Articles

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Sensitivity analysis of the economic-financial feasibility study of the Punta de Maisí Wind Farm project.

Análisis de sensibilidad del estudios de factibilidad económico - financiera del proyecto ¨del Parque Eólico Punta de Maisí

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ABSTRACT

In Maisí municipality, the easternmost municipality of Cuba, belonging to Guantánamo province, at coordinates 20,270 N and 74,220 W approximately, pre-feasibility studies are being carried out for a wind farm project in two sites known as Punta Fraile and Punta Quemado. Two variants are proposed. The objective of this work was to perform sensitivity analyses on the profitability of the parameters susceptible to change, in order to determine the limits within which they can move without the project becoming unprofitable. For the studies, a program was designed for pure and hybrid renewable sources; it has a module for the estimation of the capital cost based on the relevant parameters of the project, which guarantees equal conditions in the analysis of variants. The economic-financial evaluation is carried out using four fundamental criteria that complement each other. The results are given in the form of a comparative table of variants and influential sensitivity parameters.

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Keywords: Feasibility studies, Sensitivity analysis, Parametric cost estimation, Relevant parameters of the project

RESUMEN

En el municipio Maisí, el más oriental de Cuba, perteneciente a la provincia Guantánamo, en las coordenadas 20,270 N y-74,220 O aproximados, se realizan los estudios de pre factibilidad del proyecto de un parque eólico en dos emplazamientos conocidos por Punta Fraile y Punta Quemado. Se proponen dos variantes. El objetivo de este trabajo fue realizar los análisis de sensibilidad sobre la rentabilidad de los parámetros susceptibles de variar, con la finalidad de determinar los límites dentro de los cuales se pueden mover sin que el proyecto deje de ser rentable. Para los estudios fue diseñado un programa para fuentes renovables puras e híbridas; dispone de un módulo para la estimación del costo capital a partir de los parámetros relevantes del proyecto que garantiza igualdad de condiciones en el análisis de variantes. La evaluación económico - financiera se realiza mediante cuatro criterios fundamentales que se complementan. Los resultados se dan en forma de tabla comparativa de las variantes y parámetros influyentes de la sensibilidad.

Palabras clave: Estudios de factibilidad, Análisis de sensibilidad, Estimación paramétrica del costo, Parámetros relevantes del proyecto

INTRODUCTION

Since 1984, the Universidad de Oriente and the Centro de Investigaciones Solar (CIES) have been carrying out wind speed measurements in the municipality of Maisí, which together with the data base accumulated by the meteorological station at the lighthouse of that strategic point for navigation, made it possible to analyze the seasonal and monthly behavior of the region.(Burton et al., 2011; García et al., 2016a, 2016b).The wind map subsequently developed by the Institute of Meteorology of Cuba (Roque-Rodríguez et al. (Roque-Rodríguez et al., 2019)allowed corroborating the hypothesis that there was a good wind potential in the area. The mean annual velocity calculated with the monthly average values and extrapolated to 50 m altitude, as well as the calculation of the wind potential of the sites planned for the turbine emplacement, are in correspondence with those provided by the wind map of Cuba, Figure 1.

Currently, the pre-feasibility studies for the wind farm are being carried out in two variants: the first variant proposes to install 2.5 MW Gamesa turbines for a total of 175 MW at the Punta Fraile and Punta Quemado sites, with 87.5 MW at each site; the second variant proposes to install 4.5 MW Gamesa turbines, 46 of them at Punta Fraile and 24 at Punta Quemado, with a total installed capacity of approximately 300 MW (Apgar, n.d.; Siemens, 2020).(Apgar, n.d.; Siemens, 2020).

For the determination of the annual energy produced in each variant, the characteristic curves of the G-114-2.5MW and G120-4.5 turbines, which can be installed with tower heights of 100 and 120 meters, respectively, are used (Siemens, 2020). The capital costs of both projects are influenced by the power to be installed, but also by the number of turbines and the height of the towers, the parametric model of cost estimation solves this problem(Enriquez et al., 2019; RENEWABLE POWER GENERATION COSTS IN 2018, 2019; VGB PowerTech, 2019).

