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Performance Assessment and Optimization of Wind Turbine Models in India's National Capital Region Using RETscreen and MCDM Approach

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Abstract

India has been actively embracing the exploitation of renewable energy sources to combat carbon emissions and address global warming for nearly a decade. Although renewable energy power plants and utilization have been growing, the generation of electric power from fossil fuels still exceeds that from renewable sources by approximately 20%. By February 2022, renewable resources accounted for only 40.3% of total electricity generation, with wind energy contributing a mere 10.2%. To optimize wind power generation, an investigation was conducted in India's National Capital Region using RETscreen Expert to assess the energy production and performance of various wind turbine models. The Multi-Criteria Decision-Making (MCDM) technique was employed to rank these models based on both beneficial and non-beneficial parameters. This study seeks to shed light on the disparity between renewable and fossil fuel-based electricity generation in India and proposes an objective approach to enhance the effectiveness of wind turbines in meeting the ever-increasing power demands of industrial sectors. By focusing on this approach, India can move closer to achieving its renewable energy goals and mitigating the adverse effects of climate change.

Keywords

Renewable energy; Wind power generation; Fossil fuels; RETscreen Expert; India's national capital region

1. Introduction

Renewable energy is the energy that is harvested from renewable resources of energy. It can often be described as clean energy as well, and it is obtained from natural sources and recharged naturally [1]. Renewable resources are never-ending, but the amount of energy available for any given period is limited. Renewable energy can also be described as energy that, when extracted from its source, will not cause depletion of the source because the energy recharges naturally [2, 3].

Although renewable energy resources are unlimited, either they are available for a limited time or they replenish more quickly than the rate they are consumed [4-6]. The relevance of renewable energies has rapidly increased in recent years due to their unceasing supply and reduced carbon emissions than fossil fuels. In India, renewable energy is classified into four categories: wind, solar, small hydro, and bio-energy, with geothermal energy to be added soon [7].

Wind energy may be utilised to create mechanical power or electricity. For electricity generation, kinetic energy from the wind is extracted and transformed into mechanical energy by rotating windmill blades, which are connected to a turbine via a shaft and an alternator. The blades convert the uninterrupted kinetic energy into enough mechanical energy to move the turbine [7-9]. As the shaft moves due to the mechanical energy, it also moves the turbine, which is connected to an alternator. As the shaft moves, the turbine connected to the alternator generates electricity [10, 11].

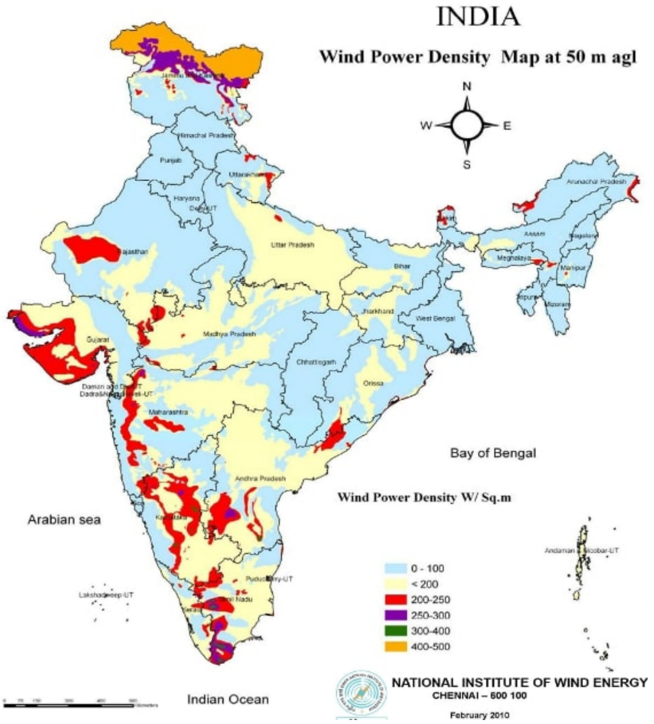


Figure 1. Wind Speed Variation in the Indian Subcontinent [12].

Wind speed density maps Indian subcontinent. Coastlines are ideal for wind farms and power plants. Wind speed density drops in the northern and eastern sections of the Indian subcontinent. However, this does not mean they are unsuitable for wind energy installations. Micro wind turbines may generate electricity from wind streams [13].

