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A Study of Vertical Axis Turbines

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Abstract:- Renewable energy has evolved substantially to meet the growing needs of this ever-advancing world. With growing environmental concern, and imminent limits to fossil fuel consumption, wind power has regained it's place as one of the most promising renewable energy source. The most primarily used wind energy conversion systems are the high-speed wind turbines. Due to the extreme effectiveness and the availability of large markets for these turbines, the potential of the Vertical axis turbine, is getting overshadowed. Very meagre amount of research has been put into this field as compared to horizontal types. There are two distinctly different types of vertical axis wind turbines: The Darrieus and the Savonius types. Although these turbines are available in the market, they have not been optimized fully. This paper seeks to fabricate and study a hybrid vertical axis turbine and shed some light on the same by virtue of exploring the possibilities the turbines have to offer. The main reason for using these turbines is that they have a very simple mechanical structure and have a very adaptive design i.e. they can use existing structures as mountings. The vertical axis turbines are capable of catching wind from all directions and, although less efficient, these turbines hardly suffer from the constantly varying gravitational loads that limit the size of horizontal turbines. Economic analysis proclaims that if a vertical axis turbine with a rated output of 10MW could be developed, with at least the same availability as a modern horizontal axis turbine, but at a lower cost per unit of rated power, then a slightly lower blade efficiency as 56% to about 19-14% would hardly be of any significance.

Keywords:- *Wind Energy, Darrieus Turbine, Savonius Turbine, H-VAWT.*

I. INTRODUCTION

A vertical-axis wind turbines(VAWT) have their main rotor shaft set oblique to the wind direction (not necessarily vertically) while the main components are located at the base of the turbine. Such a structure design allows the generator and gearbox to be located closer to the ground. These turbines work remarkably at low wind speeds. The Savonius turbine performs well at low wind speeds and even when the wind direction changes. The structure is quiet, easy to build and rather small. However, it has a very low efficiency as compare to the Darrieus turbine. A combination of both these turbines mounted on the same axis gives the advantages of both while compensating for each other's disadvantages. Since they can be mounted on existing structures, tower structures are not required. This makes for a very compact wind turbine which is easy to maintain and is able to generate ample amount of energy in lower wind speeds and unstable conditions. These turbines can also be modified to employ the use of batteries to store energy, thereby reducing and possibly eliminating the need for power grids. In light of environmental concerns among people and governments about the depleting energy resources, the recent market for these turbines are only expected to grow.

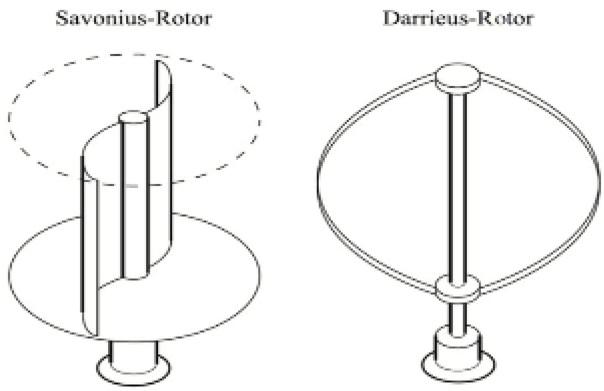

Fig 1

A. Wind Turbine Design

The wind turbine criterion [3] considered in the design process are:

- Tip speed ratio
- Blade chord
- Number of blades
- Solidity
- Initial angle of attack
- Swept area
- Power and power coefficient

B. Swept Area

The swept area is the plane of wind intersected by the turbine blades or even more simply put it is the area swept by the turbine blades. The outline of the swept area depends on the rotor dimensions; thus, the swept area of a Horizontal-Axis wind turbine is circular shaped while for a straight-bladed Vertical-Axis wind turbine the swept area has a rectangular shape and is calculated using:

$$S=2RL$$

where S is the swept area [m2], R is the rotor radius [m], and L is the blade length [m]. The amount of air passing through the turbine is controlled by the swept area. The wind drives the turbine so as to produce a rotational movement in a way that bigger the swept area more is the power generated in the same wind conditions.

