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Micro Wind Turbine Design Considerations to Utilize Maximum Wind Energy

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Abstract

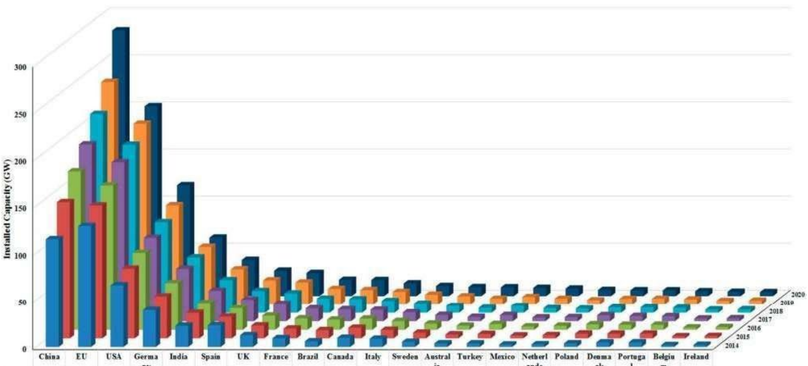
The transition to renewable energy is essential to combat climate change, ensure sustainability, guarantee energy security, and drive global socio-economic progress. Depletable energy sources, e.g. coal, oil, along with natural gas, are going to end, making the shift toward renewable alternatives like wind, solar, and geothermal energy crucial. It can be expected that wind energy will play a vital factor in the world's clean energy transition. In India, wind power contributes 10% of the total energy production, with its adoption dating back to 1985. Micro wind turbines, designed for decentralized electricity generation, differ from large wind farms by catering to individual homes, businesses, and small-scale applications. To maximize wind power efficiency, various design considerations are necessary in the pre-design phase. These include optimal turbine location, blade geometry, and material selection to ensure durability and efficiency. The surrounding buildings significantly impact wind flow patterns, influencing turbine performance. Methods such as CFD simulation, field data collection along with wind tunnel testing can help to analyze the wind potential and turbine efficiency. CFD simulations model fluid flows, heat transfer, and related dynamics, aiding in turbine optimization. Results indicate that strategic turbine placement and structural modifications enhance wind capture, accelerating power generation. With continuous advancements, wind energy is set to become a cornerstone of renewable energy solutions. Innovations in turbine technology and aerodynamics will further improve efficiency, reinforcing wind power's role in achieving a sustainable energy future.

Keywords: Computational fluid dynamics, Microgeneration, Renewable energy, Sustainability, Wind corridor

1. Introduction

Among all the regenerative resources, wind is one of the promising energy sources. Because non- renewable resources like fossil fuels, natural gas, and oils are finite, our future generation will be unable to use them if resource usage is not controlled. Non-renewable energy sources, such as coal, oil, and natural gas, have long powered the global economy, but they come with significant environmental and sustainability challenges. The extraction, processing, and burning of these fuels release vast amounts of carbon dioxide and other greenhouse gases, which are the primary drivers of global warming and climate change. In contrast, renewable energy sources such as solar, wind, hydro, and geothermal offer a cleaner, more sustainable path forward. These sources harness natural processes that are continuously replenished, meaning they will not run out over time. Renewable energy systems produce little to no greenhouse gas emissions, drastically reducing the impact on the environment and improving air and water quality. Beyond environmental benefits, renewables promote energy independence by reducing reliance on imported fuels and helping to stabilize energy prices. They also drive economic development through the creation of new industries and jobs in installation, maintenance, and research.

