UNIVERSIDAD DE LA LAGUNA

FACULTAD DE CIENCIAS

MÁSTER EN ENERGÍAS RENOVABLES

“Conversion of a traditional wind pump system as a wind turbine to produce electricity”

RUBÉN SUÁREZ CEJAS

INDEX

INDEX OF TABLES

INDEX OF FIGURES

ABSTRACT

Fuerteventura´s skyline is inconceivable without the traditional mill of several blades, type "Chicago", to pump underground water. This project aims to create an innovative system to convert this type of traditional mill to generate renewable electricity both for systems connected to the grid and for self-consumption.

Times have changed and also have the surviving economic activities. In the past, the development of agriculture on the island was unthinkable without the use of this type of machinery that greatly facilitated the work of land workers, however, today, the primary sector on the island is a minority and the use of this type of mill is almost anecdotal.

What to do, therefore, with the hundreds of mills that remain on the island of Fuerteventura? The conservation of these witnesses of history is fundamental and contributes to the cultural and scenic enrichment of the island. If, in addition, we can reconvert them to produce electricity from renewable sources, the mill becomes a machine full of possibilities with a view to a sustainable future while preserving the history and tradition of the island.

This project was conceived with the objective of recovering and transforming the traditional American-type mill, which is used to pump water from the subsoil to produce low-voltage electricity on the island of Fuerteventura, to save energy and recover and beautify the typical landscape.

1. INTRODUCTION

1.1. Fuerteventura

Fuerteventura is a Spanish island of the Canarian archipelago, located in the Atlantic Ocean, 97 km off the northwest coast of the African continent. On May 26, 2009, it was declared a biosphere reserve by UNESCO.

It belongs to the province of Las Palmas, one of the two that form the Canary Islands, an autonomous community of Spain. The capital of the island is Puerto del Rosario (Puerto Cabras until 1956), where the Island Council is located, which is the island's government. The island has a population of 107,521 inhabitants in 2016, it is the fourth most populated island of the Canarian archipelago.

With an area of 1,659.74 km², Fuerteventura is the largest island of its province, the second in the Canary Islands and the longest in the archipelago. It is, from the geological point of view, the oldest island of the Canary Islands. [1]

1.2. Multi-bladed windmills in Fuerteventura

Fuerteventura is the island where the windmill has had the most distribution to extract water in the Canary Islands, probably because it is a machine whose operation is based on the use of wind energy, abundant on the island, given its climatic conditions.

The introduction of this contraption in the island represented an important technological innovation and a leap forward with respect to the Ferris wheel, since it allowed extracting more water in less time, taking advantage of an abundant, renewable and clean energy source, as it is wind.

Apparently the first American windmill came to the island in 1910 at a price of 1500 *pesetas* and since then began to spread, replacing the canvas mills. Those had been working for some time but had lower performance in the work of laborers and livestock, facilitating the pumping of water from the subsoil.

On the island, mills were installed by Canarian workshops such as Manuel Santana, characterized by its large size, with large rotors that ranged between 16 and 22 feet (approximately between 4 and 7 m); handcrafted mills built with wood and canvas and metallic non-galvanized mills of foreign models like the English Climax or the American Star, Samson, Dempster, Dandy, Mogul and Aermotor; and from the Spanish mainland as the Velox, Star, Hercules, Hurricane. The latter, patented in 1915, of self-lubrication, was the one that achieved the greatest distribution and the one best valued by farmers for its quality, resistance and performance. In the middle of the 20th century, a total of 663 mills were counted in the eastern Canaries, of which 416 were of the Aermotor brand, with 357 units located in Fuerteventura.

The Aermotor became the most distributed brand on the island. In the 1930s its price ranged between 6,000 and 12,000 pesetas and fifty years later it was around 120,000 pesetas. This model consisted of a galvanized iron tower, which was fixed to the wellbore with foundation. Along it was the rungs and the stirrup to access the rotor. This consisted of a wheel of oblique vanes supported on a horizontal axis, whose diameter oscillated between 6 and 16 feet (approximately 2 to 5 m), with a tail or tail as a rudder that allowed to orient the multi-wing wheel "face" to the wind". As an advantage, it had a braking system for the wheel that immobilized it completely by folding it to the tail, while to start it, the tail was unfolded. Both operations were performed through a lever located at the bottom of the tower. This mill was able to fold itself when there were strong gusts of wind, avoiding damage to its mechanism. It had the rotor gears bathed in oil and were composed of gears of reduction with a slow "torque", which allowed to take advantage of the soft gusts of breeze to put into operation. The rotor was attached to a fork and this to a stick shank, so that when strong winds were produced or the water pump clogged, the wooden shank would break preventing the gear from being damaged. Attached to the stem was the metal rod that operated the pump piston.

In 1950 there were about 400 wells on the island with wind turbines and three years later, in 1953, 550 were already counted, distributed as shown in the following table:

Table 1 Multi-bladed windmills in Fuerteventura (1953)

WELLS WITH WINDMILLS IN 1953						
CITIES						TOTAL
ANTIGUA	BETANCURIA	LA OLIVA	PÁJARA	PUERTO CABRAS	TUINEJE	
116	35	0	84	27	288	**550**

This figure continued to increase in the following decades, even though, since the 19th century, they began to be replaced by combustion engines. In Fuerteventura, they continued to be installed at least until 1979, when their price was around 118,000 pesetas. The brands introduced on the island were diverse, although there was a predominance of the Aermotor, as reflected in the following table:

Table 2 Multi-bladed windmills in Fuerteventura (1953) by trademark

WELLS WITH WINDMILLS IN 1953 BY TRADEMARK							
MARK	**CITIES**						**TOTAL**
	ANTIGUA	BETANCURIA	LA OLIVA	PÁJARA	PUERTO CABRAS	TUINEJE	
Aermotor	51	13	0	32	10	251	**357**
Samson	5	0	0	5	0	12	**22**
Dempster	5	2	0	6	7	1	**21**
Climax	3	1	0	4	1	9	**18**
Estrella	0	0	0	3	0	4	**7**
Dandy	1	3	0	1	0	0	**5**
Canary	40	16	0	17	5	0	**78**
Others	11	0	0	16	4	11	**42**
Total (cities)	116	35	0	84	27	288	**550**

The table evidences the enormous diffusion reached by the windmills in the municipality of Tuineje in relation to the rest of the island, followed in descending order by those of Antigua, Pájara, Betancuria and Puerto de Cabras. Tuineje was the municipality that had the largest number of mills in the entire Canary archipelago. [2]

1.3. Technical description

To carry out the project, a technological transformation of the multi-blade mill will be necessary. The transformation will consist of the replacement of the water pumping mechanisms (original function of this type of windmill), by a mechanism adapted "multiplier-electric generator", as well as the conditioning components of the generated electric power as regulators, dissipation resistors and inverters.

In the project there are two prototypes of systems, the isolated system of the electrical network and the system connected to it (figures x and y). The expected results of the project consist of an electric mill-generator system whose main technical and functional characteristics are:

• It can adapt to an American multi-blade mill for water pumping while maintaining the aesthetics of this.

• The isolated network system can adapt to 24 / 48V DC accumulation systems.

• The system connected to the network can adapt to single-phase 230V or three-phase 400V networks with the network codes of each country.

• The system is equipped with a rotor braking resistor that is activated in the event of excessive wind, system failure, full batteries (in the case of an isolated system) or a failure of the system. power cut (in the case of grid connection systems).

• The system allows real-time monitoring of the electrical and wind production parameters of the system through an internet connection.

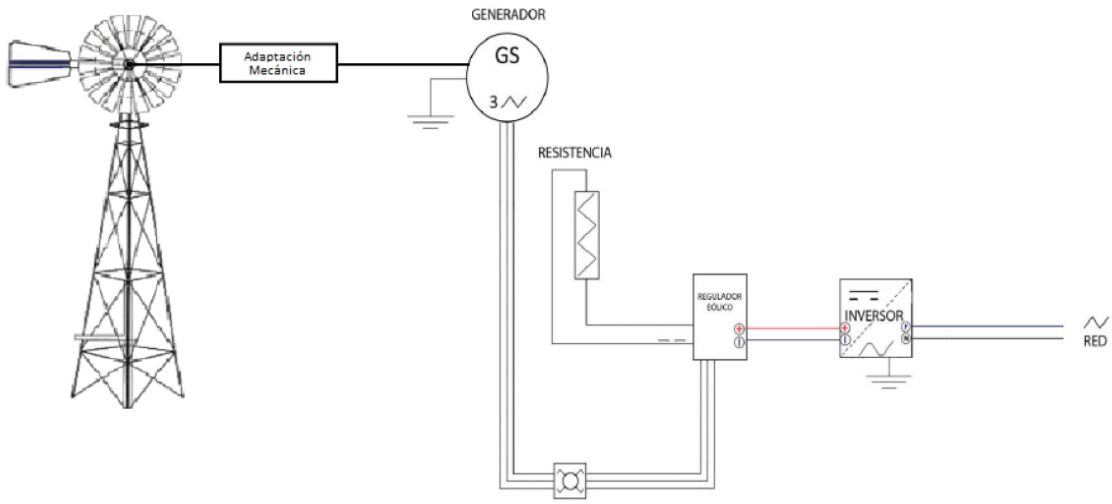


Figure 1 System diagram connected to the network

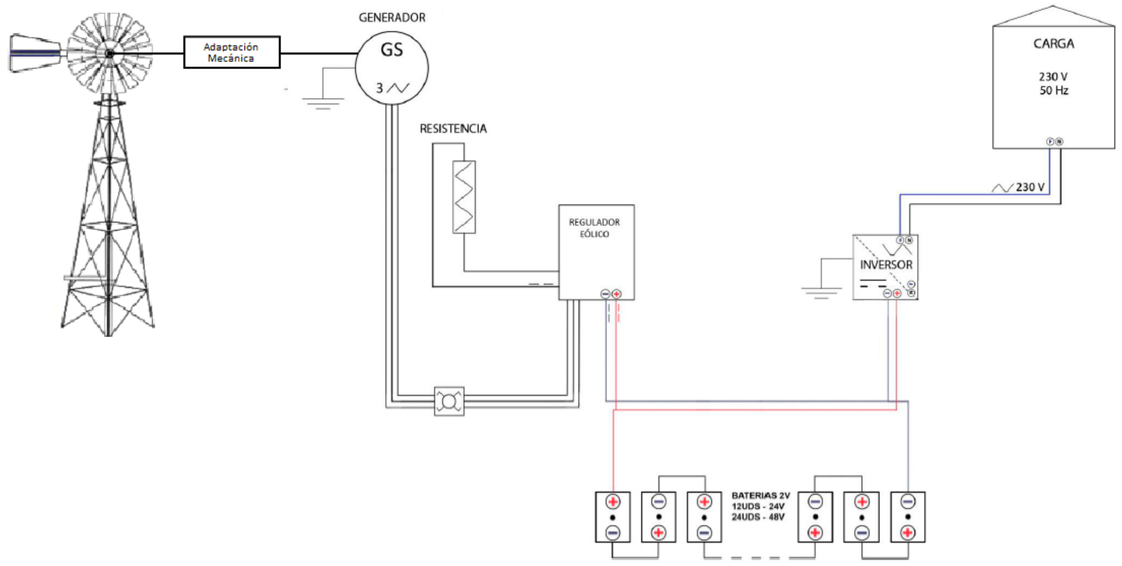


Figure 2 System diagram isolated to the network

The most significant technologies incorporated into the project are the following:

- *Universal system of mechanical adaptation of the rotor of the pumping mill to the electric generator system*: It is the most innovative element of the system and allows the direct coupling of the rotor of the pumping mill with the electric generator by means of direct drive, without intermediate multiplier stage. The saving of the multiplied stage allows a greater mechanical efficiency of the system and the adaptability to different diameters of rotors of mills.

- *Electric generator:* It is a 24-pole synchronous electric generator with direct drive with permanent magnets of high efficiency that will be designed to have a nominal 250 rpm. The generator will have high quality neodymium magnets.

- *Wind regulator and dissipation resistors:* The wind regulator rectifies and filters the alternating current, producing a direct current output to feed the grid connection inverter or the charge regulation system of the batteries. This device conducts an external dissipation load resistance that aids the turbine in case of strong wind or a missing continuous network or load. It will have an efficiency higher than 98% and it will be a sealed unit to withstand adverse environmental conditions. The main features that this device will have are:

    - Three-phase passive rectification
    - Three phase input fused
    - Activation of automatic dissipation charge

Dissipation resistance will be a coil composed of a resistive element wound in a ceramic tubular core used as a support, to ensure a high dissipation capacity and an excellent resistance to thermal shock and overload. The assembly must be capable of supporting at least a sufficient level of environmental protection in ventilated space.

- *Network connection inverter:* The designed wind inverter will be designed with high performance technology. It will be two-stage transformerless offering a unique combination of high efficiency, easy installation design and a very wide input voltage range that guarantees high energy harvesting. The high-speed tracking algorithm and precise power curve allow to better combine the power curve of the turbine electric generator. The efficiency of the inverter will be higher than 95% thanks to the technology without transformer. It will track the power curve with high granularity for a high output of electrical production. In addition, it will be a sealed unit to withstand adverse environmental conditions. The main characteristics that it will have in the investor are:
    - Single-phase output
    - Power curve customization
    - Wide range of input voltage
    - Technology without transformer
    - Standard grid configuration selectable in the field
    - Adaptability to the network code of several countries
    - Monitoring of production and operational parameters

All these technologies exist in the market in greater or lesser degree of application except the universal system of mechanical adaptation of the rotor of the pumping mill to the electric generator system that constitutes the main innovation of the project. Additionally, the greatest innovation consists in the optimized integration of all these components in the American multi-blade pumping mill.

2. PURPOSE

The main objective of this project is to carry out an analysis of the potential of the island of Fuerteventura in the use of traditional American multi-blade mills "Chicago", used to pump water from the subsoil in the agricultural sector and present throughout the surface of the island, for its subsequent reconversion and transformation into a source of electricity from a 100% renewable source. This modification of existing mills will have a dual purpose, as a means of energy saving and as recovery and embellishment of the typical landscape of Fuerteventura.

Despite an exhaustive search in sources such as Scopus [3], Mendeley [4] and ResearchGate [5], works have been found such as (Feitosa, Cirilo, & Soares Jr., 1985) [6], where it is performed an analysis of the advantages of directly attaching an air compressor to the windmill. On (Qin, Liu, Richman, & Moncur, 2005) [7], the authors developed a multi-blade windmill to convert wind energy directly into hydraulic pressure for the operation of the RO membrane to filter wastewater from aquaculture. On (Keawsuntia, 2013) [8], it is studied the use of a small multi-blade wind turbine as an alternative technology for the generation of electricity for use in a home. However, none of them addresses the problem presented here.

Since no previous work related to our objective has been found, it will be necessary to begin with a study and classification of the existing generators, followed by an analysis of the potential of traditional windmills present on the island of Fuerteventura, to finish executing an analysis of the wind potential in the environment of the existing aero-engines.

3. ANALYSIS OF THE POTENTIAL OF TRADITIONAL WINDMILLS PRESENT ON THE ISLAND OF FUERTEVENTURA.

The objective of this chapter is the definition and identification of some parameters and general classification methods, based on all the information gathered in this regard.

This classification allows us to locate those mills that are in optimal conditions for their subsequent reconversion.

In addition, a subclassification of which of these optimal mills are more appropriate for the reconversion project to produce electricity with connection to the insular electricity grid and which are more suitable for conversion to produce electricity for self-consumption.

3.1. Methodology or classification method

The first step consisted in the search for information on the status of multi-wing mills on the island of Fuerteventura. It has been necessary to consult the bibliography that deals with related topics on the island. In the book "Fuerteventura La Cultura del Agua" [2], section "El Agua en la Isla" and chapter "Sistemas tradicionales de extracción de aguas subterráneas: norias y molinos", there is a large inventory of mills that are present on the island today with their respective coordinates, as well as the state of conservation in which they are found. This inventory has been corroborated through contacting the Island Council of Fuerteventura, which has provided its own inventory from the Department of Heritage and Culture [9]. (Annex 1)

Our work in this section has been the analysis of the bulk of the information obtained previously for further classification. This classification has been made based on criteria that are detailed below. The idea of this detailed classification is to obtain a resulting table showing the optimal mills for the execution of the project.

The criteria for this exhaustive classification have been defined in such a way that we are provided with accurate information about the current state of the existing mills in Fuerteventura. Therefore, precise technical knowledge is necessary.

The most important criterion we have considered is the state of conservation of the mills. For the execution of the reconversion project we have taken as a starting point that the necessary condition for them to be reconverted is that they are in a "good" conservation state, which is determined by observing the mills, observing if they remain upright, if they keep all the machinery and it is in good condition, as well as the rotor blades, their conservation and if the mill as a whole continues to work correctly, although at present it does not exert its original function. The aero-engines that meet all the requirements will be in good condition.

Then, a subclassification of the mills that are in good condition has been made. This sub-classification is based on the criteria of its possible connection to the network or its use in self-consumption.

This classification is based on the environment of the windmill and three different categories have been defined: Integrated Urban, Isolated and Associated to building. In the case of mills that are within an urbanized environment with many buildings, whether single-family homes or residential buildings, and that, therefore, have easy access to the electricity grid, will be considered “Urban”. In the case that the windmill is in an environment in which no urban areas are observed, whose land use is likely to be agricultural or livestock and access to the electricity grid is complicated, they will be classified as “Isolated”. The last item, “Associated to building”, will be determined when the windmill is in an environment in which it is located within a plot of a single property or dwelling.

The criteria on which this classification is based are the following:

a) Urban: the parameters chosen in the observation of the environment have been: the presence of buildings, both single-family and multi-store buildings, the density of these, the presence of paved roads and closeness with electric power distribution lines, reaching to measure the distance to the network with the computer tool.

b) Isolated: they have taken into consideration the limited presence of buildings, the low density of these has been observed if there were gardens or farms or livestock in the environment and if these in turn seemed to be in use or abandoned, and the non-existent presence of tracing of electrical network lines.

c) Associated with building: the presence of windmills located in well-defined lots is observed. These lots can contain single-family homes or have an agricultural or livestock use but with buildings used for this activity, checking the state of homes, buildings or the orchards themselves. A measurement was also made with the use of the virtual tool to determine the distance from the mill to the building.

For the previous classification, the environment of the aero-engines was analysed, using the computer tools of map visualization and terrestrial cartography, Google Maps [10], Google Earth [11], property of the multinational company Google, and GRAFCAN [12], free viewer of maps of the Canary Islands owned by the Government of the Canary Islands.

3.2. Results

From all the above, we can obtain a final classification, which provides invaluable information about all the windmills present on the island in the future.

We started from an inventory [2], corroborated by the Island Council of Fuerteventura [9], with a total of 374 mills. Of those 374 windmills, we have made a classification according to state of conservation. From the starting point that the favourable mills to be reconverted are those that are in a "good" conservation status, as described in the previous section, we obtain a total amount of 92 windmills able of being used.

Below is a summary table of windmills in good condition in each municipality (the detailed description of each mill can be found in the annex 1).

Table 3 Windmills at good condition

Windmills at good condition (by Municipality)	**Quantity**
LA OLIVA	1
BETANCURIA	9
ANTIGUA	14
TUINEJE	50
PUERTO DEL ROSARIO	10
PÁJARA	8

Following the described methodology, from the previous classification, we return to make the sub-classification in three blocks: Urban, Isolated and Associated to building.