C. Power and Power Coefficient

The power attained from wind depends mainly on three factors: wind speed, air density and blade radius. For a VAWT the power obtained can be calculated from the following formula:

$$P = \frac{\rho S V^3}{2}$$

where V is the wind velocity [m/s] and ρ is the density of air [kg/m3].

The power the turbine takes from wind is calculated using the power coefficient:

$$Cp = \frac{Captured\ mechanical\ power\ by\ blades}{Available\ power\ in\ wind}$$

Cp value exhibits the fraction of the total available power which is actually taken from wind, and can also be understood as its efficiency. A theoretical limit is imposed to the efficiency due to the deceleration effect wind suffers when going through the turbine. For a HAWT, the limit is set at 59.3%, also called the Lanchester-Bentz limit. Likewise, the limit set for VWATs is 64%. These restrain are a result of the momentum theory or actuator disk theory which assumes that flow through the actuator disk is uniform and that the disk has no swirl effect on the flow. Most of the currently available wind turbines exhibit power coefficients between 0.15 to 0.2.

D. Tip Speed Ratio

The power coefficient depends excessively on tip speed ratio. For maximum power acquisition a wind turbine must be operated around its optimal tip ratio. It is the ratio of the tangential speed at blade tip and the actual wind speed.

$$TSR = \frac{Tangential\ speed\ at\ blade\ tip}{Actual\ wind\ speed} = \frac{R\omega}{V}$$

where ω is the angular speed [rad/s], R is the rotor radius [m] and V is the ambient wind speed [m/s]. Each rotor design has an optimal tip speed ratio at which the maximum power extraction is achieved.

E. Blade Chord

The blade chord is the imaginary line joining the trailing edge and the point of intersection of the leading edge and the chord line of the blade profile. However, most of the turbine blades are not rectangular, and so have a different chord at different positions along their length.

Therefore, to give a unique value which can be compared to other blade chord values, the mean aerodynamic chord or MAC is used.

F. Number of Blades

The smoothness of the operation of a turbine is closely governed by the number of blades, since they compensate for the cycled aerodynamic loads. For ease of manufacturing, three and four blades are generally taken. Researches show that the wakes formed behind rotors with different blade number have minor distinctions and the thrust force acting on the rotors is similar for the optimal operation range of the rotors. From a power optimization point of view, the mean wake velocities provide only a minor potential for improvement. Also, the number of blades has no influence on the velocity deficit and consequently, neither does it have any effect on the potential inflow velocities of a downward turbine.

G. Blade Solidity

Blade solidity is crucial design parameter for a VAWT. It depends mainly on the blade chord, number of blades and rotor radius. An increment in length of the blade chord raises the tip speed ratio at which the maximum power coefficient can be achieved, because the chord length and the tip speed ratio are inversely proportional to each other. In order to reduce the centrifugal force, a lengthier chord may prove more effective than a lighter blade. However, a bigger chord will advance the point of maximum torque. Blades with smaller chords need a bigger tip speed ratio to develop a higher torque. The blade solidity will also inadvertently affect the self-starting capabilities of the turbine.

H. Initial Angle of Attack

The initial angle of attack is the angle between the chord line of the blade and the vector of the relative motion between the turbine and the wind. The critical angle of attack is the angle which provides the best lift for the aerofoil section. At a lower angle of attack, the lift coefficient decreases and conversely, at a bigger angle of attack the air flows less smoothly and as a result tends to move away from the upper surface.

