considered to verify their impact on the levelized cost of energy.
- **d:** The discount rate will remain constant throughout the analysis at 14.21% and will be treated in nominal terms.

The inputs cost of installed capital, installed power, amount of energy generated annually, maintenance operation cost and capacity factor allow to represent the system impacts resulting from the changes in the project. The fixed charge rates resulting from

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project financing costs determine the amount of revenue needed to pay the investment charges.

4. Results and Sensitivity Analysis

Based on the specifications of the economic model presented in the previous section, the levelized cost of energy model, during the 20-year useful life of the project was computed. Using an interest rate of 8%, the result of the levelized cost of energy for the three investigated farm scenarios are presented in Table 4.

Table 4. Levelized cost of energy with an interest rate of 8%.

Scenarios	Total cost of the life cycle (EUR)	LCOE (EUR/MWh)
A	66 925 344.22	75.19
B	97 431 654.53	58.51
C	49 428 704.31	38.35

Source: Authors.

The LCOE corresponds to the mean energy price that final users (consumers) of electricity should pay to the investor of the project (energy producer).

4.1. Factors that affect the levelized cost of energy

It is important to note that the levelized cost of energy depends on several factors, some defined by the market, others by government policies, and others are difficult to characterize accurately, such as wind conditions. Therefore, it is necessary to know the sensitivity of the levelized cost of energy in relation to these factors. Next, we present five factors related to market and public policies:

- **MACRS:** The Modified Accelerated Cost Recovery System is a 5-year incentive measure that allows the depreciation of half of the farm total value in the first year for tax deduction. Depreciation is a tributary aspect that facilitates greater investment in renewables and provides lower costs of energy for final consumers. The expiration of this incentive, e.g., increases the value of the produced energy.

- **State Incentives:** Some Brazilian states offer state incentives for the development of renewables, such as exemption from property taxes and incentives for the Tax on Circulation of Goods and Services (ICMS). The expiration of the property incentive may lead to an increase in the cost of energy, and ICMS is a tax that directly affects the final consumer because it is charged for consumption. The higher the rate, the higher the cost of energy.
- **Interest rate:** Incentives to the development of renewable energy have allowed investors access to investments and low-cost capital, attributed to a low interest rate environment as an incentive to the sector. However, if long-term interest rates follow the high levels of the Selic rate used in recent years, these projects will not have a favorable financing for the development of the project and can make it unfeasible.
- **Federal Incentives:** A reduction in tax rates (PIS / PASEP and COFINS) would produce a more favorable internal return rate (IRR) and would induce a decrease in LCOE.
- **Cost of investment:** The cost of investment can be reduced once the Pumping Kite system becomes a market product. This reduction in the cost of the generation system, as a result of the mass production of the units and of the competition in the market, will lead to a fall in the cost of energy. Furthermore, it is believed that the calculations made here consider overestimated PK unit values.

These factors may influence the implementation of fiscal and market policies to encourage the development of renewable energy.

4.2. Parameter sensitivity analysis

The sensitivity analysis is performed in relation to the variation of the price of electricity and the interest rate for the three investigated wind farm scenarios. The sensitivity analysis was performed considering different interest scenarios: optimistic, realistic and pessimistic.

The optimistic scenario was conducted from a favorable economic situation in Brazil, with an interest rate of 8% per year, the realistic scenario investigated is conducted to an interest rate of 12 % per year, close to the current Selic rate, and the pessimistic scenario represents the worst analysis condition, at a rate of 16% per year. Table 5 shows the result of the levelized cost of energy calculation for the three scenarios of farms and interest.

Table 5. Levelized cost of energy - LCOE (EUR/MWh).

Interest rate	Optimistic	Optimistic	Pessimistic
Scenarios	LCOE		
A	75.19	102.09	132.30
B	58.51	79.38	102.69
C	38.35	51.87	67.10

Source: Authors.

Note that the LCOE represents the cost of energy paid by the consumer, while the IRR represents the investment return rate. Thus, the lower the LCOE, the better for the consumer. However, the investment must be profitable for the investor and this can be verified by calculating the IRR for the found LCOE value. When the value of the levelized cost of energy of the optimistic scenario is applied to the economic model, it is observed that all the investigated scenarios, (scenarios A), (B) and (C), are presented as an economically attractive undertaking for their development (IRR ≤ Benchmark), as shown in Table 6.

Table 6. Calculation of the internal investment return rate considering the levelized cost of energy as input.

Interest rate		Optimistic
Farms	Benchmark	IRR
A		13.36%
B	12.38%	13.18%
C		12.60%

Source: Authors.

