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Energy Efficiency Assessment of Four Designs of Vertical Axis And Drag Differential Wind Turbines

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Abstract: *The present study compares the energy efficiency of four different wind turbine designs with vertical axis and differential drag, keeping equal their heights and diameters. Besides the classic two bladed Savonius model, two models derived from it were studied (Schulz and Beneshi), as well as the barely known Lenz type turbine. In laboratory tests of scale models the power curves have been determined as a function of the tip speed ratio, exposing the turbines to wind velocities up to 7 m/s. To avoid any variation in friction between tests, the same base, alternator and gears have been used for all four models. The Lenz model outperformed all others having the best power coefficient.*

Keywords: *vertical axis wind turbines, differential drag turbines, power coefficient, tip speed ratio*

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I. Introduction

In Paraguay, the harness of wind power is practically limited to the pumping of water with American type multiple blade turbines, mainly in the center and south of the western region (Chaco). They are manufactured by local companies and are found mostly in cattle ranches with no access to the electric grid. Water pumped from dykes is stored in tanks only a few meters above the ground. Instead of wind power, photovoltaic solar energy is the primary source of electricity in these areas. The main reasons are the lack of adequate wind resources in great part of the national territory, and the relatively high cost of wind turbines for micro-generation (up to 1 kW), which are mostly of the horizontal axis type with aerodynamic blades.

The wind turbines with vertical axis and differential drag have a relatively simple design, which makes their cost potentially lower than turbines of greater complexity. They are also easier to build from materials available locally, but are generally less efficient than the horizontal axis turbines with aerodynamic blades. On the other hand they have the following remarkable advantages:

a) they are independent of wind direction, so there is no need for an additional device to orient themselves towards the wind direction (Omni-directionality)
b) they self-regulate with strong winds, for which reason a break system is unnecessary
c) they can take advantage of turbulent winds
d) they turn round relatively slow, which is why they operate free from loud noises.

The last two advantages mentioned make this type of turbine ideal for urban zones, where noise impact is a critical factor for neighbors, and for places where turbulence predominates due to the great amount of trees and buildings in the surroundings.

The differential drag is due to the curved shape of the blades exposed perpendicular to the wind. When the wind acts on the concave side of the blade the drag coefficient is much greater than when it acts on the convex side. For example, in the case of a hallow semi-sphere like those used for cup anemometers, the drag coefficient on the concave side is 1.42; on the convex side on the other side is just 0.34.

In most parts of the Paraguayan territory there are no favorable wind conditions to take advantage of its energy, as revealed by the last study on wind power in Paraguay [6]. The area of greater potential is the north east of the western Paraguayan region close to the border with Argentina and Bolivia, where at a height of 10 m there is an accumulated annual energy from 1500 to 2000 kWh/m^2. In a small zone over the Pilcomayo river in the Pozo Hondo area winds up to 2500 kWh/m^2 have been recorded (see Fig. 1). At a height of 50 m, values between 3500 and 4000 kWh/m^2 have been recorded. On the other hand, in almost all the rest of the country the accumulated wind energy is only between 100 and 1000 kWh/m^2 at 10 m high, and between 1000 y 2500 kWh/m^2 at 50 m high. The very high potential phenomenon in the western region is due to its relative proximity to the Andes mountain range, which channels primarily the northeastern winds.

In the past, numerous studies have been realized aiming at the design and optimization of wind turbines with vertical axis and differential drag [1], [2], [3]. Several of these studies used the classic Savonius type model, which is one of the simplest in its design, basically consisting of 2 opposed semicircular cylinders fastened to a vertical axis (see Fig. 2). The torque is produced by the difference in drag that exists between the concave and convex blades, similar to a cup anemometer. In the present study the energy efficiencies of four different wind turbine designs with vertical axis and differential drag were compared, all of them having the same height and diameter such that the area of wind incidence stays the same. Aside from the two blades Savonius model [2], two derivatives of the same were studied, the so-called Schulz [3] and Benesh [1] models, as well as the barely known Lenz type turbine [7], which has a certain similarity with the Giromill type turbine, but without the employment of aerodynamic profiles for the blades.

The present study is unique in the sense that it compares four models in order to find the design with the best performance, as opposed to earlier research work which focus on the efficiency of a single turbine considering different constructive parameters such the relation between height and diameter, the quantity of blades and their overlap at the center of the turbine.