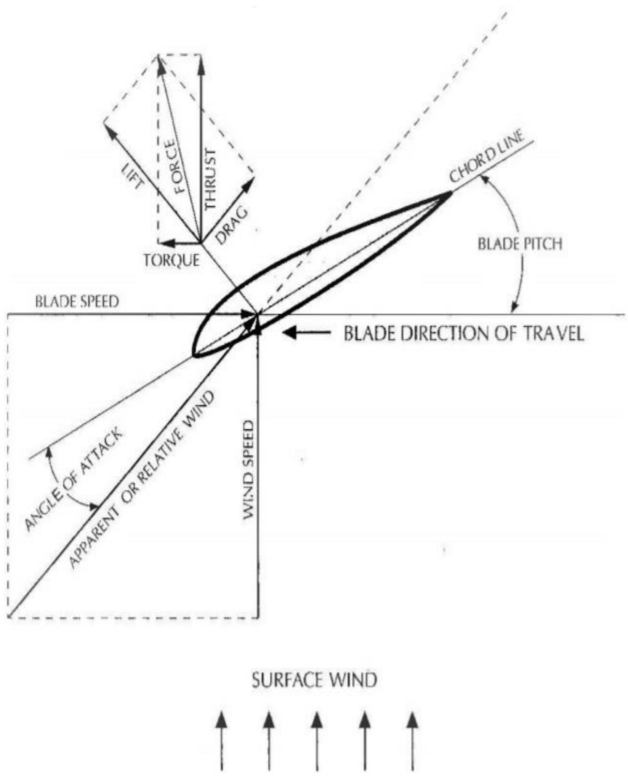

Fig 2:- Force vectors for a HAWT

II. ROTOR DESIGN

A. Starting Parameters

To make the most efficient use of time and the resources available for the design process, few parameters have to be altered, so as to concur to the objective. The design air speed, swept area, and initial angle of attack will be optimized for maximum efficiency. Most of the power coefficient values for the turbines available in the market, lie within 0.15 to 02. To produce power of 100W with a wind of speed 6m/s a swept are of 4 to 5.2 m2 is required. (Appendix 1, Table 2)

B. Air Foil Selection

The air foil considered here is the NACA0021. The aerodynamic properties of this particular air foil were determined from an air foil property synthesizer code in a journal (given in Appendix 2, Table 3). This is one of the thickest profiles available for an air foil (21% chord) and comparing with NACA0015, it is seen that the self-starting properties improve with thicker foils (Figure 3).

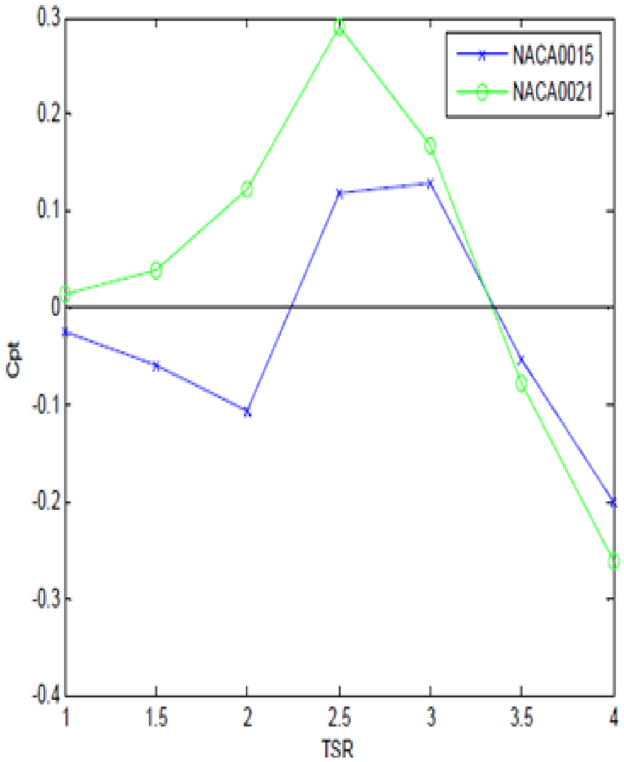

Fig 3:- Performance comparison between two different air foil.

C. Design Airspeed

A significant shift in the power coefficient is seen as the free stream velocity is varied from 0 to 15 m/s. however beyond this airspeed the power coefficient remains almost constant at each tip speed ratio as can be observed in the adjoint graph. Also, the torque increases noticeably due to its quadrate dependence on air speed. Although, the rated wind speed varies from 11.5 to 15 m/s, a lower speed lying between cut in and rated speed has the potential of producing more gross energy.