Table 4 Windmills Classified

Windmills Classified as Urbane					
Municipality of BETANCURIA					
Nº	**X coordinate**	**Y coordinate**	**DISTRICT**	**CONDITION**	**CLASSIFIED**
3	590742	3141124	Vega de Río Palmas	Good	Urbane
4	590854	3141190	Vega de Río Palmas	Good	Urbane
9	590015	3141027	Vega de Río Palmas	Good	Urbane
10	589815	3141027	Vega de Río Palmas	Good	Urbane
Municipality of ANTIGUA					
Nº	**X coordinate**	**Y coordinate**	**DISTRICT**	**CONDITION**	**CLASSIFIED**
19	594537	3145664	El Durazno	Good	Urbane
20	594537	3145791	El Durazno	Good	Urbane
22	597221	3139791	Valles de Ortega	Good	Urbane
Municipality of TUINEJE					
Nº	**X coordinate**	**Y coordinate**	**DISTRICT**	**CONDITION**	**CLASSIFIED**
25	592034	3128295	Juan Gopar	Good	Urbane
26	595759	3125530	Juan Gopar	Good	Urbane
27	595788	3124413	Juan Gopar	Good	Urbane
28	590707	3123372	Cañada del Moro	Good	Urbane
29	590047	3123669	Cañada del Moro	Good	Urbane
30	596642	3123029	Gran Tarajal	Good	Urbane
31	596299	3124041	La Fuentita	Good	Urbane
32	596698	3123878	Gran Tarajal	Good	Urbane
33	599464	3123350	Las Playitas	Good	Urbane
35	599739	3123126	Las Playitas	Good	Urbane
36	586820	3119991	Tarajalejo	Good	Urbane
48	593075	3133441	Tuineje	Good	Urbane
49	593184	3133394	Tuineje	Good	Urbane
50	593249	3133312	Tuineje	Good	Urbane
55	587244	3127994	Tesejerague	Good	Urbane
57	586680	3126523	Tirba	Good	Urbane
58	586533	3126618	Tirba	Good	Urbane
59	586472	3126690	Tirba	Good	Urbane

60	586478	3126848	Tirba	Good	Urbane
61	586674	3126883	Tirba	Good	Urbane
62	586578	3127020	Tirba	Good	Urbane
63	590014	3127560	Tirba	Good	Urbane
66	590313	3123377	Giniginamar	Good	Urbane
67	590673	3122511	Giniginamar	Good	Urbane
69	596880	3122568	Gran Tarajal	Good	Urbane
Municipality of PUERTO DEL ROSARIO					
Nº	**X coordinate**	**Y coordinate**	**DISTRICT**	**CONDITION**	**CLASSIFIED**
78	610640	3146359	El Matorral	Good	Urbane
79	603998	3151894	Tesjuates	Good	Urbane
Municipality of PÁJARA					
Nº	**X coordinate**	**Y coordinate**	**DISTRICT**	**CONDITION**	**CLASSIFIED**
90	589494	3137228	Toto	Good	Urbane
Windmills Classified as Isolated					
Municipality of LA OLIVA					
Nº	**X coordinate**	**Y coordinate**	**DISTRICT**	**CONDITION**	**CLASSIFIED**
1	614232	3180195	Isla de Lobos	Good	Isolated
Municipality of BETANCURIA					
Nº	**X coordinate**	**Y coordinate**	**DISTRICT**	**CONDITION**	**CLASSIFIED**
2	591351	3140261	Vega de Río Palmas	Good	Isolated
5	593179	3148117	Valle de Santa Inés	Good	Isolated
6	591335	3140304	Betancuria	Good	Isolated
7	592757	3147565	Valle de Santa Inés	Good	Isolated
8	592522	3147230	Valle de Santa Inés	Good	Isolated
Municipality of ANTIGUA					
Nº	**X coordinate**	**Y coordinate**	**DISTRICT**	**CONDITION**	**CLASSIFIED**
11	602624	3144234	Triquivijate	Good	Isolated
15	595312	3143697	El Carbón	Good	Isolated
21	602377	3130655	Tenicosquey	Good	Isolated
Municipality of TUINEJE					
Nº	**X coordinate**	**Y coordinate**	**DISTRICT**	**CONDITION**	**CLASSIFIED**
37	597729	3125978	Tequital-La Mata	Good	Isolated
38	598475	3127862	Tequital	Good	Isolated
39	598071	3127966	Tequital	Good	Isolated
41	586363	3129348	Tesejerague	Good	Isolated
42	588583	3127058	Tirba	Good	Isolated
44	595794	3135906	Tiscamanita	Good	Isolated
45	593712	3137225	Tuineje	Good	Isolated
46	593367	3137352	Tuineje	Good	Isolated
47	593283	3137430	Tuineje	Good	Isolated
51	590560	3125636	Violante	Good	Isolated
52	590404	3127634	Violante	Good	Isolated
53	594437	3134579	Tiscamanita	Good	Isolated
54	593695	3137323	Tiscamanita	Good	Isolated

56	587547	3126416	Tesejerague	Good	Isolated
64	589694	3127621	Tirba	Good	Isolated
65	590351	3125576	Tirba	Good	Isolated
71	597674	3127481	Tequital	Good	Isolated
72	594448	3136021	Tiscamanita	Good	Isolated
Municipality of PUERTO DEL ROSARIO					
Nº	X coordinate	Y coordinate	DISTRICT	CONDITION	CLASSIFIED
75	599066	3159106	Tefía	Good	Isolated
76	599746	3156272	Tefía	Good	Isolated
77	595148	3149732	Llanos de la Concepción	Good	Isolated
80	599225	3149951	Ampuyenta	Good	Isolated
82	600140	3159422	Tefía	Good	Isolated
Municipality of PÁJARA					
Nº	X coordinate	Y coordinate	DISTRICT	CONDITION	CLASSIFIED
85	587242	3140477	Mézquez-Buen Paso	Good	Isolated
86	587188	3140365	Mézquez-Buen Paso	Good	Isolated
87	587084	3140422	Mézquez-Buen Paso	Good	Isolated
88	583314	3131585	Fayagua	Good	Isolated
89	588465	3136779	Pájara	Good	Isolated
92	585876	3139322	Ajuy	Good	Isolated
Windmills Classified as Associated with building					
Municipality of ANTIGUA					
Nº	X coordinate	Y coordinate	DISTRICT	CONDITION	CLASSIFIED
12	595753	3141302	Valles de Ortega	Good	Associated with building
13	596492	3141033	Valles de Ortega	Good	Associated with building
14	595489	3143809	El Carbón	Good	Associated with building
16	595639	3143173	Antigua	Good	Associated with building
17	596499	3143802	Antigua	Good	Associated with building
18	595175	3138417	Agua de Bueyes	Good	Associated with building
23	597908	3141651	Majada Blanca	Good	Associated with building
24	598856	3141138	Majada Blanca	Good	Associated with building
Municipality of TUINEJE					
Nº	X coordinate	Y coordinate	DISTRICT	CONDITION	CLASSIFIED
34	599614	3123318	Las Playitas	Good	Associated with building
40	586738	3129021	Tesejerague	Good	Associated with building
43	590563	3126964	Tirba	Good	Associated with building
68	588935	3123944	Tarajalejo	Good	Associated with building
70	596161	3126111	Gran Tarajal	Good	Associated with building
73	584381	3126005	Cruce de Cardón	Good	Associated with building
74	587634	3123686	Cardón	Good	Associated with building
Municipality of PUERTO DEL ROSARIO					
Nº	X coordinate	Y coordinate	DISTRICT	CONDITION	CLASSIFIED
81	606905	3152355	Zurita	Good	Associated with building
83	603736	3151838	Tesjuates	Good	Associated with building
84	605399	3150458	Goroy	Good	Associated with building

Municipality of PÁJARA					
Nº	X coordinate	Y coordinate	DISTRICT	CONDITION	CLASSIFIED
91	583059	3119529	Valle de La Lajita	Good	Associated with building

Therefore, we have the following results: 35 windmills in an "Urban integrated" environment, 38 windmills in an "Isolated" environment and 19 windmills in an "Associated to building" environment.

- The 35 mills classified as "Urban integrated" will be chosen for the reconversion project to produce electricity with connection to the insular electricity grid.
- The 38 mills classified as "Isolated" are more suitable for reconversion to produce electricity for self-consumption.
- The 19 mills classified as "Building Associated" may be considered both for the reconversion project to produce electricity with connection to the insular electricity grid and for its reconversion to produce electricity for self-consumption, this decision will be made taken into consideration the opinion of the owner of the windmill.

4. ANALYSIS OF THE ELECTRICAL PRODUCTION OF THE WINDMILLS

In this chapter, we intend to define the calculation method to find the electrical production of each of the windmills, for the subsequent calculation of electrical production of all the windmills selected in the previous chapter. Once the characteristics of the windmills and the methodology of the treatment of the information that is going to be carried out are defined, the results obtained will be shown.

4.1. Characteristics of the windmills

To determine the characteristics of the windmill it has been considered that the predominant brand on the island is "Aermotor" and the predominant model: 12 feet in diameter [1]. From this, it has been considered that the average height of the axis is 12 meters high and that the 92 windmills are of the same model (12 feet in diameter).

From the windmill it is known that the radius is 6 feet, that is, 1.8 meters, and its CP-λ curve is shown below:

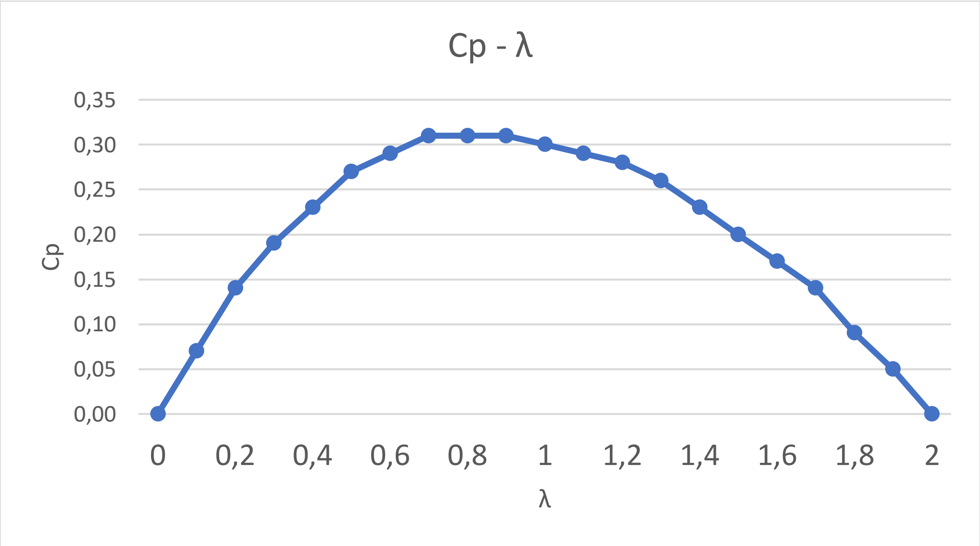


Figure 3 Power coefficient CP (defined as the ratio between the rotor power and the dynamic power in the wind) versus the tip speed ratio λ

With these data, the next step is to calculate the nominal power of the machine and its characteristic curve as a function of the wind speed. This type of windmills reaches their nominal power at the speed of 12 m/s approximately, therefore, the power at this speed will be that will mark its nominal design power. Even having winds higher than 12 m/s, the power generated will be equal to the maximum possible power or what is the same nominal design power.

To calculate the nominal power of the machine and its characteristic curve, it is necessary to transform the lambda speeds, the speed at the tip of the blade, at wind speeds to m/s. There is an expression that relates to both

$$\lambda = \frac{\omega \cdot R}{v} \quad (1)$$

where: ω: rotor speed, R: radius and v: wind speed (m/s).

The only unknown variable, until now, is the rotor speed. However, from the specification sheet of the windmill the following table is obtained:

Table 5 Aermotor windmill specifications

AERMOTOR WINDMILL SPECIFICATIONS

Model 802*	Mill Size Wheel Dia. (Ft.)	Stroke Inches		No. Of Sails	Mill Ship'g Weight (Pounds)	Back Geared	Max. Strokes Per Minute	At Wind Velocity	Max. Wheel RPM	Weight Of Crated Motor
		Long	Short							
X	6	5"	3¾"	18	210	3.91-1	32	15-18 mph	125	100
A	8	7⅛"	5½"	18	355	3.29-1	32	15-18 mph	105	175
B	10	9¼"	7¼"	18	655	3.29-1	26	15-18 mph	85	330
D	12	11¼"	8¼"	18	1130	3.50-1	21	18-20 mph	73	540
E	14	13½"	9¾"	18	1870	3.43-1	18	18-20 mph	62	805
F	16	14⅞"	11⅜"	18	2585	3.29-1	16	18-20 mph	53	1180

*Model 802 Windmills were introduced in 1981 and parts are interchangeable with Model 702 Windmills introduced in 1933.

These data show that for a speed between 18-20 mph (8-9 m/s) the rotor speed reaches 73 rpm (7.65 rad/s). With which, for these speeds it is possible to calculate its equivalent lambda and therefore its coefficient Cp by means of formula (1). In this case, we will assume the same rotor speed for the rest of the speeds.

The following table is obtained:

Table 6 Power curve Cp-Vwind

Vwind (m/s)	λ(v)	Cp	P (W)
0	0.0	0	0.0
1	14.0	0.02	0.11
2	7.0	0.04	1.80
3	4.7	0.05	9.12
4	3.5	0.07	28.83
5	2.8	0.09	70.39
6	2.3	0.11	145.96
7	2.0	0.12	270.41
8	1.7	0.14	461.30
9	1.6	0.17	797.56
10	1.4	0.23	1480.19
11	1.3	0.26	2227.10
12	1.2	0.28	3113.80
13	1.1	0.29	3113.80
14	1.0	0.30	3113.80
15	0.9	0.31	3113.80
16	0.9	0.31	3113.80
17	0.8	0.31	3113.80
18	0.8	0.31	3113.80
19	0.7	0.31	3113.80
20	0.7	0.31	3113.80
21	0.7	0.31	3113.80
22	0.6	0.29	3113.80
23	0.6	0.29	3113.80
24	0.6	0.29	3113.80

25	0.6	0.29	3113.80

The data of λ (v) for velocities between 0-7 m/s (marked in red) cannot be considered because they exceed the values found in the characteristic curve Cp-λ.

To obtain the values of "Power Coefficient" Cp and power, relative to this range of winds (blue values of Cp in Table 2), it has been calculated by extrapolation. Even knowing that the behaviour of the power curve is not linear in this section, this type of extrapolation can be carried out, since the effects that transcend the calculations are totally admissible.

In the last column, the values of P (W) marked in blue are since, as already mentioned before, the nominal power of these wind turbines is reached at 12 m/s and, therefore, although the speed increases above from 12 m/s, the power generated at that moment will be equal to the nominal power.

Once these values are calculated, the following graphs are obtained:

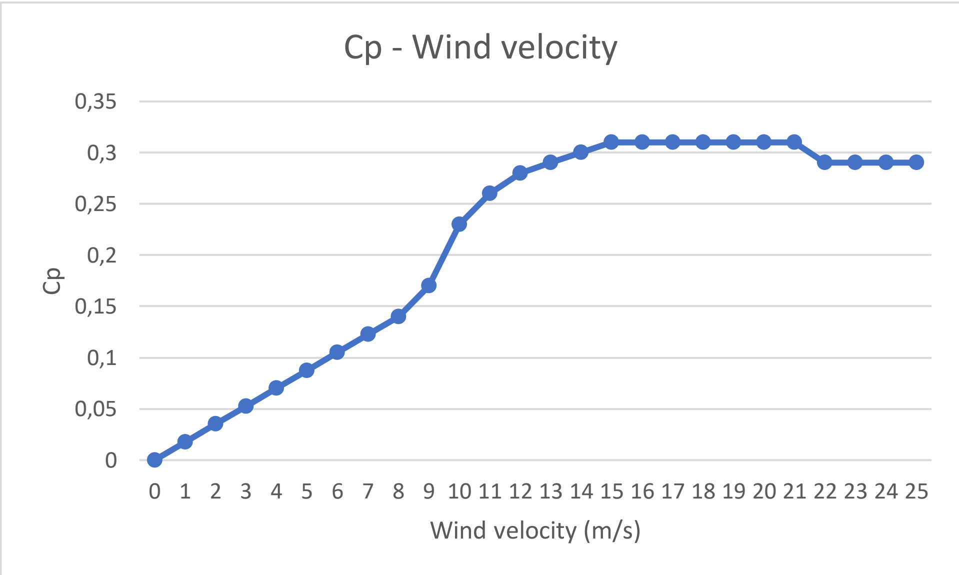


Figure 4 Cp-Vwind curve

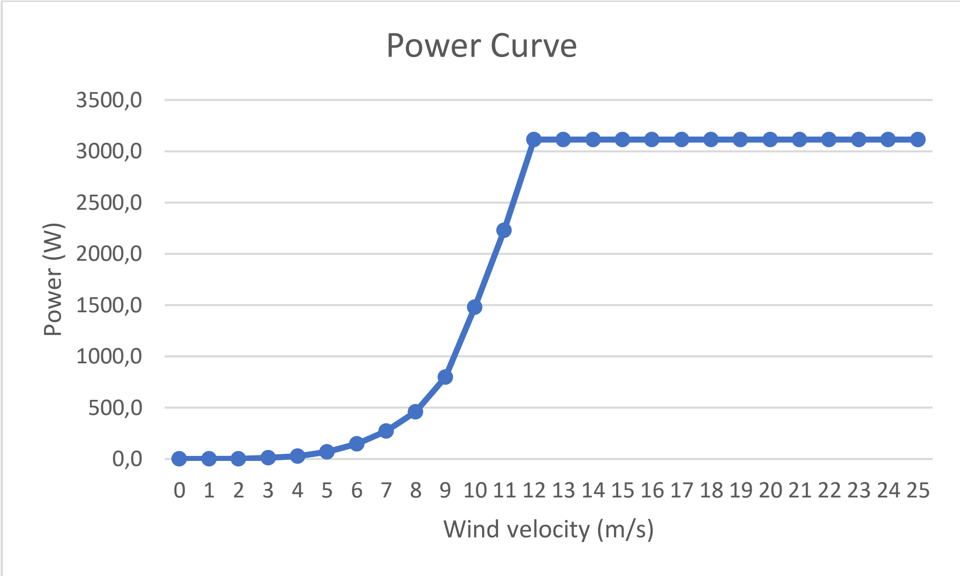


Figure 5 Power curve

From these data, it can be determined that the nominal power of this model of windmill (12 feet in diameter, marked "Aermotor"), is 3.1 kW.

4.2. Location data

Known UTM coordinates of each mill [2], using the GRAFCAN online viewer [12] and selecting the layer of "Wind resource" have been obtained for each location where there are mills in good condition, the wind resource data to a height of 40 meters. These data include (see annex 2):

- Roughness of the terrain
- Form factor of Weibull, K
- Weibull scale factor, C (m/s)
- Wind speed at 40 meters

Although the GRAFCAN viewer offers an average wind speed, it has been recalculated by using the expression of the average velocity of the Weibull distribution.

$$\bar{v} = C \cdot \gamma(1 + \frac{1}{K}) \ (2)$$

where: C: scale factor (m/s), K: shape factor, γ: gamma function, all known values.

The new average velocity values calculated by this method are between 0.2 and 2% lower (see annex 3), which are not significant. Even so, we will use these new average speeds obtained by using equation 2 for the later calculations.

It is important to point out that all the values obtained for the sites are 40 meters high, and as already mentioned, the characteristic height of the axis is 12 meters high. We will look at this difficulty in detail in the next section.