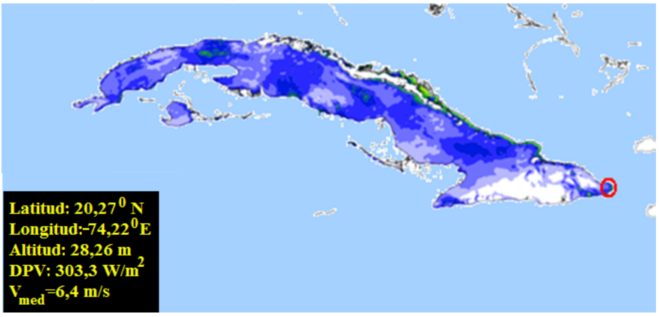
The project foresees the interconnection of the machines of both sites with the national grid, so for the analysis all the energy produced is absorbed by the system.

To ensure a good margin of reliability of the results, certain considerations must be made:

The sites are located at altitudes ranging from 20 m to 50 m above sea level, so the turbine output must be corrected for the decrease in air density. - At each

The site will have a large number of turbines, so that regardless of the arrangement adopted, the total generation of the wind farm will be affected by the wake effect that occurs behind the turbines (array efficiency)[3], In this work, an acceptable value (90%) for array efficiency is adopted because of the influence it has on the profitability of the wind farm.

Figure 1. Map of wind potential in Cuba.



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Source: Institute of Meteorology of Cuba

MATERIALS AND METHODS

Three modules of the FRE-LGV-1 program developed by Professor Luis Jerónimo García Faure[1] are used to carry out the work:

- Study of the site's wind potential, annual energy generation and capacity factor of each site.
- Economic-financial validation
- Sensitivity analysis

The wind speed distribution is used to estimate the wind potential, which will then serve as an element for calculating the energy that can be produced and the capacity factor with which the wind farm must operate. The wind power density is defined as the average value of the power per unit area of all measurements taken during the year (Manwell et al., 2010). (Manwell et al., 2010)It is given by:

$$DPV = \frac{\rho}{2 \cdot n} \sum_{i=1}^{n} v_i^3 \qquad (1)$$

Generally, hourly wind speed measurements are made, in this case n=8760, which are the hours of a normal year.

Wind potential is considered poor if the wind power density is less than 160 W/m^2 , acceptable or good up to 400 W/m^2 and excellent above 400 W/m^2 .

It is shown [5]: that the useful power produced by a wind turbine for a wind speed v_i is given by:

$$P_i = \frac{1}{2} \cdot \rho \cdot C_p \cdot \eta_t \cdot A \cdot v_i^3 \quad kW \qquad (2)$$

Normally manufacturers provide the characteristic curves of their turbines (P-v_i) evaluated in laboratory conditions in order not to have to use the coefficient C_p and the efficiency η_t and take the air density for normal atmospheric conditions ofρ =1,225 kg/m^3 , which must be corrected for local conditions. Thus, the energy produced by the turbine for each wind speed is given by:

$$E_i = \frac{\rho}{1{,}225} \cdot P(v_i) \cdot t_i \quad kWh \qquad (3)$$

And the total annual energy is determined by:

$$E = \frac{\rho \cdot n}{1{,}225} \sum_{v_i = v_a}^{v_i = v_{max}} P(v_i) \cdot p(v_i) \quad kWh/a \qquad (4)$$

If hourly wind speed measurements are taken n=8760 hours and the product p(v_i).8760 are the hours of the year that the speed v_i .

The capacity factor is given by the ratio between the annual energy produced and the energy that could hypothetically be produced if the turbine were to operate for all 8,760 hours of the year at rated power:

$$F.C. = \frac{Energía\ anual\ producida}{Potencia\ no\min al \cdot 8760} \qquad (5)$$

The values of the Weibull parameters k and c were calculated at the reference height (Z_{ref}) of 50 meters to determine if the wind potential at that height is in correspondence with the one indicated in the wind map of Cuba, then they were extrapolated for the turbine hub height (Z_{buje}) to determine the power(Enriquez Garcia & Garcia Faure, 2018;

National Aeronautic and Space Administration NASA, 2015). It is assumed that although the air speed increases with height, the frequency with which the velocities pass at the hub and reference heights is the same, that only the magnitude of the velocity varies. Under these conditions, the coefficient k practically remains constant, but the coefficient c varies according to the following relationship [6]:

$$c_{buje} = c_{ref} \cdot \frac{\ln\left(\frac{Z_{buje}}{Z_O}\right)}{\ln\left(\frac{Z_{ref}}{Z_o}\right)} \quad m/s \qquad (6)$$

