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# MULTI-CRITERIA MODELING FOR THE SELECTION OF CENTRIFUGAL PUMPS DRIVEN BY WIND TURBINES

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## ABSTRACT

This article is focused on the multi-criteria selection of centrifugal pumps driven by wind turbines, for the supply of water, whose main purposes are to reduce the consumption of electrical energy from the national electricity grid, dependence on fossil fuels and environmental pollution. In this work, a mathematical model composed of a multi-criteria function has been developed, which, through a calculation procedure, makes it possible to select the most technically and economically feasible Wind Turbine / Electro pump combination, applying the exhaustive search method. As economic criteria, the Net Present Value (NPV), the Internal Rate of Return (IRR), the Investment Payback Time (TRI) and the Levelized Cost of Electricity (LEC) are considered. As a technical criterion, the overall efficiency of the system was considered. Finally, the most economically feasible combination was obtained (combination 2). In addition, it is the optimal combination.

## INTRODUCTION

Due to the growing development of new technologies, the use of renewable energy sources (FRE) has had a direct impact, mainly on the supply of water and electricity, with greater application in isolated areas of the national electricity grid and pre-mountainous. The present work is directed to the selection of centrifugal pumps for the supply of water, through the use of the wind as an energy resource, whose main purposes are the reduction of the increasing consumption of electrical energy from the national electrical network destined for this purpose, dependence on fossil fuels, environmental pollution, as well as mitigating the large financial expenses that are generated as a result of the consumption of energy from the electricity grid, due to the high price of oil worldwide.

As a case study, the eco-tourist complex has been selected “Las Terrazas”, located at the eastern end of the Sierra del Rosario, where a pre-mountainous relief predominates. In Cuba, the pumping of water in these areas was carried out through traditional windmills (also called eolo-mechanical pumping systems) since the first decades of the 20th century, where the water is pumped through purely mechanical transmissions (Moreno, & et al, 2017). The proposal in the present work consists of depending as little as possible on the electrical network. To do this, a good solution is to select pumps capable of meeting the demand for water in the “Las Terrazas” complex and power them with the electricity produced by a wind turbine. This type of system is known as Wind-Electric Pumping System (hereinafter SBEE), which is a more advanced form of wind pumping. Figure 1 shows the schematic representation of an SBEE.

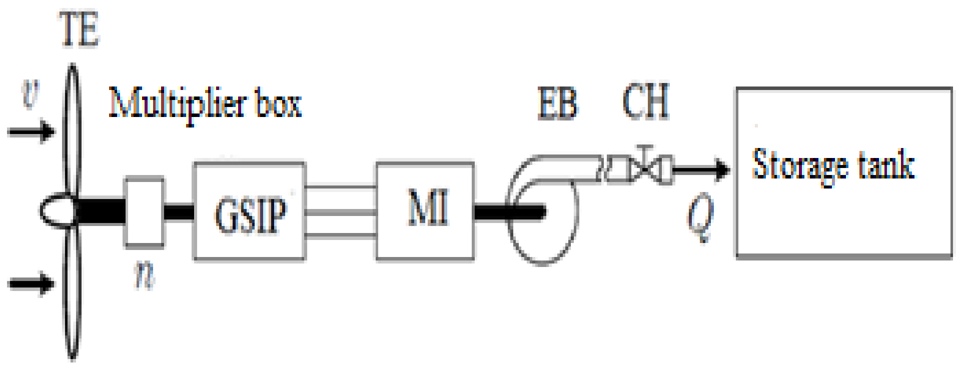


**Figure 1.** Schematic Representation Of A-Electric Pumping System (SBEE)

Where TE wind is the wind turbine, MI is the induction motor, EB is the electric pump and CH is the hydraulic circuit. These systems can deliver greater water flow than pumping systems. mechanical. Of all the components of the SBEE, the two most expensive elements are the wind turbine and the electric pump. Based on this, the scope of this work is limited to the sizing and selection of the centrifugal electric pump (s). The main purpose of this article is to develop a mathematical model that combines technical-energy and economic criteria in the sizing and selection of centrifugal pumps driven by wind turbines. The final objective of the model proposed in this work is to find the optimal size of the combinations between wind turbines and pump (TE / EB) to satisfy the water demand of the “Las Terrazas” complex. This model is known as the General Integrating Model (MGI).

