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Performance Analysis of Shrouded Micro Wind Turbine

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Abstract: A global economy growing at an average rate of 3.4% per year, a population that expands from 7.4 billion today to more than 9 billion in 2040, and a process of urbanisation that adds a city the size of Shanghai to the world's urban population every four months are key forces that underpin our projections.

The growing demand for electrical energy for industrial and domestic use, coupled with the limited amount of available fossil fuel reserves and its negative effects on the environment, have made it necessary to seek alternative and renewable energy sources. The use of renewable energy is promoted worldwide to be less dependent on conventional fuels and nuclear energy. Therefore research in the field is motivated to increase efficiency of renewable energy systems.

This study aimed to study potential of micro wind turbine and velocity profile through shroud for low wind speeds. Although there is a greater inclination to use solar panels because of the local weather conditions, there are some practical implications that have place the use of solar panels in certain areas to an end. The biggest problem is panel stealing. Also, in some parts of the country the weather is more appropriate to apply wind turbines.

Thus, this study paying attention on the design of a new concept to improve wind turbines to be appropriate for the low wind speeds in India. The concept involves the implementation of a concentrator and diffuser to a wind turbine, to increase the power coefficient. Although the wind turbine was not tested for starting speeds, the realization of the shroud should contribute to improved starting of the wind turbine at lower wind speeds.

The configuration simulated with the use of a program to obtain the power production of the wind turbine over a range of wind speeds. These values were compared to measured results of an open wind turbine developed.

The most important topic at hand when dealing with a shrouded wind turbine is to find out if the overall diameter or the blade diameter of the turbine should be the point of reference. As the wind turbine is situated in a shroud that has a larger diameter than the turbine blades, some researchers believe that the overall diameter should be used to calculate the efficiency. The benefits of shrouded wind turbines are discussed.

Index Terms: Micro Wind Turbine, Wind speed in shroud, Power Coefficient (Cp),

I. INTRODUCTION

A. Pathway for the global energy transformation

The International Renewable Energy Agency (IRENA) has explored global energy development options from two main perspectives to the year 2050 as part of the 2019 edition of its Global Energy Transformation report (IRENA, 2019). The first is an energy pathway set by current and planned policies and the second is a cleaner, climate-resilient pathway based largely on more ambitious, yet achievable, uptake of renewable energy and energy efficiency measures (the REmap Case).

Reducing energy-related CO_2 emissions is at the heart of the energy transformation. Rapidly shifting the world away from the consumption of fossil fuels that cause climate change and towards cleaner, renewable forms of energy is key if the world is to reach the agreed-upon climate goals. There are many drivers behind this transformation (Figure 1).

Firstly, the rapid decline in renewable energy costs. The global weighted average cost of electricity from all commercially available renewable power generation technologies continued to fall in 2018. For onshore wind projects commissioned in 2018, the global weighted average cost of electricity reached a low of USD 0.056 per kilowatt-hour (kWh), which was 13% lower than in 2017 and 35% lower than in 2010. (USD 0.085/kWh) (IRENA, 2019). The costs of electricity from onshore wind are already competitive at the lower end of the fossil fuel cost range and are even undercutting new fossil fuel-fired power generation costs in many cases.

Secondly, air quality improvements. Air pollution is a major public health crisis, caused mainly by unregulated, inefficient and polluting energy sources (fossil fuels, chemicals, etc.). The switch to clean, renewable energy sources would bring greater prosperity, improving the air quality in cities and preserving and protecting the environment. With the rise in the use of renewables, a drop in net energy subsidies would potentially lead to decline in health costs from air pollution and climate effects.

Thirdly, reduction of carbon emissions. The gap between observed emissions and the reductions that are needed to meet internationally agreed climate objectives is widening. The transformation of the global energy system needs to accelerate substantially to meet the objectives of the Paris Agreement, which aim to keep the rise in average global temperatures to closer to 1.5 °C in the present century, compared to pre-industrial levels. A 70% reduction in energy related emissions would be needed by 2050 compared to current levels (IRENA, 2019).