Note in Table 5 that the increase in the interest rate causes an increase in the levelized cost of energy. In addition, (scenarios A) and (C), which have the same number of machines and the same nominal power, have quite different levelized costs. In particular, for the wind farm (scenario A) to be economically viable, with an IRR = 13.36% per year, the levelized cost of energy must be 75.19 EUR/MWh, much higher and almost double that negotiated (Scenario C), with an IRR = 12.60% per year and the levelized cost of energy of 38.35 EUR/MWh. It can also be observed that the LCOE (scenario B), with an optimistic interest rate scenario, and (scenario C) with an optimistic and real interest rate scenario, presented lower than the price of sale of the electric power negotiated in the Brazilian electricity market worth 65.48 EUR / MWh. The wind farm dedicated to AWE technology with PK, (scenario

Research, Society and Development, v. 9, n. 7, e666974528, 2020
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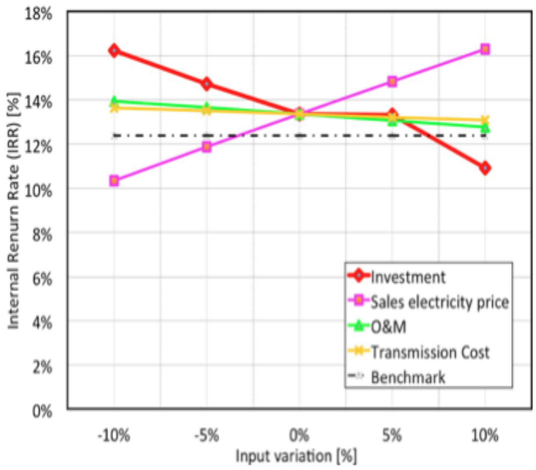
C), has been shown to be more advantageous from the point of view of presenting a higher capacity factor and being able to generate a more expressive amount of energy, in addition to lower generation costs.

The hybrid wind farm, scenario (B), is presented as an interesting alternative to improve the farm capacity factor with classic turbines, reducing the levelized cost of energy and still proving economically viable. It is observed that the farm in scenario (B) consists of the farm in scenario A with the addition of 13 PK units. Thus, in addition to using the already existent structure of the farm, such as transmission lines and ground, this hybrid farm presented itself as an economically attractive undertaking and with low LCOE. This is because PKs significantly increase the capacity factor of the farm.

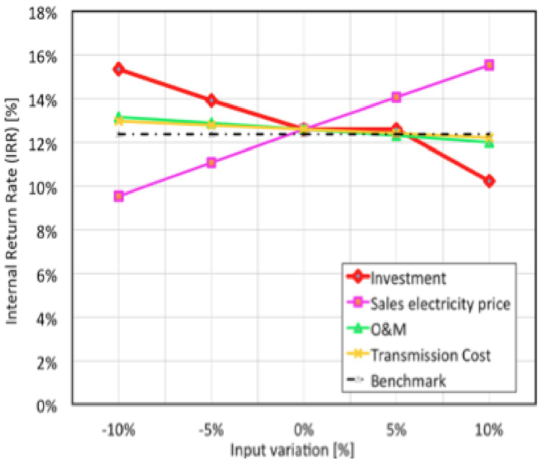
The sensitivity analysis for the optimistic scenario of the three wind farms is presented in Figures 5, 6, and 7.

Figure 5. Sensitivity analysis for scenario A.



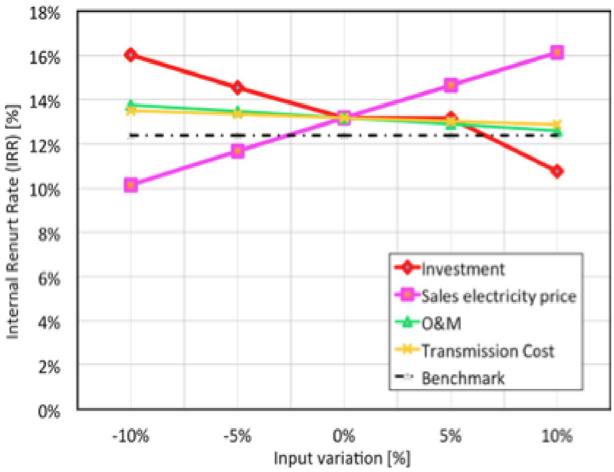
Source: Authors

Figure 6. Sensitivity analysis for scenario B.



Source: Authors

Figure 7. Sensitivity analysis for scenario C.



Source: Authors.

The parameters that had their data varied in (+) or (-) 10% were the Investment, the price of sale of energy, the Cost of O&M and the cost of transmission. It is possible to observe that all the investigated wind farm scenarios, Figures 5, 6 and 7, are attractive to the investment. For wind farms to become economically unviable at all scenarios, there must be approximately 6% more investment in the project, or a reduction in the price of electricity from 3% for scenarios A and B and from 1% for scenario C, or even an increase of around 7% in the transmission cost or a 4% increase in the cost of O&M for scenario C.

The results of the levelized cost analysis feed back the model of economic analysis that is based on the Internal Return Rate (IRR), as indicated in Table 6. In the sensitivity analysis presented in Figures 5, 6 and 7, the point corresponding to 0% variation is the one indicated in the optimistic column of table 6. These results suggest the economic advantages of a large-scale Pumping Kite system of electricity generation when compared to classic horizontal-axis wind turbine technology. This is true even if Pumping Kites are used in conjunction with traditional wind turbines in a hybrid wind farm, or in the case of farms dedicated to Pumping Kites. The reason for this is primarily a higher factor of Pumping Kite capacity and much lower transport and assembly costs when compared to the respective wind turbines.

