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A Fuzzy Logic Based Multi-Criteria Decision-Making Approach for Selection of Small Scale Vertical Axis Wind Turbines in an Urban Environment

Wind energy has emerged as an effective alternative to fossil fuels. At a commercial level, wind energy is harnessed through wind farms. However, in an urban setting, small scale wind turbines can be installed and effectively used to generate power without the requirements for a huge infrastructure. This study aims to evaluate a number of vertical axis wind turbines with rated capacity of 600 Watts. A fuzzy logic based multi-criteria decision-making (MCDM) approach is developed while considering hub height, turbine swept area, annual energy production, cut-in speed, and rated speed as the decision criteria. The assessment is done on the data collected for the city of Karachi located in the Southern Pakistan. Assessments were done using five vertical axis wind turbines with different swept areas ranging between 0.413 m^2 and 5.75 m^2, while considering hub heights of 10m, 15m, and 20m. The proposed method was also compared with two other MCDM methods, namely, weighted sum method, and goal programming. Results indicate thatall three methods produced more or less the same decisions. It was found that Maglev/ low-noise rooftop with swept areaof 2.619m^2produced the best overall fuzzy membership of 0.661, whereas Qingdao Greef / Rose-600W rooftop stood worst with an overall membership of 0.590. Furthermore, more favorable results were obtained at height of 10m as compared to heights of 15m and 20m.

Keywords: *Vertical axis wind turbines, Hub height, Swept area, Fuzzy logic, Multi-criteria decision-making, Urban environment*

1. INTRODUCTION

Renewable energy is gradually replacing the traditional sources of energy production which are mainly petro–leum, natural gas, and coal. These fossil fuels are not only depleting with time due to intense use, but are also the major source of environmental pollution. Among the renewable energy sources, the wind energy has deve–loped special interest among researchers and commer–cial service providers in the energy sector [1]. The main attraction with the wind energy is that wind is free, is readily available worldwide, and is not restricted by geo–graphical boundaries. Furthermore, environmental pollut–ion in terms of greenhouse gases is also a concern with wind energy [2]. These observations are major limita–tions of the fossil fuels. This has led to the development of wind energy sources, both at large and small scale.

The small scale wind energy systems are potentially useful in urban environments. For example, a recent initiative funded by European Union has resulted in the development of a wind turbine, which is capable of exploiting the low-velocity turbulent wind conditions found in urban environments [3]. However, a recent report published by International Renewable Energy Agency indicated that the use of wind turbines in urban environments is still not mature, thus creating opportunities for research and development [3]. The major obstacle in the use of wind energy in urban environment is the lack of useful experimental data [3].

The performance of a wind turbine is considered pivotal in generating maximum energy. The importance of design, manufacturing, and verification testing for a turbine's performance is emphasized by Rašuo et al. in several studies [4,5,6], and the process is equally imp–ortant and crucial for both horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs).

VAWTs can be classified into many types [7]. As shown in Figure 1, common types include H-rotor turbines with blades having an H shape, Savonious turbines, which are drag-type turbines, and Darrieus turbines, which are an improvement over the H-shape and are based on lift. In contrast with the widely used HAWTs, VAWTs present several advantages. As iden–tified by Azam et al. [9], some advantages are omni–directional operation, lower noise pollution, reduced visual impact, and simpler maintenance needs.

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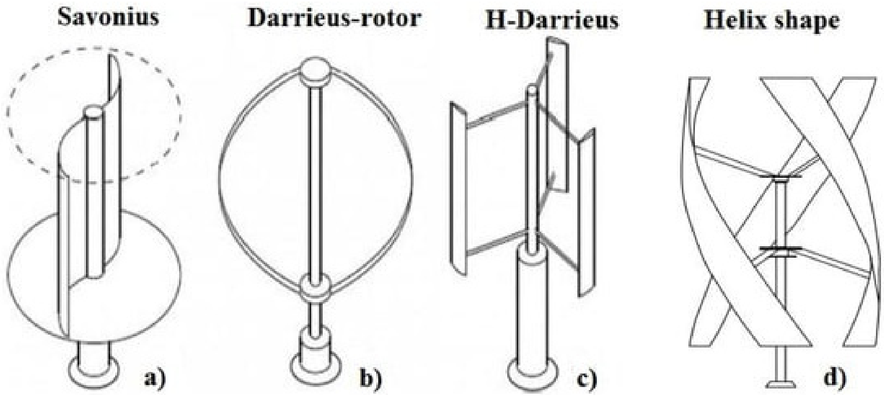

Figure 1. Different types of VAWTs: (a) Savonius, (b) Darrieus, (c) H-Darrieus, (d) Helix (Image copyright: Castellani et al. [8]).

Also, Dinulović et al. [10] highlighted that VAWTs are omnidirectional and independent of wind direction. Hand et al. [11] reported that VAWT wake recovery can occur within a much shorter distance, just 4–6 diameters. Kumar et al. [12] performed a critical review on potential advantages of small VAWTs over HAWTs in urban areas. They highlighted that VAWTs' omnidi–rectional operation and potentially lower noise emis–sions make them well-suited for these environments compared to HAWTs which require yaw control and may generate more noise. All the aforementioned cha–racteristics give VAWTs an edge over HAWTs, especially in an urban setup.

In the context of Pakistan, the energy shortfall has resulted in a negative impact on industry and household. The intensity of this impact is more visible in big cities, an ideal example of which is the city of Karachi. The gap in energy supply can effectively be filled with the use of small size wind turbines that can be installed in any household or a commercial organization. While there are several service providers in Pakistan that provide wind based energy systems, their operation in terms of installation and maintenance is often based on human experiences, rather than on proven scientific approach. Furthermore, as mentioned above, the non-availability of sufficient wind data in potential urban areas, including urban areas of Pakistan, contributes to non-optimized deployment and operation of wind turbines, leading to lack of interest of developers and investors in this domain. For example, a Chinese home would need a 1 kW turbine to generate all the energy needed for a year. This requirement is a 4 kW turbine for a European house, and a 10 kW turbine for an Ame–rican house [13]. However, such data is not available for a typical house in any urban area in Pakistan.

