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Optimization of micro wind turbine for the urban area of Ranchi

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Abstract—Ranchi, after becoming the capital city of Jharkhand state on 15 November 2000, has seen rapid economic activities, infrastructure development, and population growth. Availability of manpower from reputed technical, management, and educational institutions along with good transport and communication facilities, RIA(Ranchi Industrial Area) has attracted many companies and entrepreneurs. All this growth and development requires and has been consuming a lot of power which needs to be dealt with quickly and efficiently. The major energy provider still being the conventional TPP(Thermal Power plant), such a huge rise in demand surely brings big environmental issues in the future. This paper suggests the use of specially designed micro wind turbines for the urban environment of Ranchi to be used on rooftops of domestic and commercial infrastructures to generate part of the total demand at the load point itself. This arrangement apart from being low cost can be propelled by a wind speed as low as 2 m/s and can be easily installed on the existing rooftops of the infrastructure without seriously compromising their structural integrity. This arrangement would not only release the increasing pressure on existing power generating units but would also provide relief to the overburdened transmission and distribution lines, thereby solving various issues like power shortage, high T&D losses, collapse due to poor maintenance of existing overhead distribution systems in overpopulated areas, and high tariff and many more.

Index terms- aerodynamics, angular velocity, electrical energy, low wind speed, micro wind turbine, power coefficient, small wind turbine, tariff, Wind

1 INTRODUCTION

Energy, without doubt, can be considered the most critical parameter in the entire process of evolution, development, and survival of all living beings and is a responsible factor for determining the socio-economic development and human welfare of a state or country. Due to its key importance energy has been referred to as a 'strategic commodity in almost all countries' economies and any uncertainty in its supply threatens the functionality of the economy, especially in developing countries like India.

1.1 Situation In Ranchi, Jharkhand

There has been unprecedented economic growth in Jharkhand's economy. Presently, Jharkhand is one of the leading states in terms of economic growth. At current prices, Jharkhand's total GSDP stood at Rs. 3,61,381 crore (US$ 49.48 billion) in 2021-22, a 5% increase over FY20. Ranchi being the center of Jharkhand has always been the center of all development.

Ranchi after becoming the capital city of Jharkhand state on 15 November 2000, has seen rapid growth in terms of economic activities, infrastructure development, and population

Jharkhand is one of the richest mineral zones in the world and boasts 40% and 29% of India's mineral and coal reserves, respectively. Due to its large mineral reserves, mining and mineral extraction are the major industries in the state. Mineral production (excluding fuel minerals, atomic minerals, and minor minerals) in the state stood at Rs. 927.48 crore (US$ 127.21 million) in FY21 (until August 2020). Jharkhand is rich in mineral resources such as coal (27.3% of India's reserves), iron ore (26% of India's reserves), copper ore (18.5% of India's reserves), uranium, mica, bauxite, granite, limestone, silver, graphite, magnetite and dolomite. Jharkhand is the only state in India to produce coking coal, uranium, and pyrite. With 25.7% of the total iron ore (hematite) reserves, Jharkhand ranks second among the states. The state's industries enjoy a unique location-specific advantage as it is close to the vast market of eastern India. It is closer to the ports of Kolkata, Haldia, and Paradip, which helps transport minerals [1]. This high order of sustainable economic growth is placing enormous demand on Jharkhand's mining resources previsioning the demand and supply imbalance in energy across all sources. This pervasive requires serious efforts by the government of Jharkhand for augmenting energy supplies as Jharkhand is facing severe energy supply constraints.

In this work, we are going to consider various aspects of micro wind turbine utilization in the urban area of the Ranchi district. The aspects under investigation are micro fan-bladed wind turbines, rapid starting, efficient power extraction, minimal mass, and economic evaluation.

2 METHODOLOGY

2.1 Wind turbine Profile

The wind turbine we considered for our work is a micro fan-bladed wind turbine as shown in fig 1 below, having a fan-type blade configuration rather than an aerofoil type configuration. This configuration provides increased power efficiency. A blade of the microturbine needs to be short it must be mono thick along the blade length rather than linear taper blades from root to the tip used in large wind turbines. This will also reduce the undesirable aerodynamic behavior at the low chord Reynolds number (R_e) encountered by small blades.

Figure 1:Micro wind turbine design [2]

The turbine blade twist extent is displayed in the transactional view above, to generate torque more efficiently in different wind conditions. Important geometric parameters are shown below in the nomenclature. Another major advantage of such turbines is that they can be connected to add up the power and meet any requirement easily.