In recent years, the development of mathematical models using multi-criteria optimization has behaved as follows:

For example, in (DuPont, Cagan & Moriarty, 2016), computational modeling is presented for wind farm design, which includes accurate power and cost modeling, as well as variability in wind speed and atmospheric stability. To validate the use of this model, an Extended Pattern Search (EPS), Multi-Agent System (MAS) is carried out. The optimization algorithm used is EPS-MAS. In (Zeng, & et al., 2016), a model is developed for planning an electricity production system with renewable energy sources (wind energy and photovoltaic solar energy) through multi-objective theory. The proposed model considers utility decision making under the restrictions of the distributed Generation reaction, as well as the operating characteristics of the system. To solve the problem, a heuristic approach is used to maximize electricity production, while minimizing the costs of obtaining each kWh. In (Ming Der Y. & et al, 2016), a proposal is made for the reduction of CO2 and energy consumption. For this, the implementation of solar energy systems (photovoltaic and thermal) on the roof of buildings is proposed. To obtain the optimal configuration of the photovoltaic solar installation, a model was used that includes a classification II genetic algorithm optimizer. In (Zografidou & et al., 2016) the application of the optimal design of the energy distribution network is presented. For this, a multi-objective programming model is applied that considers social, environmental, and economic criteria. In (Wang, & et al, 2017) a new model is proposed through a multi-objective algorithm to optimize the dimensions of a hybrid system of renewable energy sources, composed of photovoltaic panels, wind.

turbines, battery banks and diesel engines. In particular, the proposed model considers the minimization of the annualized cost of the system (economy), the probability of energy supply (reliability) and the emission of greenhouse gases (environment), allowing decision-making. To solve the model, an algorithm with genetic operators (genetic algorithms) is proposed. In (Li, & et al., 2018) a decision support tool for the selection of energy storage is proposed, a multi-objective optimization approach based on an augmented restriction method is adopted. The proposed approach considers economic and environmental objectives. In (Bracco, & et al. (2018) an optimization model is developed for energy planning in urban districts in Italy, using renewable energy sources (photovoltaic parks and micro wind turbines), as well as cogeneration plants. Finally, it is concluded that the main results are the number of wind turbines, the configuration of the photovoltaic solar system and the number of cogeneration units to be installed. The objective function formulated in the work consisted of minimizing capital costs and operating costs. In (Vishnupriyan, & Manoharan, 2018) the authors present an approach to optimize energy system planning, using the Hierarchical Analytical Process (AHP). In the work it is proposed to use the proposed model in a photovoltaic solar installation. To simulate the system and obtain the results, the authors use the HOMER Energy® program. In (Yang, & et al., 2018) an approach is proposed to optimize the dimensioning of an autonomous wind-photovoltaic hybrid system (with energy storage system). In the work, a model of each of the sub-systems that make up the system is developed. For the design of the system, an algorithm based on the Fourier transform is used. The total cost of electricity and energy losses are minimized, based on the use of multi-objective theory and the optimization method of genetic algorithms is used.

From the bibliographic study, it is observed that there are several works that use modern mono- and multi-criterial optimization techniques, with non-linear and discrete optimization under stochastic conditions predominant in recent years. In addition, it was observed that multi-criteria optimization techniques are applied mainly to photovoltaic solar energy installations, solar / photovoltaic hybrid systems, biomass, among others, but the application of these methods to purely wind pumping systems was not evidenced. From the above, the novelty of the proposed mathematical model can be deduced.

## MATERIALS AND METHODS

### *Different Mathematical Models Were Used to Obtain the Results.*

### *The Proposed Mathematical Model (General Integrative Model, MGI)*

Conceptually, the MGI is the procedure through which the sizing and selection of the most feasible TE / EB combinations is carried out. economically.

### *General Structure of the MGI:*

The MGI is structured in three sub-models, divided into three blocks and a database of combinations between wind turbines and pumps (TE / EB).

### *Technical-Energy:*

Block This block is made up of sub-models: pumping requirements, evaluation of the wind resource, global efficiency of the pumping system, η and the database of TE / EB combinations. These sub-models and the database constitute the input variable to the next block (economic block).

### *Economic Block:*

The well-known economic indicators are calculated for each combination between TE and EB: Net Present Value (NPV), Internal Rate of Return (IRR), Investment Payback Time (TRI) and the levelized cost of electricity (LEC). These economic indicators constitute the input variables to the mathematical block.