4.3. Analysis of the wind resource

Known the radius of the blades, r = 1.8 m, the average speed of each windmill, considering a characteristic power coefficient of 0.3, which is the same for all the mills, and an air density, ρ, of 1,225 kg/m^3, it is possible to calculate the average power in each location by means of the following expression:

$$P = \frac{1}{2} \cdot (\pi \cdot r^2) \cdot \rho \cdot Cp \cdot v^3 \text{ (4)}$$

where: r: radius of the blades (m), ρ: air density (kg/m^3), Cp: power coefficient, v: speed (m/s)

It is important to note that, in our case study, v must be the speed at 12 m height, while the data obtained in the previous section correspond to 40 m. So, it will be necessary to use the following formula to obtain its value from the data we have available.

$$v_{12\,m} = v_{40\,m} \cdot (\frac{12}{40})^r \text{ (3)}$$

where: v: speed (m/s), r: roughness coefficient of the ground

However, the method used previously for the calculation of the power-correcting the average speed at the characteristic height as a function of the roughness (equation 3)-although it is widely used in the bibliography, does not fit perfectly to reality. This would be a Weibull distribution typical of the location and with its parameters at the specific height (12 meters high).

Therefore, in the following sections we propose and compare different power calculation methods based on the use of a Weibull distribution and not on the average speed.

4.3.1. Weibull estimation methods at work height

Weibull is an asymmetric distribution described by two parameters, form factor and scale factor, but there is no concrete procedure to calculate them. In some articles different methods are compared, it has also been investigated how the variation of the wind speed with height influences the parameters of form and scale. [13]–[17]

Other authors have researched expressions to obtain the Weibull parameters at a given height without adjusting the wind speeds to a distribution function but using the parameters at a known height. [18], [19]

In this work, we will test and check different methods. Next, the different methodologies used are described. To do this, wind turbine 1 has been selected, which will serve as a pilot. All the results presented in this section correspond, therefore, to the location of this.

Before describing and analysing the different methods proposed, we will define a Weibull distribution of reference for the analysed site. This reference distribution faithfully represents reality, since it is built with the data observed in the location. [12]

For this, the parameters of the site at 40 m height, Weibull, form factor and scale factor, obtained in GRAFCAN, have been used, and in terms of speeds, we convert them from 40 meters to 12 meters in height using the equation 3 using the roughness of the location.

Obtaining the Weibull distribution is governed by the equation:

$$p(v) = \frac{K}{C}\left(\frac{v}{C}\right)^{K-1} e^{-\left(\frac{v}{C}\right)^{K}} \quad (5)$$

where: C: scale factor (m/s), K: shape factor, v: speed (m/s)

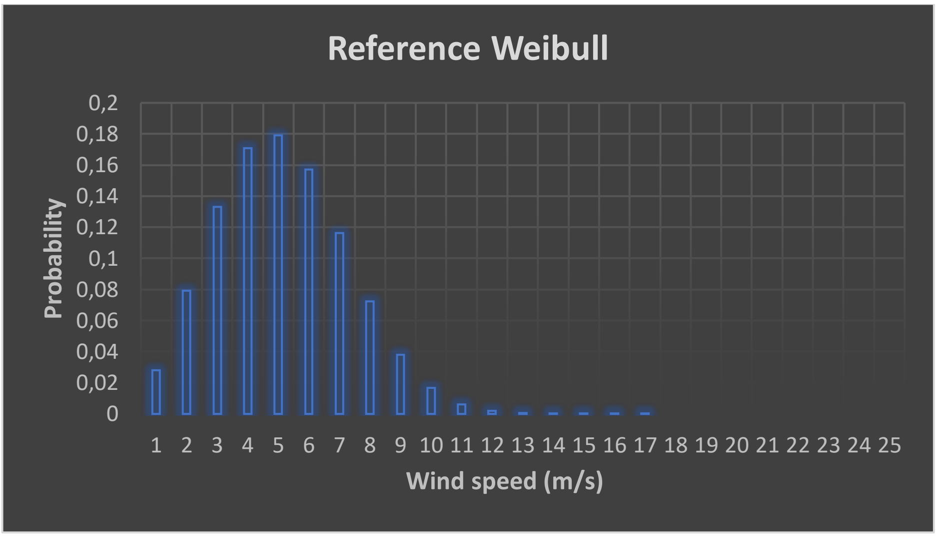


Figure 6 Reference Weibull

This distribution will serve as a basis to analyse the results of the different methods proposed.

<u>1st method</u>

The first method proposed is to perform a linear interpolation to obtain the Weibull parameters at the desired height (12 meters) from the heights provided by GRAFCAN. For this, we obtain the Weibull parameters of the location for different heights in GRAFCAN (40 meters, 60 meters and 80 meters) and execute the linear interpolation.

Height	40	60	80	12
Rugosity	0,1	0,1	0,1	0,1
C	5,41	6,19	6,8	4,4659
K	2,837	2,798	2,741	2,9072

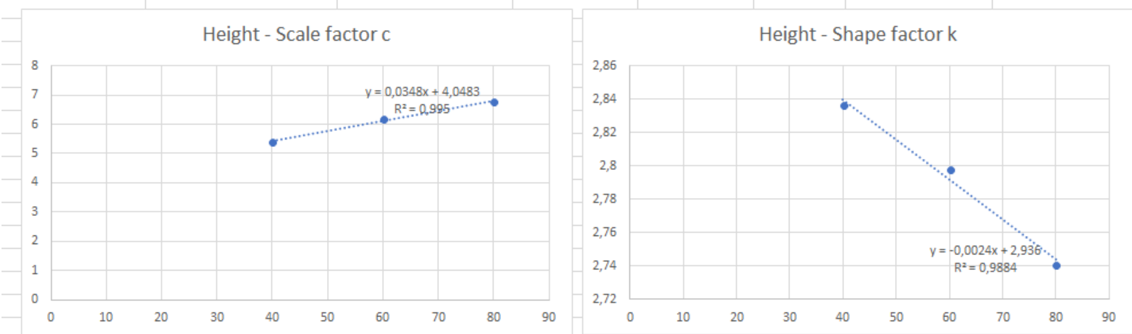


Figure 7 Interpolation

Once the Weibull parameters have been obtained for the desired height (indicated in red in the previous figure), we proceed to calculate the new distribution and represent it graphically.

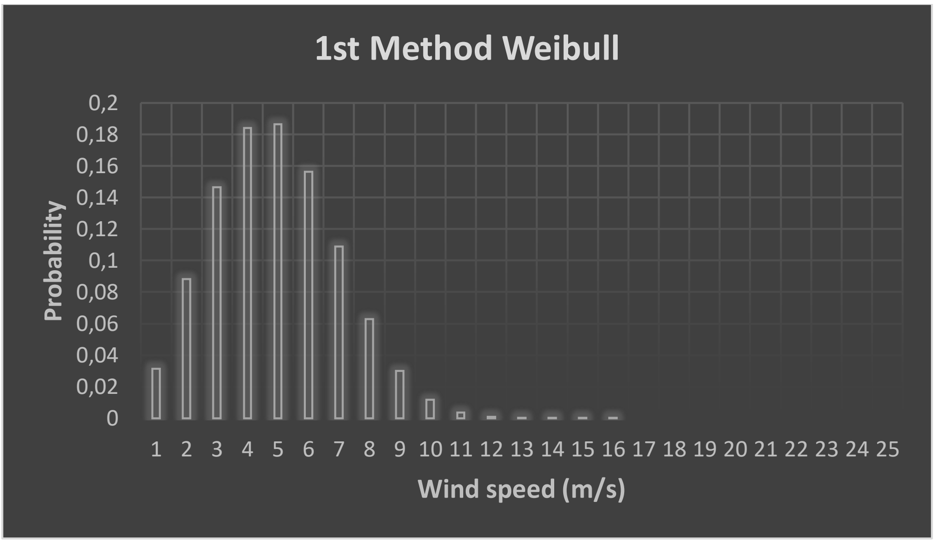


Figure 8 1st Method Weibull

If we compare this figure with the previous results, figure 4, we see that the results are quite similar but, in this case, we obtain higher values of probability.

2nd method:

In this case, we use the speeds at 12 meters of height obtained from the speeds at 40 meters by means of equation 3, and we also use the shape factor of the location at 40 meters high, as was done for the reference distribution (fig 4). The key point is to correct the scale factor from 40 meters high to 12 meters, depending on the roughness, using the equation:

$$C_{12\,m} = C_{40\,m} \cdot \left(\frac{12}{40}\right)^{r} \quad (6)$$

where: r: terrain roughness coefficient, C: scale factor (m/s)

With this method, the new distribution obtained is the following:

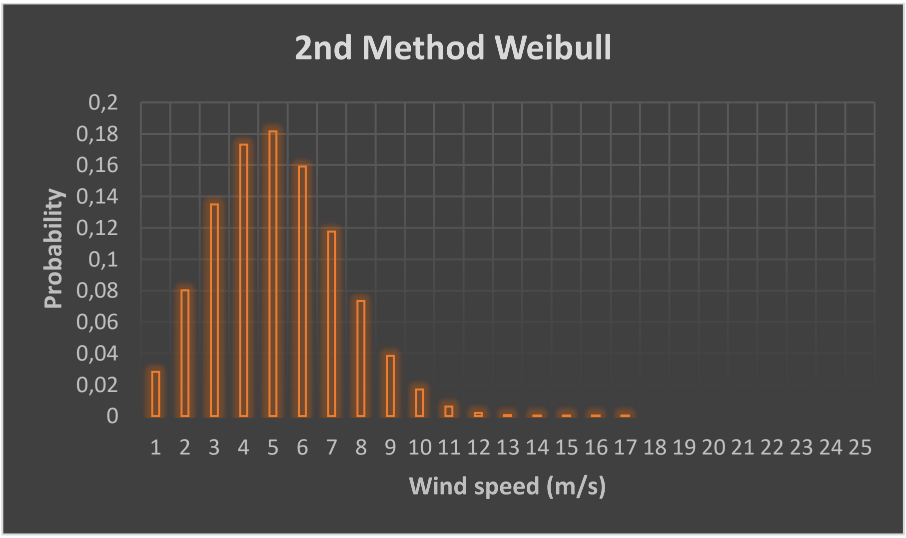


Figure 9 2nd Method Weibull

As we can see, in this case if we compare this figure with the previous results, figure 4, we see that the results are even more similar.

3rd method:

During the execution of the calculations of the 2nd method, it was observed that the error that was committed with respect to the original Weibull distribution was the same for each of the speeds. It was also found that this error depended directly on the roughness. Therefore, the hypothesis was formulated that for a certain roughness, the error that is committed is the same for each one of the wind speeds.

To verify this hypothesis, we performed the error calculations for all the windmills in our catalogue and we observed that the error was the same for the same-speed aero-motors, (see detailed calculations in annex 4). Of the 92 mills in the case study, there are only 4 different rugosities (0.01, 0.05, 0.1 and 0.75). Therefore, the error can be classified into four groups according to the roughness.

Table 7 Roughness - Error

Roughness	Error
0.01	1,2112%
0.05	6,2047%
0.1	12,7945%
0.75	146,6943%

Studying the behaviour of the results obtained, we conclude that the error can be parameterized according to the roughness, using a polynomial of degree 2, obtaining the equation.

$$y = 1.0444\ r2 + 1.1719\ r + 0.0005 \quad (7)$$

where: r: ground roughness coefficient.

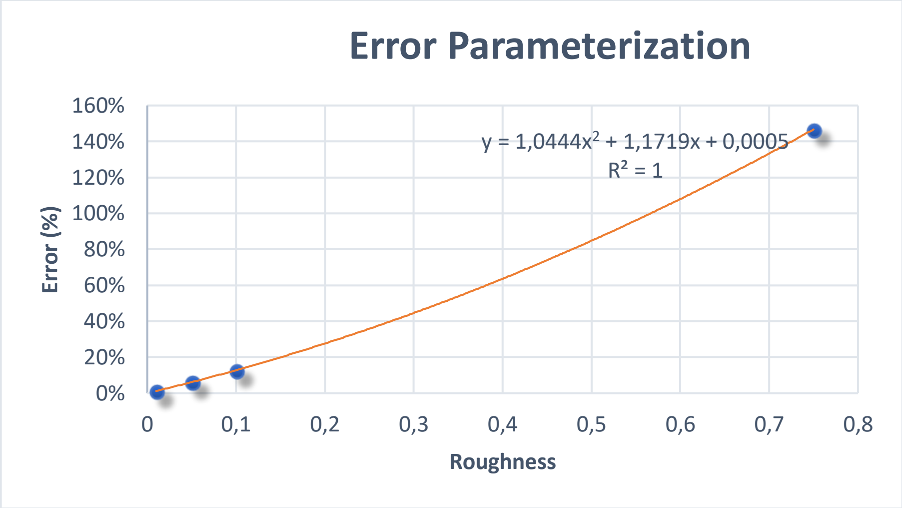


Figure 10 Error Parameterization

The third method, therefore, is to introduce the parameterized error (equation 7) into the equation for the calculation of the Weibull probability (equation 5), leaving the following formula corrected:

$$p(v) = \left(\frac{1}{1.0444\ \mathrm{r2} + 1.1719\ \mathrm{r} + 0.0005}\right)\left[\frac{K}{C}\ \left(\frac{v}{C}\right)^{K-1} e^{-\left(\frac{v}{C}\right)^{K}}\right] \quad (8)$$

where:

- r: terrain roughness coefficient
- C: scale factor (m/s), corrected from 40 meters in height to 12 meters (equation 6)
- K: form factor, 40 meters high
- v: wind speed, whose values will go from 1 m/s to 25 m/s (speed of cut of the windmill), in steps of 1 unit.

With this method, the error we make respect to the reference Weibull distribution becomes negligible (residual error of ± 0.02%).

The Weibull distribution obtained by the third method is as follows:

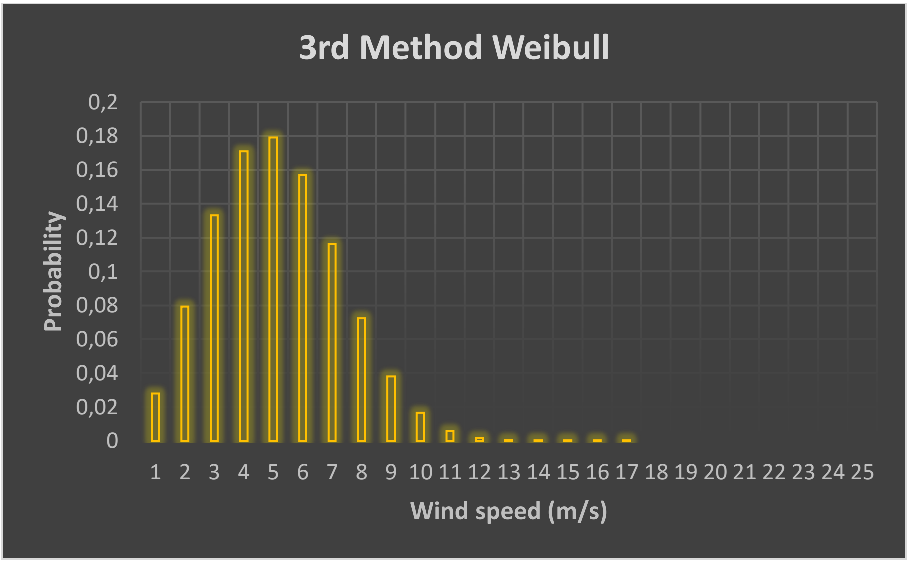


Figure 11 3rd Method Weibull

If we compare the previous figure with figure 4, we see that in this case, the results fit perfectly to the reference Weibull distribution

4.3.2. Comparison of methods

To analyse the validity of the proposed methods, we have performed all the previous calculations with a pilot windmill of each of the 4 possible roughness coefficients present in our catalogue.

The criterion to decide which of the methods is better, has been to analyse the graphical representations of the Weibull distributions of each of the methods to observe which best fits the reference Weibull distribution.

Below is a comparison of the different methods according to roughness.