D. Rotor Dimensions

The torque produced by the turbine heavily depends on the certain design factors like the blade length and rotor radius, more so than on others. In general, a longer blade and a bigger radius will result in a higher torque. These parameters are significant for solidity calculations as well. While scaling the wind turbines solidity becomes a very crucial factor and as an extension so does the rotor dimensions. To decide upon a suitable dimension, a CFD model, which tests various combinations against set parameters, is used [4]. (Figure 4)

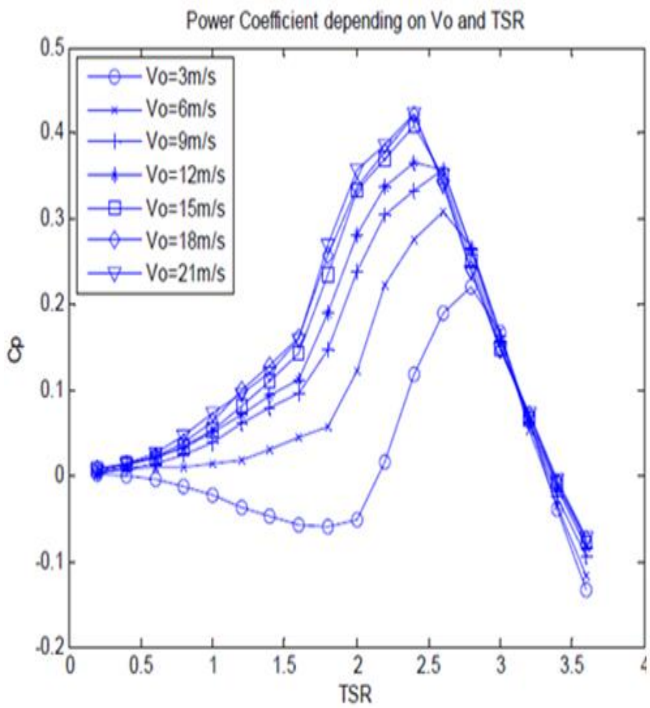

Fig 4

E. Rotor Solidity

The ratio of the total blade area and the projected turbine area is called the rotor solidity (σ). It is an important non-dimensional parameter which affects self-starting capabilities. For a straight bladed VAWT it is calculated with:

$$\sigma = \frac{Nc}{R}$$

where N is the number of blades, c is the length of blade chord, L is the blade length and S is the swept area (considering that each blade sweeps the area twice). To achieve a self-starting turbine, rotor solidity is kept at least greater than 0.4 i.e. $\sigma \geq 0.4$.

F. Initial Angle of Attack

The initial angle of attack is usually kept positive because it increases the range of angular speed operation. A negative angle of attack narrows the said range. Even the torque gets affected similarly resulting in a lower maximum power coefficient and torque for negative angles of attack. Various angles of attack will be tested for the CFD model.

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III. HYBRIDISATION

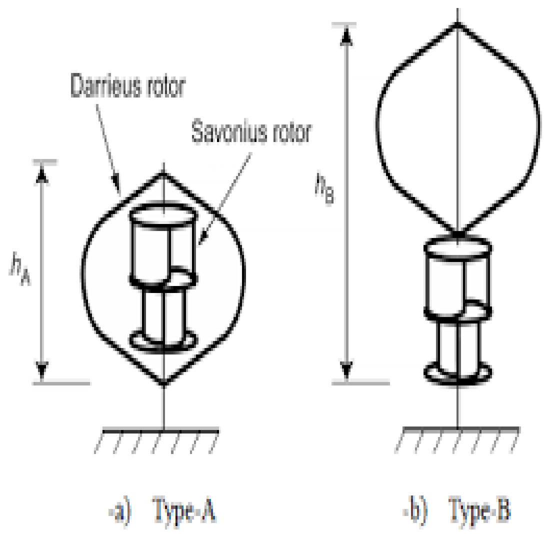

Fig 5:- Types of Hybrid Rotors

The basic two types of hybrid configurations are considered here are shown in (Figure 5). Type A installs the Savonius rotor inside the Darrieus rotor and Type B has the Savonius rotor outside the Darrieus rotor. The Type A design has an outstanding operating response to varying wind speed and can be compactly designed because of a shorter rotational axis, is an effective way for stand-alone small-scale systems

The Savonius rotor is self-starting and produces high torque at low speeds. It is used to jump start the Darrieus rotor, which is not self-starting, but has a comparatively high efficiency. [6] The original study by Savonius [7] only considered a single basic rotor design. The classic Savonius rotor does not have any airflow between "buckets" (Figure 6), rather, the buckets are either connected or a pole blocks the flow between the buckets.