Another reason to advocate the use of renewable energy, particularly wind energy in an urban setting, is to respond to disastrous situations that may occur with power grids. For example, an incident in 2021 left Pakistan in complete power blackout for over 12 hours, and in some areas, the blackout was for almost a complete day [14]. This occurred apparently due to a technical fault in the main grid supply. In order to mitigate the effect of such disasters, individual, off-grid power supply is the solution, and small scale wind energy generation is a potential option.

Motivated by the above discussion, the major contributions of the present study are enumerated as follows:

1. An AI decision-making approach based on fuzzy logic is proposed. The approach considers different hub heights, turbine swept areas,associated annual energy production, cut-in speed, and rated speed as the decision factors.
2. The performance of several small scale VAWTs with rated capacity of 600 Watts is compared.
3. Comparison with weighted sum method and goal programming is done and outcomes are assessed using the ranking approach.
4. The study utilizes real data collected from the city of Karachi, Pakistan over a period of one year and empirical results are analyzed.

The rest of the paper is organized as follows. Section 2 provides a review of recent relevant literature. This is followed by a discussion on wind characteristics and wind distribution of the site under study in Section 3. The development of a multi-criteria decision model ba–sed on fuzzy logic in discussed in Section 4. The results and discussion are presented in Section 5. The paper ends with a conclusion and future directions in Section 6.

2. LITERATURE REVIEW

Şağbanşua and Balo [15] used the Analytic Hierarchy Process (AHP) for selection of a 1.5 MW wind turbine. Four main criteria were considered which included tec–hnical, economic, environmental, and customer related factors. With these four criteria, several sub-criteria were also associated. The approach was of subjective nature, since data for many sub-criteria was collected through interviews with subject experts. Şağbanşua and Balo [16] also applied their same approach for a 3.45MW turbine. Emeksiz and Yüksel [17] developed an adaptive hybrid multi-criteria decision approach which was based on the Entropy-Based Multi-Attribute Utility Theory (MAUT) for big turbines. They also as–sumed four main criteria (technical, economic, environ–mental, and customer service) with 17 sub-criteria. Their analysis was based on the data collected from literature as well as from domain experts which was subjective. Cuadros et al. [18] used the AHP method considering six criteria and five models that met the requirements of the project, and subsequently the selec–tion of a micro-wind turbine of 2000W capacity. The decision criteria included maximum power, output voltage, swept diameter, turbine weight, startup speed, and price. Şahin and Deliktaş [19] utilized Entropy-based-TOPSIS and combined compromise solution (CoCoSo) methods for multi-criteria turbine selection. The decision criteria were price, rated power, rotor dia–meter, turbine size, noise emission value, and annual energy production. Four wind turbines were assumed, with the nominal power between 1750 kW and 2100 kW. Yu et al. [20] proposed a hybrid MCDM approach that integrated the interval 2-tuple linguistic (I2TL) model, power weighted average (PWA) operator, step–wise weighted assessment ratio analysis II (SWARA II), method based on the removal effects of criteria (MEREC), cumulative prospect theory (CPT) and CoCoSo method. Zhao [21] proposed a new multi-criteria group decision-making (MCGDM) method based on weighted Lq-ROF Hamacher average (WLq-ROFHA) operator. Four decision criteria with several sub-criteria were assumed. However, the study was at the conceptual level, and no empirical results were provided.

Table 1. Summary of recent studies on turbine selection with MCDM technqiues

Reference	Year	Technique
Şağbanşua and Balo [15]	2017	Analytic Hierarchy Process
Şağbanşua and Balo [16]	2017	Analytic Hierarchy Process
Emeksiz and Yüksel [17]	2022	Multi-Attribute Utility Theory
Cuadros et al. [18]	2024	Analytic Hierarchy Process
Şahin and Deliktaş [19]	2026	Entropy-based-TOPSIS, CoCoSo
Yu et al. [20]	2022	I2TL, PWA, SWARA II, MEREC), CPT, CoCoSo
Zhao [21]	2022	Fuzzy logic based MCGDM
Li et al. [22]	2024	D-SAISM
Zakir et al. [23]	2024	New MCDM framework
Supciller and Toprak [24]	2020	TOPSIS, EDAS, SWARA
Rehman and Khan [25]	2019	Goal Programming
Rehman et al. [26]	2020	TOPSIS
Rehman et al. [27]	2020	Fuzzy Logic

Li et al. [22] developed a new hybrid MCDM fra–mework, known as D-SAISM (squeeze adversarial interpretive structural modeling based on D numbers) for selection of offshore turbines. Zakir et al. [23] proposed a multi-criteria decision-analysis framework while using levelized cost of energy, simple payback period, net present value per kW, benefit-to-cost ratio, internal rate of return, and cost of turbine per kW as the decision metrics. Supciller and Toprak [24] developed a methodology mainly based on the TOPSIS and EDAS methods integrated with single valued neutrosophic numbers. They further employed the SWARA method to weigh the different criteria used. Rehman and Khan [25] proposed a two-tier approach based on the goal programming method, and several turbines were evaluated and ranked. Rehman et al. [26] also proposed a TOPSIS based approach for turbine selection using multiple decision criteria. These included hub height, wind speed, percentage of zero output, percentage of rated output, and annual energy production. Further–more, Rehman et al. [27] also proposed a mutli-criteria turbine selection methodology based on fuzzy logic. The methodology used hub height, wind speed, percen–tage of zero output, percentage of rated output, and net capacity factor as the decision criteria. Table 1 provides a summary of the above studies.