The capital cost, as mentioned before, is estimated by the parametric method (Apgar, n.d.; National Aeronautic and Space Administration NASA, 2015). The model used was developed based on the three relevant technical parameters that determine the cost of wind farms: power, number and heights of turbines, taking into account a representative number of farms built in recent years in 12 of the Latin American countries that make the greatest use of wind power (Enriquez García & García Faure, 2018; Enríquez et al., 2019; García et al., 2016b).. It is given by:

$$C = 18{,}02 \cdot P^{0{,}675} \cdot N^{0{,}924} \cdot Z^{1{,}55} \quad \$ \qquad (7)$$

For values of $90<Z<130$ m

This equation takes into account all costs associated with the initial investment of the wind farm including transportation and assembly of the turbines, but not the transmission lines and other external works of the wind farm. When used with any of the economic-financial validation criteria, it has the advantage of establishing a continuous relationship between the technical parameters and the criterion used (NPV, IRR, COE, etc.), which guarantees equal conditions in the evaluation of the variants(Enriquez et al., 2019; VGB PowerTech, 2019).

From the annual capital cost and the effective working hours of the turbines, operating and maintenance costs, turbine replacement costs, if any, and the residual value of the project are deducted.

The integral rate considers the part corresponding to the normal bank discount, the insurance rate plus other rates that may arise. The maximum limit that this rate can take is set by the internal rate of return (IRR) above which the NPV becomes negative.

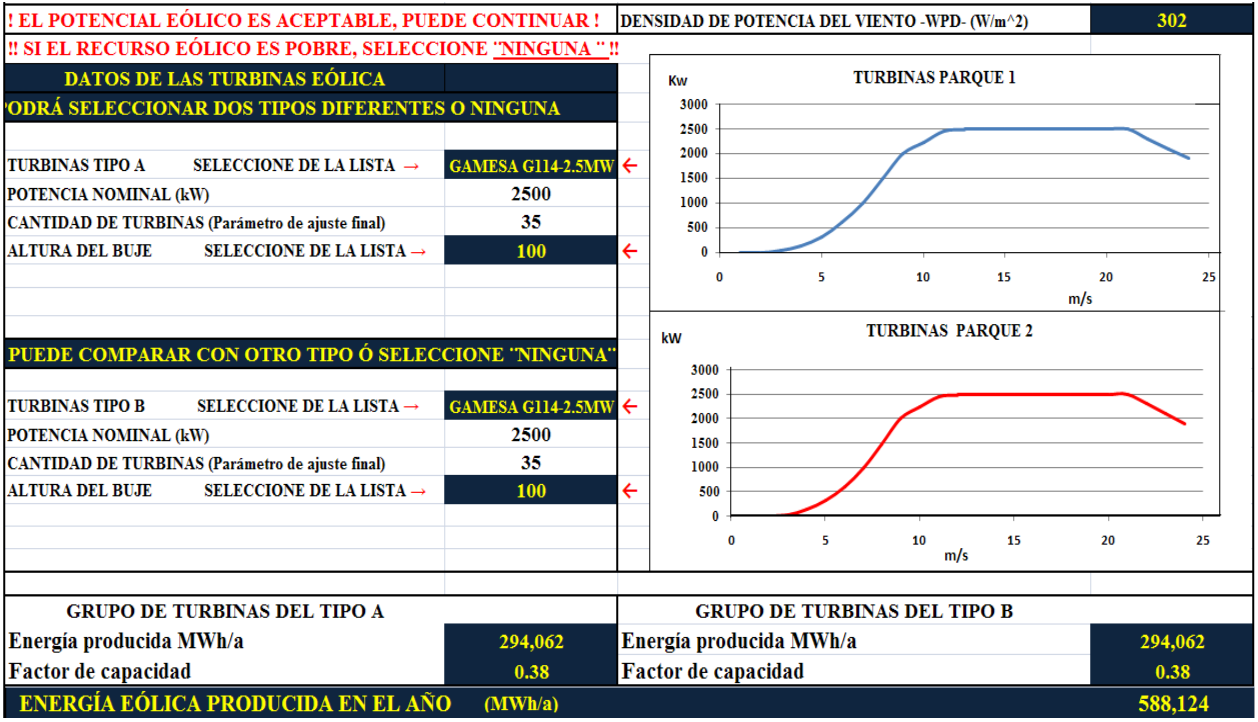
The electricity sales tariff determines the revenue; as it increases, so does the NPV. It can decrease until it becomes equal to the levelized cost of energy; below that value, the NPV becomes negative. The analysis of the behavior of the sensitivity variables is carried out by means of the *spider diagram.* (ICEAA, 2019)

RESULTS

The wind power density calculated at 50 meters height at the sites is 302 W/m2 with an average speed of 6.44 m/s, very close to those obtained with the interactive wind map of the Instituto de Meteorología shown in Figure 1.