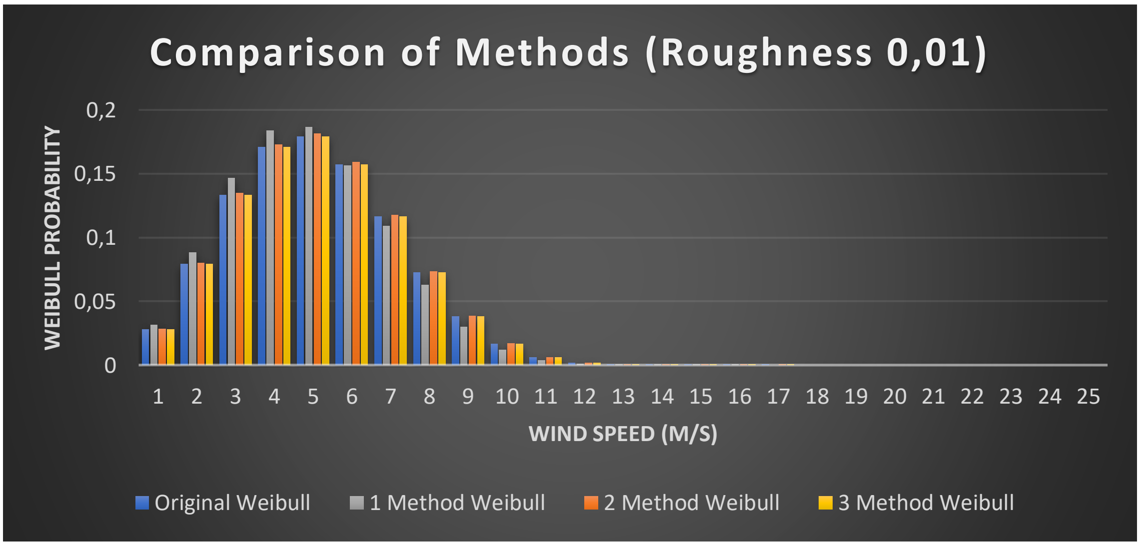


Figure 12 Roughness 0.01

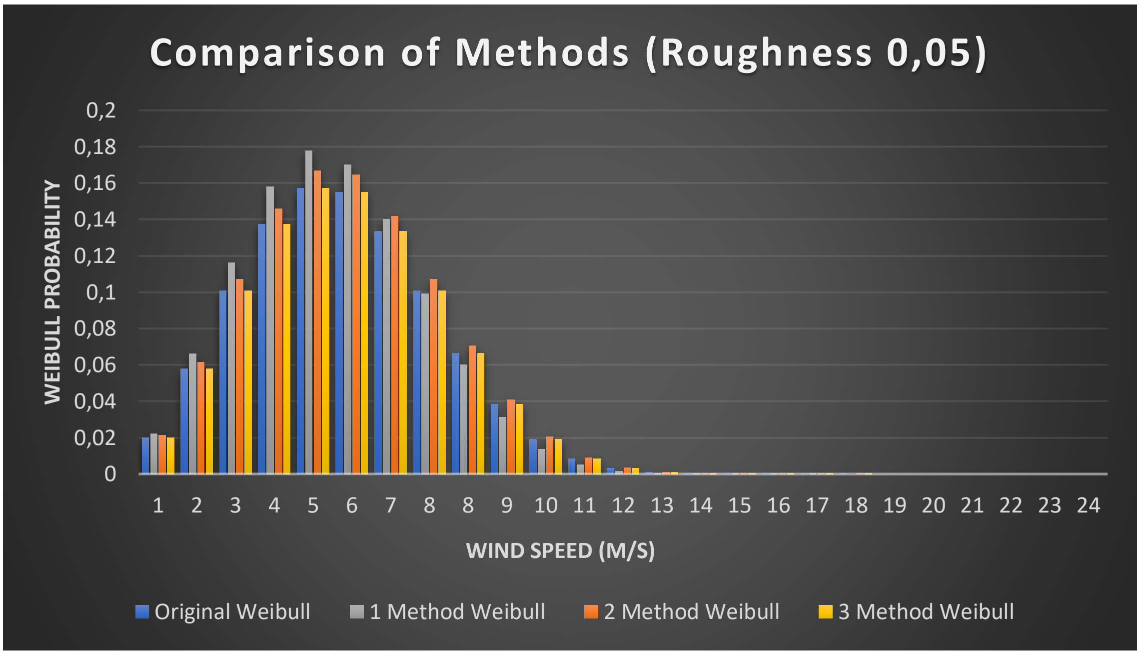


Figure 13 Roughness 0.05

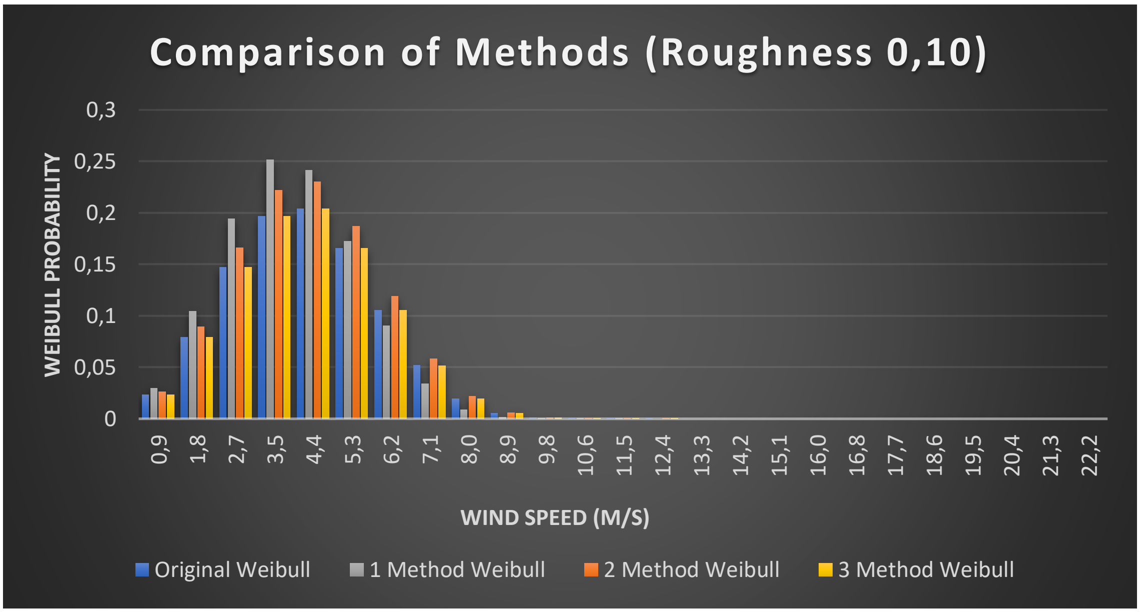


Figure 14 Roughness 0.10

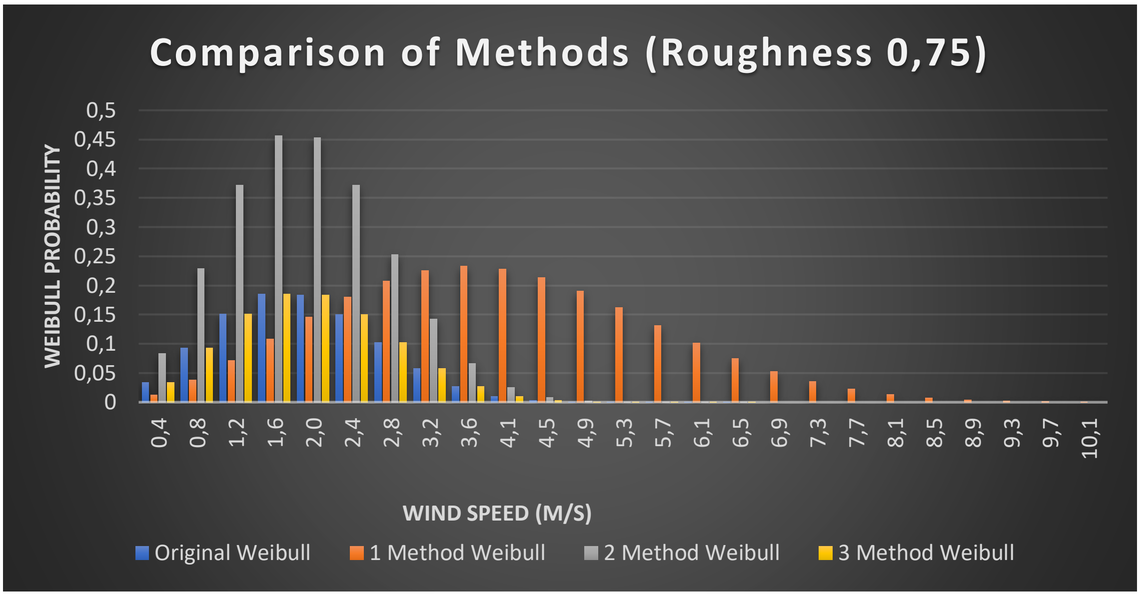


Figure 15 Roughness 0.75

As can be seen, the lower the roughness, the different Weibull distributions obtained by the different methods, adjust quite well to the reference Weibull distribution. However, for high rugosities (fig 12 and 13), the behaviour of the distributions obtained by the first and second methods, are quite far from the reference Weibull distribution, being very imprecise for roughness equal to 0.75.

With everything described above and the observation of the previous graphs, we can guarantee that the 3rd method is the one that best fits the reference Weibull distribution, regardless of the roughness. Therefore, this method will be used for the subsequent power calculations.

4.3.3. Calculation of the power

To calculate the power, we will combine the characteristic power curve (wind speed - generated power), of this model of the windmill (figure 3), with the probability Weibull for the determined speeds, for each one of the windmills.

For example: for the speed of 1 m/s, we will obtain a Weibull probability; the result of this probability, we multiply it by the power developed by the apparatus for that specific speed; thus, we will obtain the power for each of the speeds, from 1 m/s to 25 m/s (in jumps of 1 unit), and the sum of these powers will be equivalent to the average power of the windmill.

The Weibull probability, we obtain it using the equation 8 determined in the 3rd method, as we mentioned in the previous section.

$$p(v) = \left(\frac{1}{1.0444\ \mathrm{r2} + 1.1719\ \mathrm{r} + 0.0005}\right)\left[\frac{K}{C}\ \left(\frac{v}{C}\right)^{K-1} e^{-\left(\frac{v}{C}\right)^{K}}\right]\ (8)$$

where:

- r: terrain roughness coefficient
- C: scale factor (m/s), corrected from 40 meters in height to 12 meters (equation 6)

- K: form factor, 40 meters high
- v: wind speed, whose values will go from 1 m/s to 25 m/s (speed of cut of the windmill), in steps of 1 unit.

Below is an example table of the power calculation method for wind turbine number 1.

Table 8 Power calculation method

Vwind (m/s)	Power (W) Power curve	Weibull	Power (W)
1	0.11	2,85E-02	3,13E-03
2	1.80	8,05E-02	1,45E-01
3	9.12	1,35E-01	1,23E+00
4	28.83	1,72E-01	4,96E+00
5	70.39	1,79E-01	1,26E+01
6	145.96	1,55E-01	2,26E+01
7	270.41	1,12E-01	3,04E+01
8	461.30	6,86E-02	3,17E+01
9	797.56	3,50E-02	2,79E+01
10	1480.19	1,48E-02	2,20E+01
11	2227.10	5,20E-03	1,16E+01
12	3113.80	1,49E-03	4,64E+00
13	3113.80	3,48E-04	1,08E+00
14	3113.80	6,57E-05	2,05E-01
15	3113.80	9,93E-06	3,09E-02
16	3113.80	1,19E-06	3,71E-03
17	3113.80	1,13E-07	3,52E-04
18	3113.80	8,39E-09	2,61E-05
19	3113.80	4,84E-10	1,51E-06
20	3113.80	2,16E-11	6,72E-08
21	3113.80	7,36E-13	2,29E-09
22	3113.80	1,91E-14	5,94E-11
23	3113.80	3,74E-16	1,16E-12
24	3113.80	5,49E-18	1,71E-14
25	3113.80	6,00E-20	1,87E-16
Total →			Summation of all the above 171 W

The difference between the power calculated by equation 4 and the power calculated with the method described above, a summary table is shown in function of the roughness. The calculations to all the windmills in are attached in the annex 5.

Table 9 Roughness - Error

Roughness	Error
0.01	± 30 %
0.05	27 %
0.10	40 a 60 %
0.75	± 90%

4.3.4. System efficiency

However, the final power will have to consider the electrical and mechanical efficiencies of the system. As a result, the annual energy production and the number of equivalent hours will also be affected by these returns.

The following electrical performances are obtained from the technical sheets of the inverter and regulator (attached in the annexes 6 and 7) and the mechanical performance in this case is 1 (100%), since it owes to the rotor-generator coupling and, in this case, there is no gap. Therefore, for the system, the following yields will affect the global energy production:

Table 10 System efficiency

System efficiency	
Electrical efficiency	**0.962192**
Inverter	0.968
Regulator	0.994
Mechanical efficiency	**1**
Coupling rotor-Generator	1

4.4. Results

Once the work methodology has been defined, this method has been applied to all the wind turbines selected in Chapter 3 as susceptible to adaptation.

Next, the estimated energy produced by each wind turbine is shown.

Table 11 Energy produced by each wind turbine

Windmill nº	1	2	3	4	5	6	7	8	9	10	11
Annual Energy (kWh)	1441,08	561,17	543,18	564,37	587,59	636,89	576,50	554,09	645,61	757,72	850,57

Windmill nº	12	13	14	15	16	17	18	19	20	21	22
Annual Energy (kWh)	980,14	835,51	734,28	761,52	736,15	446,33	1649,05	734,59	767,25	998,32	954,46

Windmill nº	23	24	25	26	27	28	29	30	31	32	33
Annual Energy (kWh)	790,45	840,83	1035,46	926,63	864,62	761,60	453,69	995,75	878,41	939,23	1062,54

Windmill nº	34	35	36	37	38	39	40	41	42	43	44
Annual Energy (kWh)	12,53	13,32	522,02	1220,19	1403,73	1930,92	827,92	749,72	1113,94	998,35	1072,72

Windmill nº	45	46	47	48	49	50	51	52	53	54	55
Annual Energy (kWh)	1399,59	1144,04	1017,00	905,33	873,79	906,57	708,73	931,46	1429,11	1398,98	1202,37

Windmill nº	56	57	58	59	60	61	62	63	64	65	66
Annual Energy (kWh)	885,30	867,21	822,98	859,61	809,73	822,57	751,40	776,43	803,40	730,87	555,20

Windmill nº	67	68	69	70	71	72	73	74	75	76	77
Annual Energy (kWh)	556,83	627,63	1063,71	989,81	1311,84	1663,87	805,38	818,04	2075,33	773,11	587,05

Windmill nº	78	79	80	81	82	83	84	85	86	87	88
Annual Energy (kWh)	994,92	578,49	1440,03	1087,54	1054,41	618,60	807,93	328,80	395,30	337,62	502,50

Windmill nº	89	90	91	92
Annual Energy (kWh)	1071,31	848,04	525,95	628,57

These results can be used to carry out an economic feasibility study, as a decision criterion on which to modify or not, depending on the values obtained.

Finally, these results help us to estimate the total wind potential existing on the island of Fuerteventura through the park of traditional multi-bladed "American" mills that are in a good state of conservation at present. In the global calculation of the 92 windmills available on the island of Fuerteventura to carry out the conversion process, we obtain the total results shown below.

Table 12 Total results

Power (W)	Power (efficiency) (W)	Energy (Wh)	Energy (kWh)
9470,5	9112,300	79823748	79823,6

5. CONCLUSIONS

This project has the objective of recovering and transforming the traditional multi-blade mill, "American" type, used to pump water from the subsoil, for conversion as a low-voltage electric power producer on the island of Fuerteventura. With this, we will obtain energy savings and we will also contribute to the recovery and embellishment of the typical rural landscape of the island.

To do this, we have carried out an in-depth analysis of the potential of the island of Fuerteventura for the conversion and transformation into a renewable source of electric energy from the traditional American type "Chicago" multi-blade mills.

As no previous articles related to this objective have been found, we had to carry out a study and a classification of the existing mills on the island of Fuerteventura.

To do this, we have defined some parameters and general classification methods, based on all the information gathered about it. This classification allows us to locate those mills that are in optimal conditions for their subsequent reconversion. This is completed with a subclassification of which of these optimal mills are most appropriate for the reconversion project to produce electricity with connection to the insular electricity grid and which are more suitable to produce electricity for self-consumption.

These classification mechanisms that we have developed in the project are a tool with excellent potential, since they are totally extrapolated to any place in the world where these types of machines are present.

In this study, of the 92 mills that according to the classification methods we have considered adequate to carry out the reconversion, and by subclassing to determine their electrical purpose, we have obtained the following classification:

- 35 mills classified as "Urban integrated", will be chosen for the reconversion project to produce electricity with connection to the insular electricity grid.
- 38 mills classified as "Isolated" are more suitable for reconversion to produce electricity for self-consumption.
- 19 mills classified as "Associated to building", may be considered both for the reconversion project to produce electricity with connection to the insular electricity grid and for its conversion to produce electricity for self-consumption, said decision shall be taken considering the opinion of the owner of the windmill.

Once classified, our objective has been to calculate the electrical production of each one of the windmills. For this, we have defined the characteristics of the windmills and the methodology of the treatment of the information that is going to be carried out.

Our method for calculating power is innovative. To calculate the power, we decided that the most precise thing is to use a Weibull distribution and we have studied different methods of obtaining it based on the available data.

The innovation of the method resides in that, thanks to the exhaustive analysis carried out, we have managed to parameterize the error that is committed when correcting the scale factor from one height to another depending on the roughness. With this, we can introduce this parameterization of the error in the Weibull probability equation and thus obtain simple and fast results that really fit the Weibull distribution at the site.

Therefore, the method allows us to calculate the power for any wind turbine, if we know the following data:

- Wind turbine data:
  - Power curve (wind speed - power)
- Site data:
  - Soil roughness coefficient
  - v: wind speed (m/s)
  - K: form factor
  - C: scale factor (m/s)

Regardless of the height at which we have the location data, which is practical and has great potential.

With all this, we have managed to determine the annual energy produced by each of the 92 mills analysed in the project, obtaining as a conclusion that the total wind potential of the island of Fuerteventura-through the traditional "American" multi-bladed mills found in a good state of conservation-at present is 79823.6 kWh per year.

The execution of this project on the island of Fuerteventura would be a great opportunity to promote the restoration of this type of windmill and turn it into a source of renewable energy. Thus, contributing to the enrichment of the cultural and landscape heritage of the island, and with substantial energy savings.

The project under development contributes to providing a positive impact on the environment. This impact is due to the fact that it is focused on the integration of a renewable energy source such as wind power generation.

Assuming that of the 92 proposed windmills, a minimum of 46 units will be carried out, and taking the latest data published by the IDAE (Institute of Energy Saving and Diversification of Spain) on the Canarias electric energy mix, they would be generating about 40.15 MWh per year of electricity, which means:

• A saving of CO_2 emissions of 31.16 tons per year.

• A saving of NO_2 emissions of 20,754 m^3 per year.

• A savings of SO_2 emissions of 15,149 m^3 per year.

• A saving of CO emissions of 3.24 m^3 per year.

• A saving of 23.56 kg particle emissions per year.

Finally, it should be noted that these results can be used to carry out a subsequent economic feasibility study, as a decision criterion on which to modify or not, depending on the values obtained.

ACKNOWLEDGEMENTS

After two years of hard work, this stage comes to an end. I take this opportunity to thank all those people who have supported me during this period and without whom none of this would be possible.

That is why I dedicate this master's thesis to you as a symbol of my gratitude.

To PAULA, thank you for all the help you have always given me.

To my parents, who are the architects for this achievement to be possible and my brother for his understanding and support during this cycle of my life.

To all my classmates, who have supported me enormously and have always been there to help me when I needed it.

To my TFM tutor, MARIA DE LA PEÑA FABIANI BENDICHO, for leading this project.

In particular, Professor JULIAN MONEDERO ANDRES, without whom this TFM would not be possible.

And last but not least, to all the professors that I have crossed my path, who already give us minutes of their lives to try to learn something, deserve all the recognition and gratitude of the world.

Thank you

REFERENCES

[1] Wikipedia, “Fuerteventura.” [Online]. Available: https://es.wikipedia.org/wiki/Fuerteventura. [Accessed: 18-Nov-2017].

[2] I. Hernández Díaz and R. Cerdeña Ruíz, “Sistemas tradicionales de extracción de aguas subterráneas: norias y molinos.,” in *FUERTEVENTURA LA CULTURA DEL AGUA*, 2015, pp. 297–329.

[3] Scopus, “Scopus.” [Online]. Available: https://www.scopus.com. [Accessed: 21-Nov-2017].

[4] Mendeley, “Mendeley.” [Online]. Available: https://www.mendeley.com. [Accessed: 21-Nov-2017].

[5] ResearchGate, “ResearchGate.” [Online]. Available: https://www.researchgate.net/. [Accessed: 15-Dec-2017].

[6] E. A. N. Feitosa, J. A. Cirilo, and A. M. C. Soares Jr., “ANALYSIS OF WIND-POWER SYSTEMS CONNECTED TO AIR-LIFT PUMP,” 1985.

[7] G. Qin, C. C. K. Liu, N. H. Richman, and J. E. T. Moncur, “Aquaculture wastewater treatment and reuse by wind-driven reverse osmosis membrane technology: A pilot study on Coconut Island, Hawaii,” *Aquac. Eng.*, vol. 32, no. 3–4, pp. 365–378, 2005.

[8] Y. Keawsuntia, “A Study of Electricity Generating from Small Multi-Blade Wind Turbine for a Household,” *Appl. Mech. Mater.*, vol. 291–294, pp. 435–438, 2013.

[9] C. Fuerteventura, “Consejeria Patrimonio Cultural.” .

[10] “Google Maps.” [Online]. Available: https://www.google.es/maps/. [Accessed: 22-Jan-2018].

[11] Google, “Google Earth.” .

[12] Gobierno de Canarias, “IDECanarias visor 4.4.” [Online]. Available: http://visor.grafcan.es/visorweb/. [Accessed: 22-Jan-2017].

[13] K. Mohammadi, O. Alavi, A. Mostafaeipour, N. Goudarzi, and M. Jalilvand, “Assessing different parameters estimation methods of Weibull distribution to compute wind power density,” *Energy Convers. Manag.*, vol. 108, pp. 322–335, 2016.

[14] V. Bezrukovs, A. Zacepins, V. Bezrukovs, and V. Komasilovs, “Comparison of methods for evaluation of wind turbine power production by the results of wind shear measurements on the Baltic shore of Latvia,” *Renew. Energy*, vol. 96, pp. 765–774, 2016.

[15] D. Solyali, M. Altunç, S. Tolun, and Z. Aslan, “Wind resource assessment of Northern Cyprus,” *Renew. Sustain. Energy Rev.*, vol. 55, pp. 180–187, 2016.

[16] Z. R. Shu, Q. S. Li, Y. C. He, and P. W. Chan, “Observations of offshore wind characteristics by Doppler-LiDAR for wind energy applications,” *Appl. Energy*, vol. 169, pp. 150–163, 2016.

[17] S. E. Gryning, R. Floors, A. Peña, E. Batchvarova, and B. Brümmer, "Weibull Wind-Speed Distribution Parameters Derived from a Combination of Wind-Lidar and Tall-Mast Measurements Over Land, Coastal and Marine Sites," *Boundary-Layer Meteorol.*, vol. 159, no. 2, pp. 329–348, 2016.

[18] Z. Yu-qiao and Z. Rong-zhen, "Characteristics for wind energy and wind turbines by considering vertical wind shear," pp. 2393–2394, 2015.

[19] K. Tar, "Some statistical characteristics of monthly average wind speed at various heights," *Renewable and Sustainable Energy Reviews*, vol. 12, no. 6. pp. 1712–1724, 2008.