### *Mathematical Block:*

It is composed of the Conceptual Mathematical Model (MMC), which generates the most economically feasible TE / EB combinations.

### *Conceptual Formulation of The Proposed Model (Mathematical Block)*

The conceptual formulation of the mathematical model is divided into three parts: 1. Definition of the main variables involved in the MGI; 2. Definition of the multi-objective function (Conceptual Mathematical Model MMC); 3. Description of the sub-models that constitute input variables to the MMC.

### *Main Variables That Intervene in The Proposed Mathematical Model*

The main variables that intervene in the MGI are classified as follows:

#### *Coordination Variables:*

These are the essential variables that enable the dimensioning and selection of the components of a certain system. In this case, they are the water demand (Qd), the total pumping head (HT) and the average wind speed.

#### *Decision Variables:*

It is the set of combinations (between system components) ordered consecutively, which allow the decision maker to select the best options based on their preference. These are the TE / EB combinations to select.

#### *Efficiency Indicators:*

These are those that measure compliance with the requirements declared by the decision maker to achieve the identified objectives, taking into account the restrictions that may arise. These efficiency indicators can be energy or economic in nature.

#### *Significant Input Data:*

For this case, we have the desired values (Vd) of the efficiency indicators (in this case, economic and energy efficiency). These are values that, unlike the actual values, they are established according to the satisfaction of the expectations of the decision maker.

## ANALYSIS AND DISCUSSION OF THE RESULTS

### *Definition Of the Multi-Objective Function*

To define the objective function, consider any case study with high electricity consumption for pumping water and large financial expenses resulting from electricity consumption for this purpose.

#### *Therefore:*

It is necessary to find an alternative to mitigate these financial expenses.

#### *Additionally, It Is Known That the Average Wind Speed at The Site of The Case Study At 10 M Above Ground Level Is Greater Than 5 M / S.*

To satisfy the demand for water and determine the most economically feasible

SBEE options, the following multi-objective function is derived:

$$Z = min\left\{ máx\left[ \frac{\left|VAN_{ij} - VAN^d\right|}{VAN^d}; \frac{\left|TIR_{ij} - TIR^d\right|}{TIR^d}; \frac{\left|TRI_{ij} - TRI^d\right|}{TRI^d}; \frac{\left|LEC - LEC^d\right|}{LEC^d}; \frac{\left|\eta - \eta^d\right|}{\eta^d} \right] \right\}$$

(1)

Equation 1 is a function that, seen as a mathematical relationship, represents the deviation between the values of the efficiency indicators and their desired values, therefore, it is dimensionless. The values of the variable Z are those that are optimized according to the restrictions that arise. The main purpose of this multi-objective function is to **minimize the maximum deviation between the efficiency indicators and their desired values.**

***Definition Of the Desired Values***

As the problem to be solved consists of determining the most feasible TE / EB combinations from the economic point of view, the maximum value of their selected as desired values of the economic efficiency indicators. NPV and the IRR, as well as the minimum values of TRI and LEC, that is:

$$\left\{VAN^d; TIR^d; \eta^d\right\} = \left\{VAN_{máx}; TIR_{máx}; \eta_{máx}\right\}$$

(2)

$$\left\{TRI^d; LEC^d\right\} = \left\{TRI_{mín}; LEC_{mín}\right\}$$

(3)

***Other Restrictions of The Model***

As a second phase, to ensure the values established for the coordination variables, the following additional restrictions are established, represented by equations 4 and 5.

$$\{TRI\} < 8 \text{ años} \quad (4)$$

$$\{Q_e\} \geq \{Q_d\} \quad (5)$$

According to the experience of companies that carry out projects related to FRE (for example, the Cuban company INEL), the investment recovery time is approximately between 6 and 8 years. Hence, it has been established in restriction of equation 4 that the *TRI* is less than eight years.

***Procedure For the Generation of The Most Economically and Energetically Feasible TE / EB Combinations***

**Figure 2** schematically shows the sequence for generating the most economically and energetically feasible TE / EB combinations.