Variant 1
With 70 Gamesa G114-2.5 MW turbines for a total of 175 MW at the two sites with 35 turbines each.
By applying the FRE-LG-V1 program, it is determined that each site will be able to contribute 294,062 MWh/year for a total of 588,124 MWh/year, i.e. 588 GWh/year, as shown in Figure 2. This generation was obtained for a 90% efficiency of the wind farm, which should increase or decrease depending on the efficiency achieved.

Figure 2. Energy production results for variant 1.



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DENSIDAD DE POTENCIA DEL VIENTO -WPD- (W/m^2) 302

!! SI EL RECURSO EÓLICO ES POBRE, SELECCIONE "NINGUNA " !!

DATOS DE LAS TURBINAS EÓLICA

'ODRÁ SELECCIONAR DOS TIPOS DIFERENTES O NINGUNA

TURBINAS TIPO A SELECCIONE DE LA LISTA →	GAMESA G114-2.5MW ←
POTENCIA NOMINAL (kW)	2500
CANTIDAD DE TURBINAS (Parámetro de ajuste final)	35
ALTURA DEL BUJE SELECCIONE DE LA LISTA →	100 ←

PUEDE COMPARAR CON OTRO TIPO Ó SELECCIONE "NINGUNA"

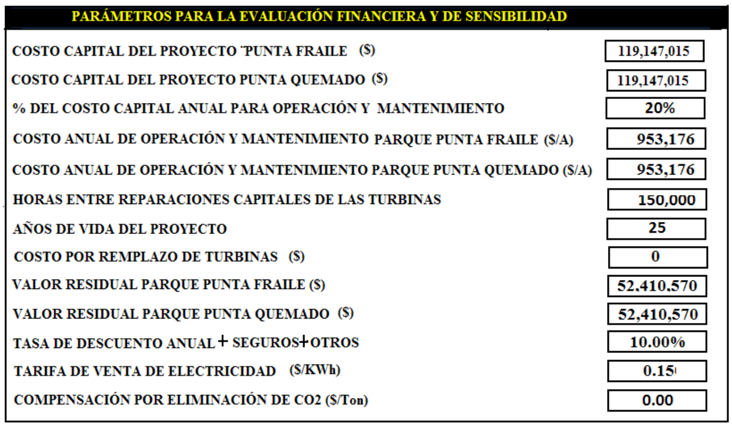
TURBINAS TIPO B SELECCIONE DE LA LISTA →	GAMESA G114-2.5MW ←
POTENCIA NOMINAL (kW)	2500
CANTIDAD DE TURBINAS (Parámetro de ajuste final)	35
ALTURA DEL BUJE SELECCIONE DE LA LISTA →	100 ←

GRUPO DE TURBINAS DEL TIPO A		GRUPO DE TURBINAS DEL TIPO B	
Energía producida MWh/a	294,062	Energía producida MWh/a	294,062
Factor de capacidad	0.38	Factor de capacidad	0.38
ENERGÍA EÓLICA PRODUCIDA EN EL AÑO (MWh/a)			588,124

Source: FRE-LGV1 Program

Table 1 shows the parameters calculated and those to be set for the profitability calculation. These values define the so-called break-even validation.

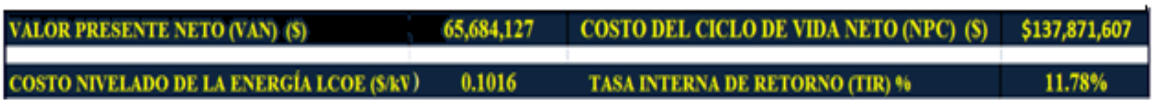
Table 1. *Summary of economic-financial parameters* of variant 1