In recent years, India has swiftly adapted to the exploitation and application of renewable energy resources and reworked many conventional energy-based processes to make them feasible for renewable energy resources. The most favored renewable resource of energy source in India is solar energy due to its availability across the boundaries of the Indian subcontinent. Even though the availability as well as accessibility of solar energy over the entire Indian subcontinent has ranked it at the top among other renewable energy resources but the period or amount of time for which solar energy will be available or accessible for a particular region is very unpredictable. There are numerous factors like smog, clouds, monsoon, pollution, dust storms, etc. that affect the availability period of solar energy. Solar energy is a very unpredictable source of energy, even though it is not easily accessible. Hence, relying only on solar energy is not very economical and optimal, considering the need for energy in India as a developing country. Wind energy has similar availability across the entire Indian subcontinent; therefore, it must be exploited across the entire nation, as it will make the energy production more reliable and efficient.

2. Literature Survey

Khan Iftekhar et al. suggested examining wind energy utilisation for power generation in South Asian countries. The power age by fuel type and public authority wind energy programmes were examined. India uses wind energy more than Bangladesh and Pakistan. Wind energy is hindered by a lack of government support. However, all three nations have ambitious wind energy plans [14].

In the review, Irfan Muhammad et al. examined low-carbon development by analysing wind energy status, potential, and government policies in Pakistan, India, and Bangladesh. These three countries' wind energy status has been reviewed. Most South Asian nations, including Pakistan, India, and Bangladesh, have a large population, which has increased the gap between energy demand and supply, limiting economic growth [15].

Jahangiri Mehdi et al. found that 23 stations in Afghanistan have a low disturbance force, indicating low exhaustion loads on wind turbine mechanical parts, and the rest have a medium choppiness force, indicating medium weariness loads [16].

Bandoc G. et. al. found that the dissemination and force of coastal breeze assets on worldwide, mainland, and public scales, in light of recently released worldwide high goal environmental information. Furthermore, notwithstanding this significant objective that involves the planning and measurable examination of worldwide breeze potential, the paper expects to momentarily explore the present status of purpose (by featuring wind energy introduced limit in light of refreshed particular reports) and need (evaluated comparable to power needs) of wind assets in various regions of the planet, Thirdly, the exploration means to bring different issues chiefly connected with current breeze energy arrangements overall up for conversation [17].

Irfan Muhammad et al., recommended a study to identify and analyse the main issues affecting the Indian breeze industry [18].

Bahrami Arian et al. reviewed 15 financially accessible wind turbines to determine the best for national use. At 10 m above ground, the mean annual wind speed, power thickness, and energy generation are 0.61-3.98 m/s, 1.74-88.55 W/m^2, and 15.27-775.72 kWh/m^2 [19].

Dawn S. et al. presented important perspectives and the Indian government's advanced strategies for increasing energy security by legally using environmentally friendly power sources. Wind power generates and distributes electricity in India. This evaluation also details India's electricity age, demand, and sustainable source obligations. Comparing India's wind power potential to other leading countries [20].

Satpute A. V. et al. examined the role of government drives for the advancement of wind power ventures in India, to provide better and more generous strategies in the development of wind energy density and to expand the use of the sustainable wellspring of energy, which reduces fossil fuel by-products from coal-based power plants and reduces social need and destitution [21].

Sitharthan R. et. al., proposed a few significant potential outcomes in India for investigation on wind power in the power age. Besides, the overview additionally sums up trend-setting innovation carried out, future opportunities, government drives, significant accomplishments, and core values on wind power utilization. It additionally addresses the main drive taken by the public authority on sponsorships and observable approaches to advance wind power use by the public authority [22].

Sherman Peter et. al. affirmed projections of onshore and offshore wind power possible in China and India under authentic and future discharge situations to decide whether and what territorial environment changes could mean for plans for wind power development [23].

3. Methodology

The methodology for this research begins with a thorough literature survey to review existing studies on hybrid power plants integrating geothermal and solar PV systems, identifying research gaps and challenges. Subsequently, we survey relevant projects to gain practical insights and analyze the strategies used to overcome challenges. Building on this analysis, we precisely formulate the research problem to guide our investigation.

The viability analysis includes site selection using GIS tools and meteorological data, estimating energy output, and evaluating economic feasibility. In the performance analysis, we optimize the hybrid power plant's components and conduct a comparative study of various turbines for suitability. Additionally, an environmental impact analysis assesses potential effects on air and water quality, land use, and biodiversity, aiming for sustainable practices.

The research concludes with summarizing key findings, implications, and contributions. We evaluate the feasibility, economic viability, and environmental sustainability of the hybrid power plant. Practical implications are discussed, and future research directions are suggested to advance renewable energy and hybrid power systems. This well-structured methodology ensures a logical and formal approach to investigating geothermal and solar PV integration in hybrid power plants, adhering to academic standards.