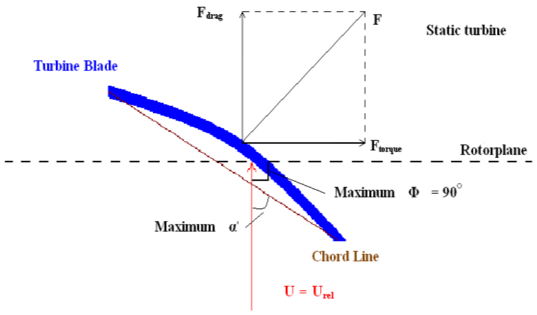

Figure 2:Blade aerodynamics for the static micro wind turbine[2]

2.2 Wind turbine optimization

The wind turbine was optimized by varying the blade subtend angle and number of turbine blades and the following parameters were recorded:

I. Maximal angular velocity for different speeds.
II. Torque value and drag force acting on blades in stationary and rotating conditions for different wind speeds.
III. Mechanical energy captured at different wind speeds by the turbine

Blade Subtend-Angle α	Blade Pitch Angle θ (tip~root)	Blade Twist Angle B	Blade No. N_B	Solidity Σ (%)
30°	46.22°~ 67.38°	21.16°	12~3	78.4~ 19.6
40°	39.07°~ 61.82°	22.76°	9~3	78.4~ 26.1
45°	36.42°~ 59.49°	23.07°	8~3	78.4~ 29.4
60°	31.07°~ 54.18°	23.12°	6~3	78.4~ 39.2
72°	28.75°~ 51.60°	22.85°	5~3	78.4~ 47.0
80°	27.91°~ 50.63°	22.71°	4~3	69.6~ 52.2
90°	27.55°~ 50.19°	22.64°	4~3	78.4~ 58.8
100°	27.91°~ 50.63°	22.71°	3	65.3
110°	29.04°~ 51.94°	22.90°	3	71.8
120°	31.07°~ 54.18°	23.12°	3	78.4

Table 1: Computation cases and parameters. [2]

2.3 Wind turbine material & structure

The material and structure of the wind turbine plays important role in deciding the aero-dynamic torque generated by the blade. Hollow blades with minimum shell thickness are used to reduce blade inertia J_B while remaining sufficiently strong. Examples of small turbine blades formed using hollow composite can be found in Clausen et al. (2013).
The first airfoil considered is SG6043 developed by Giguere and Selig in 1998. As seen in figure 3 below, it has an outstanding lift-to-drag ratio to maximize power output.

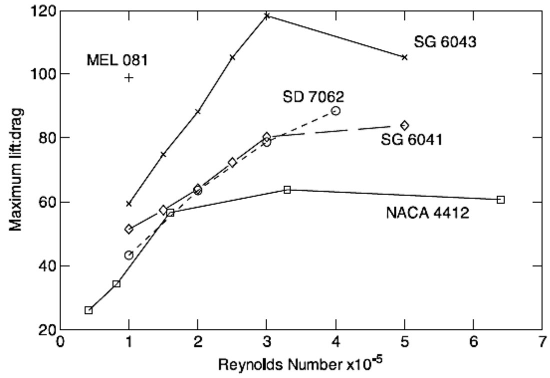

Figure 3:Airfoil lift to drag ratio at low Reynolds number from Wood (2011)

The SG6043 has a maximum thickness of 10% which causes a high-stress level at the root of the blade, so 14% thick SD7062 (Giguere and Selig 1997) was considered. Figure 3 above shows it to have a good lift and drag ratio but the power produced would be less than SG6043.

2.4 Structural analysis

The blade surface shape depends on the aerodynamic requirements but the structure is also very important. The blade material should be sufficiently strong and fatigue resistant. The interaction of material properties and aerodynamics is unique to small blades. The structural model is based on simple Euler-Bernoulli beam theory (e.g. Hansen 2008) and is a simplified version of the one used by Sessarego (2013) and Sessarego et al. (2014).