3. WIND DISTRIBUTION

The wind data used in this study spanned the period between August 2024 and August 2025 collected on ho–urly basis. This resulted in an average wind speed of 12.37 m/s at 10 meters above ground level. Figure 2 shows monthly variation of average wind speed at 10m height based on hourly data collected over one year. This provides an indication of the wind potential of the urban area of Karachi.

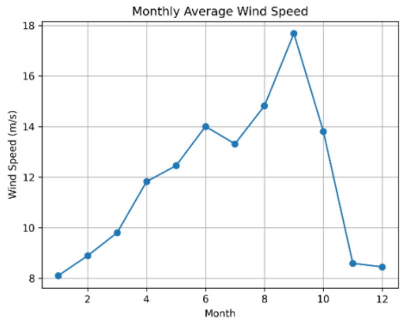

Figure 2. Monthly variation of average wind speed for Karachi

In addition to the monthly variation, attention should also be paid to the spread of the wind data. A single average does not indicate whether most of the values remain close to that number, or whether they are well spread apart. As such, the histogram in Figure 3 illus–trates how often certain wind speeds occur. This is important as the turbines do not respond the same to all wind speeds.

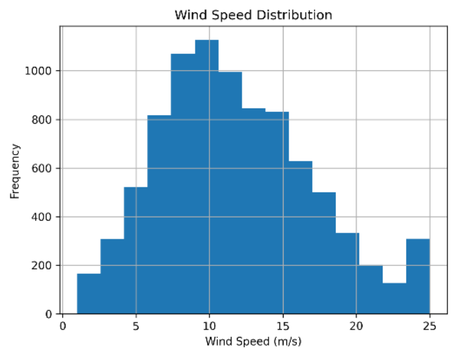

Figure 3. Histogram of wind speed showing frequency distribution based on hourly observations

The data spread can be more formally represented through the probability distribution. The standard form in many wind energy studies is a Weibull-type dist–ribution, which is also adopted herein.As shown in Fi–gure 4, the distribution reflects that the wind speeds are “spread” rather than concentrated at a given value. A reasonable chunk of data is within the operational range of the tur–bines, and this helps understand the estimates of energy.

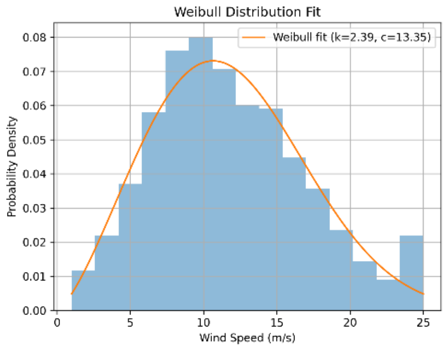

Figure 4. Weibull probability density function fitted to the measured wind speed data

Using the given data, the annual energy production (AEP) for a VAWT can be calculated. For this purpose, the power ouput, *P(V)*, at wind speed *V* is first deter–mined using the following expression:

$$P(V)=\frac{1}{2}C_p\rho AV^3 \quad (1)$$

where ρ is the air density, C_p is the power coefficient, *A* is the rotor swept area, and *V* is the wind speed. Wang et al. [28] have explained the calculation of AEP, which can be represented by the following formula:

$$AEP=Y\int_{V_{cut-in}}^{V_{cut-out}}P(V)f(V)dV \quad (2)$$

where *Y* denotes the length of a year (taken as 365 days or 8760 hours), *f(V)* is the probability density function, V_{cut-in} is the turbine cut-in speed, and $V_{cut-out}$ is the turbine cut-out speed. For details and all relevant calculations, interested reader is referred to Wang et al. [28]

4. FUZZY LOGIC BASED MULTI-CRITERIA DECISION MODEL

Multi-criteria decision-making is used in scenarios where decisions are taken while simultaneously consi–dering multiple factors, commonly called criteria or objectives[29]. Ideally, all criteria in the decision model should be optimized to their optimal values. However, due to the conflicting nature of criteria, a trade-off is obtained. That is, all criteria are optimized to a level which is acceptable by the decision-maker. Conflicting criteria refer to criteria wherein the improvement in one criterion results in the degradation in the quality of the other(s). Another concern in MCDM problems is the *incommensurability* of criteria. That is, the criteria to be optimized have different units and magnitudes, and therefore, the numerical values associated with these criteria cannot be directly added.

Many techniques exist to solve an MCDM problem. Some well-known methods include goal programming, analytic hierarchy process, weighted sum method, TOPSIS, VIKOR, ELECTRE, and others. Among these methods, fuzzy logic is also one such method that has been effectively used to solve MCDM problems. Rehman et al. [30] has argued that most MCDM app–roaches (with the exception of fuzzy logic) provide li–mited options when it comes to decision-making. For example, refer to the following three examples that depict hypothetical decision rules, with three decision criteria, namely Criterion 1, Criterion 2, and Criterion 3, and a result *X*.

Example 1. IF Criterion 1 is optimized AND Criterion 2 is optimized AND Criterion 3 is optimized THEN Result X is also optimized.

Example 2. IF Criterion 1 is optimized OR Criterion 2 is optimized OR Criterion 3 is optimized THEN the Result X is also optimized.

Example 3. IF Criterion 1 is optimized AND (Criterion 2 is optimized OR Criterion 3 is optimized) THEN the Result X is also optimized.

In Example 1, the decision is based on the opti–mization of all three criteria. If any one ofthe three decision criteria is not optimized (even if the other two are optimized) then Result *X* will not be optimized. In contrast, the decision rules in Examples 2 and 3 do not require optimization of all three decision criteria in order to optimize Result *X*. This flexibility is available with fuzzy logic only.