4.3. Analysis of the LCOE for an alternative location of wind farm

Considering the same wind farm scenarios and the same corresponding investments, the levelized cost of energy for the city of Florianópolis (SC) was analyzed for an optimistic scenario (Table 7).

Table 7. Results for scenarios in Florianopolis (SC.), Brazil.

Characteristic	A	B	C
Location	Florianópolis - SC		
Wind speed [m/s]	6.5		
Capacity factor [%]	16.49	23.31	34.33
Annual energy generation [MWh]	60,684.5	138,872.6	126,303.8
Annual equivalent time [h]	1,444.8	2,042.2	3,007.2
TLCC [EUR]	66,925,344.22	97,431,654.53	49,428,704.31
LCOE [EUR]	146.70	93.96	52.72
Equity IRR [%]	13.36	13.18	12.60
Benchmark [%] per year	12.38		
Sale price of wind energy in Brazilian market - EUR/MWh	65.48		

Source: Authors.

The results show that for the city of Florianópolis all studied farms are economically viable with an IRR ≤ Benchmark. However, note that only the wind farm (scenario C) presents the levelized cost of energy lower than the one applied in the domestic market. The levelized cost of energy for (scenarios A) and (B) is higher than the value of the energy being sold in the internal energy market, making it impossible to implement them.

The results show that for the city of Florianópolis all the studied parks are considered economically viable with an IRR ≤ Benchmark, however note that only the wind farm (scenario C) presents a levelized energy cost lower than that applied in the national market. The levelized cost of energy for (scenarios A) and (B) is greater than the value of the energy being sold in the national market, making its implementation unfeasible.

5. Conclusions

This research aimed to analyze the levelized cost of energy of wind farms with tethered airfoils. To illustrate the proposed model, the levelized cost of energy of wind farms in Fortaleza (CE) and Florianópolis (SC) was analyzed. The farms considered are of three types: (scenario A) classic wind farm with 21 wind turbines with 2 MW of horizontal axis with 3 blades; (scenario B) hybrid wind farm with 21 wind turbines as in (scenario A), and 13 generating units of 2 MW with flexible wired airfoils operating in pumping kite mode. The area of the tethered airfoils corresponds to the area of 3 blades of a wind turbine and the same aerodynamic curves for the lift and drag coefficients are considered for the wind turbine units and wired airfoils, and (scenario C) wind farm with 21 generating units 2 MW with wired airfoil operating in pumping kite mode.

The results show that the increase in the interest rate causes an increase in the leveled cost of energy in both scenarios. Considering a wind farm with wind turbines (scenario A) and another with wired airfoils (scenario C), both with 21 units of 2MW in the city of Fortaleza, Ceará, the results show that, for the wind farm of scenario A to be economically viable with an IRR = 13.36% per year (a.a.), the level cost of energy should be 75.19 EUR / MWh, much higher than that negotiated in (Scenario C), with an IRR equal to 12.60% per year (a.a.) and the level energy cost of 38.35 EUR / MWh. For the city of Florianópolis, Santa Catarina, the results show that all the studied parks are considered economically viable with an IRR ≤ Benchmark, however note that only the (scenario C) wind farm with wired airfoils presents a lower level of energy cost than the marketed in the national energy market. These results suggest that it is interesting to invest in electric power generation technology with the use of wired airfoils because better economic benefits are obtained in relation to the current classic wind technology, mainly due to lower installation and maintenance costs for the parks. An observation to be made is that the costs of the system with wired airfoils used in this research were obtained from the results De Lellis et al. (2016) and as wired airfoil technology is in full development, many progress has been made and its costs reduced since the year of publication of this reference. It is believed that the first market products of this technology should emerge soon and that the prices of these products tend to decrease as scale manufacturing occurs. Another point to be noted is that many airfoils that are being researched and developed, use a relatively high cost carbon fiber semi-rigid kite when compared to a kite surfing or paragliding kite. On the other hand, these flexible wings tend to have a lower aerodynamic efficiency than semi-rigid or rigid ones. Another interesting point in favor of wired airfoil technology is the fact that it can explore winds at higher altitudes where the wind is stronger and more frequent, allowing a more lasting energy supply over time, presenting a low energy supply only in shorter periods of time. Wind farms with wired airfoils can reduce the need for energy storage and the use of non-renewable sources to supply energy demand during periods of insufficient winds. This intermittent aspect of renewable energy sources has been the subject of many studies that transcend the scope of this work.

Acknowledgement

The authors would like to thank the Coordination for the Improvement of Higher Education Personnel (CAPES) for funding this research project.

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Percentage contribution of each author in the manuscript

Anny Key de Souza Mendonça – 70%

Antonio Cezar Bornia – 30%