This work is organized as follows: in section 2 the methodology used for building and evaluating the turbine scale models is given, in section 3 results obtained from laboratory tests of the scale models are detailed, finally section 4 provides the concluding remarks.

II. Methodology

2.1 Construction of scale models

The scale models that were built from the 4 turbine designs with vertical axis all have a height of 700 mm and a diameter of 350 mm giving a swept area of 0.245 m^2, which is later considered for calculating the maximum theoretical power. The models were designed previously using the Solid Works software.

In order to have the same conditions in regards to rotary friction when making the measurements, the same set of axis, bearing, mass, transmission and generator was used for all 4 designs (Savonius, Schulz, Benesh and Lenz). Due to the fact that the turbines with vertical axis have a relatively low rate of turn, a multiplication mechanism through gears is necessary for transmitting a higher rate of turn to the generators. The gears were manufactured from nylon and have a multiplication relation of 7:1. A “bicycle dynamo” was used as a generator, which in reality is a small alternator with permanent magnets, having nominal voltage of 6 V and nominal power of 3 W. The axis fits into a base that is used to hold the entire equipment onto a horizontal surface, which consists of a rectangular plate 8 mm thick with 150 mm sides, and a drawn pipe hub with a 30 mm external diameter soldered perpendicularly in the center of the plate. The axis is a 147 mm long steel bar machined in the upper part so as to get two ball bearings with a distance of 66 mm in-between, which get under pressure in the mass pipe (see Fig. 3).

The blades are fabricated from mild steel sheet painted with the geometry corresponding to each one of the four designs. To fix the blades among themselves on both ends, and this in turn to the rotating mass, frames made of mild steel plates were held to the blades with pop rivets. The top end of the mass has a circular flange, which was screwed to the frame underneath.

2.1.1 Savonius turbine

The Savonius scale model follows the best known and most constructed design of all turbines with vertical axis and differential drag. It was first designed by Sigurd Savonius in 1922 and patented in 1930. It has two cylindrical semicircular blades, each having a 105 mm ratio and overlapping at the center of the 70 mm turbine (see Fig. 4). Thanks to this superposition, part of the wind that reaches the concave part of one of the blades is diverted at an angle of 180° and acts additionally over the other blade providing energy, which helps to increase the positive drag.

2.1.2 Schulz turbine

The Schulz scale model follows a design from the 1970s by Heinz Schulz [3] with the objective to improve the performance in relation to the traditional Savonius turbine. It is a derivative of the latter, consisting of three cylindrical curved blades with a constant ratio of 170 mm and a secant of 210.4 mm. The ratio of the central circle, of which the blades constitute the tangential, is 58.3 mm (see Fig. 5).

2.1.3 Benesh turbine

The Benesh scale model follows the design developed by Alvin Benesh and patented in 1996 [1]. It is also a derivative of the Savonius turbine, but its two cylindrical blades, overlapped at the central part, are of a different geometry. They have a 94 mm long straight part towards the center of the turbine, a curved part in their periphery with a 98.7 mm ratio, and a 124.4 mm secant. The separation between both blades is 39.5 mm (see Fig. 6).

2.1.4 Lenz turbine

The Lens scale model follows the most modern design. It was developed by Edwin Lenz in the 2000s [7]. It consists of three cylindrical blades with a relatively short development in comparison with the other designs. (see Fig. 7). They have an almost semicircular part with a 21.5 mm ratio, whose secant is radial. From the inner end of the curve the blade continues in a straight manner with a length of 97.8 mm. It has a 9° angle in relation to the ratio perpendicular oriented towards the center of the turbine.

2.2 Typical wind conditions

In order to determine in which wind velocity range the wind turbines under study should be operating in a real environment, measures were taken by Lopez between the years 2009 and 2010 from the top of the building “Wilson Tower” located in the city center of Asuncion, Paragua. This location was chosen considering the fact these vertical axis turbines are primarily desinged to be used in urban zones of Paraguay, particularly in areas where there is a good wind exposure, as is the top of tall buildings [5].

In said measures an average of 4.4 m/s and a resulting Weibull distribution shape factor of 2.0 were obtained, as well as a scale factor 4.9 m/s (See Fig. 8).