ANNEXES

ANNEX 1 Windmills census

Aeromotores en FUERTEVENTURA				
Aeromotores del término municipal de LA OLIVA				
Nº	X	Y	LOCALIDAD	ESTADO
1	597877	3173162	El Roque	Regular
2	601642	3162842	Tindaya	Malo
3	599239	3165415	Tindaya	Malo
4	598461	3166347	Tindaya	Malo
5	602320	3167934	Lajares	Malo
6	614232	3180195	Isla de Lobos	Bueno
Aeromotores del término municipal de BETANCURIA				
Nº	X	Y	LOCALIDAD	ESTADO
1	591351	3140261	Vega de Río Palmas	Bueno
2	593533	3148872	Valle de Santa Inés	Malo
3	590742	3141124	Vega de Río Palmas	Bueno
4	590722	3141159	Vega de Río Palmas	Malo
5	593913	3148526	Valle de Santa Inés	Regular
6	590854	3141190	Vega de Río Palmas	Bueno
7	590070	3141094	Vega de Río Palmas	Malo
8	592157	3144105	Betancuria	Regular
9	591221	3141452	Vega de Río Palmas	Malo
10	589960	3141065	Vega de Río Palmas	Regular
11	591770	3149361	Valle de Santa Inés	Malo
12	593628	3149150	Valle de Santa Inés	Malo
13	592954	3147673	Valle de Santa Inés	Malo
14	591139	3140506	Vega de Río Palmas	Regular
15	590986	3140631	Vega de Río Palmas	Regular
16	592412	3144815	Betancuria	Regular
17	590668	3141044	Vega de Río Palmas	Regular
18	588628	3140328	Vega de Río Palmas	Regular
19	593162	3148112	Valle de Santa Inés	Regular
20	593929	3147928	Valle de Santa Inés	Malo
21	585479	3141211	Ajuy	Malo
22	593047	3147915	Valle de Santa Inés	Regular
23	591767	3142902	Betancuria	Regular
24	594734	3148308	Valle de Santa Inés	Regular
25	595001	3147982	Valle de Santa Inés	Malo
26	594885	3148101	Valle de Santa Inés	Malo
27	593179	3148117	Valle de Santa Inés	Bueno
28	591162	3140659	Vega de Río Palmas	Malo
29	593511	3149248	Valle de Santa Inés	Regular
30	588731	3140040	Vega de Río Palmas	Regular

31	593091	3147786	Valle de Santa Inés	Regular
32	594036	3147890	Valle De Santa Inés	Regular
33	591376	3141587	Vega de Río Palmas	Malo
34	591747	3142183	Vega de Río Palmas	Malo
35	590600	3151571	Valle de Santa Inés	Regular
36	590933	3141198	Vega de Río Palmas	Regular
37	593843	3148049	Valle de Santa Inés	Regular
38	591335	3140304	Betancuria	Bueno
39	592757	3147565	Valle de Santa Inés	Bueno
40	592522	3147230	Valle de Santa Inés	Bueno
41	593033	3147649	Valle de Santa Inés	Malo
42	591337	3141775	Vega de Río Palmas	Malo
43	590015	3141027	Vega de Río Palmas	Bueno
44	589815	3141027	Vega de Río Palmas	Bueno
Aeromotores del término municipal de ANTIGUA				
Nº	**X**	**Y**	**LOCALIDAD**	**ESTADO**
1	602624	3144234	Triquivijate	Bueno
2	595753	3141302	Valles de Ortega	Bueno
3	596387	3140904	Valles de Ortega	Malo
4	596492	3141033	Valles de Ortega	Bueno
5	599036	3139753	Mafasca	Malo
6	597789	3139891	Llanos Negros	Malo
7	597685	3139839	Llanos Negros	Regular
8	600674	3139899	Majada Blanca	Regular
9	602204	3139750	Los Alares	Regular
10	603819	3139903	Los Alares	Regular
11	605647	3139665	Los Alares	Malo
12	594693	3144076	Los Alares	Malo
13	595869	3144358	El Barrio	Malo
14	595489	3143809	El Carbón	Bueno
15	595312	3143697	El Carbón	Bueno
16	596065	3143814	Antigua	Malo
17	595993	3143167	Antigua	Regular
18	595639	3143173	Antigua	Bueno
19	596450	3143504	Antigua	Desm.
20	596331	3143817	Antigua	Desm.
21	596405	3143806	Antigua	Malo
22	596499	3143802	Antigua	Bueno
23	596514	3144042	Antigua	Regular
24	596502	3143396	Antigua	Malo
25	597097	3143228	La Corte	Malo
26	596672	3143477	La Corte	Malo
27	595608	3143951	El Carbón	Malo
28	595259	3144758	El Durazno	Malo
29	593426	3141265	Agua de Bueyes	Regular

30	593433	3140824	Agua de Bueyes	Regular
31	593962	3139192	Agua de Bueyes	Regular
32	594193	3138973	Agua de Bueyes	Regular
33	594333	3138919	Agua de Bueyes	Regular
34	595069	3139281	Agua de Bueyes	Regular
35	595070	3139158	Agua de Bueyes	Regular
36	595146	3138550	Agua de Bueyes	Regular
37	595175	3138417	Agua de Bueyes	Bueno
38	595132	3138362	Agua de Bueyes	Malo
39	594996	3138149	Agua de Bueyes	Malo
40	594976	3137968	Agua de Bueyes	Malo
41	594897	3137913	Agua de Bueyes	Malo
42	596166	3140910	Valles de Ortega	Regular
43	596916	3140946	Valles de Ortega	Regular
44	596906	3140731	Valles de Ortega	Regular
45	597309	3140191	Valles de Ortega	Malo
46	596858	3139942	Valles de Ortega	Malo
47	597340	3139802	Valles de Ortega	Malo
48	597690	3139941	Valles de Ortega	Malo
49	598167	3141424	Valles de Ortega	Regular
50	599122	3139957	Majada Blanca	Malo
51	599150	3139679	Majada Blanca	Malo
52	600092	3139314	Los Alares	Malo
53	600350	3139612	Los Alares	Malo
54	600468	3139630	Los Alares	Malo
55	600043	3139741	Los Alares	Regular
56	600136	3139827	Los Alares	Regular
57	601547	3139632	Los Alares	Regular
58	602636	3139988	Los Alares	Regular
59	604006	3139846	Los Alares	Regular
60	604202	3139756	Los Alares	Regular
61	605074	3139615	Los Alares	Regular
62	605270	3139171	Los Alares	Regular
63	606896	3139036	Los Alares	Regular
64	607060	3139029	Los Alares	Regular
65	598443	3140020	Los Alares	Regular
66	597678	3141569	Las Pocetas	Malo
67	597129	3142279	Las Pocetas	Regular
68	598912	3142712	Las Pocetas	Regular
69	598537	3142667	Las Pocetas	Regular
70	596856	3142381	Las Pocetas	Malo
71	596727	3142525	Las Pocetas	Malo
72	596986	3143260	La Corte	Malo
73	596666	3143398	Antigua	Malo
74	596415	3143678	Antigua	Malo

75	596545	3143846	Antigua	Malo
76	596226	3144351	Antigua	Malo
77	594537	3145664	El Durazno	Bueno
78	594537	3145791	El Durazno	Bueno
79	596856	3139604	Valles de Ortega	Regular
80	602507	3130593	Tenicosquey	Regular
81	602377	3130655	Tenicosquey	Bueno
82	602529	3131423	Tenicosquey	Malo
83	602684	3131590	Tenicosquey	Malo
84	597221	3139791	Valles de Ortega	Bueno
85	600362	3139803	Los Alares	Malo
86	596327	3141125	Valles de Ortega	Malo
87	593919	3140281	Agua de Bueyes	Malo
88	596612	3140990	Valles de Ortega	Malo
89	596587	3140941	Valles de Ortega	Malo
90	596839	3140982	Valles de Ortega	Malo
91	597908	3141651	Majada Blanca	Bueno
92	597438	3140300	Cruce de Casillas de Morales	Malo
93	597056	3142132	La Corte	Malo
94	597078	3142537	La Corte	Malo
95	596198	3141104	Valles de Ortega	Malo
96	596278	3140886	Valles de Ortega	Malo
97	598856	3141138	Majada Blanca	Bueno
98	596406	3143604	Antigua	Malo
99	596323	3143791	Antigua	Malo
100	595487	3142810	Antigua	Malo
101	594828	3144555	Antigua	Malo
102	594840	3145122	El Durazno	Malo
103	595280	3144850	El Durazno	Malo
104	595500	3145121	El Durazno	Malo
105	594933	3145209	El Durazno	Malo
106	594020	3145709	El Durazno	Malo
107	594241	3146100	El Durazno	Malo
108	594741	3145103	El Durazno	Malo
109	596070	3144514	El Durazno	Malo
110	595373	3144413	El Durazno	Regular
111	595412	3144209	El Durazno	Regular
112	594430	3143819	El Durazno	Regular
Aeromotores del término municipal de TUINEJE				
Nº	**X**	**Y**	**LOCALIDAD**	**ESTADO**
1	591092	3129023	Juan Gopar	Regular
2	592034	3128295	Juan Gopar	Bueno
3	594366	3126811	Juan Gopar	Malo
4	591337	3131218	Las Casitas	Malo
5	595759	3125530	Juan Gopar	Bueno

6	595788	3124413	Juan Gopar	Bueno
7	595591	3124636	El Cuchillete	Malo
8	592800	3128487	Juan Gopar	Malo
9	592695	3128603	Juan Gopar	Malo
10	590926	3121513	Giniginamar	Malo
11	590853	3121628	Giniginamar	Malo
12	590685	3122188	Giniginamar	Malo
13	590699	3122515	Giniginamar	Malo
14	590707	3123372	Cañada del Moro	Bueno
15	590522	3122838	Giniginamar	Malo
16	590786	3120499	Giniginamar	Regular
17	589439	3123843	Cañada del Moro	Regular
18	589589	3123669	Cañada del Moro	Malo
19	590047	3123669	Cañada del Moro	Bueno
20	596316	3125810	Llanos de la Higuera	Regular
21	596642	3123029	Gran Tarajal	Bueno
22	596299	3124041	La Fuentita	Bueno
23	596124	3124226	La Fuentita	Malo
24	596698	3123878	Gran Tarajal	Bueno
25	586965	3125321	Rosa Los James	Regular
26	586062	3125976	La Calabaza	Malo
27	585700	3126117	La Calabaza	Malo
28	585563	3126211	La Calabaza	Regular
29	586798	3125376	Rosa Los James	Regular
30	599464	3123350	Las Playitas	Bueno
31	599614	3123318	Las Playitas	Bueno
32	599770	3124948	Las Playitas	Regular
33	599739	3123126	Las Playitas	Bueno
34	599655	3124825	Las Playitas	Regular
35	599184	3123574	Las Playitas	Regular
36	595348	3130773	Catalina García	Regular
37	595093	3130593	Catalina García	Regular
38	586664	3119747	Tarajalejo	Regular
39	586820	3119991	Tarajalejo	Bueno
40	597729	3126261	Tequita-La Mata	Malo
41	597729	3125978	Tequital-La Mata	Bueno
42	597341	3126398	Tequital-La Mata	Malo
43	599448	3127458	Tequital	Malo
44	598475	3127862	Tequital	Bueno
45	598071	3127966	Tequital	Bueno
46	586515	3129283	Tesejerague	Malo
47	586738	3129021	Tesejerague	Bueno
48	587235	3128656	Tesejerague	Malo
49	587341	3128195	Tesejerague	Malo
50	586363	3129348	Tesejerague	Bueno

51	588269	3126258	Tirba	Malo
52	588583	3127058	Tirba	Bueno
53	588403	3126675	Tirba	Malo
54	590563	3126964	Tirba	Bueno
55	594345	3136640	Tiscamanita	Regular
56	595794	3135906	Tiscamanita	Bueno
57	594689	3134136	Tiscamanita	Malo
58	593545	3133291	Tuineje	Malo
59	593712	3137225	Tuineje	Bueno
60	593367	3137352	Tuineje	Bueno
61	593283	3137430	Tuineje	Bueno
62	592514	3137401	Tuineje	Malo
63	593125	3137345	Tuineje	Malo
64	593123	3137293	Tuineje	Malo
65	592432	3133507	Tuineje	Malo
66	593075	3133441	Tuineje	Bueno
67	593184	3133394	Tuineje	Bueno
68	593249	3133312	Tuineje	Bueno
69	593381	3133394	Tuineje	Malo
70	593504	3137348	Tuineje	Malo
71	590560	3125636	Violante	Bueno
72	590404	3127634	Violante	Bueno
73	585289	3125066	Tesejerague	Regular
74	584514	3127257	El Cardón	Malo
75	585499	3124407	Tamaretilla	Malo
76	586983	3123939	Tarajalejo-Cruce El Cardón	Regular
77	586940	3123300	Tarajalejo-Cruce El Cardón	Regular
78	586735	3123097	Tarajalejo-Cruce El Cardón	Regular
79	586999	3123494	Tarajalejo-Cruce El Cardón	Regular
80	594437	3134579	Tiscamanita	Bueno
81	593695	3137323	Tiscamanita	Bueno
82	586817	3127994	Tesejerague	Regular
83	587244	3127994	Tesejerague	Bueno
84	587547	3126416	Tesejerague	Bueno
85	587537	3126282	Tesejerague	Malo
86	584714	3125862	Tamaretilla	Malo
87	585289	3125066	Tamaretilla	Malo
88	585450	3124502	Tamaretilla	Malo
89	586688	3125087	Tirba	Malo
90	586680	3126523	Tirba	Bueno
91	586533	3126618	Tirba	Bueno
92	586472	3126690	Tirba	Bueno
93	586478	3126848	Tirba	Bueno
94	586674	3126883	Tirba	Bueno
95	586578	3127020	Tirba	Bueno

96	586046	3127119	Tirba	Regular
97	586008	3127151	Tirba	Regular
98	587056	3128056	Tirba	Regular
99	587345	3129531	Los Adejes	Malo
100	588631	3130284	Los Adejes	Malo
101	590014	3127560	Tirba	Bueno
102	589694	3127621	Tirba	Bueno
103	590351	3125576	Tirba	Bueno
104	590313	3123377	Giniginamar	Bueno
105	590123	3123459	Giniginamar	Malo
106	589863	3123751	Giniginamar	Malo
107	590673	3122511	Giniginamar	Bueno
108	588935	3123944	Tarajalejo	Bueno
109	590737	3121846	Giniginamar	Malo
110	598119	3125425	Gran Tarajal	Regular
111	598368	3125440	Gran Tarajal	Regular
112	597841	3124585	Gran Tarajal	Regular
113	596861	3122988	Gran Tarajal	Regular
114	596880	3122568	Gran Tarajal	Bueno
115	596524	3123417	Gran Tarajal	Malo
116	597204	3124302	Gran Tarajal	Regular
117	597018	3125445	Gran Tarajal	Malo
118	597183	3125703	Gran Tarajal	Regular
119	596161	3126111	Gran Tarajal	Bueno
120	595369	3126945	Gran Tarajal	Regular
121	597674	3127481	Tequital	Bueno
122	595639	3128061	Gran Tarajal	Malo
123	595631	3128108	Gran Tarajal	Regular
124	595185	3128704	Gran Tarajal	Regular
125	596678	3128861	Gran Tarajal	Regular
126	597544	3129319	Gran Tarajal	Malo
127	595973	3130872	Gran Tarajal	Malo
128	595211	3130352	Gran Tarajal	Malo
129	594179	3134209	Tiscamanita	Malo
130	594225	3135570	Tiscamanita	Malo
131	594439	3135830	Tiscamanita	Regular
132	594448	3136021	Tiscamanita	Bueno
133	594803	3136977	Tiscamanita	Malo
134	594725	3137036	Tiscamanita	Malo
135	594661	3137110	Tiscamanita	Malo
136	594694	3137708	Tiscamanita	Regular
137	594749	3137376	Tiscamanita	Malo
138	594624	3137427	Tiscamanita	Malo
139	594417	3137495	Tiscamanita	Malo
140	594346	3137544	Tiscamanita	Malo

141	594468	3137614	Tiscamanita	Malo
142	599640	3128458	Tequital	Regular
143	600345	3129146	Tequital	Regular
144	599776	3128401	Tenicosquey	Malo
145	587311	3125173	Rosa de Los James	Malo
146	587232	3125257	Rosa de Los James	Regular
147	593237	3124889	Violante	Malo
148	593040	3124812	Violante	Malo
149	594319	3125234	Violante	Malo
150	594358	3125250	Violante	Malo
151	593697	3124982	Violante	Malo
152	584381	3126005	Cruce de Cardón	Bueno
153	587634	3123686	Cardón	Bueno
154	589315	3123858	Cruce de Giniginama	Malo
155	594329	3126682	Juan Gopar	Malo
156	593988	3138136	Tiscamanita	Malo

Aeromotores del término municipal de PUERTO DEL ROSARIO				
Nº	**X**	**Y**	**LOCALIDAD**	**ESTADO**
1	599066	3159106	Tefía	Bueno
2	599746	3156272	Tefía	Bueno
3	599367	3156309	Tefía	Malo
4	598970	3156672	Tefía	Malo
5	598569	3156876	Tefía	Malo
6	598435	3156980	Tefía	Malo
7	595148	3149732	Llanos de la Concepción	Bueno
8	595250	3149805	Llanos de la Concepción	Malo
9	595064	3151246	Llanos de la Concepción	Regular
10	610640	3146359	El Matorral	Bueno
11	598478	3149526	Ampuyenta	Malo
12	600764	3159727	La Matilla	Malo
13	603998	3151894	Tesjuates	Bueno
14	599225	3149951	Ampuyenta	Bueno
15	601810	3152101	Casillas del Ángel	Decorativo
16	606905	3152355	Zurita	Bueno
17	595375	3149985	Llanos de la Concepción	Decorativo
18	598889	3156087	Tefía	Decorativo
19	600140	3159422	Tefía	Bueno
20	603736	3151838	Tesjuates	Bueno
21	605399	3150458	Goroy	Bueno
22	600516	3151781	Casillas del Ángel	Decorativo
23	601432	3148400	Rosa del Taro	Malo
24	598103	3158043	Tefía	Malo

Aeromotores del término municipal de PÁJARA				
Nº	**X**	**Y**	**LOCALIDAD**	**ESTADO**
1	587242	3140477	Mézquez-Buen Paso	Bueno

2	587188	3140365	Mézquez-Buen Paso	Bueno
3	587084	3140422	Mézquez-Buen Paso	Bueno
4	580690	3125681	Chilegua	Malo
5	579861	3125730	Chilegua	Malo
6	559222	3104132	Jandía-Jorós	Malo
7	583314	3131585	Fayagua	Bueno
8	583144	3137013	Garcey	Malo
9	579997	3123480	Las Hermosas	Malo
10	588465	3136779	Pájara	Bueno
11	583678	3121746	Tarajal de Sancho	Malo
12	583282	3121194	Tarajal de Sancho	Malo
13	582991	3119793	Tarajal de Sancho	Malo
14	582926	3118800	Tarajal de Sancho	Malo
15	589494	3137228	Toto	Bueno
16	589532	3137318	Toto	Malo
17	589516	3137104	Toto	Regular
18	589419	3137127	Toto	Regular
19	589456	3137194	Toto	Malo
20	590178	3136652	Toto	Malo
21	590345	3136976	Cortijo de Tetui	Malo
22	590081	3136692	Cortijo de Tetui	Malo
23	583616	3123467	Valle de La Lajita	Regular
24	584427	3126976	Cardón	Regular
25	584346	3126912	Cardón	Regular
26	582906	3122905	Valle de La Lajita	Regular
27	582993	3121688	Valle de La Lajita	Regular
28	583059	3119529	Valle de La Lajita	Bueno
29	582993	3119584	Valle de La Lajita	Malo
30	585876	3139322	Ajuy	Bueno
31	588132	3136465	Pájara	Regular
32	588362	3136327	Pájara	Regular