A fundamental requirement to solve a problem using fuzzy logic is to form a decision rule and employ an aggregation function that transforms the decision rule into a mathematical representation. This mathematical repre–sentation is able to aggregate the criteria such that the issue of incommensurability is resolved. This is done by converting the criteria into a uniform, unit-less scale. The conversion is done through the formation of membership functions, which are explained later in this section.

The fuzzy logic approach proposed in this study considers the decision among five criteria. These are hub height (HH), annual energy production (AEP), tur–bine swept area (SA), cut-in speed (C), and rated speed (R) of the VAWT. The five criteria are important and conflicting with each other. For example, more wind is absorbed at a higher altitude, and thus results in more AEP. However, higher altitude requires more hub height which in turn affects the financial cost and maintenance issues. Moreover, the swept area also affects the wind energy, and more swept area contributes towards more absorption of wind energy by the VAWT [30], inclu–ding the impact of angular velocity [31]. However, due to the densely populated urban structure of the city of Karachi, where a notable majority of houses have a plot size of 40 to 133 square yards [32], turbines with high swept areas are less appealing. Considering these obser–vations, the first step toward solving this MCDM prob–lem is the requirement of a decision rule, which can be formed as follows:

Rule 1: IF a solution *X* has *low hub height* AND *high annual energy production* AND *low swept area* AND *low cut-in speed* AND *low rated speed*THEN it is a *good solution*.

In the above rule, X refers to a solution that aggregates the impact of hub height, turbine swept area, annual energy production, cut-in speed, and rated speed. The terms "low hub height", "high annual energy production", "low swept area", "low cut-in speed", "low rated speed", and "good solution" are linguistic values, each of which defines a fuzzy subset of solutions. Each fuzzy subset is represented by a membership function, $\mu(x)$. The membership function returns a value in the interval [0,1], thus converting the crisp values of the five decision criteria into a [0,1] range, and without any units. The membership functions for the five criteria are formulated as explained in the following sections.

It should be noted that many decision rules are possible considering the t-norm and s-norm based struc–tures, as well as assigning preferences to certain criteria in the decision rule. Rehman et al. [27] presented a detailed methodology for formation of rules for the turbine selection problem. According to that methodo–logy, Rule 1 presented above is unique in the sense that it considers all criteria in the decision with equal prefe–rence. Therefore, the rule is adopted for the present study.

With regard to the structure of the membership fun–ction, a linear design has been adopted. A number of structures for the membership functions have been reported in the literature. Some common ones are linear, triangular, trapezoidal, Gaussian, and Sigmoidal. How–ever, not all types are applicable in all cases. For exam–ple, Gaussian and Sigmoidal are more appropriate where a smooth transition is required, or the decisions are very sensitive to precision in calculations and requ–ire high granularity. As suggested by Belyadi and Hag–highat [33], linear membership functions are effective for illustration and initial design of a fuzzy system due to their simplicity. Smooth membership functions, e.g., Gaussian and Sigmoidal, are more effective for auto–mated controlbut are more complicated to design.

4.1 Membership Function for Hub Height

The membership function for the hub height (HH) is developed by determining the upper and lower bounds for the criterion. The two bounds, MnH (the minimum hub height) and MxH (the maximum hub height), are found based on the technical specifications of the tur–bines, as will be discussed in Section 5. Using the above two thresholds, the membership function for the hub height, $\mu_H(x)$, is mathematically represented as follows:

$$\mu_H(x) = \begin{cases} 1 & \text{if } HH(x) \le MnH \\ \dfrac{MxH - HH(x)}{MxH - MnH} & \text{if } MnH(x) \le MxH \\ 0 & \text{if } HH(x) > MxH \end{cases} \tag{3}$$

where HH(x) represents the hub height of solution x.

4.2 Membership Function for Swept Area

The membership function for the swept area is defined similar to that of hub height. The swept area has to be minimized, so the upper and lower bounds for wind speed are determined. The lower bound, MnS, as well as the upper bound, MxS, are found based on the collected data (as explained in Section 5). Equation (4) represents the membership function, $\mu_S(x)$, for the wind speed.

$$\mu_S(x) = \begin{cases} 1 & \text{if } SA(x) \le MnS \\ \dfrac{MxS - SA(x)}{MxS - MnS} & \text{if } MnS(x) \le MxS \\ 0 & \text{if } SA(x) > MxS \end{cases} \tag{4}$$

where $SA(x)$ represents the swept area of solution x.

4.3 Membership Function for Annual Energy Production

Finally, the membership function for annual energy production can be formed as follows. The upper and lower bounds for AEP are determined first, using the collected data. Equation (5) represents the membership function, $\mu_E(x)$ for annual energy production. In this equation, MxE and MnE correspond to the upper and lower bounds, respectively.

$$\mu_E(x) = \begin{cases} 1 & \text{if } AEP(x) \ge MxE \\ \dfrac{AEP(x) - MnE}{MxE - MnE} & \text{if } MnE \le AEP(x) \le MxE \\ 0 & \text{if } AEP(x) > EMin \end{cases} \tag{5}$$

where $AEP(x)$ represents the annual energy production associated with solution x.

4.4 Membership Function for Cut-in Wind Speed

The membership function for the cut-in wind speed is found through the use of upper and lower bounds for the criterion. The two bounds, MnC and MxC, represent the the minimum and maximum cut-in wind speeds, res–pectively. These are found using the technical specifi–cations of the turbines, as discussed in Section 5. The membership function for the cut-in wind speed, $\mu_C(x)$ is mathematically represented as follows:

$$\mu_C(x) = \begin{cases} 1 & \text{if } C(x) \le MnC \\ \dfrac{MxC - C(x)}{MxC - MnC} & \text{if } MnC \le C(x) \le MxC \\ 0 & \text{if } C(x) > MxC \end{cases} \tag{6}$$

where $C(x)$ defines the cut-in wind speed of solution x.