2.3 Measure of turbine performance

Performance measures of the four scale models was realized in the Laboratory of Mechanics and Energy in the department of Engineering at the National University of Asunción. An educational open circuit wind tunnel of type Aerolab EWT was used as a wind generator.; but since its test chamber is too small (30.5x30.5x61 cm) to accommodate the wind turbine scale models that were built, the air exhaust area was used, taking advantage of the wind generated by the fan. The wind velocity was varied by changing the fan’s rate of turn by means of the engine frequency converter.

To calibrate the wind velocity as a function of fan speed an anemometer was used distanced 1 m from the wind tunnel’s exit in the direction of its axis extension, which corresponds to the same distance the scale models were placed afterwards.

The engine’s revolutions per minute (*RPM*) were recorded for velocities of 1 to 7 m/s with 1 m/s steps. In order to verify that the air flux over the whole turbine attack surface was sufficiently homogeneous, new point measures were realized in said surface with a 3x3 matrix (see Fig. 9), with the central point being in the direction of the fan axis. It was found that the air velocities wre practically constant among the different points. The maximum variation was only 5 % in relation to the nominal value.

The measures had as a principal objective determining the power coefficient (*Cp*) of the four turbine models as a function of the wind velocity respectively of the specific velocity (*TSR*), which is a dimensionless parameter that relates the velocity of the tip of the turbine and the wind velocity. *Cp* is defined as the relation between the energy generated by the wind turbine and the kinetic energy possessed by the wind, for which in this case an air density of 1.225 kg/m^3 was considered. At 7 m/s the power contained in the wind is then 51.5 W considering an attack area of 0.245 m^2.

For each wind velocity, the voltage and output current of the generator were measured with a multi-meter, and the quantity of RPM of the turbines were recorded with a tachometer. To simulate the charge for the alternator, a resistance of 5 Ω was placed between both of its poles. For each velocity and each type of turbine 3 measures were taken and averaged. From the voltage and current the electrical power of the generator was calculated.

III. Results

The measured results from the four turbines are presented in Tables 1 through 4. For each wind velocity from 1 to 7 m/s, the tables show the RPM of the wind turbine, the voltage between the alternator poles in Volts (V), the current the alternator generates in Amps (A), the electrical power generated by the alternator resulting from the product of the latter two parameters, the specific velocity TSR and the power coefficient Cp. In the four models only from 4 m/s upwards the turbines began to rotate and thus the alternator started to generate energy.

In all four cases, with increasing wind velocity all parameters increased as well, up to a maximum at 7 m/s velocity. Amongst the wind turbine designs considered, the Lenz model clearly stands out from the rest, with a 0.305 power coefficient at 7 m/s (see Table 4), while the other designs reached values of just 0.127 y 0.219 at the same velocity (see Tables 1 to 3).

In order to obtain the value of the combined performance of the alternator and the transmission system, the Savonius turbine power coefficient was used at a specific velocity close to unity obtained by a previous study with a value of 18 % [4]. This *TSR* of almost 1 was obtained at a wind velocity of 7 m/s (see Table 1). The Savonius turbine power multiplied by the power contained in the wind at that wind velocity with a power coefficient assumed to be 18 % comes to 9.72 W; but the electric power that was measured with the Savonius turbine at 7 m/s was only 0.103 W. The combined performance of the alternator and the transmission system is then only 0.00111, which is a very low value indeed. It is assumed that the bad performance is primarily due to the low efficiency of the alternator. For all other measures this same value was used considered as a constant to calculate the respective coefficients of power in the wind turbines. This assumption is valid, since for all 4 wind turbine designs the same mass, transmission system and alternator were used, having in this way the same friction magnitudes in different rotating parts.

From the *TSR* and *Cp* values obtained from the measures, power curves for the four wind turbine designs were plotted using an Excel trend tool based on a third degree polynomial function. As expected, in the Savonius turbine the maximum power coefficient occurs at a *TSR* close to unity (see Fig. 10).

In the case of the Lenz turbine, the maximum power coefficient occurred at a *TSR* close to 1.4, reaching a value of 0.338, which matches a wind velocity of 6.5 m/s (see Fig. 11).

In Fig. 12 the power curves of the four wind turbines studied in this work are plotted. The superiority of the Lenz turbine over the other designs is clearly seen.