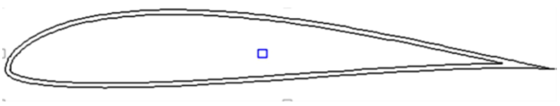

Figure 4: Structural model of a small blade

Quantity (units)	E-glass-polyester	Flax-polyester	ABS M-30	Hoop pine	Bamboo-petroleum resin
Elastic modulus (Gpa)	36.9	23.4	2.4	12.1	20.5
Blade density (kg/m3)	1640	1290	1040	550	Not given
Max.Strain	7684	5420	7500	3250	4270

data from table 2 of Shah et al.(2013)(first two), ABS M-30 material data sheet, table 1 of Peterson and Clausen (2004) for hoop pine and Holmes et al.(2009) for last who gave no information on the resin.

Figure 5: Material properties used for blade optimization

A safety factor of 2 between UTS (ultimate tensile strength) and yield strength was used to calculate the composite strength as 283.5 MPa. The resulting maximum strain is found using Hook's law:

$$283.5 \times 10^{6} = 36.9 \times 10^{9}\ \varepsilon$$

where ε denotes strain and is taken as 7,684 μstrain.

2.5 Blade material Optimization

For optimizing starting torque and power extraction we use,

$$\text{minimize}\left(\max\left[w\frac{1/C_p(i)-1/C_{p,\min}}{1/C_{p,\max}-1/C_{p,\min}},\ (1-w)\frac{T_s(i)-T_{s,\min}}{T_{s,\max}-T_{s,\min}}\right]\right)$$

For blade I, C_p is the conventional power coefficient at the design wind speed, taken to be 5m/s. The weight w (0 <w <1) determines the relative significance of power starting and extraction. When w=1, the optimization is for power. T_s is the starting time required to reach the tip speed ratio at desired wind speed [2].

The three composite blades used hollow sections and the timber blade was solid. The minimum shell thickness was set as 0.01 of the chords. The thickness of the blade section was between 0.02*c* to 0.24*c*. No calculations were done for the bamboo composite, whose overall performance is similar to the flax polyester blade.

2.6 Cost of Energy (COE) Model

The design objective of maximizing annual energy production or using sequential aerodynamic and structural optimization is suboptimal compared to the aero structural integrated methods [3]. In variable rotor diameter and hub height, the optimal rotor diameter becomes misleading as the tower mass is dominating factor of turbine total mass. Hence, COE minimization is a better option than minimizing turbine mass to annual energy production ratio. The cost of energy is calculated as

$$\mathbf{COE = F_{CR} \times I_{CC} + A_{OC} / A_{EP}}$$

here, F_{CR} – Fixed charge rate
I_{CC} – Initial capital cost
A_{OC} – Annual operating cost
A_{EP} – Annual Energy production

The FCR, ICC, and AOE are obtained from the National Renewable Energy Laboratory wind turbine design and scaling model [4]. The BEM code and the Weibull probability distribution with a wind speed of 6 m/s were used to calculate AEP [4]. The total cost of a wind turbine is defined by adding the value of the initial cost multiplied by the fixed charge rate to the annual operating expenses. The fixed charge rate is the annual amount used to cover the capital cost and other fixed charges. The FCR value is taken 0.1158/ year [4].

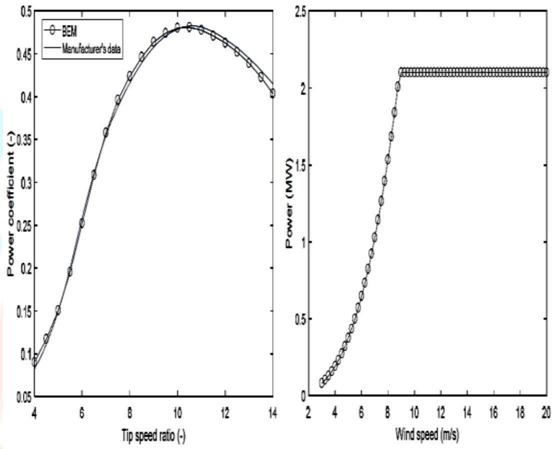

Figure 6:comparison between the power coefficient and power curves obtained by blade element

2.7 Cost optimization

According to the wind turbine blades used in class I, the same turbine family used in class III has a length of 130 to 140% [5]. When the length of the blades increases, the blade mass, and tip deflection also increase. For structural and aerodynamic performance, the function to minimize the cost of energy is given by f, where:

$$\textbf{Maximize } f = 1/\text{COE}$$

Figure 7 below shows the flowchart of the optimization process. The aerodynamic and structural variables for the blades and the tower are randomly generated as the initial population. The aerodynamic variables are used to control the shape of the blade, the structural variables are used to control the webs locations and number of layers along the blade, and the variables for the tower are used to control the tower height and structural parameters. BEM theory is applied to calculate the annual energy production and the aerodynamic loads which causes the blade deflection and tower deformation.