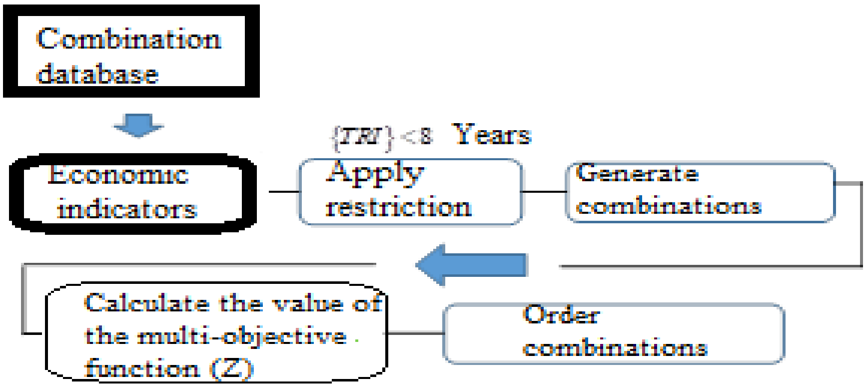


**Figure 2.** Scheme of the sequence to follow to generate the most feasible TE / EB combinations. According to the previous figure, the economic indicators are the *NPV*, the *IRR*, the *TRI* and the *LEC*.

***Selection Procedure***

- Each of the component TE / EB combinations of the database is analyzed, the corresponding restriction to equation 4 is applied and those that do not satisfy this restriction are eliminated. This optimization method is known as exhaustive search (Arzola, 2011).
- A population of TE / EB combinations is generated that meet the restriction of equation 4.
- Determination of the values of the *Z* function (multi-objective function) and ordering of the generated TE / EB combinations as they are different indicators between Yes, the combinations must be ordered according to the multi-objective function *Z*, represented by equation 1. To order the selected options with respect to *Z*, proceed as follows:

1. Select the highest value of the difference between all the indicators efficiency of each combination or option generated (since it is about minimizing the maximum difference). This is the result. of the multi-objective function Z for each generated SBEE option.

**ORDER THESE VALUES Z FROM LEAST TO GREATEST.**

***Description Of the Sub-Models That Constitute Input Variables to the MMC***

***Technical-Energy Block***

***Pumping:***

Requirements The pumping requirements are the water demand (Qd) and the total pumping load (HT). In the case of Qd, this can be known by direct information from the case study, or by identifying the types of existing consumers. In the case of HT, this can also be known by direct information, or by knowing the characteristics of the hydraulic circuit that leads the water to the consumer. Table 1 shows the distribution of water demand in the “Las Terrazas” complex, depending on the types of consumers.

**Table 1.** Distribution of water demand in the “Las Terrazas” complex

| Concept of water consumption | Current quantity | Annual population growth rate (%) | Future quantity in 20 years | Unit consumption $m^3$/ consumer / day | Water demand in $m^3$/ day |
|---|---|---|---|---|---|
| Inhabitants of the community | 1 000 | 0.1 | 1 020 | 0.3 | 306 |
| Inhabitants in surrounding areas | 250 | 0.1 | 255 | 0.1 | 25.5 |
| Children's circle (children) | 150 | - | - | 0.11 | 16.5 |
| School (students) | 300 | - | - | 0.06 | 18 |
| Shelters (people) | 48 | - | - | 0.2 | 9.6 |
| Moka hotel and services | - | - | - | - | 110 |
| Animals (pigs) | 170 | 6 | 545 | 0.16 | 87.2 |
| **Total** | | | | | **572.8** |

***Estimated The Total Pumping Head ($H_T$). Characterization Of the Source of Water Supply to The Complex "Las Terrazas"***

Figure 3 shows the current hydraulic scheme for the supply of water to the complex "Las Terrazas"

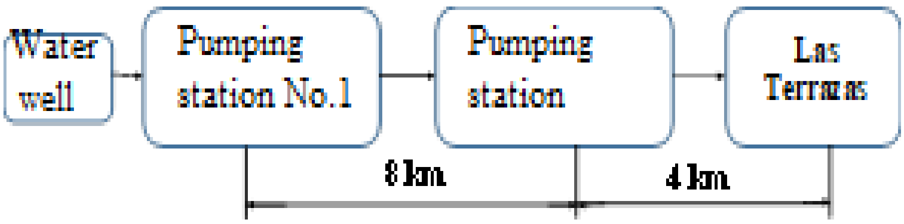


**Figure 3.** Scheme Of the Hydraulic System of Water Supply to The Complex "Las Terrazas”

As can be seen in figure 3, the water supply to the “Las Terrazas” complex is carried out from two wells located at a distance of 12 km from the complex and through two pumping stations. The pumping station is located 4 km from the storage tank and given its proximity to the complex and the highest places in the area (hills). The present work focuses on this station, with the purpose of replacing this station fed with electricity from the national grid by a TE / EB set, in order to reduce electricity consumption. According to information provided by operators of the pumping station, the difference in height between the station and the storage tank located in the community is approximately 70 m, according to the topography of the place. Additionally, the conductive pipe is known to be cast iron and 6 inches in diameter. Hydraulic losses are estimated at approximately 35 m of the water column. Hence the total pumping head is approximately 105 m.