As technology advances, renewable energy is becoming more efficient and affordable, making it an essential solution for addressing both the energy demands of the future and the urgent need to protect our planet.Wind energy is increasingly favored among renewable energy sources due to its wide availability, environmental friendliness, and declining cost. Unlike solar energy, which depends on sunlight and can only operate during the day, wind turbines can generate electricity both day and night, provided wind is present. This allows for more consistent energy production in suitable locations. In comparison to hydropower, wind energy has a much lower ecological impact, as it does not require damming rivers or altering aquatic ecosystems. Wind farms also occupy relatively small land areas and can coexist with agricultural activities, making them efficient in terms of land use. Governments and politicians are developing new concepts and tactics to employ wind power as a renewable resource. According to data from the World Wind Energy Association, global wind capacity was 215,000 MW in June 2011 (Joselin Herbert et al., 2007). China, Spain, the USA, Germany, and India are the top five nations that produce wind energy. The most is produced in China. Some South Asian nations, like Bangladesh, Pakistan, and India, generate 80–85% of their electricity from natural gas and fossil fuels (Dincer, 2011). Additionally, it produces unsustainable pollution and greenhouse gas emissions (Mlilo et al., 2021). These renewable energy sources have two drawbacks: their power supply, like solar, is not consistent, and their radiation strength varies throughout the year.



	China	EU	USA	Germany	India	Spain	UK	France	Brazil	Canada
2014	114.8	128.8	65.88	39.17	22.47	22.99	12.44	9.285	5.939	9.694
2015	145.1	141.6	74.47	44.95	27.15	23.03	13.6	10.36	8.715	11.21
2016	168.7	153.7	82.18	50.02	28.67	23.08	15.03	12.07	10.74	11.9
2017	188.2	169.3	89.08	56.13	32.85	23.17	18.87	13.76	12.76	12.24
2018	211.4	178.8	96.67	59.31	35.13	23.49	20.97	15.31	14.71	12.82
2019	236.32	192.02	105.47	61.357	37.506	25.808	23.515	16.643	15.452	13.413
2020	281.99	201.51	117.74	62.184	38.559	27.089	24.665	17.382	17.198	13.577

	Italy	Sweden	Australia	Turkey	Mexico	Netherlands	Poland	Denmark	Portugal	Belgium	Ireland
2014	8.663	5.425	3.806	3.763	2.551	2.805	3.834	4.845	4.914	1.959	2.272
2015	8.958	6.025	4.187	4.718	3.073	3.431	5.1	5.063	5.079	2.229	2.486
2016	9.257	6.519	4.327	6.101	3.527	4.328	5.782	5.227	5.316	2.386	2.83
2017	9.479	6.691	4.557	6.516	4.005	4.341	6.397	5.476	5.316	2.843	3.127
2018	9.958	7.407	5.362	7.369	4.935	4.471	5.864	5.758	5.38	3.36	3.564
2019	10.512	8.804	6.199	8.056	6.215	4.6	5.917	6.128	5.437	3.879	4.155
2020	10.839	9.688	9.457	8.832	8.128	6.6	6.267	6.235	5.239	4.692	4.3

Figure 1. Wind energy generation of different countries
Source: (Singh et al., 2022)

This strategy met the need for energy while reducing the usage of natural gas, fossil fuels, and other resources. Clean wind energy is captured by wind turbines. Windmills use large wind turbines to generate electricity, and they require a minimum wind speed of 10 to 15 meters per second to produce energy. These massive wind turbines, however, are not appropriate for small projects, such as residences. A micro wind turbine requires a minimum wind speed of 4 to 7 meters per second. Although the amount of wind varies throughout the year, small-scale turbines have the strength to generate electricity on airy days. A 1.2-meter-tall, 2.4-meter-diameter micro wind turbine with a 0.32-meter blade radius generates 10 watts of electricity. The turbine costs approximately A$ 767.30 (Akour et al., 2018). Depending on the local wind speed, the dimensions of wind turbine can be customized. The size of the wind turbine should be appropriate for the local wind speed and the energy needs of the home. Smaller turbines might be sufficient for individual homes, whereas larger turbines might be suitable for community-scale applications. Regular maintenance is necessary to keep residential wind turbines operating at their best. Homeowners must be prepared to monitor and address issues like wear and tear, malfunctioning equipment, and other issues that can lower productivity (Bahaj et al., 2007).