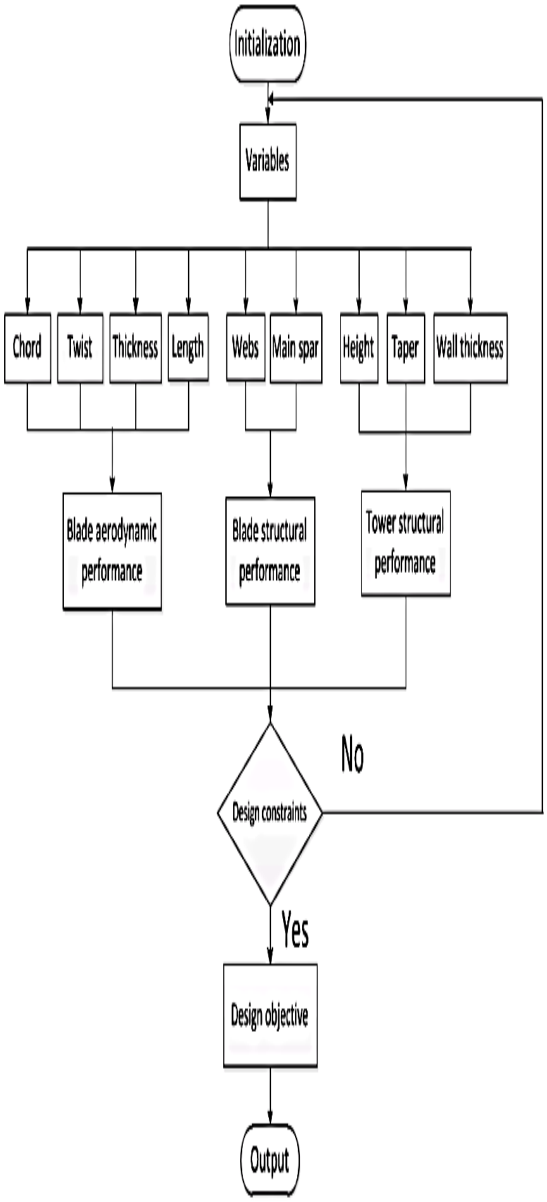

Figure 7:Flowchart of the optimization process.

Most of the components are functions of the parameters such as rotor diameter and rated power as shown in fig 8 below.

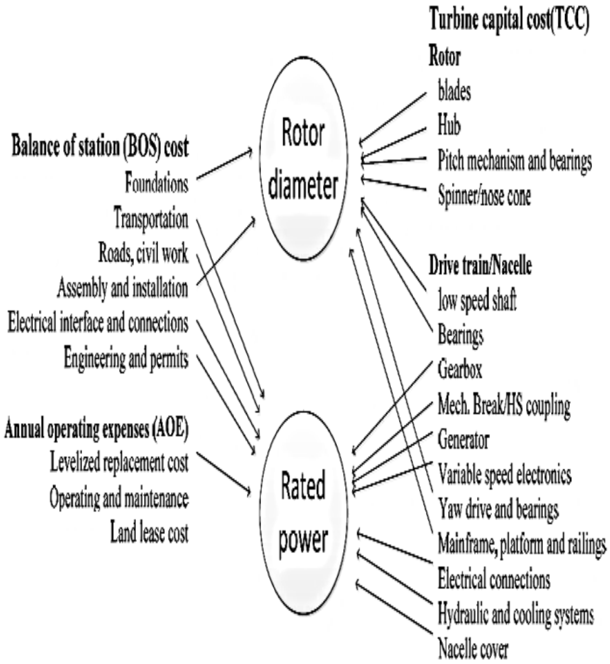

Figure 8:Relationship of the rotor diameter and rated power to the components of the wind turbine.

The relationship shows that the rated power also has a strong impact on COE. Thus, the optimization procedure considering rated power has to be set.

3 RESULTS

Figure 9 shows the comparison of the CFD and experimental results on the maximal angular velocity of the wind turbine at different speeds. Without any load, the wind turbine rotates freely and the angular velocity is increasing linearly with wind speed.