***Wind Resource Evaluation:***

In this stage the available wind data is collected and analyzed. The most common is that when evaluating the wind resource, the data comes from meteorological stations. There are several methods for estimating the wind resource at a site, which are summarized in (Manwell, McGowan, & Roger, 2011).

***The Wind Resource In "Las Terrazas"***

Some points around "Las Terrazas" can be advantageous for the installation of wind machines. The complex is surrounded by three elevations: one to the southwest, “El Salón”, another further east, “La Gloria” and a closer one, “El Taburete”. Of the three hills, "El Salón" is the highest (544 m). In the area where the complex is located, the most favorable winds come from the northeast, and this elevation is the only one that faces this direction perpendicularly. It is also the closest to the pumping station (it is located only 1.3 km away). Therefore, it is proposed to locate the wind turbine on the hill "El Salón". Given the lack of measurements of the wind parameters, to estimate the average wind speed in the “El Salón” hill, four data sources were consulted, the results of which are presented in table 2.

**Table 2.** Average wind speed at 50 m high, according to the different data sources consulted Data

| **Source** | **Average wind speed (m / s)** |
|---|---|
| Atlas Eolic de Cuba | 5.9 |
| NASA Langley Research Center Atmospheric Sciences Data Center | 5.84 |
| Global Wind Atlas | 5 |
| Web de Renewable Energies | 5.9 |
| **Average speed** | **5.7** |

- Sizing and selection of the equipment (wind turbine and electric pump)
- Sizing and selection of the centrifugal pump (s): In this case, according to the pumping requirements, catalogs are consulted and those machines capable of satisfying the water demand and the pumping load are selected. Subsequently, a database is made, which is composed of a sample of 5 models of surface centrifugal pumps, including their respective technical characteristics and the market price. The most important thing is to show how the proposed model is solved, through an example. The following table shows the available pumps.

**Table 3.** Models Of Electric Pumps Available Electric Pump

| No | Model | Nominal power (kW) | Maximum load H (m) | speed Rotation(rpm) | Cost (USD) |
|---|---|---|---|---|---|
| **1** | INH 50-250 ϕ249 | 30 | 118.4 | 3 450 | 4 977.65 |
| **2** | INH 50 -250 ϕ264 | 37 | 136.5 | 3 450 | 5 412.70 |
| **3** | INH 65-250 ϕ236 | 37 | 113.8 | 3 450 | 6 020.64 |
| **4** | INH 65-250 ϕ250 | 45 | 128.9 | 3 450 | 7 626.37 |
| **5** | INH 65-250 ϕ264 | 55 | 145.4 | 3 450 | 9 985.81 |

- Sizing and selection of the wind turbine: In this step the minimum rotor diameter is determined to satisfy the pumping requirements (Qd and HT). The following table shows a sample of wind turbines that will make up the database. Additionally, annual energy production is offered, operating under the effects of the existing turbulence on the hill "El Salón", located near "Las Terrazas".

**Table 4.** Available Wind Turbine Models

| No. | Wind turbine | Rotor diameter (m) | Nominal power (kW) | Energy production (kWh / year) | Cost (USD) |
|---|---|---|---|---|---|
| **1** | Nordex N27 / 150 | 27 | 150 | 779 800 | 376 227.76 |
| **2** | NEPC | 29, 8 | 200 | 598 300 | 485 959 |
| **3** | Bonus B30-150 | 30 | 150 | 397 700 | 376 599 |
| **4** | WESPA 200/31 | 31 | 200 | 703 300 | 486 083 |
| **5** | Norwin 29-STALL-200 | 29 | 200 | 676 900 | 485 835 |

***The Database of TE / Combinations EB:***

The database of combinations is made from the databases of TE and EB. The total number of combinations is obtained by multiplying the number of TE by the number of BEs selected from catalogs (5x5 = 25 possible TE / BE combinations).