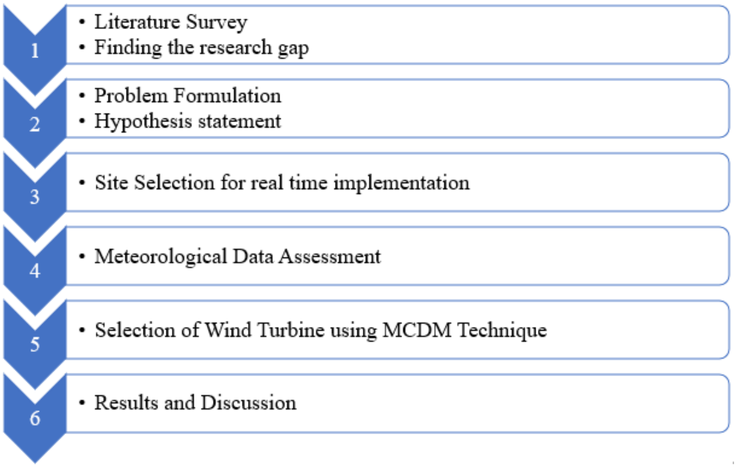


Figure 2. Methodology Flow chart.

3.1 Site Selection and Meteorological Data

Delhi, in northern India, has lower wind speeds than coastal locations. However, the city's outskirts have wind power potential. Delhi has made many steps to tap this potential. The Delhi government and the Solar Energy Corporation of India (SECI) agreed to build a 1,000 MW wind power plant in Rajasthan to power the city in 2016. The government aims to satisfy 25% of Delhi's power consumption using renewable energy by 2022. Addressing difficulties is necessary to fully realise Delhi's wind power potential. Low wind speeds are a problem. The National Institute of Wind Energy (NIWE) reports a yearly average wind speed of 4.5 m/s in Delhi. The average wind speed in coastal India is 6-9 m/s. Wind power projects need land. Delhi's dense population limits wind turbine sites. The government investigated small-scale wind power plants for residential and commercial usage to solve this issue. A 1.2 MW wind turbine in the Okhla Industrial Area provides electricity for the Delhi State Industrial and Infrastructure Development Corporation and feeds surplus power to the grid. The Delhi administration is also promoting wind power to the public while solving these issues. Wind power and other renewable energy advantages are promoted by the government. Net metering enables homeowners and businesses to sell surplus renewable energy to the grid.

Delhi has wind power potential despite the obstacles. Delhi has 300 MW of wind power potential, according to C-WET research. This analysis found various city-area wind power project sites. The Yamuna River bed is a huge, unobstructed region. Delhi's southern Aravalli range has promise too. Elevation and distance from the city centre make this location windier. Delhi has other small-scale wind power plant prospects. Rooftop wind turbines are one example. These turbines may be put on residential, apartment, and business rooftops to produce power for on-site consumption or sale to the grid.

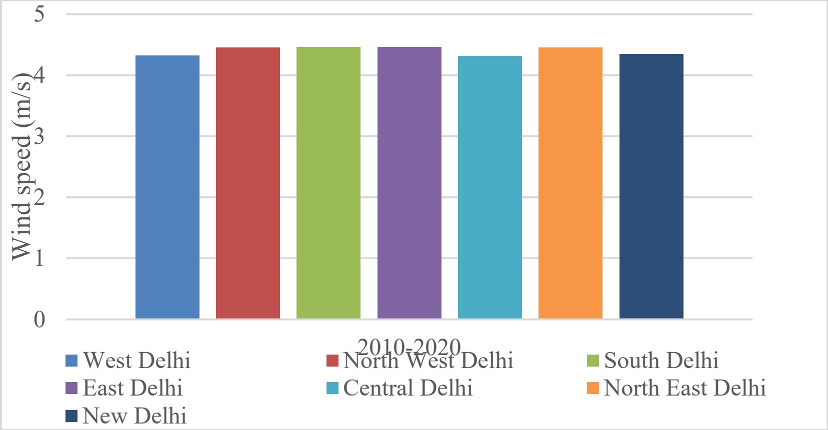


Figure 3. Average Wind Speed for 2010-20.

The data in Figure 3 presents the average wind speeds (in m/s) observed in various districts of Delhi from 2010 to 2020. The wind speed trends over the decade display relatively stable values, with fluctuations between 4.316 m/s in Central Delhi to 4.466 m/s in East Delhi. These consistent wind speeds suggest that Delhi experiences moderate and reliable wind conditions.