ANNEX 2 Location data

La Oliva - recurso eólico a 40 mde altura (datos de GRAFCAN)						
Nº	**Coordenadas UTM**	**Localidad**	**Rugosidad**	**V_{media} (m/s)**	**C**	**K**
1	X: 614232 Y: 3180195	Isla de Lobos	0,01	5,12	5,75	2,581
Betancuria - recurso eólico a 40 mde altura (datos de GRAFCAN)						
Nº	**Coordenadas UTM**	**Localidad**	**Rugosidad**	**V_{media} (m/s)**	**C**	**K**
1	X: 591351 Y: 3140261	Vega del Río Palmas	0,1	4,88	5,41	2,837
2	X: 590742 Y: 3141124	Vega del Río Palmas	0,1	4,85	5,38	2,865
3	X: 590854 Y: 3141190	Vega del Río Palmas	0,1	4,89	5,43	2,864
4	X: 593179 Y: 3148117	Valle de Santa Inés	0,1	4,93	5,49	2,878
5	X: 591335 Y: 3140304	Betancuria	0,1	5,03	5,58	2,84
6	X: 592757 Y: 3147565	Valle de Santa Inés	0,1	4,92	5,47	2,89
7	X: 592522 Y: 3147230	Valle de Santa Inés	0,1	4,88	5,42	2,896
8	X: 590015 Y: 3141027	Vega de Río Palmas	0,1	5,06	5,61	2,864
9	X: 589815 Y: 3141027	Vega de Río Palmas	0,1	5,26	5,83	2,865
Antigua - recurso eólico a 40 mde altura (datos de GRAFCAN)						
Nº	**Coordenadas UTM**	**Localidad**	**Rugosidad**	**V_{media} (m/s)**	**C**	**K**
1	X: 602624 Y: 3144234	Triquivijate	0,1	5,39	5,98	2,843
2	X: 595753 Y: 3141302	Valles de Ortega	0,1	5,57	6,18	2,84
3	X: 596492 Y: 3141033	Valles de Ortega	0,1	5,36	5,95	2,834
4	X: 595489 Y: 3143809	El Carbón	0,1	5,22	5,79	2,872
5	X: 595312 Y: 3143697	El Carbón	0,1	5,26	5,84	2,871
6	X: 595639 Y: 3143173	Antigua	0,1	5,21	5,79	2,865
7	X: 596499 Y: 3143802	Antigua	0,1	4,62	5,13	2,873
8	X: 595175 Y: 3138417	Agua de Bueyes	0,1	6,25	6,93	2,791
9	X: 594537 Y: 3145664	El Durazno	0,1	5,22	5,8	2,891
10	X: 594537 Y: 3145791	El Durazno	0,1	5,27	5,86	2,89
11	X: 602377 Y: 3130655	Tenicosquey	0,1	5,5	6,07	2,626
12	X: 597221 Y: 3139791	Valles de Ortega	0,1	5,52	6,12	2,802
13	X: 597908 Y: 3141651	Majada Blanca	0,1	5,29	5,88	2,848
14	X: 598856 Y: 3141138	Majada Blanca	0,1	5,37	5,96	2,836
Tuineje - recurso eólico a 40 mde altura (datos de GRAFCAN)						
Nº	**Coordenadas UTM**	**Localidad**	**Rugosidad**	**V_{media} (m/s)**	**C**	**K**
1	X: 592034 Y: 3128295	Juan Gopar	0,1	5,53	6,12	2,624
2	X: 595759 Y: 3125530	Juan Gopar	0,1	5,36	5,94	2,589
3	X: 595788 Y: 3124413	Juan Gopar	0,1	5,27	5,82	2,554
4	X: 590707 Y: 3123372	Cañada del Moro	0,1	5,14	5,67	2,583
5	X: 590047 Y: 3123669	Cañada del Moro	0,1	4,53	5,01	2,586
6	X: 596642 Y: 3123029	Gran Tarajal	0,1	5,44	6,01	2,549
7	X: 596299 Y: 3124041	La Fuentita	0,1	5,29	5,84	2,552
8	X: 596698 Y: 3123878	Gran Tarajal	0,1	5,36	5,93	2,55
9	X: 599464 Y: 3123350	Las Playitas	0,1	5,51	6,1	2,548
10	X: 599614 Y: 3123318	Las Playitas	0,75	4,9	5,42	2,548

11	X: 599739 Y: 3123126	Las Playitas	0,75	4,97	5,5	2,542
12	X: 586820 Y: 3119991	Tarajalejo	0,1	4,69	5,18	2,58
13	X: 597729 Y: 3125978	Tequital-La Mata	0,1	5,69	6,31	2,564
14	X: 598475 Y: 3127862	Tequital	0,1	5,9	6,53	2,581
15	X: 598071 Y: 3127966	Tequital	0,05	5,9	6,53	2,586
16	X: 586738 Y: 3129021	Tesejerague	0,1	5,27	5,83	2,654
17	X: 586363 Y: 3129348	Tesejerague	0,1	5,16	5,7	2,661
18	X: 588583 Y: 3127058	Tirba	0,1	5,62	6,21	2,605
19	X: 590563 Y: 3126964	Tirba	0,1	5,47	6,05	2,598
20	X: 595794 Y: 3135906	Tiscamanita	0,1	5,65	6,26	2,757
21	X: 593712 Y: 3137225	Tuineje	0,1	6,02	6,67	2,782
22	X: 593367 Y: 3137352	Tuineje	0,1	5,74	6,37	2,783
23	X: 593283 Y: 3137430	Tuineje	0,1	5,59	6,2	2,784
24	X: 593075 Y: 3133441	Tuineje	0,1	5,4	5,99	2,711
25	X: 593184 Y: 3133394	Tuineje	0,1	5,35	5,94	2,71
26	X: 593249 Y: 3133312	Tuineje	0,1	5,41	5,99	2,708
27	X: 590560 Y: 3125636	Violante	0,1	5,05	5,58	2,591
28	X: 590404 Y: 3127634	Violante	0,1	5,39	5,96	2,607
29	X: 594437 Y: 3134579	Tiscamanita	0,1	6	6,65	2,706
30	X: 593695 Y: 3137323	Tiscamanita	0,1	6,01	6,67	2,783
31	X: 587244 Y: 3127994	Tesejerague	0,1	5,74	6,34	2,632
32	X: 587547 Y: 3126416	Tesejerague	0,1	5,33	5,89	2,607
33	X: 586680 Y: 3126523	Tirba	0,1	5,31	5,87	2,619
34	X: 586533 Y: 3126618	Tirba	0,1	5,25	5,8	2,621
35	X: 586472 Y: 3126690	Tirba	0,1	5,3	5,86	2,622
36	X: 586478 Y: 3126848	Tirba	0,1	5,23	5,78	2,624
37	X: 586674 Y: 3126883	Tirba	0,1	5,25	5,8	2,622
38	X: 586578 Y: 3127020	Tirba	0,1	5,14	5,68	2,625
39	X: 590014 Y: 3127560	Tirba	0,1	5,17	5,71	2,604
40	X: 589694 Y: 3127621	Tirba	0,1	5,21	5,76	2,61
41	X: 590351 Y: 3125576	Tirba	0,1	5,09	5,62	2,59
42	X: 590313 Y: 3123377	Giniginamar	0,1	4,76	5,26	2,584
43	X: 590673 Y: 3122511	Giniginamar	0,1	4,77	5,26	2,578
44	X: 588935 Y: 3123944	Tarajalejo	0,1	4,9	5,42	2,589
45	X: 596880 Y: 3122568	Gran Tarajal	0,1	5,53	6,1	2,546
46	X: 596161 Y: 3126111	Gran Tarajal	0,1	5,45	6,03	2,587
47	X: 597674 Y: 3127481	Tequital	0,1	5,8	6,43	2,582
48	X: 594448 Y: 3136021	Tiscamanita	0,1	6,26	6,93	2,77
49	X: 584381 Y: 3126005	Cruce de Cardón	0,1	5,24	5,78	2,635
50	X: 587634 Y: 3123686	Cardón	0,1	5,23	5,77	2,589
Puerto del Rosario - recurso eólico a 40 mde altura (datos de GRAFCAN)						
Nº	**Coordenadas UTM**	**Localidad**	**Rugosidad**	**V_{media} (m/s)**	**C**	**K**
1	X: 599066 Y: 3159106	Tefía	0,01	5,71	6,42	2,836
2	X: 599746 Y: 3156272	Tefía	0,1	5,22	5,86	2,869

3	X: 595148 Y: 3149732	Llanos de la Concepción	0,1	4,92	5,48	2,859
4	X: 610640 Y: 3146359	El Matorral	0,1	5,58	6,16	2,77
5	X: 603998 Y: 3151894	Tesjuates	0,1	4,9	5,46	2,858
6	X: 599225 Y: 3149951	Ampuyenta	0,1	6,06	6,77	2,871
7	X: 606905 Y: 3152355	Zurita	0,1	5,7	6,34	2,856
8	X: 600140 Y: 3159422	Tefía	0,1	5,6	6,3	2,865
9	X: 603736 Y: 3151838	Tesjuates	0,1	4,98	5,55	2,859
10	X: 605399 Y: 3150458	Goroy	0,1	5,32	5,91	2,847

Pájara - recurso eólico a 40 mde altura (datos de GRAFCAN)						
Nº	**Coordenadas UTM**	**Localidad**	**Rugosidad**	**V_{media} (m/s)**	**C**	**K**
1	X: 587242 Y: 3140477	Mézquez-Buen Paso	0,1	4,28	4,73	2,808
2	X: 587188 Y: 3140365	Mézquez-Buen Paso	0,1	4,48	4,95	2,805
3	X: 587084 Y: 3140422	Mézquez-Buen Paso	0,1	4,31	4,76	2,805
4	X: 583314 Y: 3131585	Fayagua	0,1	4,72	5,2	2,701
5	X: 588465 Y: 3136779	Pájara	0,1	5,64	6,26	2,76
6	X: 589494 Y: 3137228	Toto	0,1	5,35	5,93	2,762
7	X: 583059 Y: 3119529	Valle de La Lajita	0,1	4,7	5,19	2,581
8	X: 585876 Y: 3139322	Ajuy	0,1	5,01	5,53	2,776

ANNEX 3 Difference between GRAFCAN speed and calculated speed

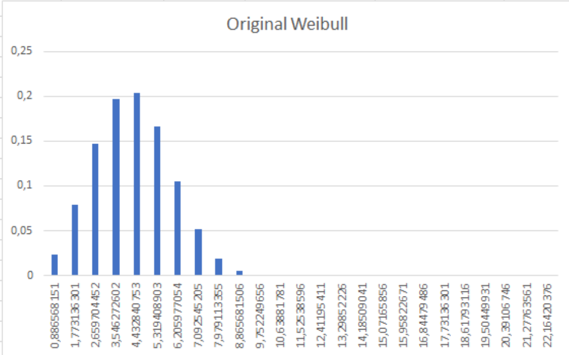
District	Rugosity	V_{medium} (m/s)	C	K	$V_{weibull}$ (m/s)	Error
Isla de Lobos	0,01	5,12	5,75	2,58	5,1	-0,39%
Vega del Río Palmas	0,1	4,88	5,41	2,58	4,8	-1,64%
Vega del Río Palmas	0,1	4,85	5,38	2,58	4,8	-1,03%
Vega del Río Palmas	0,1	4,89	5,43	2,58	4,8	-1,84%
Valle de Santa Inés	0,1	4,93	5,49	2,58	4,9	-0,61%
Betancuria	0,1	5,03	5,58	2,58	5,0	-0,60%
Valle de Santa Inés	0,1	4,92	5,47	2,58	4,9	-0,41%
Valle de Santa Inés	0,1	4,88	5,42	2,58	4,8	-1,64%
Vega de Río Palmas	0,1	5,06	5,61	2,58	5,0	-1,19%
Vega de Río Palmas	0,1	5,26	5,83	2,58	5,2	-1,14%
Triquivijate	0,1	5,39	5,98	2,58	5,3	-1,67%
Valles de Ortega	0,1	5,57	6,18	2,58	5,5	-1,26%
Valles de Ortega	0,1	5,36	5,95	2,58	5,3	-1,12%
El Carbón	0,1	5,22	5,79	2,58	5,1	-2,30%
El Carbón	0,1	5,26	5,84	2,58	5,2	-1,14%
Antigua	0,1	5,21	5,79	2,58	5,1	-2,11%
Antigua	0,1	4,62	5,13	2,58	4,6	-0,43%
Agua de Bueyes	0,1	6,25	6,93	2,58	6,2	-0,80%
El Durazno	0,1	5,22	5,8	2,58	5,2	-0,38%
El Durazno	0,1	5,27	5,86	2,58	5,2	-1,33%
Tenicosquey	0,1	5,5	6,07	2,58	5,4	-1,82%
Valles de Ortega	0,1	5,52	6,12	2,58	5,4	-2,17%
Majada Blanca	0,1	5,29	5,88	2,58	5,2	-1,70%
Majada Blanca	0,1	5,37	5,96	2,58	5,3	-1,30%
Juan Gopar	0,1	5,53	6,12	2,58	5,4	-2,35%
Juan Gopar	0,1	5,36	5,94	2,58	5,3	-1,12%
Juan Gopar	0,1	5,27	5,82	2,58	5,2	-1,33%
Cañada del Moro	0,1	5,14	5,67	2,58	5,0	-2,72%
Cañada del Moro	0,1	4,53	5,01	2,58	4,4	-2,87%
Gran Tarajal	0,1	5,44	6,01	2,58	5,3	-2,57%
La Fuentita	0,1	5,29	5,84	2,58	5,2	-1,70%
Gran Tarajal	0,1	5,36	5,93	2,58	5,3	-1,12%
Las Playitas	0,1	5,51	6,1	2,58	5,4	-2,00%
Las Playitas	0,75	4,9	5,42	2,58	4,8	-2,04%
Las Playitas	0,75	4,97	5,5	2,58	4,9	-1,41%
Tarajalejo	0,1	4,69	5,18	2,58	4,6	-1,92%
Tequital-La Mata	0,1	5,69	6,31	2,58	5,6	-1,58%
Tequital	0,1	5,9	6,53	2,58	5,8	-1,69%
Tequital	0,05	5,9	6,53	2,58	5,8	-1,69%
Tesejerague	0,1	5,27	5,83	2,58	5,2	-1,33%
Tesejerague	0,1	5,16	5,7	2,58	5,1	-1,16%
Tirba	0,1	5,62	6,21	2,58	5,5	-2,14%

Tirba	0,1	5,47	6,05	2,58	5,4	-1,28%
Tiscamanita	0,1	5,65	6,26	2,58	5,6	-0,88%
Tuineje	0,1	6,02	6,67	2,58	5,9	-1,99%
Tuineje	0,1	5,74	6,37	2,58	5,7	-0,70%
Tuineje	0,1	5,59	6,2	2,58	5,5	-1,61%
Tuineje	0,1	5,4	5,99	2,58	5,3	-1,85%
Tuineje	0,1	5,35	5,94	2,58	5,3	-0,93%
Tuineje	0,1	5,41	5,99	2,58	5,3	-2,03%
Violante	0,1	5,05	5,58	2,58	5,0	-0,99%
Violante	0,1	5,39	5,96	2,58	5,3	-1,67%
Tiscamanita	0,1	6	6,65	2,58	5,9	-1,67%
Tiscamanita	0,1	6,01	6,67	2,58	5,9	-1,83%
Tesejerague	0,1	5,74	6,34	2,58	5,6	-2,44%
Tesejerague	0,1	5,33	5,89	2,58	5,2	-2,44%
Tirba	0,1	5,31	5,87	2,58	5,2	-2,07%
Tirba	0,1	5,25	5,8	2,58	5,2	-0,95%
Tirba	0,1	5,3	5,86	2,58	5,2	-1,89%
Tirba	0,1	5,23	5,78	2,58	5,1	-2,49%
Tirba	0,1	5,25	5,8	2,58	5,2	-0,95%
Tirba	0,1	5,14	5,68	2,58	5,0	-2,72%
Tirba	0,1	5,17	5,71	2,58	5,1	-1,35%
Tirba	0,1	5,21	5,76	2,58	5,1	-2,11%
Tirba	0,1	5,09	5,62	2,58	5,0	-1,77%
Giniginamar	0,1	4,76	5,26	2,58	4,7	-1,26%
Giniginamar	0,1	4,77	5,26	2,58	4,7	-1,47%
Tarajalejo	0,1	4,9	5,42	2,58	4,8	-2,04%
Gran Tarajal	0,1	5,53	6,1	2,58	5,4	-2,35%
Gran Tarajal	0,1	5,45	6,03	2,58	5,4	-0,92%
Tequital	0,1	5,8	6,43	2,58	5,7	-1,72%
Tiscamanita	0,1	6,26	6,93	2,58	6,2	-0,96%
Cruce de Cardón	0,1	5,24	5,78	2,58	5,1	-2,67%
Cardón	0,1	5,23	5,77	2,58	5,1	-2,49%
Tefía	0,01	5,71	6,42	2,58	5,7	-0,18%
Tefía	0,1	5,22	5,86	2,58	5,2	-0,38%
Llanos de la Concepción	0,1	4,92	5,48	2,58	4,9	-0,41%
El Matorral	0,1	5,58	6,16	2,58	5,5	-1,43%
Tesjuates	0,1	4,9	5,46	2,58	4,8	-2,04%
Ampuyenta	0,1	6,06	6,77	2,58	6,0	-0,99%
Zurita	0,1	5,7	6,34	2,58	5,6	-1,75%
Tefía	0,1	5,6	6,3	2,58	5,6	0,00%
Tesjuates	0,1	4,98	5,55	2,58	4,9	-1,61%
Goroy	0,1	5,32	5,91	2,58	5,2	-2,26%
Mézquez-Buen Paso	0,1	4,28	4,73	2,58	4,2	-1,87%
Mézquez-Buen Paso	0,1	4,48	4,95	2,58	4,4	-1,79%
Mézquez-Buen Paso	0,1	4,31	4,76	2,58	4,2	-2,55%

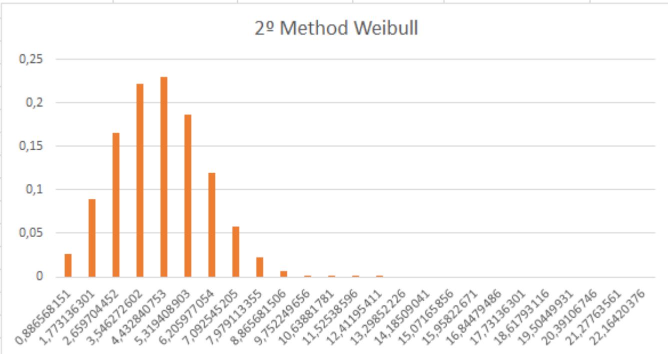
Fayagua	0,1	4,72	5,2	2,58	4,6	-2,54%
Pájara	0,1	5,64	6,26	2,58	5,6	-0,71%
Toto	0,1	5,35	5,93	2,58	5,3	-0,93%
Valle de La Lajita	0,1	4,7	5,19	2,58	4,6	-2,13%
Ajuy	0,1	5,01	5,53	2,58	4,9	-2,20%