IV. Conclusion

Laboratory tests were carried out to compare the efficiency of four dfferent wind turbine designs with vertical axis and differential drag. It was found that the Lenz turbine model outperformes all others with a maximum power coefficient of 32.5 %, followed by the Benesh model with 21.4 %, Savonius with 18 % and Schulz with 13 %. Due to the fact that the present research work was conducted with scale models of wind turbines, they are not suitable for the generation of electricity at full-scale. To continue with this line of research, a larger scale prototype of a Lenz type wind turbine should be designed and built, with a nominal electrical power of 100 W, for example. The prototype should be subjected to a series of tests under real operational conditions at a site with adequate wind potential.

FIGURES AND TABLES

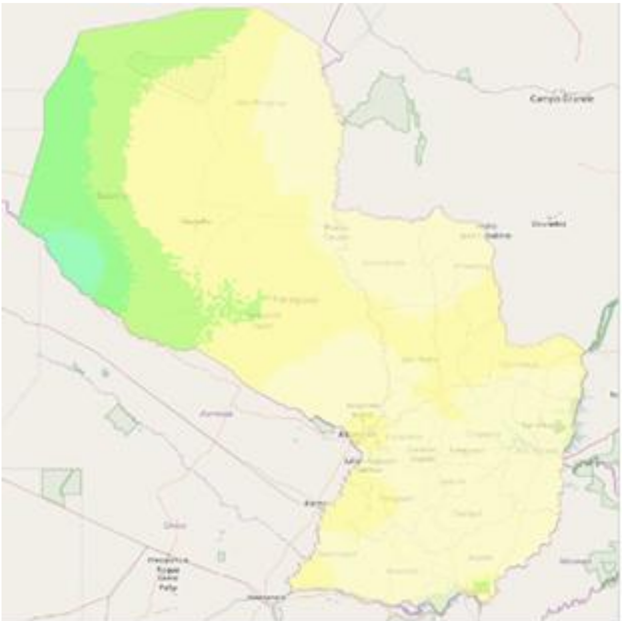

Figure 1. Wind energy potential in Paraguay at a height of 10 m in kWh/ m^2 year. **Source** [6]

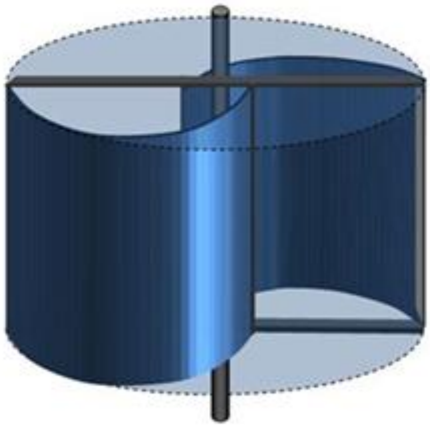

Figure 2. Typical design of vertical axis turbine of type Savonius. **Source** elnegrillo.blogspot.com

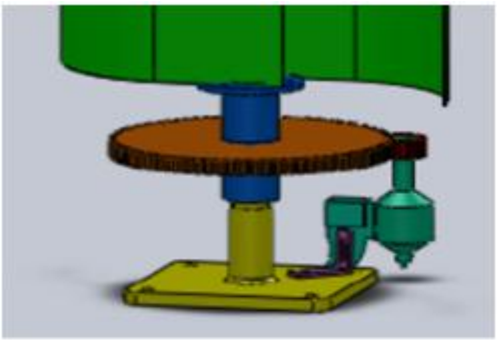

Figure 3. Set of base, axis, mass, transmission y generator.

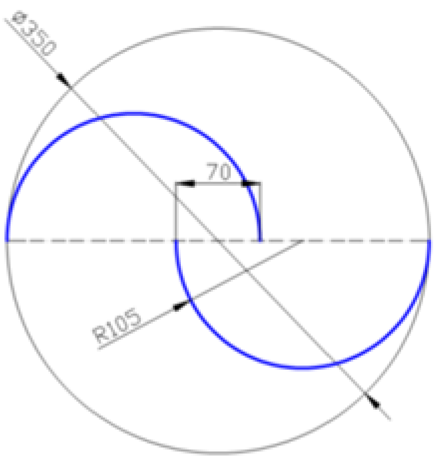

Figure 4. Savonius turbine cross section with measures.