PARÁMETROS PARA LA EVALUACIÓN FINANCIERA Y DE SENSIBILIDAD	
COSTO CAPITAL DEL PROYECTO 'PUNTA FRAILE ($)	119,147,015
COSTO CAPITAL DEL PROYECTO PUNTA QUEMADO ($)	119,147,015
% DEL COSTO CAPITAL ANUAL PARA OPERACIÓN Y MANTENIMIENTO	20%
COSTO ANUAL DE OPERACIÓN Y MANTENIMIENTO PARQUE PUNTA FRAILE ($/A)	953,176
COSTO ANUAL DE OPERACIÓN Y MANTENIMIENTO PARQUE PUNTA QUEMADO ($/A)	953,176
HORAS ENTRE REPARACIONES CAPITALES DE LAS TURBINAS	150,000
AÑOS DE VIDA DEL PROYECTO	25
COSTO POR REMPLAZO DE TURBINAS ($)	0
VALOR RESIDUAL PARQUE PUNTA FRAILE ($)	52.410.570
VALOR RESIDUAL PARQUE PUNTA QUEMADO ($)	52,410,570
TASA DE DESCUENTO ANUAL + SEGUROS+OTROS	10.00%
TARIFA DE VENTA DE ELECTRICIDAD ($/KWh)	0.15
COMPENSACIÓN POR ELIMINACIÓN DE CO2 ($/Ton)	0.00

Source: Authors, 2022

Results of validation of variant 1

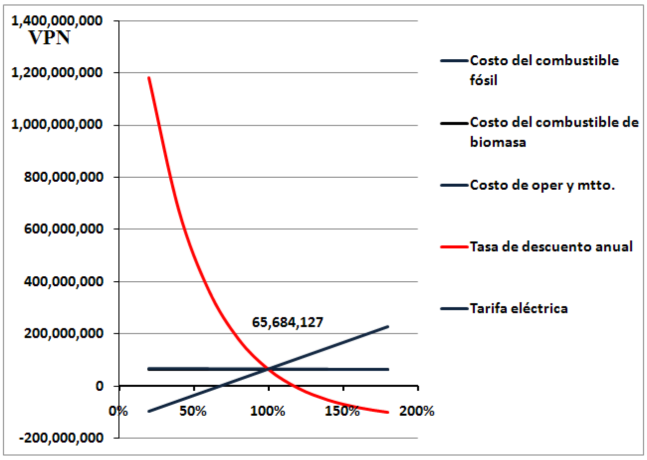


VALOR PRESENTE NETO (VAN) ($)	65,684,127	COSTO DEL CICLO DE VIDA NETO (NPC) ($)	$137,871,607
COSTO NIVELADO DE LA ENERGÍA LCOE ($/kV)	0.1016	TASA INTERNA DE RETORNO (TIR) %	11.78%

Sensitivity analysis of variables on NPV

In the spider type graph. (ICEAA, 2019)in Figure 3 shows the value taken by the NPV ($65, 684,127) for the values in Table 1. It can be observed, that there are two parameters that exert a notable influence on the profitability: the integral discount rate and the electricity sales tariff. The operation and maintenance cost has practically no influence on the NPV.

Figure 3. Spider diagram for sensitivity analysis.



Source: FRE-LGV1) program.

Influence of the cost of capital of variant 1 on NPV sensitivity.

The cost of capital also has a marked influence on the profitability of the project: a 25% decrease in cost represents an increase in NPV of approximately 50%, while a 25% increase in cost represents a 50% decrease in NPV. Table 2 shows this behavior.

Table 2. *Behavior of NPV with the cost of capital*

	Capital cost ($)	$/kW	VPN
Parametric estimate	238,294,030	1,362	65,684,127
25% decrease	180,764,508	1,032	98,969,425
25 % increase	297,867,537	1,702	29,985,664