***Determination Of the Efficiency of Each Combination:***

The overall efficiency of the system ($\eta$) is obtained by multiplying the efficiency of each component (as shown in equation 6). In this case, the components are the wind turbine and the centrifugal pump. For this, computer programs such as Matlab can be used.

$$\eta = \eta_{TE} \cdot \eta_{B} \cdot 100[\%] \quad (6)$$

Where: $\eta_{TE}$ is the efficiency of the wind turbine, when the machine works under the effects of turbulence. The efficiency of the wind turbine is calculated through equation 7.

$$\eta_{TE} = \frac{P}{P_d \cdot FPE} = \frac{P}{\frac{1}{2}\rho_{aire} A\overline{v}^3 \cdot FPE} \quad (7)$$

Where: $P$ is the power delivered by the machine, operating under the effects of turbulence existing at the site, in W; $P_d$ is the Power available in the wind, in W; $\rho$ is the density of air (1,225 kg / $m^3$); $A$ is the area swept by the wind turbine rotor, in $m^2$; $\overline{v}$ is the mean wind speed, in m / s and *FPE*, the energy pattern factor, which is determined through the methodology described in (Medrano, Moreno, & Vaillant, 2019). In the case of the "El Salón" hill, FPE = 1.95.

On the other hand, the efficiency of the pump is determined through the simulation of the operation of each TE / EB combination operating under the conditions existing in the case study site (considering the effect of turbulence). For the simulation of the pumping system, Matlab Simulink is used. As input variables for the simulation, there are: in the case of the wind turbine, the rotation speed of the electric generator in rad / s, type of electric generator, electric characteristics of the electric generator, number of pairs of poles, nominal power, nominal frequency in Hz, output voltage. For the case of the water pump, the pressure increases in the pump in bar, nominal power, number of pole pairs, electrical characteristics of the induction motor, nominal frequency in Hz. The pressure increase (*IP*) is determined from the following equation 8:

$$IP = \frac{\rho g H_b}{10^5}[\text{bar}] \quad (8)$$

Where $H_b$ is the head delivered by each water pump, in meters (data provided in table 3).

***Economic Block:***

It is made up of the Economic Analysis sub-model, where the economic indicators VAN, IRR, TRI and LEC are determined. For this, the prices of the pumps and wind turbines are taken (values summarized in tables 3 and 4. To the total of the costs summarized in tables 3 and 4, 10% of the total investment cost is added, for the solution of unforeseen events that may arise.

To calculate the NPV, the following have been considered: IRR: 12%; Approximate cost of electricity production in a thermoelectric plant: 0.23 USD / kWh (according to information provided by the Ministry of Energy and Mines of Cuba ); Lifetime of the wind turbine: 20 years; Annual expenses: 3% of the initial investment (for operation and maintenance tasks); Energy consumed annually by each pump that is installed: 135 050 kWh / year (they work independently 10 hours a day); Annual income: 31,061.5 USD / year (cost of the energy that is no longer produced in the thermoelectric plant, which represents savings and therefore profits).Table 5 shows thecombinations TE / EBthat satisfy the constraint of l to equation 4.

**Table 5.** TE / EB Combinations That Satisfy the Restriction Represented by Equation 4 With Their Respective Economic Indicators.

| **Comb** | **TE** | **$\eta_{TE}$ (%)** | **EB** | **$\eta_{EB}$ (%)** | **Investment Cost (USD)** | **VAN (USD)** | **TRI (años)** | **LEC (USD/kWh)** | **TIR (%)** |
|---|---|---|---|---|---|---|---|---|---|
| **1** | 1 | 27,139 | 1 | 42,81 | 381 205,4 | 375 396,8 | 6,3 | 0,14 | 15 |
| **2** | 1 | 27,139 | 2 | 42,9 | 387 053,2 | 375 019,6 | 6,2 | 0,14 | 15 |
| **3** | 1 | 27,139 | 3 | 42,82 | 388 269 | 374 491,4 | 6,3 | 0,14 | 15 |
| **4** | 1 | 27,139 | 4 | 42,87 | 391 480,5 | 373 098,16 | 6,3 | 0,14 | 15 |
| **5** | 1 | 27,139 | 5 | 42,87 | 396 199,4 | 301 364,54 | 7,5 | 0,14 | 12 |
| **11** | 3 | 16,85 | 1 | 64,3 | 386 554,5 | 375 313,94 | 6,2 | 0,27 | 15 |
| **12** | 3 | 16,85 | 2 | 64,33 | 387 424,6 | 374 935,95 | 6,2 | 0,27 | 15 |
| **13** | 3 | 16,85 | 3 | 64,27 | 388 640,5 | 374 408,51 | 6,3 | 0,27 | 15 |
| **14** | 3 | 16,85 | 4 | 64,34 | 391 851,9 | 373 014,5 | 6,3 | 0,27 | 15 |
| **15** | 3 | 16,85 | 5 | 64,31 | 396 570,8 | 370 967,05 | 6,4 | 0,28 | 14 |