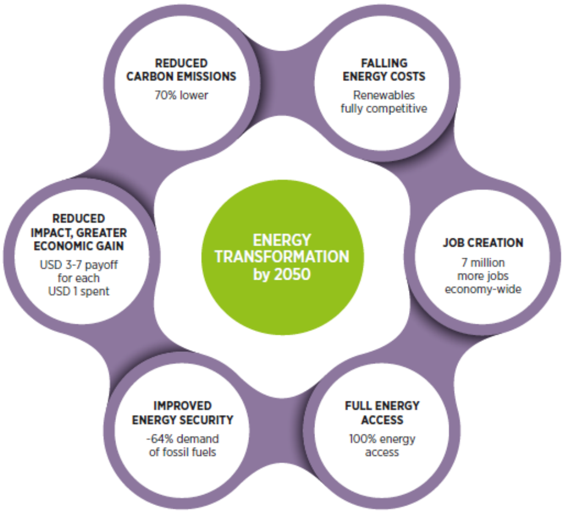

Figure 1 : Pressing needs and attractive opportunities are d riving the transformation of the world's energy system.(IRENA, 2019b)

B. **Global Energy Deficit**

In spite of numerous developments in energy technology, there are still over 1.3 billion people without access to electricity and 1 billion more only have intermittent access (see Figure.2) [2]. The majority of this population depends on candles, kerosene lanterns, or biomass cook stoves to fulfill the basic needs of nutrition, warmth and light. In addition to their lower efficiencies, these energy sources can release damaging toxins and pose dangers to children who may either burn themselves or swallow toxic fuel stored in soft drink bottles. Beyond household needs, there is an increasing energy demand in developing countries to provide water, health care and education. For these reasons, lack of access to electricity is one of the clearest indications of a country’s poverty status.

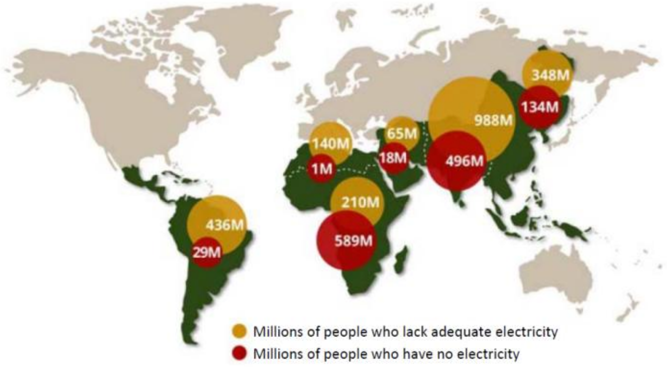

Figure 2: Global energy shortfall represented by region [2].

Conventionally, electrical energy is derived from conventional sources such as fossil fuels or nuclear energy. In these systems, electrical energy is generated by a large power plant and transmitted over long distances through distribution lines. While this may be the status quo, there are numerous consequences to using these energy sources. Not just are fossil fuels rapidly depleting as a resource, but the process of converting this source into electricity releases greenhouse gases and adversely influences both the quality and availability of water. Nuclear power poses its own threats as it continuously releases dangerous radiation and has been linked to increasing cancer occurrences. In current decades, there has been a growing effort to obtain energy from more sustainable sources, such as hydroelectric plants or solar panels. While they are less harmful to the health of the environment and population, these sources demand either advanced machinery or specialized materials to construct. The greater part of the world population without access to electricity lives in rural areas where there is restricted access to the specific parts and materials needed to construct technologies such as solar panels. Moreover, they lack the capacity to build large dams for hydroelectric plants.

C. Potential of Small Wind Turbines

As a substitute, wind turbine technology may provide electricity in these rural locations. In particular, small wind turbines are a smart option for developing markets that at present lack electricity or are energy undersupplied. As a general instruction, Micro wind turbines are classified up to 1 kW. Micro wind turbines have many benefits. They are easy and quick to install as they come in small sizes and have a lower construction lead time than extending the utility grid lines. Small wind turbines can operate for extended periods without attention; with only a few moving parts, these systems have very low maintenance requirements compared to other energy options. Additionally, small wind turbines are not difficult to produce. In this context, local built-up is often a suitable option for developing countries that could, in turn, stimulate local economic development and lower production costs. Wind systems replace existing household expenditures for kerosene, candles and dry-cell batteries. Finally, wind systems require little to no water to operate and do not contribute greenhouse gases or other toxins to the environment. Figure 3 illustrates the growing cumulative ability of small wind power across the globe.