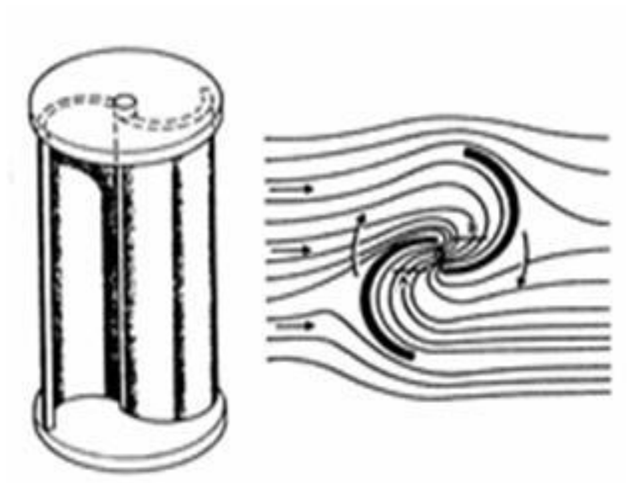

Fig 6:- Classic Savonius Rotor with no air flow between buckets

Subsequent studies [8] have shown that allowing air to flow between each side of the rotor can improve efficiency significantly. A simple modification to the original Savonius model, was by overlapping the rotors (Figure 7). This allowed air to flow between each of the sides, thus improving the efficiency.

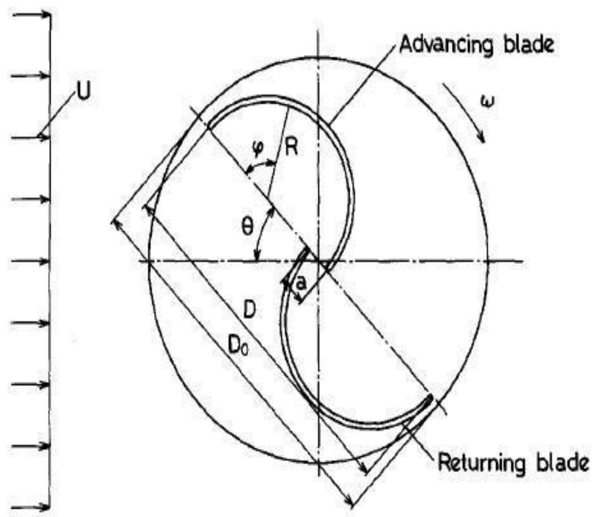

Fig 7:- Overlapping Savonius rotors

The hybrid vertical axis turbine is supposed to be very versatile, and able to perform in many different environments. The Savonius VAWT rotor is a basic rotor that is characterised by its simple construction and its ability to excel at low wind speeds. It can accept wind from any direction and provide high torque at low rotational speeds. However, the Savonius rotor is restricted to a lower efficiency level as compared to other rotors and low rotational speeds.

The operation of Darrieus rotor is based on lift forces. Although it excels in moderate wind speeds, and is able to perform in low wind speeds, the torque produced is very modest. It also lacks the self-starting capability of the Savonius rotor. In the proposed design for the hybrid VAWT, the Savonius rotor provides the external assistance needed to jump start the Darrieus rotor.

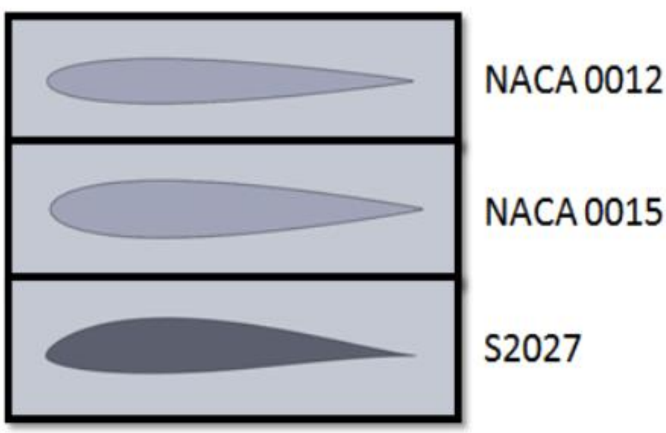

Fig 8:- Various Air Foil Profiles for Darrieus rotor

Accordingly, design aspects need to be considered and final decisions made for the Darrieus part of the HVAWT. All the data currently available for Darrieus turbines are optimized for high speed winds. Even the standard design rules were devised for high speed winds.