Several factors contribute to the wind speed variations in the region. Delhi's geographical location plays a significant role, as it lies in the Indo-Gangetic plain, with proximity to the Thar Desert and the Himalayas. The presence of these geographical features influences wind patterns, causing regional variations. Seasonal changes also affect wind speed. During the summer, Delhi experiences high temperatures, leading to lower atmospheric pressure. This creates thermal gradients and stronger winds, resulting in higher wind speeds during these months. Urbanization and local topography are other influential factors. The growth of concrete structures and high-rise buildings may create obstacles and alter wind flow patterns, leading to localized wind speed changes. Moreover, green spaces and open areas within specific districts can contribute to minor wind speed variations. Parks, forests, and water bodies may enhance or obstruct wind flow, impacting the average wind speeds in those regions.

The wind speed data provided for different districts of Delhi from 2010 to 2020 suggests that the average wind speeds range from approximately 4.316 m/s to 4.466 m/s. These wind speeds indicate a moderately windy environment. For such wind conditions, certain types of wind turbines are more suitable than others. Here are the types of wind turbines that could be considered for installation in this region:

(1) Small to Medium-Sized Horizontal Axis Wind Turbines (HAWTs): Small to medium-sized HAWTs are commonly used in areas with moderate wind speeds. They have a horizontal axis and are suitable for locations where the wind direction is relatively consistent. These turbines are available in various capacities and can be installed individually or in small wind farms. The power curve exhibits a relatively smooth and linear increase in power output within the operational wind speed range. Beyond the rated wind speed, the power output remains constant or slightly decreases to protect the turbine from extreme wind conditions. HAWTs are known for their relatively high efficiency (45-50%), especially in moderate to high wind speed conditions. They are widely used in various applications and can achieve a reasonable level of energy conversion.

(2) Low Cut-In Speed Turbines: Wind turbines with low cut-in speeds (around 3 to 4 m/s) are well-suited for areas with moderate wind speeds. They can start generating electricity at lower wind speeds, maximizing energy production. The power curve shows a slower initial increase in power output, but once the wind speed reaches the rated wind speed (usually around 6-10 m/s), the power output increases more rapidly and levels off. Low cut-in speed turbines are designed to start generating power at very low wind speeds. While they are efficient in capturing energy from low-speed winds, their overall efficiency (20-30%) might be lower compared to larger turbines operating in higher wind regimes.

(3) Modern Onshore Wind Turbines: Modern onshore wind turbines are designed to operate efficiently in moderate wind conditions. They come in various capacities and are commonly used for utility-scale wind projects. The power curve displays a steady increase in power output within the operational wind speed range, reaching its rated power at the rated wind speed (around 10-15 m/s). Similar to HAWTs, the power output remains constant or slightly decreases beyond the rated wind speed. Modern onshore wind turbines are designed for utility-scale applications and have higher efficiency (47-55%) compared to smaller turbines. They can achieve optimal energy conversion, especially in favorable wind conditions.

(4) Downwind Turbines: Downwind turbines are a type of HAWT where the rotor faces away from the wind. They are more suitable for lower wind speeds and are less sensitive to wind direction changes. The power curve follows a similar pattern to HAWTs, reaching its rated power at the rated wind speed. They can have slightly lower efficiency (35-45%) than traditional upwind HAWTs but are often preferred in certain applications due to reduced noise and mechanical stress on the structure.

(5) Small Vertical Axis Wind Turbines (VAWTs): Small VAWTs can be considered for decentralized power generation in urban areas where space is limited. They are less affected by turbulent wind conditions and can start producing power at lower wind speeds. VAWTs have a unique vertical-axis rotor design and are generally less efficient (20-30%) compared to HAWTs and modern onshore turbines. They are often used in urban or low wind speed environments, where their compact size and aesthetics are advantageous.

The provided table presents the power rating, rotor diameter, and hub height specifications of different types of wind turbines, including Horizontal Axis Wind Turbines (HAWTs), Low Cut-In Speed Turbines, Modern Onshore

Wind Turbines, Downwind Turbines, and Small Vertical Axis Wind Turbines (VAWTs). These specifications hold significant importance in wind energy projects and play a crucial role in determining the turbine's performance, efficiency, and suitability for specific applications. The power rating denotes the capacity of each turbine type to generate electricity, with values ranging from 1 kW to 5000 kW. HAWTs and Modern Onshore Wind Turbines offer higher power ratings, making them suitable for utility-scale applications and large wind farms. In contrast, Low Cut-In Speed Turbines and Small VAWTs cater to distributed power generation with relatively lower power capacities. The rotor diameter indicates the size of the turbine's blades, with larger diameters capturing more wind energy, leading to higher energy production. Modern Onshore Wind Turbines and Downwind Turbines boast larger rotor diameters, making them ideal for locations with ample wind resources, while Small VAWTs have smaller rotor diameters, suitable for urban settings and areas with limited space. Hub height is a critical parameter affecting wind resource accessibility. Taller hub heights enable turbines to access stronger and more consistent winds, enhancing overall efficiency. Modern Onshore Wind Turbines demonstrate taller hub heights, making them suitable for sites with higher wind speeds [24-28].