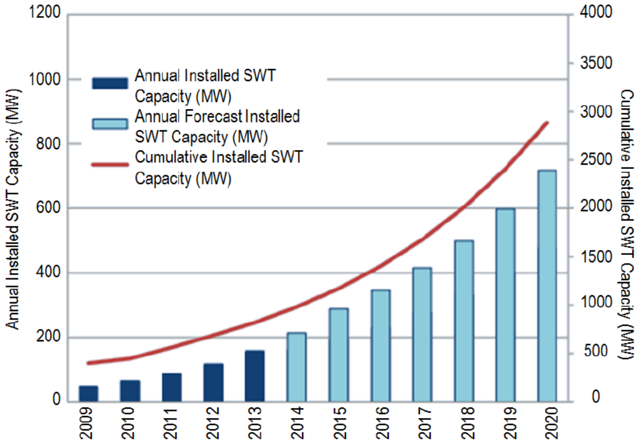

Figure 3: Small wind turbine worldwide installed capacity and forecast [3]

There are about 330 companies in 26 countries manufacturing small wind turbines, and the global market for small wind technologies is forecast to more than double between 2010 and 2015, getting USD 634 million. The installed capacity could increase threefold in the same period [4]. Much of this growth will take place in developing and emerging markets.

D. Design Rationale

While small wind turbines are associated with numerous benefits, their market penetration and social impact still faces certain limitations. Since wind turbines operate in a specified ideal wind velocity range, locations with lower or unpredictable wind speeds are deemed unsuitable for small wind turbine installation. Moreover, locations that are capable to justify an investment in small wind turbines often find that their energy demand quickly increases and that energy yield of the wind turbine is no longer sufficient. In these cases, a reliance on dangerous energy such as diesel persists. This project is aimed at developing a solution that will help rural communities both justify a wind turbine installation and contain growth in energy demand. Figure 4 illustrates the annual frequency of wind speeds collected from a rural village along with the corresponding energy yield of a wind turbine operating at that speed in megawatt-hours.

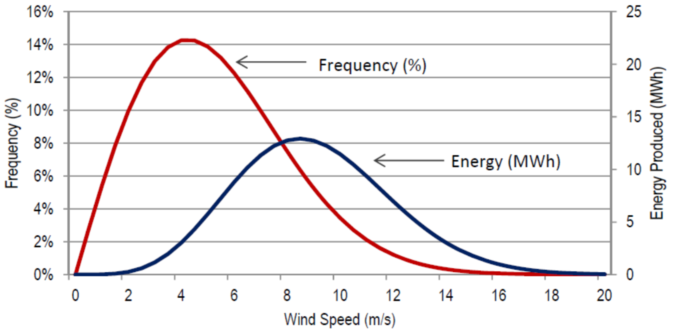

Figure 4: Frequency and energy yield of wind speeds [5]

Equally, Figure 5 models how the annual energy yield would be prejudiced by an increase in the frequency of higher wind speeds. This drastic energy boost is connected with a adjusting the mean annual wind speed from about 4 m/s to about 7 m/s, a factor of 1.75.

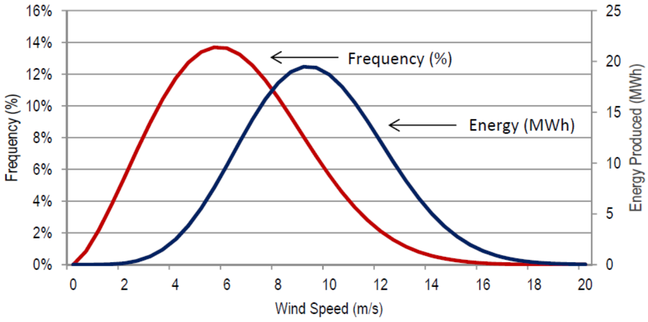

Figure 5: Frequency and energy yield of wind speeds with shroud

Even a slight increase in the frequency of higher wind speeds could result in enough energy yield to justify the construction of a small wind turbine. By revisiting small wind turbine technology and executing design modifications that increase the local incoming velocity, small wind power can become a more reliable and easily reached source of electricity for up to 2.3 billion people across the globe.