The efficiency of each component of the TE / EB combinations was made based on the behavior of the two wind turbines when operating under the conditions of wind existing in the hill "El Salón". Table 6 shows the wind speed values resulting from the Kaimal turbulence model (equivalent speed) and the rotation speed of the electric generator of each turbine.

**Table 6.** Behavior Of Wind Turbines Under the Existing Wind Conditions on the “El Salón” Hill

| **Wind turbine wind** | **Average speed (m / s)** | **Equivalent speed (m / s)** | **Rotation speed (rpm)** |
|---|---|---|---|
| Nordex N27 / 150 | 5, 7 | 5.476 | 36 |
| Bonus B30-150 | 5.7 | 5.12 | 34.1 |

***Mathematical Block:***

The same procedure described in figure 2 is applied.

***Determination Of the Value of The Function Z (Equation 1)***

The value of the function Z is the result of the largest difference between the efficiency indicators and their desired values. According to the total number of existing combinations and equations 2 and 3, the desired values are presented in table 7.

**Table 7.** Desired Values of Efficiency Indicators

| Efficiency indicator | Desired value | value |
|---|---|---|
| ***NPV*** | $NPV^d = NPV_{max.}$ | 375 396.8 USD (combination 1) |
| ***IRR*** | $IRR^d = IRR_{Max.}$ | 15% (combinations 1-5 and 11-14) |
| ***TRI*** | $TRI^d = TRI_{min.}$ | 6.2 years (combinations 2, 11 and 12) |
| ***LEC*** | $LEC^d = LEC_{min.}$ | $ 0.14 / kWh (combinations 1-5) |
| ***η*** | $\eta^d = \eta_{max.}$ | 11.64% (combination 2) |

**Table 8.** Shows The Results Regarding the Calculation of The Deviations, The Value of The Function *Z* and The Ordering of The TE / EB Combinations Generated.

**Table 8.** Deviations, Values of The Function *Z* and Ordering of The Generated TE / EB Combinations

| Comb | TE | EB | ΔVAN | ΔTRI | ΔLEC | ΔTIR | Δη | Z |
|---|---|---|---|---|---|---|---|---|
| **2** | 1 | 2 | -0.001 | **0** | 0 | 0 | 0 | 0 |
| **1** | 1 | 1 | 0 | **0.0161** | 0 | 0 | -0.001718 | 0.0161 |
| **3** | 1 | 3 | -0.0024 | **0.0161** | 0 | 0 | -0.001718 | 0.0161 |
| **4** | 1 | 4 | -0.00612 | **0.0161** | 0 | 0 | -0.000859 | 0.0161 |
| **5** | 1 | 5 | -0.197 | **0.2097** | 0 | -0.2 | -0.000859 | 0.2097 |
| **11** | 3 | 1 | -0.00022 | 0 | **0.928** | 0 | -0.66 | 0.928 |
| **12** | 3 | 2 | -0.00123 | 0 | **0.928** | 0 | -0.0655 | 0.928 |
| **13** | 3 | 3 | -0.00263 | 0, 0161 | **0.928** | 0 | -0.0664 | 0.928 |
| **14** | 3 | 4 | -0.00634 | 0.0161 | **0.928** | 0 | -0.0654 | 0.928 |
| **15** | 3 | 5 | -0.0118 | 0.0322 | **1** | -0.0666 | -0.0658 | 1 |

As seen in Table 8 the maximum value of the deviations in each combination, corresponds to the result of the function *Z* (in bold). These values of the function *Z* are ordered from least to greatest. The combination that came first is the optimal one **(combination 2, see table 8)**.