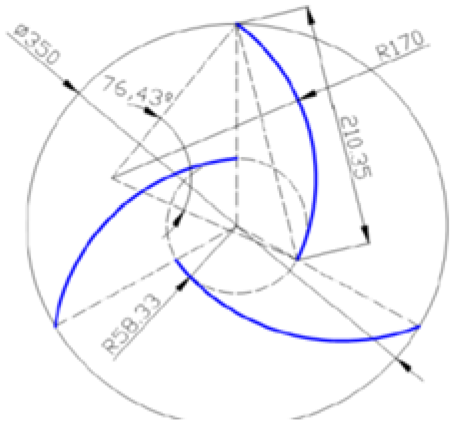

Figure 5. Schulz turbine cross section with measures

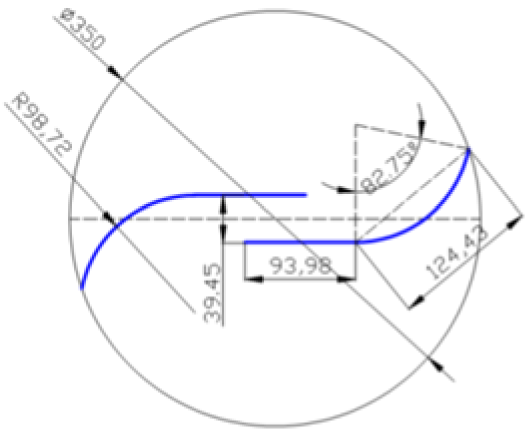

Figure 6. Benesh turbine cross section with measures.

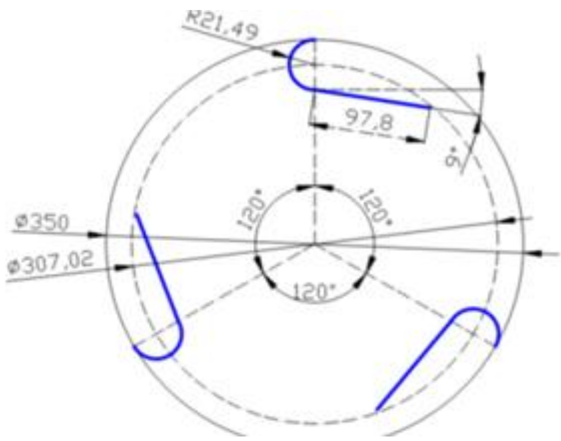

Figure 7. Lenz turbine cross section with measures

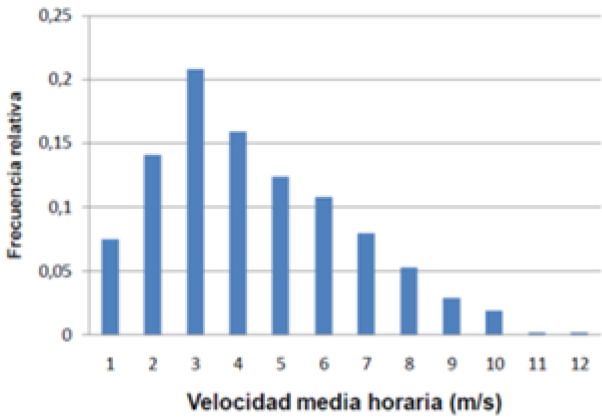

Figure 8. Wind velocity distribution measured at the top of the Wilson Tower in Asuncion, Paraguay. **Source** [5]

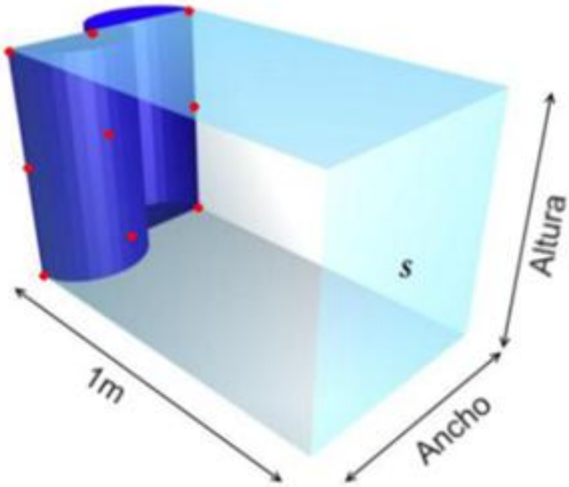

Figure 9. Measure points of wind velocity (in red) and attack surface (S) of wind turbines.