II. SHROUDED WIND TURBINE

A. Generating High Output Power with Wind-lens Technology

A new advance in wind technology is the wind lens. It acts as a diffuser, mounted behind the wind turbine, to generate a lower pressure area resulting in increased wind speeds through turbine. The diffuser augmented wind turbine (DAWT) was designed for use on a 5 kW, three blade wind turbine that was to be applied on the shore of Hakata Bay in Japan [8]. Initial tests were performed in order to see whether a nozzle or diffuser would better amplify wind speeds and, between the two different designs, the diffuser performed appreciably better. The data shows that for the prototypes they construct, the high pressure area in the nozzle prevented significant flow through the turbine. This prompted the building of a model that would increase the wind velocity through the wind turbine that included a minor inlet shroud and a diffuser with a brim. A low-pressure region is generated at the rear the brim as vortices are produced. After this general design, four different designs were created, each with a different cross-sectional area. With each of these models the repetitive design method was utilized in order to produce the greatest power coefficient.

Another system for increasing the wind speed through a wind turbine is a proportioned nozzle and diffuser. Nine different models were tested in which the main parameters investigated were the ratio of inlet to turbine diameters, the ratio of outlet to turbine diameters, and the length of transition from inlet to reduction and outlet [9]. Through the use of different geometric variations and CFD modeling, it was determined that a mirrored system where the inlet corresponding the outlet would produce the best results. In order to best investigate the data from modeling and testing, the energy in the airflow and the ratio between energy at the inlet and energy at the turbine blades was calculated by

$$W = 1/2\rho A U^3 \,, \qquad (1)$$

$$\frac{W_2}{W_1} = \frac{\rho_2 A_2 {U_2}^3}{\rho_1 A_1 {U_1}^3} = \left(\frac{U_2}{U_1}\right)^2 \qquad (2)$$

Where W is the wind energy available, ρ is the density of air, A is the cross-sectional area, and U is the velocity of the air. Along with their design, data from the modeling and wind tunnel testing is provided. This data gives the differences in power output from the turbine when provided with a stable wind speed.

B. Small-Scale Wind Energy Portable Turbines (SWEPT)

Not simply is there growth in the wind industry relating to the power production of wind turbines, but also related to the usefulness and portability of turbines. This development of a very small and movable turbine with the combination of a shroud attachment shows that the improvement of wind speeds can be used in many different conditions, large or small [10]. In addition, SWEPT shows that researchers are continually finding ways to improve and increase the effectiveness and applicability of wind turbines.

C. CFD Analysis for Optimization of Shroud for a Micro Wind Turbine

Four distinct scaled shroud geometries were designed in CATIA V5 R17 and were tested using ANSYS Fluent Computational Fluid Dynamics (CFD) software. Because the CFD models were compared to a scaled physical model tested in actual wind conditions, the CFD model used the same sizing constraints that would be applied to the scaled physical testing.

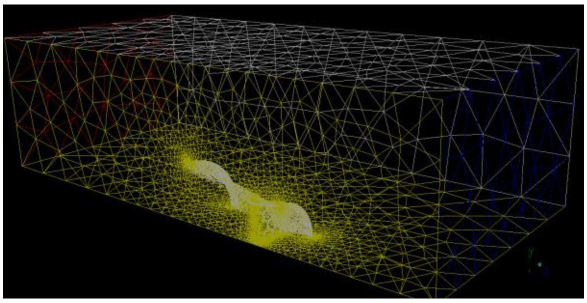

Figure 6: Tetrahedron mesh used to model a quarter of the shroud geometry.

A tetrahedron mesh was used in the CFD modeling of the shroud geometry as can be seen in Figure 6.

D. Efficient Micro Wind Turbine with a Shroud

There exists a simplified blade element theory in with it is assumed that the power (torque from lift) and thrust (from drag) that a wind turbine blades produces depend on the two dimensional lift and drag coefficients of the airfoil selected . The angle of attack α together with the Reynolds number, influence this lift and drag coefficients and ultimately the power production from torque. Figure 7 shows how the lift/drag ratio is dependent of Reynolds numbers and angle of attack for a specific airfoil. A higher Reynolds number gives a better ratio, that also shows the benefit of increased air velocity.

For a specific blade design with a fixed design angle ϴp and α for the blade, the pressure drag (or form drag) on the blade will increase with a higher tip speed ratio as the inflow angle will become less favourable. If this blade design was made at a higher tip speed ratio the airfoil would have encountered stall losses at lower tip speed ratio's, as the relative velocity will influence the inflow angle.