Table 1. Sizing Parameters of Wind Turbines

Turbine Type	Cut-in Wind Speed (m/s)	Power Rating (kW)	Rotor Diameter (m)	Hub Height (m)
HAWTs	Low (3-4 m/s)	10-500	10-40	20-120
Low Cut-In Speed Turbines	Very Low (<3 m/s)	1-100	5-25	10-80
Modern Onshore Wind Turbines	Moderate (4-5 m/s)	500-5000	70-150	80-160
Downwind Turbines	Moderate (4-6 m/s)	100-3000	40-150	50-120
Small Vertical Axis Wind Turbines (VAWTs)	Low (2-3 m/s)	100-1000	5-20	10-50

In the evaluation of wind turbines for deployment in a region like Delhi with moderate wind conditions, it is crucial to consider both the power output potential and the cut-in wind speed. While Modern Onshore Wind Turbines and Downwind Turbines boast high power ratings and efficiency, their relatively higher cut-in wind speeds (ranging from 4-6 m/s) pose significant challenges. In a region where wind speeds may not consistently meet the required threshold, these turbines may face prolonged periods of inactivity, leading to a less reliable power supply. Consequently, despite their capability to provide higher power output, it is prudent to explore alternative options. Wind turbines with lower cut-in wind speeds, such as HAWTs and Small Vertical Axis Wind Turbines (with cut-in wind speeds of 3-4 m/s and 2-3 m/s, respectively), become more promising choices for consistent energy generation in the given context. By prioritizing turbines with lower cut-in wind speeds, we can ensure a stable and continuous energy supply, thus contributing to a sustainable and resilient energy infrastructure for the region.

3.2 Wind Power Estimation

To estimate the power generation of each type of wind turbine in the specified districts of Delhi, a multi-step process is employed. Firstly, the Wind Power Density (WPD) is calculated as a measure of available wind energy. With the WPD determined, the energy production of each wind turbine type is estimated using its respective power curves or energy production curve, which relate wind speed to expected power output. Subsequently, the estimated energy production is multiplied by the number of hours in the specified period (2010-2020) to obtain the total energy generated in kilowatt-hours (kWh) for each turbine type in every district. Comparing the results enables the identification of the most efficient turbine type based on the given wind conditions. However, it is crucial to consider that this estimation solely relies on wind speed data and lacks consideration of turbine efficiency, losses, or specific site conditions. For more accurate and detailed power generation estimates, a comprehensive wind resource assessment and turbine-specific performance data are necessary. The formula for Wind Power Density (W/m²) is shown in equation (1)

$$WPD = (\rho\, v^{3})/2 \qquad (1)$$

where ρ represents air density, and v denotes the wind speed in m/s.

The expression for the actual available power due to wind energy at any desired location is shown using equation (2)

$$P_a = (K\, C_p\, \pi\, r^2 \rho\, v^3)/4 \tag{2}$$

where,
P_a = Electrical power extracted from wind stream (KW)
C_p = Power coefficient (theoretical maximum = 0.59)
ρ = Density of air at 25°c (kg/m^3)
r = Length of the rotor blade (m)- wind turbine
v = Velocity of wind (m/s)- district based

The formula calculates wind turbine power. The blade radius (r), wind velocity (v), air density (ρ), number of blades (K), and coefficient of performance (C_p) affect power output. The formula illustrates that wind turbine power is exactly proportional to the cube of wind velocity; hence, increasing wind speed may boost power production. The formula also demonstrates that power output depends on blade radius and number of blades; therefore, bigger blades and more blades enhance power output. A greater coefficient of performance (C_p) suggests a more efficient wind turbine. The formula helps calculate wind power production and emphasises the relevance of wind speed, blade size, and efficiency. The renewable energy industry uses this method to estimate wind turbine energy output and develop efficient wind energy systems [29]. At 25°C, air density is considered to be 1.184 kg/m^{3,} and the maximum power coefficient is 0.45. Wind power generation is calculated using these characteristics. Wind turbines may be optimized to create the most power by considering these parameters. Other variables, such as terrain, climate, and wind turbine height, can also affect wind power generation. Understanding wind power's elements allows for the construction and operation of efficient, dependable, and sustainable wind turbines [24-26].