ANNEX 4 Calculation of error respect to roughness

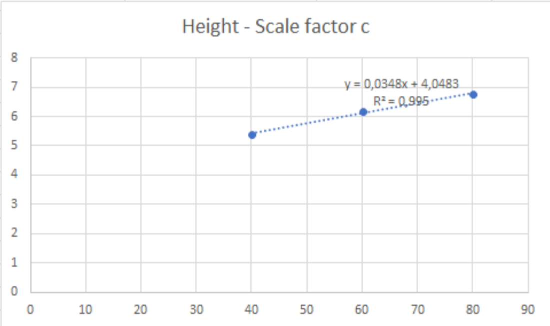
Weibull distribution with speeds corrected to 12 m, scale factor to 40 m and shape factor to 40 m		
Vwind 40m (m/s)	Vwind 12m (m/s)	Weibull
1	0,886568151	0,023397371
2	1,773136301	0,07942633
3	2,659704452	0,147137827
4	3,546272602	0,196955648
5	4,432840753	0,203941286
6	5,319408903	0,165848638
7	6,205977054	0,10547272
8	7,092545205	0,051784088
9	7,979113355	0,0192938
10	8,865681506	0,005349822
11	9,752249656	0,001081273
12	10,63881781	0,000155906
13	11,52538596	1,56892E-05
14	12,41195411	1,07779E-06
15	13,29852226	4,94319E-08
16	14,18509041	1,48033E-09
17	15,07165856	2,83102E-11
18	15,95822671	3,38172E-13
19	16,84479486	2,46809E-15
20	17,73136301	1,07665E-17
21	18,61793116	2,74655E-20
22	19,50449931	4,00915E-23
23	20,39106746	3,27701E-26
24	21,27763561	1,46798E-29
25	22,16420376	3,52764E-33

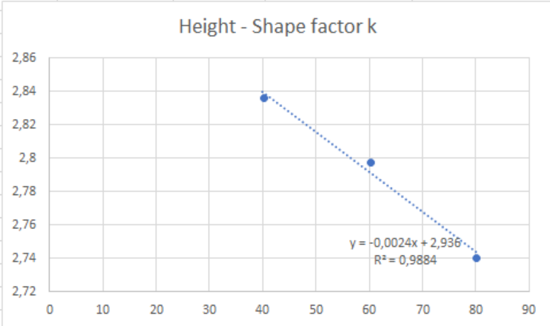


Weibull distribution with speeds corrected to 12 m, scale factor corrected to 12 m and shape factor to 40 m	
Scale factor corrected to 12 m	4,796333695
Vwind 12m (m/s)	Weibull
0,886568151	0,026390945
1,773136301	0,089588522
2,659704452	0,165963358
3,546272602	0,222155114
4,432840753	0,230034528
5,319408903	0,187068121
6,205977054	0,118967414
7,092545205	0,058409596
7,979113355	0,021762342
8,865681506	0,006034304
9,752249656	0,001219617
10,63881781	0,000175853
11,52538596	1,76965E-05
12,41195411	1,21569E-06
13,29852226	5,57565E-08
14,18509041	1,66974E-09
15,07165856	3,19324E-11
15,95822671	3,81439E-13
16,84479486	2,78387E-15
17,73136301	1,2144E-17
18,61793116	3,09795E-20
19,50449931	4,5221E-23
20,39106746	3,69629E-26
21,27763561	1,6558E-29
22,16420376	3,97898E-33



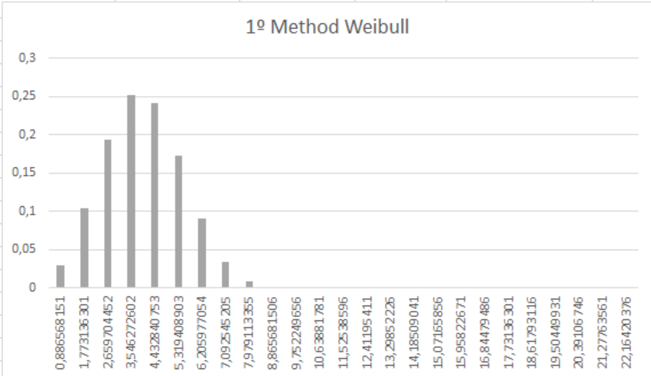
Height	40	60	80	12
Rugosity	0,1	0,1	0,1	0,1
C	5,41	6,19	6,8	4,4659
K	2,837	2,798	2,741	2,9072





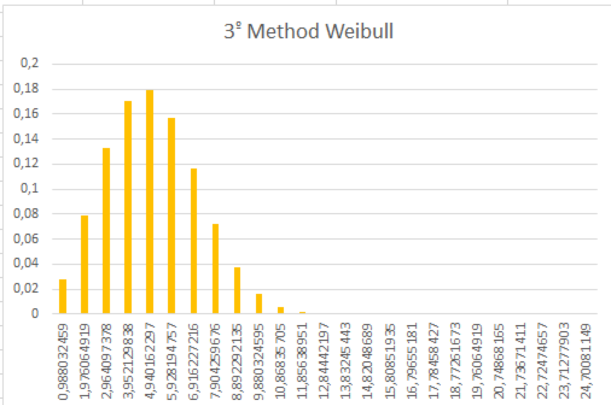
Weibull distribution with speeds corrected to 12 m, scale factor and corrected to 12 m by linear interpolation

Vwind a 12m (m/s)	
0,886568151	0,029538486
1,773136301	0,104434848
2,659704452	0,194107363
3,546272602	0,251434345
4,432840753	0,24121133
5,319408903	0,172315182
6,205977054	0,090307014
7,092545205	0,033896115
7,979113355	0,008854589
8,865681506	0,001560443
9,752249656	0,000179571
10,63881781	1,30503E-05
11,52538596	5,78983E-07
12,41195411	1,51538E-08
13,29852226	2,26083E-10
14,18509041	1,85762E-12
15,07165856	8,12156E-15
15,95822671	1,82547E-17
16,84479486	2,0382E-20
17,73136301	1,09237E-23
18,61793116	2,71579E-27
19,50449931	3,02701E-31
20,39106746	1,46201E-35
21,27763561	2,95787E-40
22,16420376	2,42333E-45



Weibull distribution with speeds corrected to 12 m, scale factor corrected to 12 m and shape factor to 40 m, including error correction

Scale factor corrected to 12 m	5,681186642	
Vwind 12m (m/s)	Weibull + Error	Error = 1,0444*R^2+1,1719*R+1,0005
0,988032459	0,02794091	
1,976064919	0,079154568	
2,964097378	0,13314192	
3,952129838	0,170858425	
4,940162297	0,179179845	
5,928194757	0,157229122	
6,916227216	0,11628477	
7,904259676	0,072491961	
8,892292135	0,037960041	
9,880324595	0,016607884	
10,86835705	0,006032391	
11,85638951	0,001806524	
12,84442197	0,00044283	
13,83245443	8,81996E-05	
14,82048689	1,41679E-05	
15,80851935	1,82192E-06	
16,79655181	1,8618E-07	
17,78458427	1,50087E-08	
18,77261673	9,47585E-10	
19,76064919	4,65217E-11	
20,74868165	1,76357E-12	
21,73671411	5,1264E-14	
22,72474657	1,13484E-15	
23,71277903	1,90029E-17	
24,70081149	2,39097E-19	



Nº	UTM Coordinates	District	Rugosity
1	X: 614232 Y: 3180195	Isla de Lobos	0,01
Weibull distribution with speeds corrected at 12 m, scale factor corrected at 12 m			
and shape factor at 40 m			
Scaled factor corrected to 12 m		5,681186642	
Vwind 12m (m/s)	Weibull (Calculated)	Weibull (Original)	Error (%)
0,988032459	0,028285238	0,027946733	1,2112%
1,976064919	0,080130024	0,079171065	1,2112%
2,964097378	0,134782686	0,133169669	1,2112%
3,952129838	0,172963988	0,170894035	1,2112%
4,940162297	0,181387957	0,17921719	1,2112%
5,928194757	0,159166725	0,157261891	1,2112%
6,916227216	0,117717798	0,116309006	1,2112%
7,904259676	0,073385311	0,072507069	1,2112%
8,892292135	0,038427839	0,037967952	1,2112%
9,880324595	0,016812551	0,016611346	1,2112%
10,86835705	0,006106731	0,006033648	1,2112%
11,85638951	0,001828787	0,001806901	1,2112%
12,84442197	0,000448287	0,000442923	1,2112%
13,83245443	8,92865E-05	8,82179E-05	1,2112%
14,82048689	1,43425E-05	1,41708E-05	1,2112%
15,80851935	1,84437E-06	1,8223E-06	1,2112%
16,79655181	1,88475E-07	1,86219E-07	1,2112%
17,78458427	1,51937E-08	1,50118E-08	1,2112%
18,77261673	9,59262E-10	9,47782E-10	1,2112%
19,76064919	4,7095E-11	4,65313E-11	1,2112%
20,74868165	1,78531E-12	1,76394E-12	1,2112%
21,73671411	5,18957E-14	5,12746E-14	1,2112%
22,72474657	1,14882E-15	1,13507E-15	1,2112%

Nº	UTM Coordinates	District	Rugosity
75	X: 599066 Y: 3159106	Tefía	0,01
Weibull distribution with speeds corrected at 12 m, scale factor corrected at 12 m and shape factor at 40 m			
Scaled factor corrected to 12 m		6,34316839	
Viento a 12m (m/s)	Weibull (Calculated)	Weibull (Original)	Error (%)
0,988032459	0,014639937	0,014464733	1,2112%
1,976064919	0,050647613	0,050041486	1,2112%
2,964097378	0,098527432	0,097348301	1,2112%
3,952129838	0,144421487	0,142693117	1,2112%
4,940162297	0,172715222	0,170648246	1,2112%
5,928194757	0,172974511	0,170904431	1,2112%
6,916227216	0,145995705	0,144248495	1,2112%
7,904259676	0,103583825	0,102344181	1,2112%
8,892292135	0,061341464	0,060607357	1,2112%
9,880324595	0,030029859	0,029670476	1,2112%
10,86835705	0,012019308	0,011875467	1,2112%
11,85638951	0,003886308	0,003839799	1,2112%
12,84442197	0,00100252	0,000990522	1,2112%
13,83245443	0,000203688	0,00020125	1,2112%
14,82048689	3,21723E-05	3,17873E-05	1,2112%
15,80851935	3,8987E-06	3,85205E-06	1,2112%
16,79655181	3,57705E-07	3,53424E-07	1,2112%
17,78458427	2,45208E-08	2,42274E-08	1,2112%
18,77261673	1,23933E-09	1,2245E-09	1,2112%
19,76064919	4,5575E-11	4,50296E-11	1,2112%
20,74868165	1,20342E-12	1,18902E-12	1,2112%
21,73671411	2,25183E-14	2,22488E-14	1,2112%
22,72474657	2,94704E-16	2,91177E-16	1,2112%

Nº	UTM Coordinates	District	Rugosity
39	X: 598071 Y: 3127966	Tequital	0,05
Weibull distribution with speeds corrected at 12 m, scale factor corrected at 12 m and shape factor at 40 m			
Scaled factor corrected to 12 m		6,148500943	
Vwind 12m (m/s)	Weibull (Calculated)	Weibull (Original)	Error (%)
0,94157748	0,021282138	0,020038782	6,2047%
1,88315496	0,061443456	0,057853775	6,2047%
2,82473244	0,107154598	0,100894356	6,2047%
3,766309919	0,145880345	0,137357648	6,2047%
4,707887399	0,166811065	0,157065542	6,2047%
5,649464879	0,164680132	0,155059103	6,2047%
6,591042359	0,141881308	0,133592245	6,2047%
7,532619839	0,107032554	0,100779442	6,2047%
8,474197319	0,070668192	0,066539578	6,2047%
9,415774799	0,040735761	0,038355875	6,2047%
10,35735228	0,020426456	0,019233091	6,2047%
11,29892976	0,00887157	0,008353271	6,2047%
12,24050724	0,003321598	0,003127542	6,2047%
13,18208472	0,001066789	0,001004465	6,2047%
14,1236622	0,000292404	0,000275321	6,2047%
15,06523968	6,80489E-05	6,40734E-05	6,2047%
16,00681716	1,33765E-05	1,2595E-05	6,2047%
16,94839464	2,20954E-06	2,08045E-06	6,2047%
17,88997212	3,05115E-07	2,8729E-07	6,2047%
18,8315496	3,50437E-08	3,29964E-08	6,2047%
19,77312708	3,33077E-09	3,13618E-09	6,2047%
20,71470456	2,60671E-10	2,45442E-10	6,2047%
21,65628204	1,67149E-11	1,57383E-11	6,2047%

Nº	UTM Coordinates	District	Rugosity
2	X: 591351 Y: 3140261	Vega del Río Palmas	0,10
Weibull distribution with speeds corrected at 12 m, scale factor corrected at 12 m			
and shape factor at 40 m			
Scaled factor corrected to 12 m		4,796333695	
Vwind 12m (m/s)	Weibull (Calculated)	Weibull (Original)	Error (%)
0,886568151	0,026390945	0,023397371	12,7945%
1,773136301	0,089588522	0,07942633	12,7945%
2,659704452	0,165963358	0,147137827	12,7945%
3,546272602	0,222155114	0,196955648	12,7945%
4,432840753	0,230034528	0,203941286	12,7945%
5,319408903	0,187068121	0,165848638	12,7945%
6,205977054	0,118967414	0,10547272	12,7945%
7,092545205	0,058409596	0,051784088	12,7945%
7,979113355	0,021762342	0,0192938	12,7945%
8,865681506	0,006034304	0,005349822	12,7945%
9,752249656	0,001219617	0,001081273	12,7945%
10,63881781	0,000175853	0,000155906	12,7945%
11,52538596	1,76965E-05	1,56892E-05	12,7945%
12,41195411	1,21569E-06	1,07779E-06	12,7945%
13,29852226	5,57565E-08	4,94319E-08	12,7945%
14,18509041	1,66974E-09	1,48033E-09	12,7945%
15,07165856	3,19324E-11	2,83102E-11	12,7945%
15,95822671	3,81439E-13	3,38172E-13	12,7945%
16,84479486	2,78387E-15	2,46809E-15	12,7945%
17,73136301	1,2144E-17	1,07665E-17	12,7945%
18,61793116	3,09795E-20	2,74655E-20	12,7945%
19,50449931	4,5221E-23	4,00915E-23	12,7945%
20,39106746	3,69629E-26	3,27701E-26	12,7945%

Nº	UTM Coordinates	District	Rugosity
3	X: 590742 Y: 3141124	Vega del Río Palmas	0,10
Weibull distribution with speeds corrected at 12 m, scale factor corrected at 12 m and shape factor at 40 m			
Scaled factor corrected to 12 m		4,76973665	
Vwind 12m (m/s)	Weibull (Calculated)	Weibull (Original)	Error (%)
0,886568151	0,02583575	0,022905153	12,7945%
1,773136301	0,089462699	0,07931478	12,7945%
2,659704452	0,167522621	0,14852022	12,7945%
3,546272602	0,225312285	0,199754696	12,7945%
4,432840753	0,232926924	0,206505592	12,7945%
5,319408903	0,187659218	0,166372686	12,7945%
6,205977054	0,117117654	0,103832782	12,7945%
7,092545205	0,055785665	0,049457794	12,7945%
7,979113355	0,019892387	0,017635957	12,7945%
8,865681506	0,005196219	0,004606803	12,7945%
9,752249656	0,00097164	0,000861425	12,7945%
10,63881781	0,000126993	0,000112588	12,7945%
11,52538596	1,13228E-05	1,00384E-05	12,7945%
12,41195411	6,71982E-07	5,95758E-07	12,7945%
13,29852226	2,58983E-08	2,29606E-08	12,7945%
14,18509041	6,32343E-10	5,60615E-10	12,7945%
15,07165856	9,54256E-12	8,46013E-12	12,7945%
15,95822671	8,68338E-14	7,69841E-14	12,7945%
16,84479486	4,64875E-16	4,12143E-16	12,7945%
17,73136301	1,42873E-18	1,26667E-18	12,7945%
18,61793116	2,45992E-21	2,18088E-21	12,7945%
19,50449931	2,31564E-24	2,05297E-24	12,7945%
20,39106746	1,16326E-27	1,03131E-27	12,7945%

Nº	UTM Coordinates	District	Rugosity
34	X: 599614 Y: 3123318	Las Playitas	0,75
Weibull distribution with speeds corrected at 12 m, scale factor corrected at 12 m and shape factor at 40 m			
Scaled factor corrected to 12 m		2,197051452	
Vwind 12m (m/s)	Weibull (Calculated)	Weibull (Original)	Error (%)
0,405360046	0,083612832	0,033893301	146,6943%
0,810720093	0,229023054	0,092836796	146,6943%
1,216080139	0,371957561	0,150776734	146,6943%
1,621440186	0,456933628	0,185222636	146,6943%
2,026800232	0,453439828	0,18380639	146,6943%
2,432160279	0,371533419	0,150604804	146,6943%
2,837520325	0,252883232	0,102508759	146,6943%
3,242880372	0,14286355	0,057911175	146,6943%
3,648240418	0,066708101	0,027040799	146,6943%
4,053600464	0,02559241	0,01037414	146,6943%
4,458960511	0,008011891	0,003247701	146,6943%
4,864320557	0,002031664	0,000823556	146,6943%
5,269680604	0,00041415	0,00016788	146,6943%
5,67504065	6,73446E-05	2,72988E-05	146,6943%
6,080400697	8,66831E-06	3,51379E-06	146,6943%
6,485760743	8,76429E-07	3,55269E-07	146,6943%
6,89112079	6,90788E-08	2,80018E-08	146,6943%
7,296480836	4,21264E-09	1,70763E-09	146,6943%
7,701840882	1,97299E-10	7,9977E-11	146,6943%
8,107200929	7,04504E-12	2,85578E-12	146,6943%
8,512560975	1,90418E-13	7,71878E-14	146,6943%
8,917921022	3,86831E-15	1,56806E-15	146,6943%
9,323281068	5,86539E-17	2,3776E-17	146,6943%

Nº	UTM Coordinates	District	Rugosity
35	X: 599739 Y: 3123126	Las Playitas	0,75
Weibull distribution with speeds corrected at 12 m, scale factor corrected at 12 m and shape factor at 40 m			
Scaled factor corrected to 12 m		2,229480255	
Vwind 12m (m/s)	Weibull (Calculated)	Weibull (Original)	Error (%)
0,405360046	0,081214554	0,032921135	146,6943%
0,810720093	0,221988977	0,089985462	146,6943%
1,216080139	0,361429243	0,146508975	146,6943%
1,621440186	0,447110575	0,181240763	146,6943%
2,026800232	0,449049029	0,182026535	146,6943%
2,432160279	0,374487301	0,15180219	146,6943%
2,837520325	0,261069382	0,105827097	146,6943%
3,242880372	0,152110779	0,061659632	146,6943%
3,648240418	0,073806177	0,029918075	146,6943%
4,053600464	0,029664211	0,012024686	146,6943%
4,458960511	0,009814027	0,003978215	146,6943%
4,864320557	0,002654494	0,001076026	146,6943%
5,269680604	0,000582866	0,000236271	146,6943%
5,67504065	0,000103155	4,18149E-05	146,6943%
6,080400697	1,4609E-05	5,92189E-06	146,6943%
6,485760743	1,64376E-06	6,66314E-07	146,6943%
6,89112079	1,45901E-07	5,91423E-08	146,6943%
7,296480836	1,01443E-08	4,1121E-09	146,6943%
7,701840882	5,48683E-10	2,22414E-10	146,6943%
8,107200929	2,29289E-11	9,29444E-12	146,6943%
8,512560975	7,35327E-13	2,98072E-13	146,6943%
8,917921022	1,79778E-14	7,28747E-15	146,6943%
9,323281068	3,32899E-16	1,34944E-16	146,6943%

ANNEX 5 Power calculated by equation 4 and the power calculated with the case study method

Nº	Power (W) equation 4	Power (W) case study method	Nº	Power (W) equation 4	Power (W) case study method	Nº	Power (W) equation 4	Power (W) case study method
1	241,3	170,971	41	175,9	88,948	81	241,3	129,026
2	153,5	66,578	42	227,1	132,159	82	241,3	125,096
3	153,5	64,443	43	213,5	118,444	83	153,5	73,392
4	153,5	66,957	44	241,3	127,269	84	187,9	95,854
5	153,5	69,713	45	271,5	166,048	85	97,8	39,009
6	164,5	75,561	46	256,1	135,730	86	114,5	46,899
7	153,5	68,396	47	227,1	120,658	87	97,8	40,055
8	153,5	65,737	48	200,4	107,409	88	133,1	59,617
9	164,5	76,595	49	200,4	103,667	89	241,3	127,101
10	187,9	89,897	50	200,4	107,556	90	200,4	100,612
11	200,4	100,913	51	164,5	84,085	91	133,1	62,399
12	227,1	116,284	52	200,4	110,510	92	153,5	74,574
13	200,4	99,126	53	271,5	169,550			
14	175,9	87,115	54	271,5	165,977			
15	187,9	90,347	55	241,3	142,650			
16	175,9	87,337	56	187,9	105,033			
17	133,1	52,953	57	187,9	102,886			
18	321,2	195,645	58	187,9	97,639			
19	187,9	87,152	59	187,9	101,984			
20	187,9	91,027	60	175,9	96,067			
21	213,5	118,442	61	187,9	97,591			
22	213,5	113,238	62	164,5	89,147			
23	187,9	93,780	63	175,9	92,116			
24	200,4	99,757	64	175,9	95,316			
25	213,5	122,847	65	164,5	86,711			
26	200,4	109,936	66	143,0	65,869			
27	187,9	102,580	67	143,0	66,062			
28	164,5	90,357	68	153,5	74,462			
29	114,5	53,826	69	213,5	126,199			
30	200,4	118,136	70	213,5	117,432			
31	187,9	104,215	71	256,1	155,637			
32	200,4	111,431	72	321,2	197,403			
33	213,5	126,061	73	175,9	95,551			
34	13,2	1,486	74	175,9	97,053			
35	15,4	1,580	75	339,1	246,219			
36	133,1	61,933	76	187,9	91,723			
37	241,3	144,764	77	153,5	69,648			
38	256,1	166,540	78	227,1	118,038			
39	321,2	229,085	79	153,5	68,633			
40	187,9	98,226	80	287,4	170,847			

ANNEX 6 Regulator

Small wind inverters

ABB generator interfaces 4000/7200-WIND-INTERFACE 4 to 7.2 kW

The 4000/7200-WIND-INTERFACE rectifies and filters the alternating current, thus producing a direct current output to feed ABB small wind turbine inverters. This device is suitable for turbines that produce 20 A current maximum.