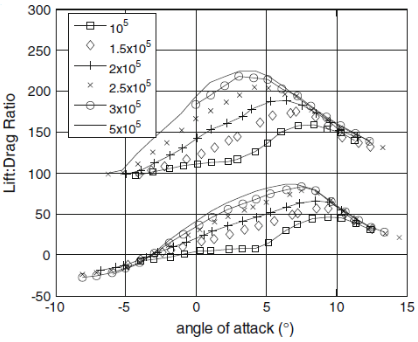

Figure 7: Lift to Drag ratio of two types of airfoils with the top one lifted one unit. Legend gives Reynolds numbers. [31]

E. Blade Design Procedure:

1. Determine the rotor diameter required as for supposed power output of 100 W at low wind velocity of 5 m/s as,

2. According to the type of application, choose a tip speed ratio λ. For a water-pumping windmill, for which greater torque is needed, use $1< \lambda < 3$, For electrical power generation, use $4< \lambda < 10$.
3. Choose the number of blades, B.
4. Select an airfoil. If $\lambda <3$, curved plates can be used, If $\lambda >3$, use a more aerodynamic shape.
5. Obtain and examine lift and drag coefficient curves for the airfoil. Note that different airfoils may be used at different spans of the blade; a thick airfoil may be selected for the hub to give greater strength.
6. Choose the design aerodynamic conditions for each airfoil.
7. Choose a chord distribution of the airfoil. There is no easily physically accessible way of doing this but a simplification of an ideal blade is given by:

$C = 8\pi r\cos\beta/3B\ \lambda T$

This gives a moderately complex shape and a linear distribution of chord may be considerably easier to make. So, β can be calculated from equation as

$\beta = 900 - 2/3 \tan-1(1/ \lambda T)$

The obtainable power from a cylinder of fluid with cross sectional are A and velocity V1 is,

$P = Cp\ .\ ½\ .\ \rho\ .\ A\ .\ V13$

The total power is

$Pw = ½\ .\ \rho\ .\ A\ .\ V13$

The power coefficient

$Cp = P/ Pw$

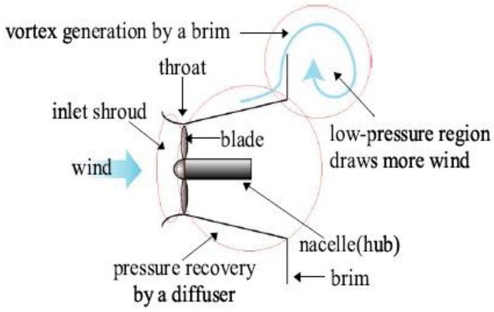

Figure 8: DAWT with inlet shroud and brim [13]

The product built had a diffuser length of 305 mm, diffuser angle of 15^0 and a brim height of a 10 mm. A wind turbine with ten blades was incorporated inside the diffuser. The same type of wind turbine without a diffuser and brim was constructed near this shrouded wind turbine to compare the energy output over a certain period of time. Some troubles were experienced with the adjusting of the field device to the wind direction. Thus, the researchers fixed the bare wind turbine and shrouded wind turbine in the direction where the frequency distribution of the wind was high. The total energy generated for the entire day was measured and it was found that the shrouded wind turbine produced 3.1 times more energy than the conventional wind turbine. The performance of the wind turbine depends strongly on the loading coefficient and the angle of the diffuser. This significantly affects the nature of the separation in the diffuser.

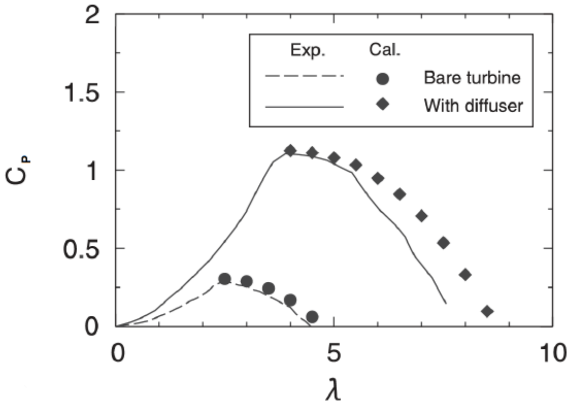

Figure 9: Power coefficient / tip speed ratio of a wind turbine with brim tested by Abe et al.[14]

It will be possible to have a higher pressure drop over the area of the wind turbine with a lower air velocity or a lower pressure drop with a higher air velocity. The second seems to increase the energy output of the turbine in this type of configuration. From various results obtained in the CFD investigation, it became clear the optimum loading coefficient for every variation of the diffusers angle, length and brim height needs to be determined. The wind turbine used in the experiment had a diameter of 400mm. Figure 9 prove that the power coefficient of the wind turbine with the diffuser was substantially higher than the bare wind turbine. The energy output is much higher than the diffuser with brim of, this can be devoted to the larger diffuser angle and brim. From the investigation it was also found that the shrouded wind turbines' peak performance was at a higher tip speed ratio than that of the open wind turbine. Figure 10 also shows that the experimental data and CFD modeled power coefficient results correspond well.