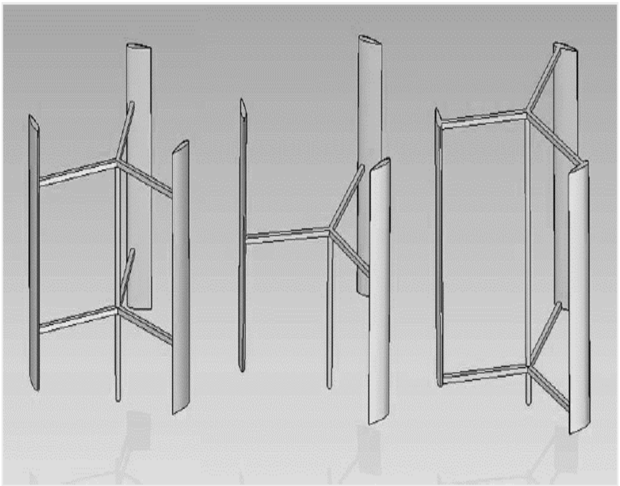

Fig 9:- Various Rotor Configurations of Darrieus Design

Since no data was available for a Darrieus turbine optimized for low speed winds, the available statistics were considered for the design. The most common Darrieus blade profiles are the NACA 0012 and NACA 0015 -which are both symmetrical profiles. Guillaume [10] studied the difference between the standard symmetrical profiles and specially designed cambered profiles.

According to his report, the S2027 blade profile increased the overall energy produced, by about 16% over the standard NACA 0015. Another crucial design parameter in the Darrieus turbine is the number of blades. Commercially available Darrieus turbines use between three to nine blades. Although, some of them use an unusually large number of blades. The number of blades finally decided upon for any turbine is based on two major factors: the power produced by each blade and the interference of each blade on the others. More the number of blades more is the interference on each blade. But, since a greater number of blades results in a higher efficiency, same as lesser interference results in a higher efficiency, an optimal number of blades are selected, considering the aim of the turbine and conditions at which it's going to perform in. The last design parameter considered is the chord length. The chord length has the most impact on the torque produced. The standard design convention for Darrieus turbines used in high wind regions, is a chord length of about 10-20% of the length of the blade. However, the data available for the chord length for a low wind speed region is very clouded. As mentioned before, Darrieus turbines produce very low torque values at lower wind speeds. To compensate for this low torque, the chord length can be increased. Although this will solve the problem of having a lower torque, it will give rise to other issues like, a higher manufacturing cost and an increased weight which will interfere with the turbine's ability to gain momentum quickly.

The vertical axis turbine is a versatile turbine that performs admirably in lower wind speeds, is able to accept wind from any direction without having to break down or stall under heavier loads. However, this the VAWTs do face the issue of a constant back track due the wind flowing in the opposite direction (due to the circular motion). This reduces the efficiency of the turbine by almost 30 times as compared to a Horizontal VAWT. [11]

IV. CONCLUSION

After studying various publications and journals done in the wind turbine field it has been observed that a lot of research has been done in the high wind speed types i.e. the large-scale grid operating wind turbines. The reason for this being is a larger market and potential profits. Although small scale turbines are available in the market, they have not been optimized fully and are not a viable option in many areas either. Especially in case of Vertical axis turbines the amount of research is lower compared with horizontal types. This is partly due to the complexity in manufacturing and maintaining them. But for small scale operations these vertical axis types have a greater possibility to operate at low wind speeds and with this project the aim is to bring in a more efficient design for the same. The research in this regard have not performed CFD modelling to check the working of their designs in multiple conditions other than the ones they have tested in their wind labs with their physical model. This research gap is an opportunity for this project to move forward. This CFD model can be created and compared to the actual data retrieved by Letcher [12] and determine the accuracy of the model. A further analysis can be done considering the Savonius rotor to be placed in between the Darrieus rotor and check for the feasibility of such design alteration.