1.1 Types of Wind Turbines depend on the Location

Building-integrated turbines- These wind turbines are positioned between two buildings or near the building. This kind of turbine provides energy to the building environment on its own.

Building Mounted Turbines- a different kind of wind turbine frequently found in contemporary structures. It is positioned on a building's roof, balcony, parapet wall, or any other portion of a structure.

Building Augmented Turbines- Like a component of architecture, these turbines serve as a design element. One kind of a building structure is created with aerodynamics in mind, meaning that a given area of the building experiences strong wind flows and may be selected for the turbine. The second method involves building a duct to catch more wind flow and harnessing wind energy with a wind turbine (Li et al., 2010)(Huang et al., 2024).

1.2 Types of Wind Turbines depend on the Axis

Horizontal Axis Wind Turbine (HAWT)- It is one of classification of turbine**,** where horizontal axis is used to rotate all of the turbine's blades. HAWT's drawback is that, to maximize power output, the blades will always face the direction of the wind; however, wind flows are not fixed in a single direction.

Vertical Axis Wind Turbine (VAWT)- This is another kind of turbine in which the perpendicular axis is the center of rotation for all of the turbine's blades. Unlike HAWTs, which depend on wind direction, VAWTs generate power regardless of where the wind comes from. It works well in areas with modest wind speeds (Johari et al., 2018) (Hannun, 2012).

A wind turbine's electricity generation process is an extremely effective and environmentally responsible way to generate power. Wind turbines play a major responsibility in the shift to green energy by harnessing wind energy and using a sequence of mechanical and electromagnetic processes to transform it into electrical energy. Wind energy will remain essential in lowering carbon footprints and supplying the world's energy needs as technology develops. The figure depicts the power that is produced due to the rotating activity of the turbines. Wind energy is first transformed into mechanical energy, which is then transformed into electrical energy (Najd et al., 2020).

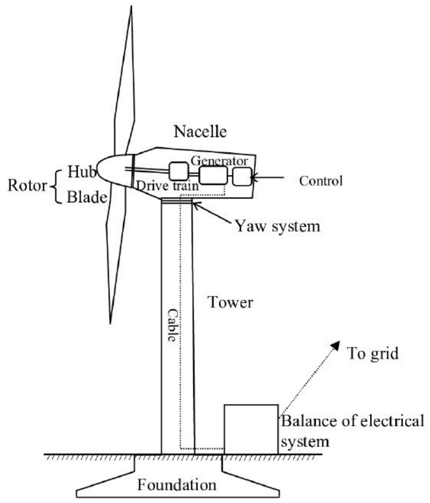


Figure 2. Different parts of wind turbine
Source: (Albadi, 2010)

2. Guidelines

We must take into account a few factors during the pre-design phase to realize the good potential of micro wind turbines. The factors determine the perfect position for the wind turbine to generate maximum turbine-generated power along with the blade's structure of the turbine is also be considered. For improved weather resistance, the turbine and its blade are manufactured by appropriate materials. We talk about how a wind turbine should be processed after these criteria have been chosen (DNV/Riso, 2002).