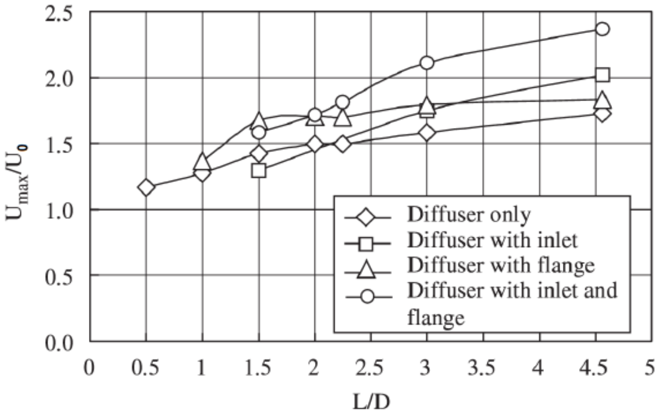

Figure 10: Velocity increase with different configurations of components and length ratio's (Ohyaet al. 2008)

Ohya et al. [15] did some experiments with variuos configurations of components. The results are presented in Figure 8. The total length divided by the inlet diameter is denoted on the horizontal axis of the graph. The free wind speed is U_0 and U_{max} is the maximum airspeed as obtained at the throat. It is evident that the configuration with diffuser, brim and inlet shroud offers the best velocity ratio. Another important feature to be taken into account is the length of such a pattern. Findings proved that the air speed inside increases when the diffuser is lengthened. However, carefulness to apply a very long structure is emphasized as it will have realistic constraints, for example when to be constructed on a tower. For the field test an 8mtower was erected by Ohya et al. (2008) and a diffuser inlet diameter of 0:72m was decided upon with a total length of 0.9m and brim height of 0:36m was applied. The practical and calculated results show a power coefficient Cp = 1.4 compared to a Cp = 0.35 for the open turbine. Ohya et al. (2008) also deviced and constructed a number of compact shrouded wind turbines with the same configuration as above with total length divided by the inlet diameter of 0.22 and a total diameter of 2.5m. The wind turbines were rated as 5 kW. A Cp = 0.54 was obtained when the total outer diameter (brim included) was used to find the power coefficient. This is still an exceptional performance as most wind turbines on the market only have a power coefficient of Cp = 0.4.

From the field devices that were tested it could be observed that the Cp value of a DAWT was larger. This is also the case even though the outer diameter of the angle is used as reference and not the blade maximum diameter.

The numerical investigation by Abe and wind tunnel experimental results by Abe et al. also discovered the advantages of a shrouded wind turbine compared to an open wind turbine. This arrangement could thus be used to improve the drawing out of energy from low speed wind for more efficient power production.

F. Concentrators

Concentrated wind will increase the power yield in relation with the rotor-swept area [16]. A wind turbine in the concentrator will come across a higher air speed and rotate at a higher revolution per minute. This wind turbine will also start rotating at a lower free wind speed as the concentrator enhances the air speed. Therefore, the concept of a concentrator should be advantageous. Recent work, as will be investigated further, will give some insight into this idea. The experimental work with concentrators by Shikha et al. [17] found that a concentrator with an outlet to inlet ratio of 0.15 displays the best increase of 4 to 4.5 times the free wind speed, at the outlet. If the increase was found with continuity and incompressibility (at low Reynolds numbers) the speed at the outlet should have been 6.7 times that of the free wind speed. From this it can be accomplished that some of the mass flow tends to avoid the concentrator. This is a result of the abrupt increase in area at the outlet of the concentrator, skin friction drag and pressure drag. These losses create a obstacle to flow while a free wind stream usually evades such restrictions. Ohya et al. [15] also experimented with concentrators and the conclusion is presented in Figure 9 which confirms the results of Shikha et al. [17]. Ohya et al. [15] found that the wind tends to avoid the nozzle-type model.