4.5 Membership Function for Rated Wind Speed

The membership function for the rated wind speed is determined using the upper and lower bounds. This rated wind speed is to be minimized. The lower bound, MnR, as well as the upper bound, MxR, are found using the collected data as explained in Section 5. Equation (7) represents the membership function, $\mu_R(x)$, for the rated wind speed.

$$\mu_R(x) = \begin{cases} 1 & \text{if } R(x) \le MnR \\ \dfrac{MxR - R(x)}{MxR - MnR} & \text{if } MnR \le R(x) \le MxR \\ 0 & \text{if } R(x) > MxR \end{cases} \tag{7}$$

where $R(x)$ signifies the rated wind speed of solution x.

4.6 Calculation of the Overall Membership Function

The next step is to aggregate all individual memberships for the three criteria. This requires Rule 1 to be trans–formed into a mathematical representation. For this pur–pose, the fuzzy arithmetic mean operator [34] can be used. The operator is particularly selected due to its simplicity, although any other aggregation operator can be used. The fuzzy arithmetic mean operator places all membership functions into a single aggregation function which measures the degree of satisfaction of the overall membership function. The mathematical representation of the overall membership function for solution *x, OM(x),* is given by the following equation.

$$OM\left(x\right)=\frac{\mu_H\left(x\right)+\mu_s\left(x\right)+\mu_E\left(x\right)+\mu_C\left(x\right)+\mu_R\left(x\right)}{5} \quad (8)$$

In (8) above, *OM(x)* represents the overall mem–bership of the three criteria collectively. The solution that results in the maximum value for (8) is reported as the best solution found.

5. RESULTS AND DISCUSSION

In this section, empirical results are presented and discussed to evaluate the performanceoffive different VAWTs. All VAWTs were of 600W rated capacity. Specifications of these VAWTs are given in Table 2. The wind data was collected from the city of Karachi which is located in Southern Pakistan at the coastal belt with the Arabian Sea. As mentioned earlier, the duration for data collection was from 24 August 2024 to 25 August 2025, with an average wind speed of 12.37 m/s at a height of 10 meters above ground level. This data was then extrapolated for heights of 15 and 20 meters. Four sets of analyses were performed. In the first set, the optimal combination of hub height, swept area, AEP, cut-in speed, and rated speed were found for each turbine. In the second set, the impact of hub height and swept area on the overall solution was analyzed. The third set of analyses discussed implementation of two other MCDM methods, namely weighted sum and goal programming. The fourth set of experiments compared the three methods. Details of these experiments and analyses are given below.

As discussed earlier, the quantities that contribute in the decision-making are hub height, turbine swept area, annual energy production, cut-in speed, and rated speed. Among these, calculation of hub height is simple and is measured in meters with ground level as reference. The entities of turbine swept area, turbine cut-in speed, and rated speed are available from manufacturers. Only AEP requires a calculation, which is provided in Section 3.

Table 3 provides the wind related parameters. Two important parameters that affect turbine's performance are *drivetrain efficiency* and *power coefficient*. Drive–train efficiency directly impacts total energy yield and the Levelized Cost of Energy (LCOE) by converting mechanical rotor energy into electrical power. A typical value is between 0.9 and 0.95 [40]. Furthermore, power coefficients refer to the fraction of power extracted from the wind relative to the total energy available. Typical values range between 0.15 and 0.40 for Darrieus types, and 0.15 to 0.25 for Savonius types.However, some studies have shown that some Savonius designs (e.g. Helical Savonius) can reach values between 0.28 and 0.32 under controlled conditions [41][42], with studies also reporting a level of 0.41 [43].

To utilize the membership functions defined in the previous sections, the upper and lower limits (maximum and minimum values) need to be defined. Table 4 provides these values. These values are calculated con–sidering the maximum and minimum values achieved by all criterion. Then, the limits are defined considering approximately 10% values at both extremes. For example, the hub heights were 10, 15, and 20 meters. So, the upper limit for hub height is taken as 20 plus 10% of 20 (which is 2), resulting in 22. Similarly, the lower limit is 10 minus 10% of 10 (which is 1), resulting in lower limit of 9. Thus, the two extreme values for hub height of 22 and 9 were used in the experimentation. The limits for other criteria were cal–culated in the same manner.These limits were used in all methods used, details of which are provided in the upcoming sections.

Table 2. Specifications of the turbines used

Turbine	Swept area (m^2)	Cut-in speed (m/s)	Rated speed (m/s)	Type
ATO-VAWT-X5-600 [35]	0.413	2	12	Helix
Generic Alibaba Savonius [36]	0.48	2.5	10	Savonius
HICORPWELL Darrieus–Savonius hybrid [37]	5.75	1	15	Darrieus Savonius hybrid
Maglev / low-noise rooftop [38]	2.619	2	12	Helix
Qingdao Greef / Rose-600W rooftop[39]	1.8	2.8	12	Helix

Table 3. Wind related parameters for the evaluation site

Parameter	Value
ρ(air density)	1.225
C_p(power coefficient)	0.3
η(drivetrain efficiency)	0.9
Mean wind speed (at 10m AGL)	12.37 m/s
α (wind shear exponent)	0.14

Optimal Combination of the Five Criteria

Tables 5 to 9 present the results of fuzzy logic based aggregation for the five turbines. These tables provide the raw data for hub height, swept area, annual energy production, cut-in wind speed, and rated wind speed, along with their fuzzified values. These fuzzified values were obtained using (3) to (7). The last column of the tables indicate the overall membership as calculated through (8).