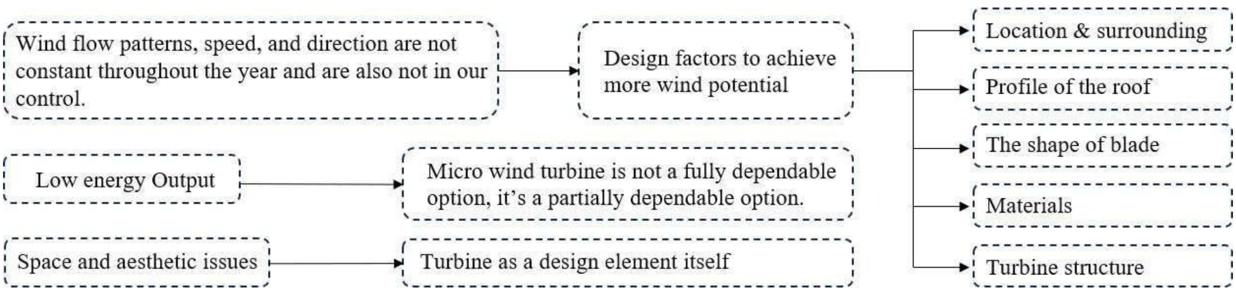


Figure 3. Short coming to wayout

2.1 Surrounding of the micro wind turbine

The form, height, and separation between two buildings affect wind speed along a corridor or between two buildings. Let's consider two options to determine the spacing. The widths of the two corridors are 6 and 12 meters, respectively (Cui et al., 2024). A 6-meter corridor has the largest wind speed, whereas a 12-meter corridor has a lower wind speed, according to the results of testing both choices using CFD modelling. The wind speed increases because of the small channel. This experiment demonstrates the significance of setbacks in any constructed form for appropriate wind circulation in the surrounding area, and it is similar to the wind tunnel effect (Agharabi & Darzi, 2023).

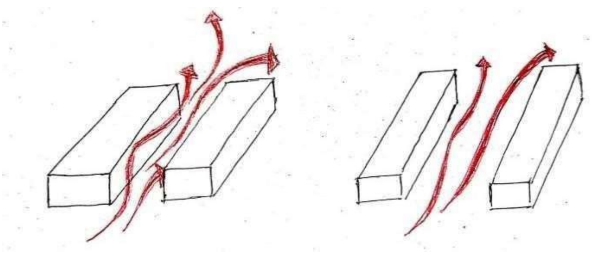


Figure 4. Wind flow pattern in between buildings

2.2 Roof Profile

A building's location, roof height, roof profile, edges, and surroundings affect the velocity of wind at the structure's peak. The velocity of wind closest to roof level is about zero, and it increases as height increases. According to the CFD modelling, a micro wind turbine can be installed about three meters above the roof. Additionally, the nearly 8-meter height is a great location. Next, we experimented with the greatest wind effect using three different roof kinds. There are three types: pyramidal, pitched, and flat. Results are obtained using several CFD simulation techniques. Turbulence intensity, wind speed, and wind flow pattern—0, 45, and 90 degrees- are the basis for this simulation. It demonstrates that the best location for micro wind turbines is on a flat roof (Ledo et al., 2011).

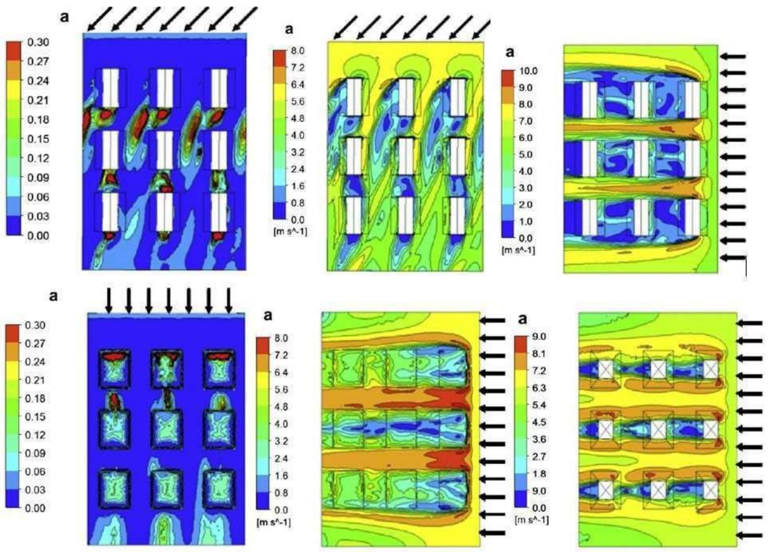


Figure 5. Turbulence intensity for pitched, Flat, pyramidal roof with 0, 45, 90-degree wind direction

Source: (Ledo et al., 2011)