Source: Authors, 2022

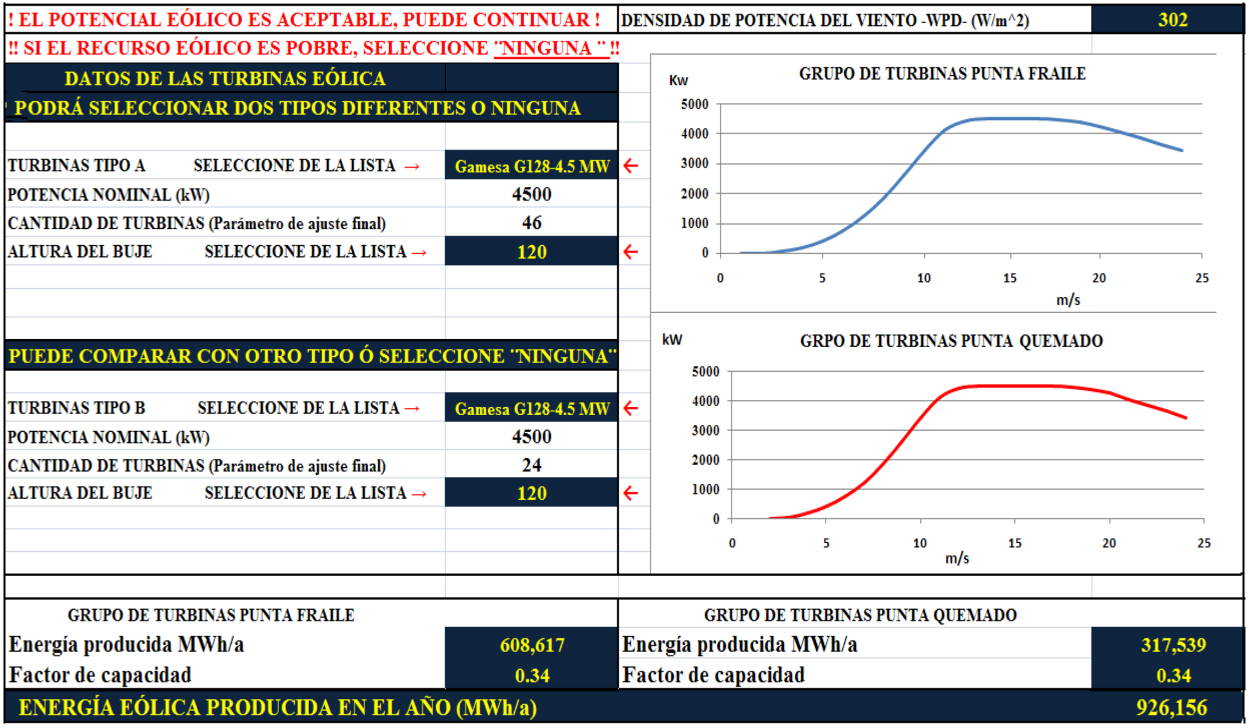
Variant 2

With 300 MW installed, 67 Gamesa G124-4.5 MW turbines and 120 meters hub height, 43 at the Punta Fraile site and 24 at the Punta Quemado site. Figure 4 shows the annual energy production. The Punta Fraile site will be able to produce 608,617 MWh/year while the Punta Quemado site will be able to produce 317,539 MWh/s, for a total of 926,156 MWh/year.

The first curious and apparently contradictory fact observed is that despite the increase in the energy produced by the increase in installed power and the hub height of the machines, there is a decrease in the capacity factor.

In order to understand this behavior, it is necessary to refer to equations 2, 4 and 6 on the calculation of power, turbine energy and capacity factor. In equation 2, the power calculation is a function of the power coefficient and the turbine efficiency, both parameters depending on the type of turbine and the power at which it is working. In similar turbines the behaviors of Cp and η follow similar curves, but as the turbine power increases, their higher values move towards higher powers. In the case of the turbines analyzed, for the G114-2.5 MW the highest values are obtained at lower wind speed. When plotting the Weibull probability curves, it can be seen that as the hub height varies from 100 m to 120 m, the curves maintain their shape, but below 9 m/s the probabilities of occurrence are higher for the lower power turbine, which is where its power and efficiency coefficients are higher. Figure 5 shows both probability distributions, and although they appear very close (at 120 m it shifts to the right), the values of the ordinates p(vi) differ sufficiently to produce the results obtained. From 9 m/s the situation is reversed; in this case the higher probabilities of occurrence of the velocities occur at higher altitudes, so that a relative increase of energy is obtained in the turbine of higher power, but not enough to achieve the same capacity factor as with the turbine of lower power. If the wind potential were higher, the turbines would work most of the time at speeds higher than 9 m/s, the situation would be different.

Figure 4. Energy production results for variant 2.