Table 4. Upper and lower limits for membership functions

Criterion	Upper Limit	Lower Limit
Hub height	22	9
Swept area	6.3	0.37
Annual energy production	4400	1315
Cut-in wind speed	3	0.9
Rated wind speed	16.5	9

It is observed from the tables that the best overall membership values at the three hub heights were obtained by Maglev / low-noise rooftop which showed overall membership values of 0.661, 0.587, and 0.512 for 10m, 15m, and 20m, respectively. This is followed by Generic Alibaba Savonius/ hybrid which showed overall memberships of 0.622, 0.552, and 0.479 for 10m, 15m, and 20m, respectively. The worst performance was shown by Qingdao Greef / Rose-600W rooftop which had very low memberships of 0.590, 0.518, and 0.443 for hub heights of 10m, 15m, and 20m, respectively.

5.2 Effect of Hub Height and Swept Area on Overall Membership

Among the five criteria, hub height and turbine swept area are two factors that represent physical characteristics of a turbine and are independent of the wind. The other three criteria (AEP, cut-in speed, and rated speed) are related to wind and therefore are not in the control of the decision-maker. Therefore, the impact of hub height and swept area on the overall membership was evaluated. Details of the analysis is presented below.

Table 5. Overall membership for ATO / ATO-VAWT-X5-600

HH (m)	SA (m^2)	AEP (kWh per year)	Cut-in wind speed (m/s)	Rated wind speed (m/s)	$\mu_H(x)$	$\mu_s(x)$	$\mu_E(x)$	$\mu_C(x)$	$\mu_R(x)$	$OM(x)$
10	0.413	1464.24	2	12	0.923	0.993	0.048	0.476	0.600	0.608
15	0.413	1564.98	2	12	0.538	0.993	0.081	0.476	0.600	0.538
20	0.413	1626.75	2	12	0.154	0.993	0.101	0.476	0.600	0.465

Table 6. Overall membership for Generic Alibaba Savonius/ hybrid

HH (m)	SA (m^2)	AEP (kWh per year)	Cut-in wind speed	Rated wind speed	$\mu_H(x)$	$\mu_s(x)$	$\mu_E(x)$	$\mu_C(x)$	$\mu_R(x)$	$OM(x)$
10	0.48	1631.24	2.5	10	0.923	0.981	0.103	0.238	0.867	0.622
15	0.48	1735.9	2.5	10	0.538	0.981	0.136	0.238	0.867	0.552
20	0.48	1799.22	2.5	10	0.154	0.981	0.157	0.238	0.867	0.479

Table 7. Overall membership forHICORPWELL Darrieus–Savonius hybrid

HH (m)	SA (m^2)	AEP (kWh per year)	Cut-in wind speed (m/s)	Rated wind speed (m/s)	$\mu_H(x)$	$\mu_s(x)$	$\mu_E(x)$	$\mu_C(x)$	$\mu_R(x)$	$OM(x)$
10	5.75	3994.96	1	15	0.923	0.093	0.869	0.952	0.200	0.607
15	5.75	4007.4	1	15	0.538	0.093	0.873	0.952	0.200	0.531
20	5.75	3998.74	1	15	0.154	0.093	0.870	0.952	0.200	0.454

Table 8. Overall membership for Maglev / low-noise rooftop

HH (m)	SA (m^2)	AEP (kWh per year)	Cut-in wind speed (m/s)	Rated wind speed (m/s)	$\mu_H(x)$	$\mu_s(x)$	$\mu_E(x)$	$\mu_C(x)$	$\mu_R(x)$	$OM(x)$
10	2.619	3421.76	2	12	0.923	0.621	0.683	0.476	0.600	0.661
15	2.619	3476.16	2	12	0.538	0.621	0.701	0.476	0.600	0.587
20	2.619	3496.59	2	12	0.154	0.621	0.707	0.476	0.600	0.512

Table 9. Overall membership for Qingdao Greef / Rose-600W rooftop

HH (m)	SA (m^2)	AEP (kWh per year)	Cut-in wind speed (m/s)	Rated wind speed (m/s)	$\mu_H(x)$	$\mu_s(x)$	$\mu_E(x)$	$\mu_C(x)$	$\mu_R(x)$	$OM(x)$
10	1.8	3078.27	2.8	12	0.923	0.759	0.572	0.095	0.600	0.590
15	1.8	3152.76	2.8	12	0.538	0.759	0.596	0.095	0.600	0.518
20	1.8	3187.77	2.8	12	0.154	0.759	0.607	0.095	0.600	0.443

With respect to the swept area, it is observed in Tables 5 to 9 that higher overall membership values are directly correlated with the turbine swept area. For the three hub heights, the overall memberships were high at swept area of 2.619m^2, which is associated with Maglev / low-noise rooftop.Note that for swept areas smaller or greater than 2.619m^2, the overall membership values were low. As an example, if we look at Column 2 of all the tables, and analyze the results of all turbines at hub height of 10m, it is noted that with swept area of 0.413m^2, the overall membership was 0.608 (Table 5). For turbine with a swept area of 0.48m^2, the overall membership was 0.622 at 10m (Table 6). However, when the swept area was 5.75m^2, the overall mem–bership was 0.607 as shown in Table 7. Similar trends were observed for hub heights of 15m and 20m. Citing the above observations, it could be claimed that VAWTs with very small and very big swept areas did not produce favorable results, and most appealing mem-bership values are expected to occur with turbines having swept areas around 2.619m^2. Figure 5 illustrates the behavior of the swept area on the overall mem–bership values. The figure further strengthens the above observations; the best performance (overall member–ship) was obtained for swept areas at 2.619m^2.

The effect of hub height on the overall membership was also analyzed. Figure 6 shows the impact of hub height on the five turbines with different swept areas. It is clear from the figure that the highest membership values for all five turbines were obtained at hub height of 10m, whereas the worst overall membership for all five tur–bines was obtained at the height of 20m. The figure shows a downward linear trend, where the best member–ships lie between 0.5 and 0.7 for hub height of 10m, while the worst memberships were between 0.45 and 0.55 for the hub height of 20vm. Another trend observed from Figure 6 is that for Maglev / low-noise rooftop with swept areaof 2.619 m^2, the membership values were the highest than turbines with low swept area (0.4125 m^2, 0.48 m^2, and 1.8 m^2) and high swept area (5.75 m^2). This finding is interesting and favorable since due to the population density of the site under consideration, turbines with moderate swept area would require less space, and therefore can be installed on houses with small area. Furthermore, these turbines would also generate less noise compared to turbines with higher swept area.