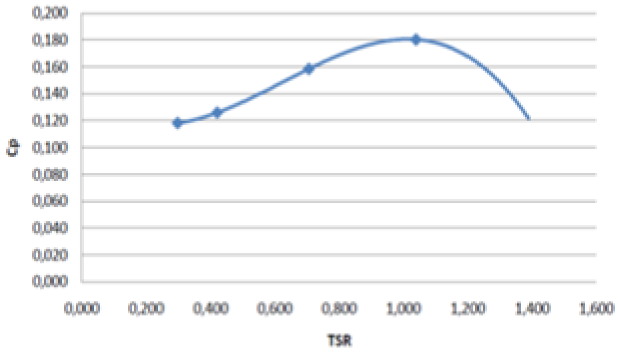

Figure 10. Power coefficient vs. specific velocity of the Savonius turbine.

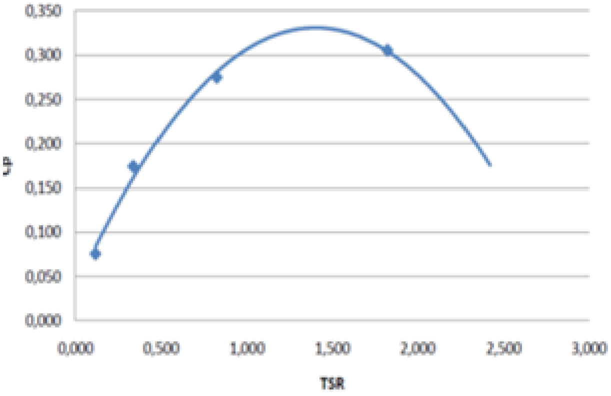

Figure 11. Power coefficient vs. specific velocity of the Lenz turbine.

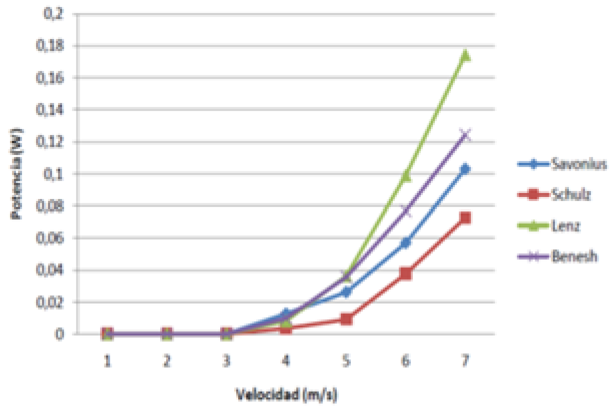

Figure 12. Power curves of the 4 wind turbines.

Table 1. Average data from measures of the Savonius turbine

Velocidad (m/s)	RPM	Tensión (V)	Corriente (A)	Potencia (W)	TSR	Cp
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	40,48	0,247	0,051	0,013	0,297	0,118
5	45,87	0,360	0,073	0,026	0,420	0,126
6	64,27	0,533	0,107	0,057	0,706	0,158
7	81,15	0,723	0,142	0,103	1,040	0,180

Table 2. Average data from measures of the Schulz turbine

Velocidad (m/s)	RPM	Tensión (V)	Corriente (A)	Potencia (W)	TSR	Cp
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	15,47	0,198	0,018	0,004	0,113	0,034
5	20,80	0,366	0,025	0,009	0,190	0,045
6	43,96	0,575	0,066	0,038	0,483	0,105
7	49,03	0,677	0,108	0,073	0,629	0,127

.

Table 3. Average data from measures of Benesh turbine

Velocidad (m/s)	RPM	Tensión (V)	Corriente (A)	Potencia (W)	TSR	Cp
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	21,99	0,219	0,045	0,010	0,161	0,092
5	45,40	0,415	0,086	0,036	0,416	0,171
6	65,16	0,620	0,124	0,077	0,716	0,214
7	73,08	0,789	0,158	0,125	0,937	0,219

Table 4. Average data from measures of Lenz turbine.

Velocidad (m/s)	RPM	Tensión (V)	Corriente (A)	Potencia (W)	TSR	Cp
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	15,96	0,198	0,041	0,008	0,117	0,076
5	36,93	0,423	0,086	0,036	0,338	0,174
6	75,03	0,701	0,141	0,099	0,825	0,275
7	142,24	0,931	0,187	0,174	1,824	0,305

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