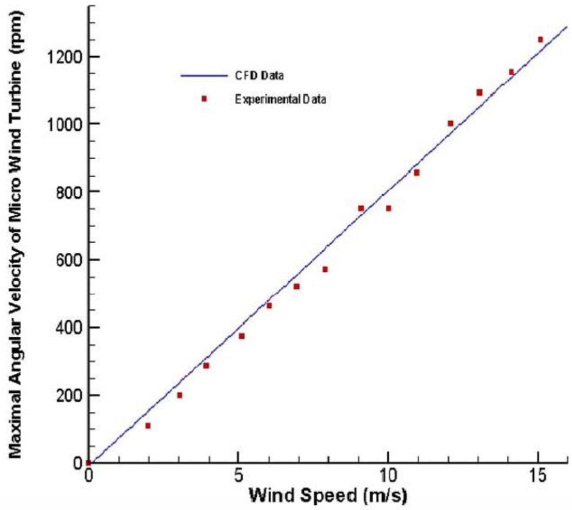

Figure 9:Maximal angular velocity Vs wind speed.

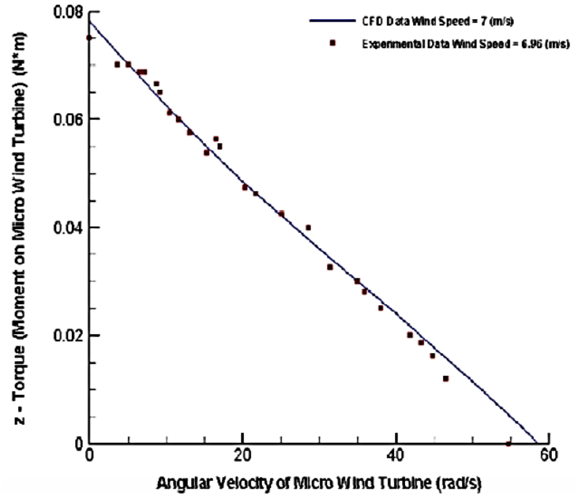

Figure 10:Torque Vs angular velocity at wind speed 6m/s

Figure 10 shows the relationship between the torque and the angular velocity of the wind turbine at a medium wind speed (6m/s). It is clear that torque decreases with the rotational velocity of the wind turbine. The torque and maximal angular velocity relation are not strictly linear.

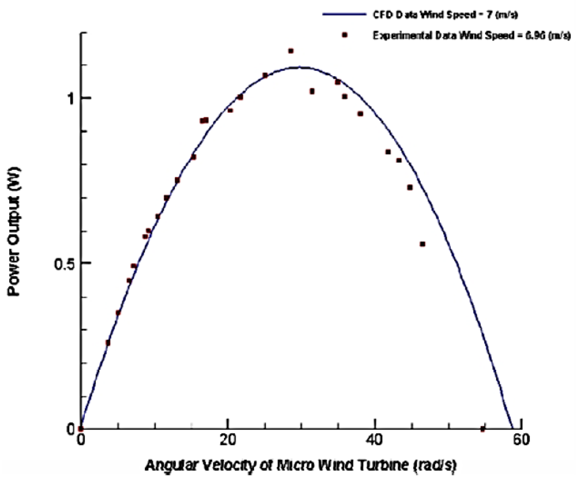

Figure 11:Power Vs angular velocity at wind speed 6m/s

The power output is obtained by multiplying the angular velocity of the turbine with the torque value captured by the turbine, rotating at a given angular velocity. The curve in figure 11 shows that the mechanical power output of the turbine increases angular velocity, reaching its maximum at the optimal angular velocity, and then decreases.

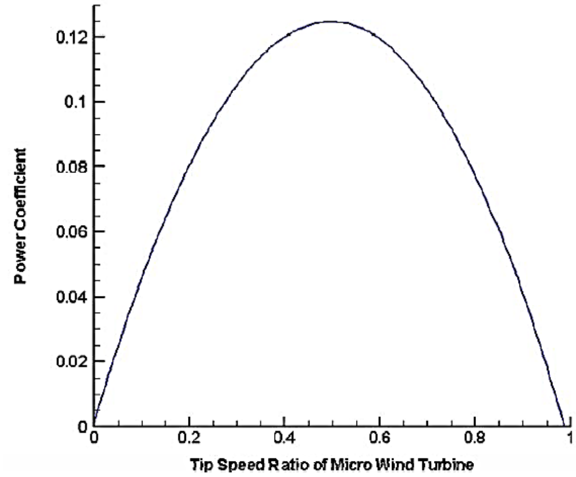

Figure 12:Cp- λ characteristic of a micro wind turbine.