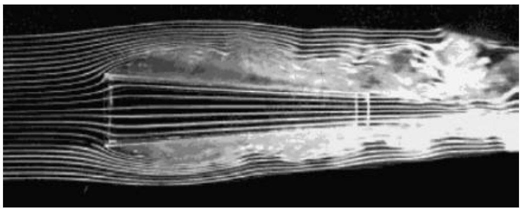

Figure 11: Concentrator in a wind tunnel [15]

Recently, concentrators are mostly used in combination with vertical axis wind turbines. The air flow is intensed and deflected away from the one side of the horizontal blades, thus reducing drag and increasing the power output of the wind turbine [18]. However, for HWAT's there is an only new development with a concentrator in conjunction with a diffuser (Figure 10). As the diffuser is fixed to the outlet of the concentrator, the losses of energy that happen with the sudden increase in area are avoided. Recently did CFD simulations and wind tunnel tests on a concentrator with diffuser configuration [19]. When the wind turbine was fitted into the shroud the captured energy amplified with 43% for the same free wind speed. This emphasizes the significance of a shrouded wind turbine. It is further proposed that the configuration should rather be build-in or mounted on a structure than mounted on a pole. Wang et al. (2008c) concluded after extensive research that an existing wind turbine cannot be used in the shroud. The need was confirmed for newly devised blades and hub to set the conditions in the shroud.

A new advance in wind technology is the wind lens. It acts as a diffuser, mounted at the back of the wind turbine, to create a lower pressure area resulting in increased wind speeds throughout turbine. The diffuser augmented wind turbine (DAWT) was devised for use on a 5 kW, three blade wind turbine that was to be applied on the shore of Hakata Bay in Japan [8]. Initial tests were performed in order to see whether a nozzle or diffuser would further increase wind speed sand, between the two different designs, the diffuser performed drastically better. The data indicates that for the prototypes they built, the high pressure area in the nozzle prevented significant flow through the turbine. This encouraged the construction of a model that would increase the wind velocity through the wind turbine that added a slight inlet shroud and a diffuser with a brim. A low-pressure region is generated behind the brim as vortices are formed. After this common design, four different designs were formed, each with a different cross-sectional area. With each of these models the iterative design process was used in order to produce the greatest power coefficient.

The eventual objective of this paper is to provide information on the velocities through the turbine of shroud design using CFD (computational fluid dynamic) modeling. Wind turbines have a specified wind speed operating range at which they generate energy at higher efficiencies. A successful shroud model increases the incoming wind speeds with a nozzle/diffuser shroud mounted to the turbine to amend the wind flow convergence. Particularly, the shroud increases wind speeds through the turbine, is structurally sound, and minimizes drag.

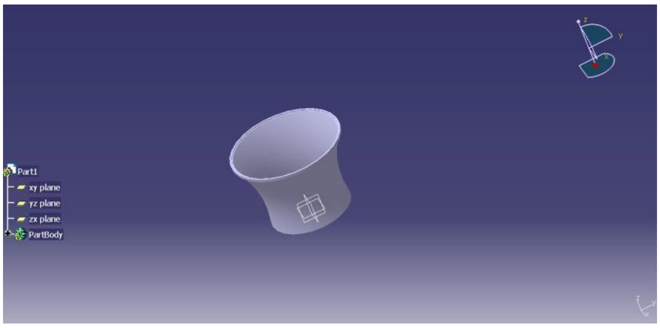

Figure 12 : Model of Shrouded wind turbine

III. RESULTS AND DISCUSSION

The primary analysis included four factors: flange angle, angle of openings, nozzle length, and diffuser length. The factors were measured at a maximum and minimum value selected based on insights provided in available literature. In this case, wind velocity at the location of the turbine blades was used as the output for each iteration. The two levels analyzed for each factor were as follows:

Table 1: High and Low Values of Four-Factor DoE

Isolated Factor	High Value	Low Value
A) Flange Angle	25^0	0^0
B) Opening Angle	25^0	5^0
C) Nozzle Length	5.0 in	0.20 in
D) Diffuser Length	14.0 in	0.50 in

The geometric specifications of the selected shroud are shown in Table 2. The final design features a 3:1 ratio between diffuser length and nozzle length as well as a 3:1 ratio between the opening angle of the diffuser and the opening angle of the nozzle.