2.3 Turbine Structure

Diffuser-augmented turbines and bare turbines are two major varieties of turbines. Diffuser, nozzle-diffuser, and brimmed diffuser micro wind turbines are basic three types of shrouded or diffuser-augmented turbines. Comparing the geometry of diffuser-augmented and naked turbines in the context of capturing wind energy is the main moto. The results of wind tunnel testing experiments indicated that the spatial aspects like (Length/Depth) and (Height/Depth) of the shrouded micro wind turbine improve its performance (Kosasih & Tondelli, 2012). A miniature wind turbine is designed using an algorithm based on BEM. The mini wind turbine's duct, which combines a fixed and diffuser ring, can easily rotate from 0 to 180 degrees. Six distinct cases—the wind tunnel test is conducted on various configurations, including duct-free, duct-ring, entire duct, and closed ducts at 300, 240, and 180 degrees. The findings of examining various duct-augmented wind turbine types revealed that fully covered

(360-degree) micro wind turbines are more capable of producing more energy, which is simply the result of capturing more wind power. On average, power is increased by 37%, as well as rotor speed also increases upto 60% (Keramat Siavash et al., 2020) (Aghajanzadeh et al., 2023).

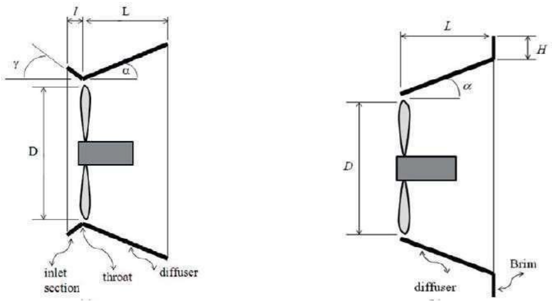


Figure 6: Comparison of different turbine structures
Source: (Kosasih & Tondelli, 2012)

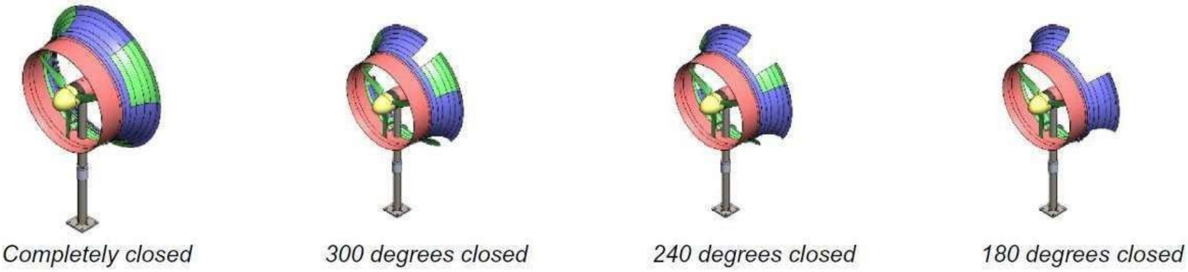


Figure 7. Various diffuser openings
Source: (Siavash et al., 2019)

2.4 Shape of the Blade

The root, midspan, tip, and chord length are the four components of a typical microturbine blade. The relationship between the relative velocity of wind and the rotor blade is commonly considered as the tip speed ratio. A faster tip speed necessitates smaller chord widths, which results in narrower blade profiles, depending on centrifugal and aerodynamic effects. Lower production costs and material utilization may result from this. Three-bladed designs are claimed to appear more aesthetically beautiful and smoother in rotation, according to various studies and wind tunnel test results. Conversely, designs with one or two blades appear to move jerkily (Schubel & Crossley, 2012) (Najar & Harmain, 2013).