Figure 12 shows the relationship between the power coefficient (C_P) and the tip speed ratio (λ) of the micro wind turbine. It can be seen that the microturbine operates at a tip speed ratio between 0-2 range while large-scale turbines operate at a tip speed ratio higher than 4 [6]. Also, the maximum power coefficient of the turbine shows the efficiency of transformation to be approximately 12%.

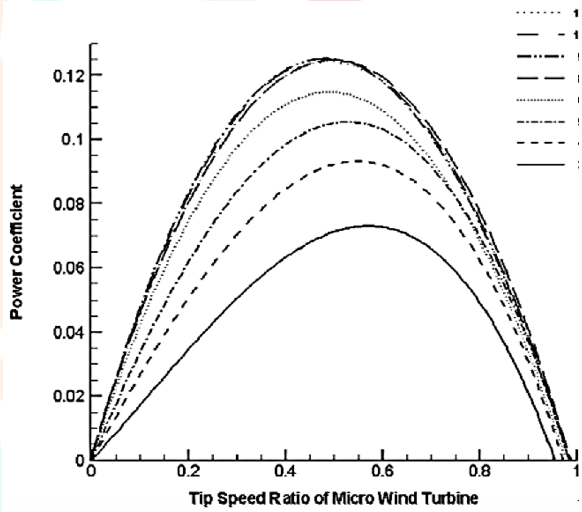

Figure 13:Power coefficient of the micro wind turbine

For a given blade subtend angle, a greater number of blades give better performance, still, a fully occupied rotor plane is not recommended for both power output and starting torque of a micro wind turbine. A blade with more than 90^0 subtend angles is not recommended as it would affect the starting performance poorly.

Solidity	Blade Subtend-Angle	Blade No.	Maximal Power Coefficient
19.6%	30°	3	0.073
26.1%	40°	3	0.103
29.4%	45°	3	0.120
32.6%	30°	5	0.105
34.8%	40°	4	0.131
39.2%	45°	4	0.149
43.5%	40°	5	0.145
47.0%	72°	3	0.170
49.0%	45°	5	0.163
52.2%	80°	3	0.188
58.8%	90°	3	0.186
62.7%	72°	4	0.189
65.3%	60°	5	0.193
69.6%	80°	4	0.203
71.8%	110°	3	0.185
78.4%	72°	5	0.191

Table 1Solidity of the micro wind turbines and their maximal power coefficient.

Table 1 lists the solidity of the micro wind turbines and their maximal power coefficient in the optimization analysis. These data indicate that turbines with high solidity have, in general, higher power coefficients than that with low solidity. For the low-solidity turbines, the power coefficient increases with increasing blade subtend-angle for certain solidity. For high-solidity rotors, however, the maximal power coefficient occurs at a certain blade subtend angle.

Material	w	C_p	T_s (s)	Mass (kg)	Frequency (rad/s)	Tip deflection (m)
E-glass/polyester	1.0	0.477	1.42	0.288	156	0.146
	0.75	0.476	1.28	0.331	175	0.231
	0.5	0.427	0.87	0.262	149	0.169
Flax/polyester	1.0	0.477	1.18	0.203	135	0.245
	0.75	0.476	1.04	0.259	146	0.202
	0.5	0.457	0.79	0.240	141	0.226
ABS M-30	1.0	0.474	1.79	0.698	81	0.447
	0.75	0.470	0.90	0.520	114	0.352
	0.5	0.464	0.84	0.523	115	0.346
Hoop pine	1.0	0.477	1.71	0.351	124	0.200
	0.75	0.475	1.54	0.516	164	0.116
	0.5	0.391	1.00	0.525	149	0.136

Table 2:Blade optimization results for the SG6043 airfoil

For all materials, the decrease in C_P is significant only for w = 0.5; for all other w, it is unlikely that a small difference can be noticed in terms of the actual power production of a real turbine using these blades.