Figure 4 presents power output data from different wind turbine types across various districts of Delhi, revealing valuable insights for wind energy utilization. Horizontal Axis Wind Turbines (HAWTs) consistently demonstrate the highest power output, ranging from 82.73 kW to 91.66 kW, making them a robust choice for energy generation in regions with relatively higher wind speeds. On the other hand, Low Cut-In Speed Turbines exhibit moderate power output, ranging from 29.78 kW to 33 kW, and are advantageous in areas with lower wind speeds due to their ability to initiate power generation at lower wind velocities. Small Vertical Axis Wind Turbines (VAWTs) show the lowest power output, ranging from 20.68 kW to 22.91 kW, but their unique design makes them suitable for urban environments and constrained spaces where wind direction may vary. The significance of these findings lies in the tailored selection of wind turbine types based on local wind conditions and energy requirements. By strategically deploying appropriate turbines, Delhi can optimize wind energy utilization and advance its renewable energy goals, fostering a more sustainable and eco-friendly future for the city.

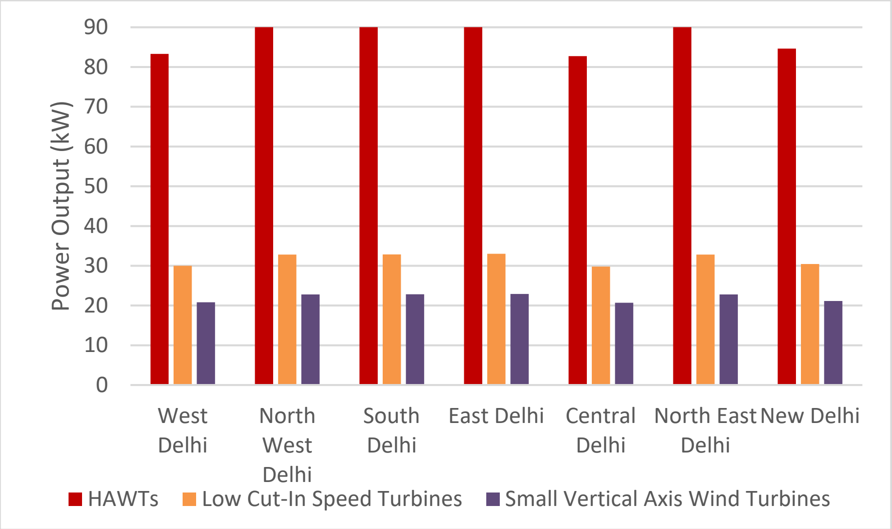


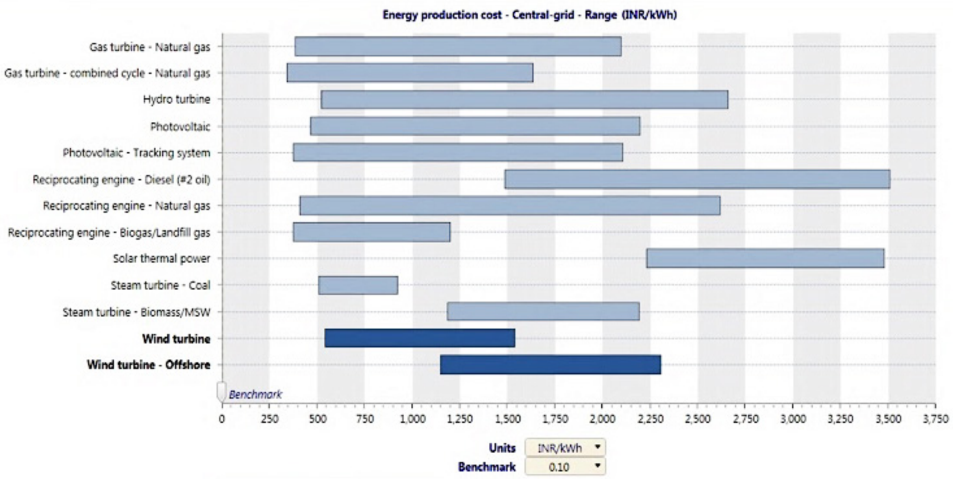
Figure 4. Instantaneous Power Generation Comparison from Wind Turbine.

HAWTs are a preferred choice for wind energy generation in a developed city like Delhi due to their superior efficiency and compact rotor blade sizes. The smaller rotor blade sizes are particularly suitable for urban installations where space constraints are a crucial consideration. Additionally, HAWTs boast hub heights ranging from 20 to 120 meters, providing the necessary elevation for capturing higher and more consistent wind speeds in built-up areas. The combination of higher efficiency, smaller blade sizes, and adequate hub height enhances the viability of HAWTs in metropolitan environments like Delhi, where optimized land utilization and reliable power generation are essential goals. Moreover, their mature technology and well-established infrastructure make HAWTs a reliable and cost-effective choice for harnessing wind energy in urban settings. By strategically deploying HAWTs, Delhi can capitalize on its wind resources and further its commitment to sustainable energy solutions, contributing to a greener and environmentally responsible future for the city.