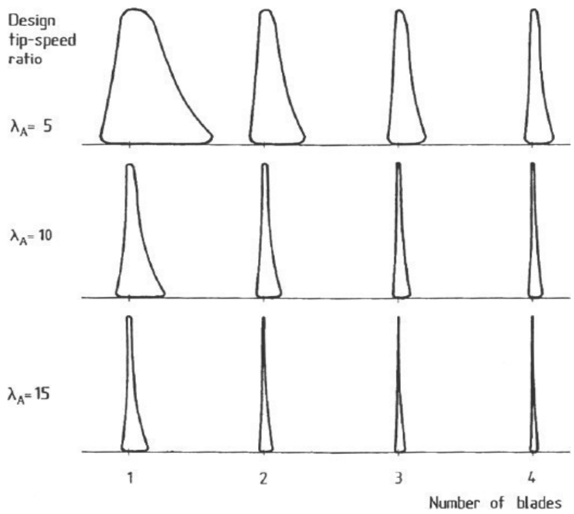


Figure 8. Blade shape with tip speed ratio

Source: (Schubel & Crossley, 2012b)

2.5 Materials Aspect

The build-in materials for the blades of wind turbine includes wood, steel, glass fiber, carbon fiber, natural fiber, and nanocomposites. Every material has a variety of characteristics, including its mechanical, electrical, chemical, and physical behavior. Also, those materials have some sustainability aspects, including affordability, availability, biodegradability, recyclability, and eco- friendliness, among many more (Kale, 2021).

Here, we contrast a few appropriate materials based on their characteristics. The analysis indicates:

that wood, aluminum, and plant fiber are the three best materials for miniature wind turbines. We concluded that plant fiber is the best of these three materials due to its high material performance and sustainability. This is one kind of polymer reinforced with natural fibers. Materials that are readily available and require little processing include agave fiber, flax, cannabis fiber, hibiscus cannabinus, bagasse, musa fiber, jute, manila hemp, and bambusa vulgaris. Natural fiber composites are still being researched by numerous nations and firms, such as Siemens Gamesa and Vestas, to produce more environment friendly micro wind turbine blades.

Table 1: Properties and sustainability factors of different materials

Sl.no.	Material List	Material Properties					Sustainability factors				
		Den	Ym	B.Sth	B.Stn	Co	Ren	Rec	Eco	Cor	Ava
1	Wood	400	0.5	40	0.5	0.3	yes	yes	yes	least	high
2	Steel	8000	200	200	3	0.6	no	yes	no	med	med
3	Aluminum	2500	70	50	4	2.5	no	yes	no	med	med
4	Glass fiber	2660	30	2000	2.5	2	no	no	no	high	least
5	Carbon fiber	1600	100	380	1.6	7	no	no	no	high	least
6	Plant fiber	1350	73	400	1.4	1	yes	yes	yes	least	least
7	nanocomposites	Depends upon the type of constituents.					no	no	no	high	least

Source: (Sandip A. Kale, Swanand R. Kulkarni, Suraj D. Shravagi et al.)

Den: Density (kg/cub.m), Ym: Young modulus (Gpa), B.Sth: Breaking strength (Mpa), B.Stn: Breaking strain, Ren: Renewable source, Co: Cost/kg ($), Rec: Recyclable, Eco: Eco-friendly manufacturing, Cor: Corrosion resistant, Ava: Availability, Med: Medium.

3. Power generation: Case Study of a Residential Building

For computing power generation in watts from a micro wind turbine, use this formula (In & Wind, n.d.).

$$P = \frac{1}{2}\rho A v^3 C_p$$

where:

- P = **Power output (W)**
- ρ = **Air density (kg/m³)** (~1.225 kg/m³ at sea level)
- A = **Swept area of the turbine blades (m²)** ($A = \pi r^2$)
- v = **Wind speed (m/s)**
- C_p = **Power coefficient** (typically **0.3 to 0.5**, maximum limit = 0.593 due to Betz's law)

For determining the power coefficient of a mini wind turbine, use this following equation (Manyonge et al., 2012).

$$\lambda = \frac{\text{blade tip speed}}{\text{wind speed}} \quad C_p = \frac{(1+\lambda)(1-\lambda^2)}{2}$$

$$\text{blade tip speed} = \frac{\text{angular speed of turbine}(\omega) \times R}{\text{wind speed}}$$

Here, we compute the output power for the small wind turbine in watts for easier comprehension. Many of the parameters we covered above affect how much power a turbine can generate. According to the golden rule, greater production is produced in a more appropriate atmosphere. We selected a two-story residential structure in Howrah, India, for this experiment.