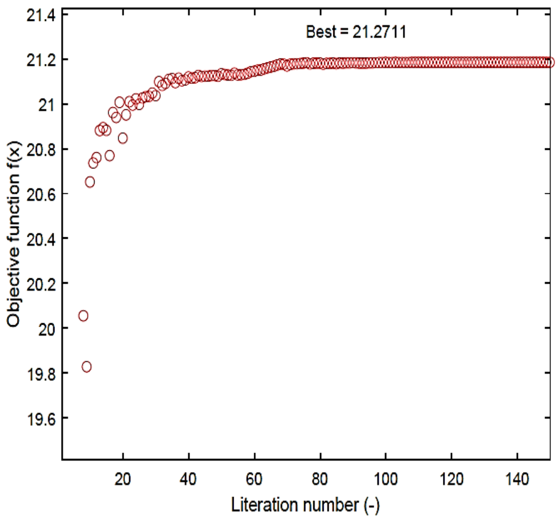

Figure 144:course for the optimization process considering rated power

After finishing the design process, the iterative course of the optimization process is shown in figure 14 above for the given rated power. The optimum result is obtained when the iteration steps reach 80.

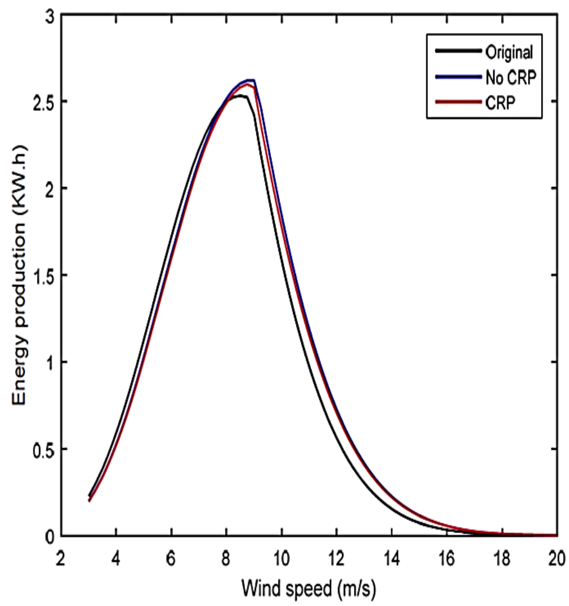

Figure 155: comparison of annual energy production between optimal blades and original ones.

Figure 15 shows the comparison of the power curves between the optimal blades and the original ones. The new blade without considering the design value of rated power as a variable can achieve the power of 2.1KW at the rated wind speed of about 6m/s. The design value of the rated power of the optimal wind turbine by considering rated power as the variable is 1.9 KW.

4 CONCLUSION

This study investigates the variation of the performance of micro wind turbines with different design parameters. The results showed that the performances of high-solidity wind rotors are better than those of low-solidity ones. However, for turbines with identical blade subtend-angles, one with a fully-occupied rotor may not be the best profile, since its blades block the wind acting on neighboring blades. The optimization results also show that the preferable solidity of the micro wind turbine is higher than 50%. From the optimization analysis, it is known that rotors with a larger number of blades can produce higher torque when they are stationary. As a result, a multi-blade approach is preferable for a micro-scale wind turbine system. Considering the power coefficient and the starting effect, the 5-bladed micro wind turbine with a 60-degree blade subtend angle is the optimal turbine profile. Its maximal power coefficient is much higher than that of the preliminary turbine design (8-bladed rotor with 30-degree blade subtended angle) and its higher power coefficient range is much wider.

For materials 1,2 and 4, the better performing SG6043 airfoil produces better output and starting time, because shell thickness did not exceed any design, meaning the materials were sufficiently strong. It was also seen that rapid prototyping has great potential for small blade manufacture since it does not require expensive molds and can produce blades designed for specific conditions. ABS M-30, while a relatively strong plastic, was weaker than materials 1,2, and 4. But, the blades were not significantly inferior and the shell thickness exceeded the minimum.

The results presented here show the complex interaction between the multiple aerodynamic requirements of micro wind turbine blades and the strength and density of the material from which they are made.

The arrangement seems suitable and feasible to be used in the urban areas of Ranchi, but still, the overall system needs to be checked for fatigue which is very important as the IEC 61400-2 procedure stipulates that the blade designed would experience an excess of 10^{10} fatigue cycles over a 20-year lifetime. Also, the wind shadow effect was not considered during the investigation which would be a very critical point in deciding the overall feasibility of the project as the surrounding areas if having tall structures would obstruct the wind flow. The same would occur in densely populated areas where the buildings are made near each other as they will interrupt the flow of wind and we can not get the desired wind speed for the wind towers to generate enough power to make the overall cost of the project viable.

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