V. APPENDICES

➢ *Appendix 1: Market Analysis*

Product	Manufacturer	Rated Power (W)	Rated Wind Speed (m/s)	Rated rpm	N	Price €
Turby		2500	14	120/ 400	3	11466
Windspire	Windspire Energy, US	1200	10,7		3	11354
P-1000	Shanghai Aeolus Windpower	1000	12		5	2826
Easy Vertical	Ropatec	1000	12	240	3	
FL1KWVAWT	Flexienergy	1000	10	55		
Windterra Eco 1200	Windterra systems	1000	11	270 max	3	
VENCO-Twister 1000 T	VENCO Power GmbH	1000	12		3	
Mini Vertical	Ropatec	750	14	180	3	
Aeolos-V 600w	Aeolos Wind Turbine	600	10			
P-500	Shanghai Aeolus Wind-power	500	13		5	1680
FSW Gyro.5	Four Seasons Windpower	500	10,72		5	1949
Seahawk 500	Wepower	500	12,5	608	6	
FLEX500VAWT	Flexienergy	500	13			
FSW Gyro.3	Four Seasons Windpower	300	9,92		5	1383
Aeolos-V 300w	Aeolos Wind Turbine	300	10			
VENCO-Twister 300 T	VENCO Power GmbH	300	14		3	
FSW Gyro.2	Four Seasons Windpower	200	9,92		5	1207
Wind Smile 200W	Wind Smile	200	13		4	
ELY-100	Qingdao	100	10	200	5	

Table 1:- Blade Ratings of Different Manufacturers

Product	Blade Lenght (m)	Rotor radius (m)	Swept Area (m^2)	Total Height (m)	Min Wind (m/s)	Max Wind (m/s)	Survival Wind (m/s)	Calc. Cp
Turby	2,6	1,9	9,88		4	14	55	0,15
Windspire	5,79	0,61	7,06	9,1	3,8		47	0,23
P-1000	2	0,9	3,60	5,5	4	25	50	0,26
Easy Vertical	1,9	0,95	3,61	6,8	3		53	0,26
FL1KWVAWT	1,65	1,25	4,13	8	3	25	40	0,40
Windterra Eco 1200	2,66	1,125	5,99		3		53	0,20
VENCO-Twister 1000 T	1,9	0,95	3,61		3,5	20	50	0,26
Mini Vertical	1,5	1,5	4,50		3		53	0,10
Aeolos-V 600w	1,6	0,65	2,08		2		50	0,47
P-500	1,05	0,68	1,43	5,5	4	25	45	0,26
FSW Gyro.5	2,21	0,68	3,01	5,49	1,96	24,6	40,2	0,22
Seahawk 500	1,2	0,381	0,91		1,35		54	0,46
FLEX500VAWT	1	0,6	1,20		4,5			0,31
FSW Gyro.3	1,29	0,68	1,75	5,49	1,96	24,6	40,2	0,29
Aeolos-V 300w	1,4	0,6	1,68		2		50	0,29
VENCO-Twister 300 T	1	0,5	1,00		3,5	25	50	0,18
FSW Gyro.2	0,89	0,68	1,21	5,49	1,96	24,6	40,2	0,28
Wind Smile 200W	1	0,5	1,00	1,4	2,5		60	0,15
ELY-100	0,8	0,8	1,28	6	1,5	25	50	0,13

Table 2:- Specifications of different Blades

➢ *Appendix 2: Air foil Dimensions*

Ordinates		chord	28 cm
x(%c)	y(%c)	x	y
0	0,000	0	0
1,25	3,315	0,35	0,9282
2,5	4,576	0,7	1,2813
5	6,221	1,4	1,7419
7,5	7,350	2,1	2,058
10	8,195	2,8	2,2946
15	9,354	4,2	2,6191
20	10,040	5,6	2,8112
25	10,397	7	2,9112
30	10,504	8,4	2,9411
40	10,156	11,2	2,8437
50	9,265	14	2,5942
60	7,986	16,8	2,2361
70	6,412	19,6	1,7954
80	4,591	22,4	1,2855
90	2,534	25,2	0,7095
95	1,412	26,6	0,3954
100	0,221	28	0,0619
L.E. radius (%c)		4,85	

Table 3:- NACA0021 Air foil Dimensions

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