With regard to the annual energy production, the results in Tables 5 to 9 indicated that in general, high AEP values were obtained at higher altitude. This is logical since more wind absorption is expected at higher altitudes, resulting in higher AEP values.

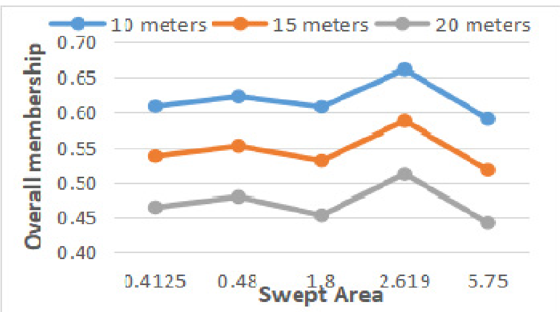

Figure 5. Effect of swept area on the overall membership

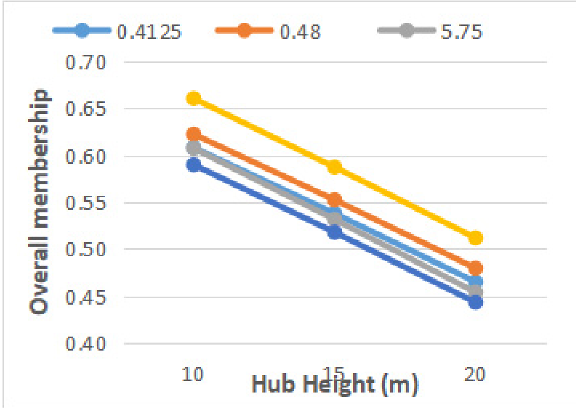

Figure 6. Effect of hub height on the overall membership

5.3 Application of Weighted Sum Method

The weighted sum method (WSM) has been effectively applied to MCDM problems, due to the simplicity and time efficiency [44]. The method works on the concept of aggregation of criteria to form an overall decision function. In order to carry out the aggregation, decision criteria are first normalized to address the issue of incommensurability. After normalization, each criterion is assigned a weight as per the aspiration of the deci–sion-maker. These weighted criteria are aggregated using an aggregation function. The output of this aggre–gation is a scalar value. A necessary requirement for this aggregation is that the sum of all weights should be exactly equal to 1.

In the present study, the application of WSM requires that the upper limit for each criterion be defined for normalization. For his purpose, the upper limits mentioned in Table 2 are used. Furthermore, in the context of the turbine selection problem, the WSM approach treats the problem as a maximization problem. We intend to find a solution where hub height, swept area, cut-in wind speed, and rated wind speed are to be minimized, and annual energy production is maximized. Accordingly, the following equation is used for the decision.

$$W_t = w_1\left(1-\frac{HH(x)}{MxH}\right)+w_2\left(1-\frac{SA(x)}{MxS}\right)+w_3\left(1-\frac{AEP(x)}{MxE}\right)$$
$$+w_4\left(1-\frac{C(x)}{MxC}\right)+w_5\left(1-\frac{R(x)}{MxR}\right) \quad (9)$$

In (9), W_t represents the weighted sum of turbine t. Each fraction in the equation represents the normalized value of a selection criterion. A higher value of W_t signifies a better turbine, and vice versa. Furthermore, all criteria are treated with equal preference and there–fore equal weights are taken as $w_1 = w_2 = w_3 = w_4 = w_5 =$ 0.2.

The above equationcan also be written in a simpli–fied form as follows:

$$W_t = w_H + w_S + w_A + w_C + w_R \quad (10)$$

Tables 10 to 14 present the results for the weighted sun method. It is observed from the tables that in general, the best results are obtained by Maglev / low-noise rooftop which shows the highest values of W_t for all hub heights. To be specific, the values of W_t were 0.503, 0.460, and 0.415 for hub heights of 10m, 15m, and 20m, respectively, as shown in Table 13. These values were the highest among all turbines.

In contrast, the worst performance was displayed by HICORPWELL Darrieus–Savonius hybrid as shown in Table 12. An interesting observation in the results is that at the height of 10m, both HICORPWELL Dar–rieus–Savonius hybrid and Qingdao Greef / Rose-600W rooftop showed equal performance, with W_t = 0.460. However, for 15m height, HICORPWELL Darrieus–Savonius hybrid had W_t = 0.415 whereas Qingdao Greef / Rose-600W rooftop showed W_t = 0.418. Similarly, for 20m height, W_t = 0.369 for HICORPWELL Darrieus–Savonius hybrid and W_t = 0.374 for Qingdao Greef / Rose-600W rooftop. So, comparing the overall results for the two turbines, HICORPWELL Darrieus–Savonius hybrid was the worst.