The ground floor was rented to someone else, while the building owner occupied the first story. Taking into account the building's owners, we compute the daily power consumption of a few electrical fixtures (fans, lights, etc.) and contrast it with the generating power due to the operation of a mini wind turbine. 10 m/s is the maximum wind speed of the region, as well as the average speed is near about 2.6 m/s (*Maintenance @ Www.Indianclimate. Com*, n.d.). We install a 600mm-diameter micro wind turbine, which costs 55000/-per minute at 100 revolutions per minute and is readily accessible at Indiamart (*Index @ Www.Indiamart. Com*, n.d.). We propose that ten micro wind turbines to be installed. However, as this project is not yet finished, only solar panels have been installed till now. In the future after installing all the wind turbines, the efficiency will be noticed concerning the power consumption.

3.1 Power Calculation

Values we have:

Air density (p)= 1.225 kg/cub.m.

Swept area (A)= πr^2 = 0.282 sq.m. (if diameter 600mm)

Power Coefficient (C_p)= ?

Wind Velocity (v)= ?

$$(\lambda) \quad \text{blade tip speed} = \frac{\text{angular speed of turbine}(\omega) \times R}{\text{wind speed}}$$

Angular speed (ω) = (2 x Π x 100)/60 = 10.4 rad/s

(when revolution per minute is 100)

Figure 9. (a) Residential Building at Howrah, India; (b) Wind Rose Diagram for Howrah

Source: (https://www.indianclimate.com/showdata.php?request=U5IMMPWMUA)

Table 2: Generated Wattage Calculation

Sl.no.	Wind speed (m/s)	Duration (hour)	Blade tip speed (m/s)	Power coefficient (Cp)	Wattage/hour	Wattage/day
1	2.5	10	1.24	0.60	1.61	16.1
2	3.5	6	0.89	0.19	1.40	8.4
3	4.5	6	0.69	0.44	6.92	41.52
4	Below 2	2	-	-	-	-
Total power production by micro wind turbine in 24 hours						66.02
For the 10-micro wind turbine, the power production						660.2

4. Result and Discussion

Here, we first determine how much power (wattage) is consumed daily by the electrical fixtures in the corresponding residential building in Howrah, India. Their daily power consumption is 2902 watts, which includes 4 LED tube lights (40 watts, 10 hours), 2-night lamps (0.5 watts, 6 hours), 2 LED bulbs (12 watts, 4 hours), and 2 ceiling fans (50 watts, 12 hours). There are two flat terraces on this residential building: a little one and a large one. After examining the wind pattern of Howrah region, three wind velocity criteria were identified: 2.5, 3.5, and 4.5 m/s respectively. Below 2 m/s, the velocity is not optimal for producing sufficient wind energy. A micro wind turbine produces 66.02 watts of power when all the parameters in the formula above are entered. According to the computation's outcome, miniature wind turbines generate 660.2 watts of power every day. That amounts to about 23 percent of the daily power usage.

The overall raw power consumption for a month is around 87060 watts without wind turbines. The total power usage comes to about 67260 watts after considering wind turbine-generated power. The electricity bill is 623 INR when a micro wind turbine is installed, compared to 807 INR when it is not. So,184 INR is saved. If we successfully implemented these wind turbines across our nation, that will save nature besides that, it will reduce electricity expenses. Let’s assume one house owner can avail up to 15 small turbines in all aspects, and the electronic power consumption remains constant like the previous case, then it contributes 34% of total expenditure and it save of INR 276/- whereas if there are10 micro wind turbine saves of INR 184/-. Moreover, the main attraction of the usage of small wind turbine is that if 20 percent inhabitants of any locality can forge ahead to introduce the custom of use of micro wind, then it can not only save the monthly expenditure but it has great impact on ecological restoration.