3.3 RETscreen Expert

RETscreen is a clean energy management software programme that lets users assess clean energy project energy output, savings, expenses, and environmental implications. It analyses and advises renewable energy, energy efficiency, and greenhouse gas reduction initiatives. RETscreen may analyse renewable energy project technical and economic viability, perform energy audits, design clean energy policy, educate stakeholders, promote project finance, and monitor and evaluate energy projects. With its user-friendly interface and extensive database, RETscreen is a valuable tool for policymakers, investors, energy managers, and anyone interested in clean energy technologies. The all-in-one tool RETscreen clean energy project analysis programme estimates wind energy power by analysing cost and revenue effectiveness, financial feasibility, pollution, and risk in replacing conventional energy with renewable energy. NRC invented it in 1996. The data required for the assessment of desired renewable resources are obtained from and RETscreen Expert Software.

Benchmark analysis in RETscreen, as presented in Figure 5, holds significant importance as it allows thorough evaluation and validation of energy efficiency and renewable energy projects. Comparing proposed projects against established benchmarks or baseline scenarios enables decision-makers to assess the project's viability, potential benefits, and risks [30]. This analysis aids in making informed choices about technology selection, policy compliance, and investment decisions. Moreover, it offers a reliable means to verify projected outcomes and ensures compliance with regulatory standards. Through continuous monitoring, benchmark analysis facilitates ongoing improvement in project performance, contributing to sustainable practices and successful energy initiatives. Overall, benchmark analysis in RETscreen serves as a crucial tool for stakeholders to optimize project planning, achieve energy goals, and enhance financial attractiveness for investors.



Units INR/kWh
Benchmark 0.10

Figure 5. Energy Production Cost for Wind Turbine Power Plant.

3.4 MCDM Technique

The Multi-Criteria Decision Making (MCDM) technique is a robust and systematic approach utilized to make well-informed decisions when faced with complex situations involving multiple criteria [31]. By considering qualitative and quantitative factors simultaneously, MCDM enables decision-makers to comprehensively evaluate and prioritize alternative options. MCDM encompasses a range of methods, such as the Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and Elimination and Choice Expressing Reality (ELECTRE), each tailored to address specific decision-making scenarios. MCDM aids in achieving optimal outcomes by striking a balance between competing objectives and facilitating resource allocation efficiency. Its structured approach and ability to handle conflicting criteria make it an indispensable tool for addressing complex decision challenges and arriving at sound, well-justified conclusions.

Table 2. Parameters Considered in MCDM

Turbines	Cost (₹)	Installation Area (m^2)	Avg. Power Output (W)
	Non-Beneficial	Non-Beneficial	Beneficial
HAWTs	1,05,000	2300	87.99
Low Cut-in Speed Turbine	95,000	1200	31.67
Small VAWTs	35,000	700	21.99

The Multi-Criteria Decision Making (MCDM) technique is an invaluable tool for assessing and selecting the most suitable wind turbine technology for a given project. By considering multiple criteria simultaneously, as shown in Table 2, MCDM aids in making well-informed and rational decisions. In this context, three types of wind turbines have been evaluated based on cost, installation area, and average power output. The Horizontal Axis Wind Turbines (HAWTs) exhibit a higher cost of ₹1,05,000 with a corresponding installation area of 2300 m^2 and an average power output of 87.99 W. On the other hand, the Low Cut-in Speed Turbine offers a more economical option with a cost of ₹95,000, requiring a smaller installation area of 1200 m^2 and producing an average power output of 31.67 W. The Small VAWTs, with the least expensive price tag of ₹35,000, demand a mere 700 m^2 of installation area while delivering an average power output of 21.99 W. Utilizing the MCDM technique allows decision-makers to comprehensively evaluate these parameters and make an optimal choice that aligns with project requirements and objectives in the realm of wind energy.

In Multi-Criteria Decision Making (MCDM), the terms beneficial and non-beneficial play a crucial role in evaluating the suitability of various options. These terms represent the impact of each criterion on the overall objective. In this analysis, Cost and Installation Area are considered as non-beneficial, whereas Average Power Output is considered as beneficial. The term beneficial indicates that an increase in the value of a specific criterion is advantageous and contributes positively to the overall objective of the decision-making process. A higher Average Power Output (W) is considered beneficial, as it implies a more productive and efficient wind turbine, resulting in greater electricity generation. Conversely, the term non-beneficial suggests that an increase in the value of a particular criterion is not advantageous or may have a negative impact on the overall objective. By categorizing the parameters into beneficial and non-beneficial, MCDM allows decision-makers to assess and compare various wind turbine options effectively. Through this analysis, an optimal choice can be made, considering the relative importance of each criterion and aligning with the project's specific requirements and objectives in the realm of wind energy.