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DENSIDAD DE POTENCIA DEL VIENTO -WPD- (W/m^2)	302

DATOS DE LAS TURBINAS EÓLICA

PODRÁ SELECCIONAR DOS TIPOS DIFERENTES O NINGUNA

TURBINAS TIPO A SELECCIONE DE LA LISTA →	Gamesa G128-4.5 MW ←
POTENCIA NOMINAL (kW)	4500
CANTIDAD DE TURBINAS (Parámetro de ajuste final)	46
ALTURA DEL BUJE SELECCIONE DE LA LISTA →	120 ←

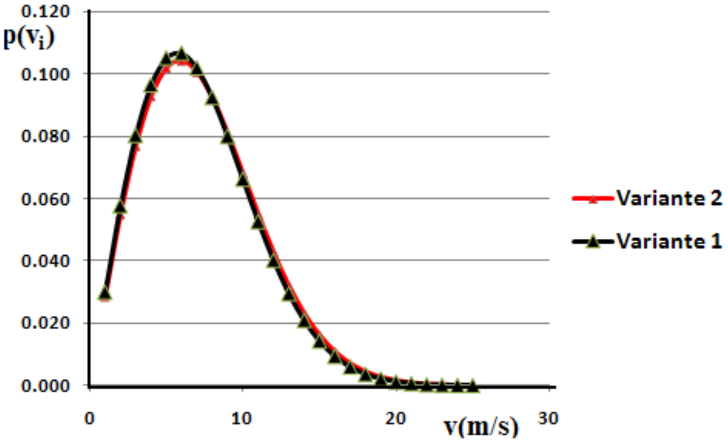
PUEDE COMPARAR CON OTRO TIPO Ó SELECCIONE "NINGUNA"

TURBINAS TIPO B SELECCIONE DE LA LISTA →	Gamesa G128-4.5 MW ←
POTENCIA NOMINAL (kW)	4500
CANTIDAD DE TURBINAS (Parámetro de ajuste final)	24
ALTURA DEL BUJE SELECCIONE DE LA LISTA →	120 ←

GRUPO DE TURBINAS PUNTA FRAILE		GRUPO DE TURBINAS PUNTA QUEMADO	
Energía producida MWh/a	608,617	Energía producida MWh/a	317,539
Factor de capacidad	0.34	Factor de capacidad	0.34
ENERGÍA EÓLICA PRODUCIDA EN EL AÑO (MWh/a)			926,156

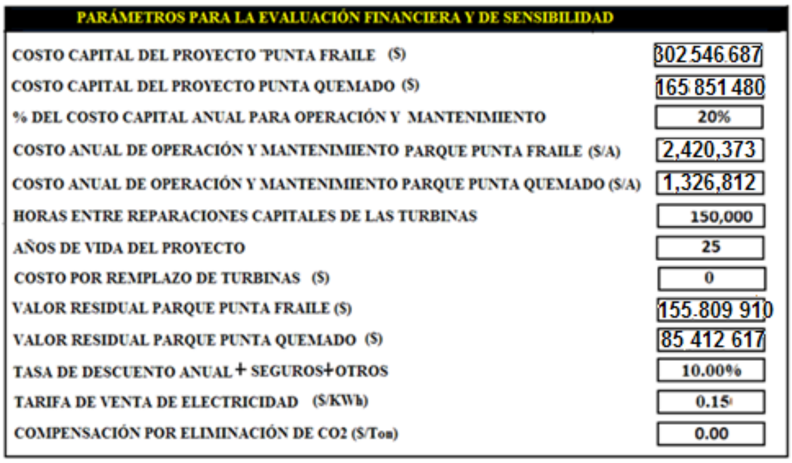
Source: FRE-LGV1 program

Figure 5. Weibull velocity distribution curves at 100 m and 120 m altitude.



Source: FRE-LGV1 program

Table 3. *Summary of economic-financial parameters of variant* 2



PARÁMETROS PARA LA EVALUACIÓN FINANCIERA Y DE SENSIBILIDAD	
COSTO CAPITAL DEL PROYECTO PUNTA FRAILE (\$)	302 546 687
COSTO CAPITAL DEL PROYECTO PUNTA QUEMADO (\$)	165 851 480
% DEL COSTO CAPITAL ANUAL PARA OPERACIÓN Y MANTENIMIENTO	20%
COSTO ANUAL DE OPERACIÓN Y MANTENIMIENTO PARQUE PUNTA FRAILE (\$/A)	2,420,373
COSTO ANUAL DE OPERACIÓN Y MANTENIMIENTO PARQUE PUNTA QUEMADO (\$/A)	1,326,812
HORAS ENTRE REPARACIONES CAPITALES DE LAS TURBINAS	150,000
AÑOS DE VIDA DEL PROYECTO	25
COSTO POR REMPLAZO DE TURBINAS (\$)	0
VALOR RESIDUAL PARQUE PUNTA FRAILE (\$)	155.809 910
VALOR RESIDUAL PARQUE PUNTA QUEMADO (\$)	85 412 617
TASA DE DESCUENTO ANUAL + SEGUROS+OTROS	10.00%
TARIFA DE VENTA DE ELECTRICIDAD (\$/KWh)	0.15
COMPENSACIÓN POR ELIMINACIÓN DE CO2 (\$/Ton)	0.00