This can be explained like that, if I consider the 25% of total household of total household of Kolkata, India that is 251841 according to CENSUS 2011, are installed 15 micro wind turbines and 2.9 kW is the total power consumption in one day for each household, then it saves (1.4*10^10) W of power which is the 34% of total power of (2.19*10^10) W monthly, as well as the cost also be saved. In terms of environmental impact, to produce (2.19*10^10) W, a sufficient amount of conventional energy is deployed. As conventional energy is a key driver of environmental pollution, relying solely on it to generate large amounts of power can degrade the purity of the atmosphere. So, if micro wind turbines can come in picture, then 34% of total wattage can be reduced that not only save the cost as well as it will be reason of saving our environment. This calculation is done by similar process.

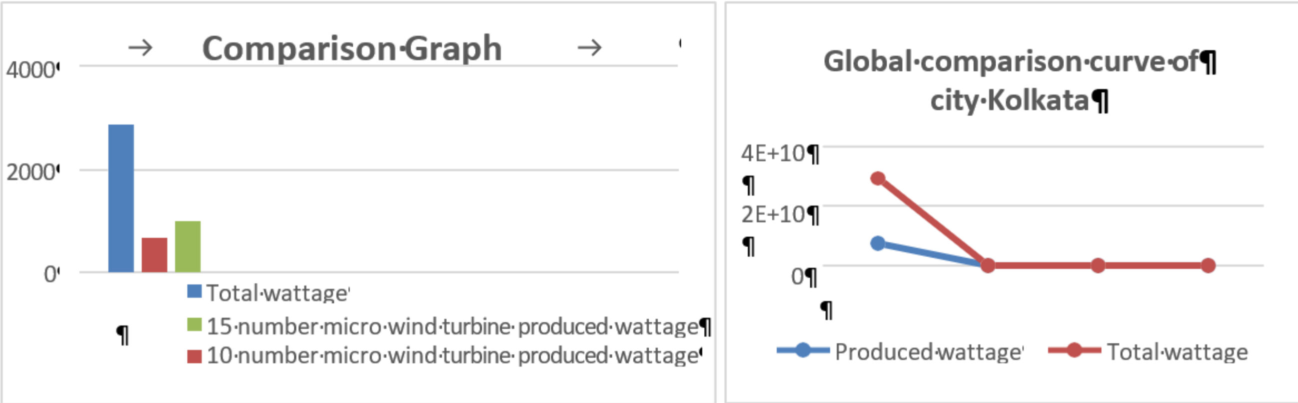


Figure 10. Comparison between different number of micro-winds produced wattage(a) locally and (b)throughout a city of Kolkata

5. Conclusion

It is crucial to use non-depletable energy like radiant, wind, hydro, and others for wattage generation because exhaustible energy sources like coal, fossil gas, and others are limited and will become scarce for future generations if we use them extensively without any limitation. The usage of wind turbines is not so common in the small-scale sector for a variety of reasons, but solar power or solar panels are highly well-known in that sector. The goal of the study is to offer some implementary ways to set up small wind turbines in our community where it is not commonly used. The suggested guidelines must cover the optimal site, the advantageous roof profile construction, the effective micro wind turbine structure, and the ideal turbine blade shape.

We next use some power output estimations to validate the findings. We determine the watts generated bya mini wind turbine that is readily available on the market. We receive 23% of the benefits from micro wind turbines when compared to the power or wattage needed for a residential structure in Howrah, India. Even though the amount of wind energy generated is far less than what is required. The environment, climate, and atmosphere will be benefitted if at least 30% of the houses in a given area install micro wind turbines. Globally, the tiny wind turbine's widespread adoption has an impact. My Suggestion is that the pace of adoption of micro wind turbines may accelerate if the government of any nation, like the Indian government, offers tax breaks and incentives for these wind turbines. We scaled down pollution, the greenhouse effect, carbon emissions, and adverse environmental effects by switching to wind or renewable energy and accomplishing sustainability.

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