***Estimation Of the Water Flow Delivered by The TE / EB Combinations***

The results regarding the prediction of the water flow delivered by each combination are determined through equation 9, which is presented below: Table 9 shows present the results obtained.

$$Q_e = \frac{3,6 \cdot 24 \cdot \frac{\pi}{4} \cdot D^2 \cdot \eta \cdot \frac{1}{2} \cdot \rho_{aire} \cdot \overline{v}^3 \cdot FPE}{g \cdot H_T} \left[ \mathrm{m^3/día} \right] \quad (9)$$

Where: D is the diameter of the wind turbine rotor, in m; η is the overall efficiency of the pumping system; ρ is the density of air, (1,225 kg / m3); is the mean wind speed, in m / s; FPE: is the standard energy factor (equal to 1.95, determined through the methodology described in [13]); g is the acceleration of gravity, in m / s2; HT is the total pumping head, in m.

**Table 9.** Water Flow Delivered by Each Combination TE / EB

| **Combination** | **TE** | **EB** | **Efficiency of the system overall (%)** | **$Q_{and}$ ($m^3$/** |
|---|---|---|---|---|
| | | | | |
| **2** | 1 | 2 | 11,64 | 1 046,2 |
| **1** | 1 | 1 | 11,62 | 1 048,4 |
| **3** | 1 | 3 | 11,62 | 1 046,5 |
| **4** | 1 | 4 | 11,63 | 1 047,7 |
| **5** | 1 | 5 | 11,63 | 1 047,7 |
| **11** | 3 | 1 | 10,83 | 984,5 |
| **12** | 3 | 2 | 10,84 | 985 |
| **13** | 3 | 3 | 10,83 | 984,1 |
| **14** | 3 | 4 | 10,84 | 985,2 |

***Validation Of the Results Obtained***

This section compares the results regarding the flow of water delivered by the wind system of pumping (main parameter to be satisfied), in accordance with the methodology described in the work and with the experimental results offered by the renowned North American firm Bergey Wind power. Table 10 shows the comparison of the results in terms of the flow of water delivered by the pumping system, offered by the company Bergey Windpower and those obtained applying the methodology proposed in this work, taking as an example, for when the wind speed is 4 m / s (Bergey Windpower &1998).

**Table 10.** Results In Terms of Water Flow Delivered by the EXCEL-PD System and Those Obtained Applying the Methodology Proposed in This Work, V = 4 M/S

| **Height (m)** | **$Q_{exp.}$ ($m^3$/day)** | **$Q_1$ ($m^3$/day)** | **ΔQ (%)** | **Height (m)** | **$Q_{exp.}$ ($m^3$/day)** | **$Q_1$ ($m^3$/day)** | **ΔQ (%)** |
|---|---|---|---|---|---|---|---|
| **160** | 21,1 | 21,26 | 0,76 | **60** | 56,4 | 56,9 | 0,89 |
| **140** | 24,5 | 24,4 | 0,41 | **40** | 84,5 | 84,7 | 0,24 |
| **120** | 28,1 | 28,3 | 0,71 | **30** | 113,4 | 114,3 | 0,79 |
| **100** | 34 | 34,2 | 0,59 | **20** | 167,5 | 168,8 | 0,77 |
| **80** | 42,5 | 42,5 | 0 | **13,3** | 253,5 | 255,8 | 0,91 |

In table 10, $Q_1$ represents the value of the water flow according to the methodology proposed in this paper and $\Delta Q$, the percentage difference between these values. In addition, the table above shows that the results obtained applying the proposed methodology, provides a sample of the proximity of the water flow values, with deviations of less than 1%, which demonstrates the validity of the sub-models used.

## CONCLUSIONS

The main purpose of this paper is to develop a completely reproducible mathematical model for any place, aimed at sizing and selecting the most feasible TE/EB combinations, considering technical-energetic and economic criteria. The proposed model allows you to select the most economically feasible TE/EB combinations. This could be corroborated through the complex "Las Terrazas", which was used as a case study, obtaining a total of 25 TE /EB combinations, of which 10 turned out to be the most feasible from the economic point of view. The results obtained were validated, based on the main parameter to be satisfied, the water flow delivered, obtaining similar values (with deviations less than 1%) to those obtained experimentally by the manufacturer of the pumping system taken as a reference (Bergey Windpower), so the work carried out lays the foundations to carry out the study, sizing and selection of more feasible TE/EB combinations, for the composition of Aeolus-Electric Pumping Systems, facilitating the development of future research.

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