The 4000/7200-WIND-INTERFACE has the possibility to drive an external diversion load resistor (opt.) that can help the turbine in case of high wind or missing grid.

Efficiency of up to 99.4%

The 4000/7200-WIND-INTERFACE has an efficiency of up to 99.4 percent and is compatible with all ABB small wind turbine single-phase inverters.
It is a sealed unit to withstand harsh environmental conditions.

Highlights

- Three-phase passive rectification
- Fused three-phase input
- Automatic diversion load activation at 530 V

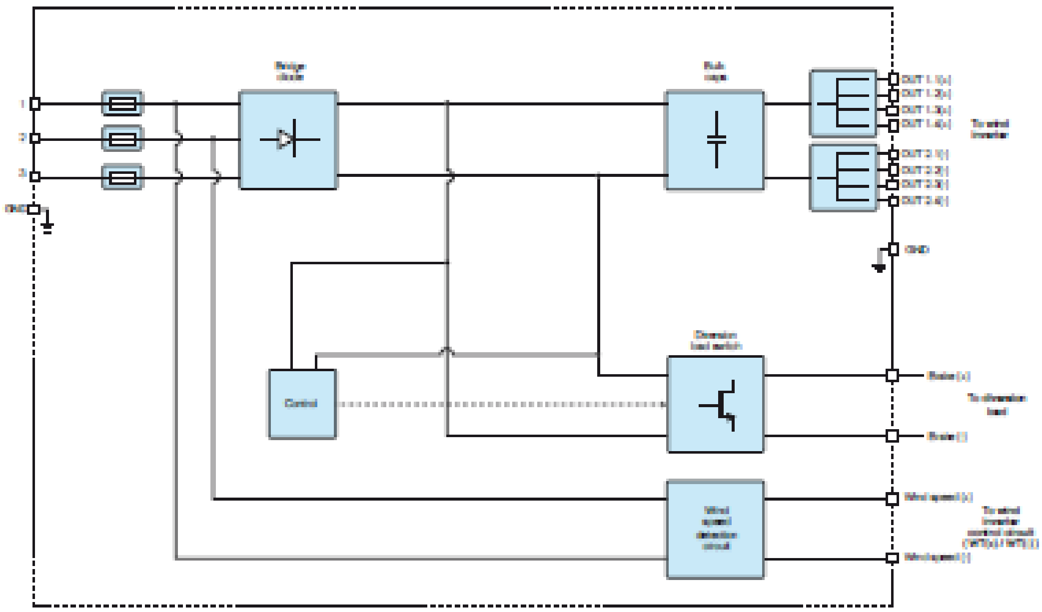
Power and productivity for a better world™ ABB

4000/7200-WIND-INTERFACE

Technical data and types

Type code	4000-WIND-INTERFACE-EU	7200-WIND-INTERFACE-EU
Input Side		
AC input voltage range (no damage) ($V_{ac,min}$...$V_{ac,max}$)	0...400 V	
Operating AC input voltage range (V_{acmin}...V_{acmax})	35...400 V	
Operating frequency range (f_{min}...f_{max})	0...500 Hz	
Maximum AC input current (I_{acmax})	16.5 A	
Voltage range in main brake resistor (V_{BRmin}...V_{BRmax})	0...600 V	
Maximum current in auxiliary brake (diversion load) resistor ($I_{BR,max}$)	5 A	15 A (20 A)
DC voltage range in auxiliary brake (diversion load) resistor (V_{BRmin}...V_{BRmax})	Fixed at 530 V	
Wiring termination	Push wire	
Input protection devices		
Overvoltage protection type	Varistors, 3	
Input fuse size	3 x 5 A	3 x 15 A (opt. 20 A)
Output side		
Maximum output power (P_{dcmax})	4 kW	7.2 kW
Output voltage range ($V_{dc,min}$...$V_{dc,max}$)	0...600 V	
Maximum output current ($I_{dc,max}$)	5 A	15 A (20 A)
Wiring termination	Push wire	
Output protection devices		
Inverter overvoltage protection type	No	

Block diagram of 4000/7200-WIND-INTERFACE

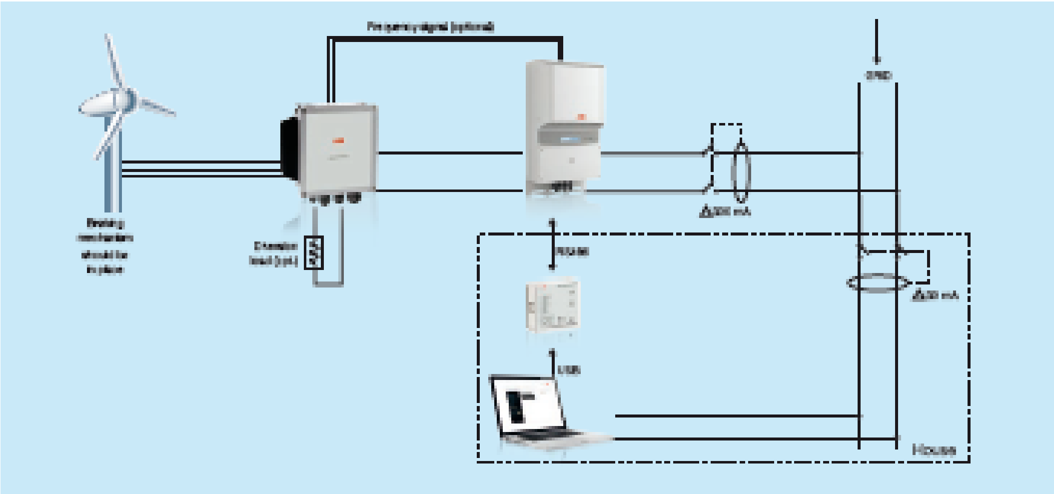


Technical data and types

Type code	4000-WIND-INTERFACE-EU	7200-WIND-INTERFACE-EU
Operating performance		
Peak efficiency (η_{peak})	99.4 %	
Stand-by consumption	< 3 W	
Environmental		
Ambient air operating temperature range	-25...+55°C (-13...131°F)	
Relative humidity	0...100 % condensing	
Acoustic noise emission level	<40 db(A)@1m	
Maximum altitude without derating	2000 m (6560 ft)	
Physical		
Enclosure rating	IP 65	
Cooling	Natural	
Dimension (H x W x D)	252 mm x 287 mm x 85.7 mm (9.9 in x 11.3 in x 3.37 in)	
Weight	1.8 kg (4.0 lb)	
Mounting system	Wall bracket	
Safety		
Safety approval	CE	
Safety and EMC standard	EN 50178, EN 61000-6-2	

Remark. Features not specifically listed in the present data sheet are not included in the product

Block diagram of 4000/7200-WIND-INTERFACE



BCD00042 EN 05.08.2014

Support and service

ABB supports its customers with a dedicated, global service organization in more than 60 countries and strong regional and national technical partner networks providing the complete range of life cycle services.

For more information please contact your local ABB representative or visit:

www.abb.com/converters-inverters

www.abb.com/windpower

Power and productivity
for a better world™

ANNEX 7 Inverter

Wind turbine converters

ABB small wind inverters
PVI-3.0/3.6/4.2-TL-OUTD-W
3 to 4.2 kW

The PVI-3.0/3.6/4.2-TL-W wind turbine inverter is designed with ABB's proven high performance technology. This dual stage transformerless wind turbine inverter offers a unique combination of high efficiency, installer-friendly design and very wide input voltage range ensuring high energy harvesting.

The high speed and precise power curve tracking algorithm allows to best match the power curve of each turbine.

Efficiency of up to 96.8%

The PVI-3.0/3.6/4.2-TL-W features an efficiency up to 96.8 percent thanks to transformerless technology.

It has power curve customization with high granularity, up to 16-point, for high production yield.

It is a sealed unit to withstand harsh environmental conditions.

Highlights

- Single phase output
- Power curve customization
- Wide input voltage range
- Transformerless technology
- Field-selectable grid standard settings

Power and productivity for a better world™ ABB

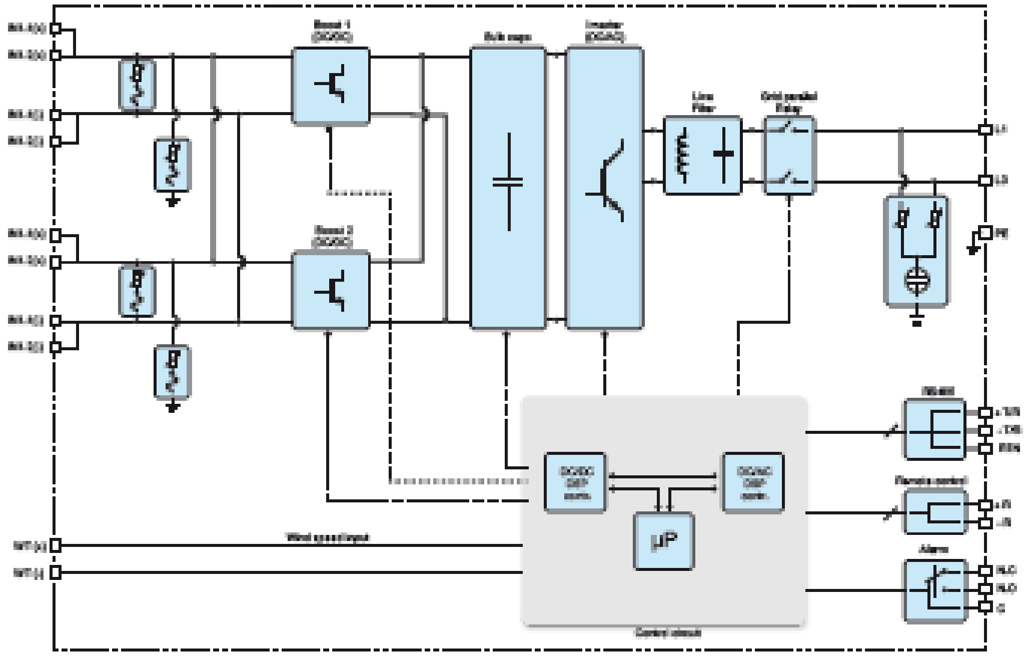
Additional highlights

- Flexible data monitoring options to view inverter performance
- Compatible with ABB 7200-WIND-INTERFACE
- Compatible with ABB 15/25kW-WIND-INTERFACE

Technical data and types

Type code	PVI-3.0-TL-OUTD-W	PVI-3.6-TL-OUTD-W	PVI-4.2-TL-OUTD-W
Input side			
Maximum absolute DC input voltage ($V_{max,abs}$)	600 V		
Operating DC input voltage range ($V_{dcmin}...V_{dcmax}$)	50...580 V		
DC input voltage range at P_{acr} ($V_{dcmin}...V_{dcmax}$)	160...520 V	120...520 V	140...520 V
Rated DC input voltage (V_{dcr})	360 V		
Dc power limitation	Linear derating from MAX to Null [530V≤Vdc≤580V]		
Maximum DC input current (I_{dcmax})	20 A	32 A	32 A
Maximum input short circuit current	25 A	40 A	40 A
DC connection type	Screw terminal block		
Input protection			
Reverse polarity protection	Yes, from limited current source		
Input over voltage protection - varistor	4		
Generator isolation control	According to local standard		
Output side			
AC grid connection	Single phase		
Rated AC power (P_{acr} @cosφ=1)	3000 W	3600 W	4200 W
Maximum AC output power (P_{acmax} @cosφ=1)	3300 W [1]	4000 W [1]	4600 W [1]
Maximum apparent power (S_{max})	3330 VA	4000 VA	4670 VA
Rated grid AC voltage (V_{acr})	230 V		
AC voltage range	180...264 V [1]		
Maximum output AC current ($I_{ac,max}$)	14.5 A	17.2 A(3)	20 A
Contributory fault current	16.0 A	19.0 A	22.0 A
Rated frequency (f_r)	50 Hz / 60 Hz		
Frequency range ($f_{min}...f_{max}$)	47...53 Hz / 57...63 Hz [2]		
Nominal power factor and adjustable range	> 0.995, adj. ± 0.9 with P_{acr} =3.0 kW	> 0.995, adj. ± 0.9 with P_{acr} =3.6 kW	> 0.995, adj. ± 0.9 with P_{acr} =4.2 kW
Total harmonic distortion	< 3.5 %		
AC connection type	Screw terminal block		
Output protection			
Anti-islanding protection	According to local standard		
Maximum AC overcurrent protection	16.0 A	19.0 A	22.0 A
Output over voltage protection - varistor	2 (L - N / L - PE)		

Block diagram of PVI-3.0/3.6/4.2-TL-OUTD-W



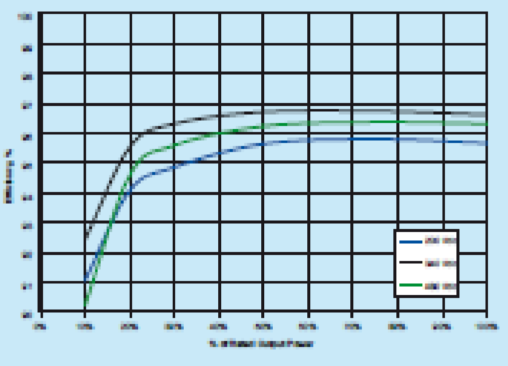
Technical data and types

Type code	PVI-3.0-TL-OUTD-W	PVI-3.6-TL-OUTD-W	PVI-4.2-TL-OUTD-W
Operating performance			
Maximum efficiency (η_{max})	96.8 %		
Stand-by consumption	< 8 W		
Feed in power threshold	10.0 W		
Communication			
Wired local monitoring	PVI-USB-RS232_485 (opt.)		
Remote monitoring	VSN300 Wifi Logger Card[7] (opt.), PVI-AEC-EVO (opt.), VSN700 Data Logger (opt.)		
Wireless local monitoring	VSN300 Wifi Logger Card[7] (opt.)		
User interface	16 characters x 2 lines LCD display		
Environmental			
Ambient temperature range	-25...+ 60°C (-13...140°F) with derating above 45°C (113°F)	-25...+ 60°C (-13...140°F) with derating above 50°C (122°F)	-25...+ 60°C (-13...140°F) with derating above 45°C (113°F)
Noise emission	< 50 db(A) @ 1 m		
Maximum operating altitude without derating	2000 m (6560 ft)		
Physical			
Environmental protection rating	IP 65		
Cooling	Natural		
Dimension (H x W x D)	618 mm x 325 mm x 222 mm (24.3 in x 12.8 in x 8.7 in)		
Weight	17 kg (37.4 lb)		
Safety			
Isolation level	Transformerless		
Marking	CE (50 Hz only)		
Safety and EMC standard	EN62109-1, EN62109-2, AS/NZS3100, AS/NZS 60950, EN61000-6-1, EN61000-6-3, EN61000-3-2, EN61000-3-3		
Grid standard	CEI 0-21, VDE 0126-1-1, VDE-AR-N 4105, G83/2, EN 50438 (not for all national appendices), RD1699, AS 4777, C10/11, IEC 61727, ABNT NBR 16149, CLC/FprTS 50549	CEI 0-21, VDE 0126-1-1, VDE-AR-N 4105, G83/2, EN 50438 (not for all national appendices), RD1699, AS 4777, C10/11, IEC 61727, ABNT NBR 16149, CLC/FprTS 50549	CEI 0-21, VDE 0126-1-1, VDE-AR-N 4105, G83/2, G59/3, EN 50438 (not for all national appendices), RD1699, AS 4777, C10/11, IEC 61727, ABNT NBR 16149, CLC/FprTS 50549, PEA, MEA
Available products variants			
Standard	PVI-3.0-TL-OUTD-W	PVI-3.6-TL-OUTD-W	PVI-4.2-TL-OUTD-W

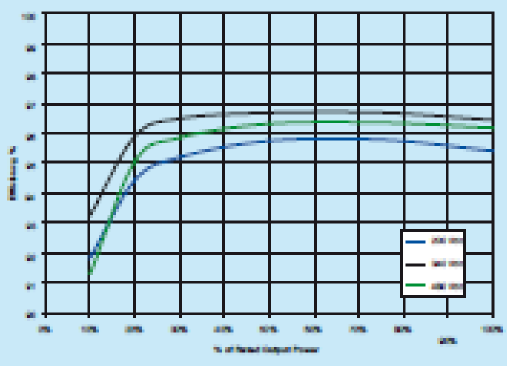
1. The AC voltage range may vary depending on specific country grid standard
2. The Frequency range may vary depending on specific country grid standard
3. For UK G83/2 setting, maximum output current limited to 16A up to a maximum output power of 3.68kW
4. Limited to 3000 W for Germany
5. Limited to 3600 W for Germany
6. Limited to 4200 W for Germany
7. Check availability before to order

Remark. Features not specifically listed in the present data sheet are not included in the product

Efficiency curves of PVI-3.6-TL-OUTD-W



Efficiency curves of PVI-4.2-TL-OUTD-W



Support and service
ABB supports its customers with a dedicated, global service organization in more than 60 countries and strong regional and national technical partner networks providing the complete range of life cycle services.

For more information please contact your local ABB representative or visit:

www.abb.com/converters-inverters

www.abb.com/windpower