Source: Authors, 2022

Table 3 shows that only those variables involved in cost and profitability are considered; the remaining parameters remain the same as in variant 1 in order to establish a comparison between the validation criteria.

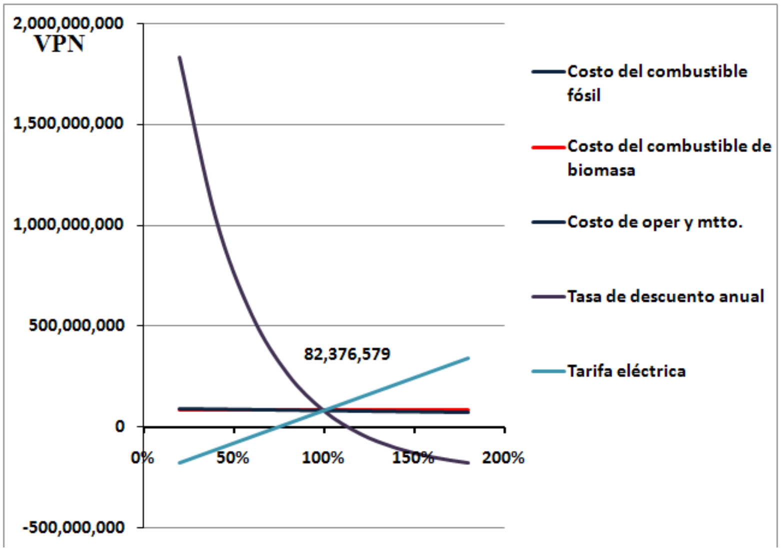
Results of the validation of variant 2

VALOR PRESENTE NETO (VAN) (\$)	82,376,579	COSTO DEL CICLO DE VIDA NETO (NPC) (\$)	\$238,175,154
COSTO NIVELADO DE LA ENERGÍA LCOE (\$/kV	0.1115	TASA INTERNA DE RETORNO (TIR) %	11.36%

Sensitivity analysis

As can be seen in Figure 6, as in variant 1, the two parameters that have the greatest influence on NPV are the integral discount rate and the electricity tariff. In order to establish the comparison between the two variants, equal values were taken for both parameters.

Figure 6. Sensitivity analysis of variant 2.



Source: FRE-LGV1 program

Table 4. *Comparative summary*

Item to compare	*Variant 1 (175 MW)*	*Variant 2 (300 MW)*	*Difference (V2-V1)*
Energy production (GWh/a)	588	926	+57%
Capacity factor	0,38	0,34	-11%
Capital cost ($)	238,294,030	468,398,167	+96,5%
Life cycle cost ($)	137,871,607,	238,175,154	+73%
Net Present Value ($)	65,684,127	82,376,579	+25%
Levelized cost of energy ($/kWh)	0,1016	0,1115	+9%
Internal rate of return (%)	11,78	11,36	-3.5%

Source: Authors, 2022

CONCLUSIONS

The calculations made for both variants were performed for the same conditions and equal equilibrium values as shown in tables 1 and 3 and whose results are summarized in table 4. If the same wind potential is maintained, any variation that occurs in the sensitivity parameters (integral rate of return, electricity sales tariff, capital cost), produces an alteration (positive or negative) on the NPV and the remaining validation criteria, but the ratio of the variants given in table 4 must be maintained.

The increase in power from 175 MW and height from 100 m of variant 1 to 300 MW and 120 m height in variant 2 represents:

1. 57% increase in energy but must increase 96.5% of capital cost and 73% of life cycle cost

2. A 25% increase in net present value
3. An increase in the cost of energy production (COE) of 9%.
4. A decrease in the internal rate of return (IRR) of 3.5%.

However, as explained above, if the wind potential of the site were higher, all indices for variant 2 would be expected to improve.

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