Table 2: Geometric specifications of selected shroud

Nozzle angle	5^0
Diffuser angle	15^0
Nozzle length	4 in.(102 mm)
Diffuser length	12 in. (305 mm)
Flange angle	90^0

According to the CFD modeling results, this shroud design effective in reaching the performance requirements of increasing the velocity by a factor of 1.46, which theoretically would result in a power increase greater than 3. The 90^0 flange angle helps maintain the requirement of manufacturability as perpendicular angles are common in machining and therefore easier to produce. These results justified the construction and fabrication of a scaled model to be tested in actual wind conditions for data validation.

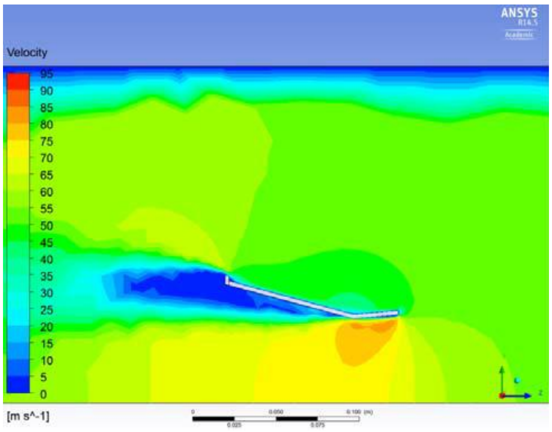

Figure 13: Cross sectional view of a quarter shroud geometry showing wind velocity contours around shroud

In order to simplify the calculations done and increase the detail of the mesh by the CFD analysis, only a quarter of the geometry was modeled assuming the flow would be symmetrical through the shroud. The average wind speeds available is 4.5 m/s.

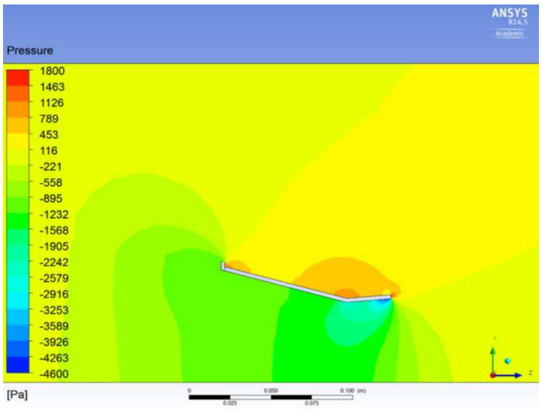

Figure 14: Cross sectional view of a quarter shroud geometry showing pressure contours around shroud

This software was useful in that it allows a visual comparison of how geometric factors affect the presentation of the shroud through the analysis of velocity and pressure curves. For example, Figure 13 and 14 displays Cross sectional view of a quarter shroud geometry showing wind velocity and pressure contours around shroud.

IV. CONCLUSION

This paper investigated one approach to improve the utility of micro wind turbines. By attaching a flanged concentrator and diffuser shroud, the wind velocity at the blades is locally increased, thereby improving the energy production at lower wind speeds. The design of the shroud was accomplished through CFD modeling in ANSYS Fluent by isolating geometric factors and determining their influence on the performance. The most influential factor on the performance of the shroud was determined to be the length of the diffuser. Several attempts were made to model the effect of rotating turbine blades in ANSYS but none were able to accomplish this accurately.

A shroud design that met the design and performance criteria was selected and a scale model was fabricated locally and tested in actual conditions. The factor by which wind turbine power production was increased by the addition of the shroud was measured to be 3.1, which is associated with a wind speed increase of 1.46. When scaled to full-size, this raises concerns for the structural integrity of the turbine base. Further structural analysis will be required as the turbine used for full scale implementation is selected. Pressure drop across the shroud validated the CFD modeling results. This encourages the use of ANSYS Fluent as a tool to model the system at a larger scale.

If the blade area is used as reference at 3:5m/s, then Cp;max = 0:72 and Cp;max = 0:883 at 9m/s at a generator efficiency of 88%, that was in the reach of the shrouded wind turbine. When the outer area has been taken as reference, a Cp;max = 0:25 which increased to Cp;max = 0:28 at a free wind speed of 9m=s at a generator efficiency of 88%. The value of Cp;max was lower with the effect being reduced in the higher wind speeds.

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