Table 3. Normalised Decision Matrix

Turbines	Cost (₹)	Installation Area (m^2)	Avg. Power Output (W)
HAWTs	0.333333333	0.304347826	1
Low Cut-in Speed Turbine	0.368421053	0.583333333	0.35992726
Small VAWTs	1	1	0.24991476

The normalized decision matrix in Table 3 represents the relative significance of different attributes for three types of turbines: HAWTs, Low Cut-in Speed Turbines, and Small VAWTs. The values, ranging from 0 to 1, indicate the importance of each attribute for evaluating the turbines' effectiveness. Lower costs and smaller installation areas have higher significance, denoted by values closer to 0, while higher power output is considered more significant, indicated by values closer to 1. The matrix aids in identifying the most viable option based on cost, installation area, and power output, ensuring an informed and efficient decision-making process in selecting the appropriate turbine type.

Table 4. Equal Weighted Normalised Decision Matrix

Turbines	Cost (₹)	Installation Area (m^2)	Avg. Power Output (W)	Performance Score	Rank
HAWTs	0.11	0.100434783	0.33	0.54043478	2
Low Cut-in Speed Turbine	0.121578947	0.1925	0.118776	0.43285494	3
Small VAWTs	0.33	0.33	0.08247187	0.74247187	1

The Equal Weighted Normalized Decision Matrix in Table 4 serves as a systematic tool to assess and rank three turbine types: HAWTs, Low Cut-in Speed Turbines, and Small VAWTs. The values, ranging from 0 to 1, represent the relative importance of each attribute when given equal weight in the decision-making process. Lower normalized values for cost and installation area indicate these factors are more desirable, while higher values for average power output signify their significance in turbine evaluation. The performance score combines these attributes, with smaller values reflecting better overall performance. Consequently, Small VAWTs receive the highest rank due to their low cost, small installation area, and reasonably good power output, making them the most suitable option in this analysis. The matrix aids decision-makers by simplifying complex data, enabling a rational and unbiased selection of the most effective turbine type based on equal-weighted attributes.

Table 5. Unequal Weighted Normalised Decision Matrix

Turbines	Cost (₹)	Installation Area (m^2)	Avg. Power Output (W)	Performance Score	Rank
HAWTs	0.08333333	0.07608696	0.5	0.65942029	1
Low Cut-in Speed Turbine	0.09210526	0.14583333	0.17996363	0.41790223	3
Small VAWTs	0.25	0.25	0.12495738	0.62495738	2

In the Unequal Weighted Normalized Decision Matrix shown in Table 5, the values represent the relative significance of different attributes, considering varying weights assigned to each criterion. Lower normalized values for cost and installation area imply higher importance of these factors, while higher values for average power output indicate their relatively lower significance in turbine evaluation. The performance score combines these attributes based on their respective weights, determining the overall performance of each turbine type. In this analysis, HAWTs obtain the highest rank due to their superior performance score, signifying their suitability as the most effective option with the given unequal weights.

4. Conclusion

Due to the low average wind speed in and around the area, the result of the data analysis is that it would not be a viable choice to build a wind energy-based power plant in Delhi because of the high population density in the region. Despite the fact that the measurements suggest that the wind speed is sufficient to run a tiny wind turbine, it is not sufficient to meet the cut-in wind speed requirement of typical windmills. Based on the analysis from both the Equal Weighted Normalized Decision Matrix and the Unequal Weighted Normalized Decision Matrix, meaningful conclusions about the three turbine types: HAWTs, Low Cut-in Speed Turbines, and Small VAWTs were drawn. In the Equal Weighted Matrix, Small VAWTs received the highest rank due to their favorable combination of low cost, small installation area, and reasonably good power output. However, in the Unequal Weighted Matrix, HAWTs obtained the top rank, primarily because of their significant power output, which was assigned a higher weight. These results highlight the importance of considering different weights for each attribute in decision-making. The Equal Weighted Matrix emphasizes a balanced approach, where all attributes carry equal importance, favoring Small VAWTs. On the other hand, the Unequal Weighted Matrix reflects the prioritization of certain attributes, favoring HAWTs due to the emphasis on power output.

Author Contributions Statement

Parminder Singh: Conceptualization, Methodology, Software, Data Analysis, Writing—original draft preparation.
Harpreet Kaur: Validation, Visualization, Supervision, Writing—review and editing.
Both authors have read and approved the final manuscript.

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