Table 10. Weighted sum for ATO / ATO-VAWT-X5-600

HH (m)	SA (m^2)	AEP (kWh per year)	Cut-in wind speed (m/s)	Rated wind speed (m/s)	w_H	w_S	w_E	w_C	w_R	W_t
10	0.413	1464.24	2	12	0.545	0.935	0.333	0.333	0.273	0.484
15	0.413	1564.98	2	12	0.318	0.935	0.356	0.333	0.273	0.443
20	0.413	1626.75	2	12	0.091	0.935	0.370	0.333	0.273	0.400

Table 11. Weighted sum for Generic Alibaba Savonius/ hybrid

HH (m)	SA (m^2)	AEP (kWh per year)	Cut-in wind speed (m/s)	Rated wind speed (m/s)	w_H	w_S	w_E	w_C	w_R	W_t
10	0.48	1631.24	2.5	10	0.545	0.924	0.371	0.167	0.394	0.480
15	0.48	1735.9	2.5	10	0.318	0.924	0.395	0.167	0.394	0.439
20	0.48	1799.22	2.5	10	0.091	0.924	0.409	0.167	0.394	0.397

Table 12. Weighted sum forHICORPWELL Darrieus–Savonius hybrid

HH (m)	SA (m^2)	AEP (kWh per year)	Cut-in wind speed (m/s)	Rated wind speed (m/s)	w_H	w_S	w_E	w_C	w_R	W_t
10	5.75	3994.96	1	15	0.545	0.087	0.908	0.667	0.091	0.460
15	5.75	4007.4	1	15	0.318	0.087	0.911	0.667	0.091	0.415
20	5.75	3998.74	1	15	0.091	0.087	0.909	0.667	0.091	0.369

Table 13. Weighted sum for Maglev / low-noise rooftop

HH (m)	SA (m^2)	AEP (kWh per year)	Cut-in wind speed (m/s)	Rated wind speed (m/s)	w_H	w_S	w_E	w_C	w_R	W_t
10	2.619	3421.76	2	12	0.545	0.584	0.778	0.333	0.273	0.503
15	2.619	3476.16	2	12	0.318	0.584	0.790	0.333	0.273	0.460
20	2.619	3496.59	2	12	0.091	0.584	0.795	0.333	0.273	0.415

Table 14. Weighted sum for Qingdao Greef / Rose-600W rooftop

HH (m)	SA (m^2)	AEP (kWh per year)	Cut-in wind speed (m/s)	Rated wind speed (m/s)	w_H	w_S	w_E	w_C	w_R	W_t
10	1.8	3078.27	2.8	12	0.545	0.714	0.700	0.067	0.273	0.460
15	1.8	3152.76	2.8	12	0.318	0.714	0.717	0.067	0.273	0.418
20	1.8	3187.77	2.8	12	0.091	0.714	0.724	0.067	0.273	0.374

5.4 Application of Goal Programming

In goal programming, target/ideal values are assigned by the decision-maker, with the aim of reaching the target value in the decision-making process. For each decision criterion, the absolute deviation between the target value and the actual achieved value is measured. Finally, all deviations are added. This is done for each solution. The solution that results in the minimum deviation is identified as the best solution.

Many variants of goal programming exist. In the present study, fuzzy goal programming is adopted due to its ability to deal with levels of imprecision in the goal programming model [45]. In fuzzy goal prog–ramming, a set of target goals is initialized for each of the five decision criteria. Each goal has a fuzzified ma–ximum achievement level that is determined a priori. That is, the crisp values of each criteria are converted into a fuzzified form through a membership function, and deviations are measured in form of fuzzified values.

In the context of the underlying problem, the fuzzified values are already calculated in Section 4. Furthermore, the ideal value for each criterion is 1, since a fuzzy value is always in the [0,1] range. Therefore, the deviation is calculated with reference to this ideal value, with the aim of minimizing the resulting total deviation. The following equation is used to calculate the overall deviation, D_t:

$$D_t = |1-\mu_H| + |1-\mu_S| + |1-\mu_A| + |1-\mu_C| + |1-\mu_R| \quad (11)$$

Alternatively, the equation can be written as

$$D_t = d_H + d_S + d_A + d_C + d_R \quad (12)$$

Tables 15 to 19 present the results for goal prog–ramming. The best performance is demonstrated by Maglev / low-noise rooftop. As shown in Table 18, for all three hub heights, the deviation D_t is the lowest compared to the corresponding hub heights of other turbines. Specifically, the deviation D_t for Maglev / low-noise rooftop is 1.697, 2.064, and 2.442 for 10m, 15m, and 20m, respectively. These are the lowest compared to other turbines. In contrast, the worst performance is shown by Qingdao Greef/Rose-600W rooftop which shows the highestD_t with 2.051, 2.412, and 2.785 for 10m, 15m, and 20m, respectively, as shown in Table 19.

Table 15. Goal programming deviation for ATO / ATO-VAWT-X5-600

HH (m)	SA (m^2)	AEP (kWh per year)	Cut-in wind speed (m/s)	Rated wind speed (m/s)	d_H	d_S	d_E	d_C	d_R	D_t
10	0.413	1464.24	2	12	0.077	0.007	0.952	0.524	0.400	1.960
15	0.413	1564.98	2	12	0.462	0.007	0.919	0.524	0.400	2.311
20	0.413	1626.75	2	12	0.846	0.007	0.899	0.524	0.400	2.676

Table 16. Goal programming deviation for Generic Alibaba Savonius/ hybrid

HH (m)	SA (m^2)	AEP (kWh per year)	Cut-in wind speed (m/s)	Rated wind speed (m/s)	d_H	d_S	d_E	d_C	d_R	D_t
10	0.48	1631.24	2.5	10	0.077	0.019	0.897	0.762	0.133	1.888
15	0.48	1735.9	2.5	10	0.462	0.019	0.864	0.762	0.133	2.239
20	0.48	1799.22	2.5	10	0.846	0.019	0.843	0.762	0.133	2.603

Table 17. Goal programming deviation forHICORPWELL Darrieus–Savonius hybrid

HH (m)	SA (m^2)	AEP (kWh per year)	Cut-in wind speed (m/s)	Rated wind speed (m/s)	d_H	d_S	d_E	d_C	d_R	D_t
10	5.75	3994.96	1	15	0.077	0.907	0.131	0.048	0.800	1.963
15	5.75	4007.4	1	15	0.462	0.907	0.127	0.048	0.800	2.344
20	5.75	3998.74	1	15	0.846	0.907	0.130	0.048	0.800	2.731

Table 18. Goal programming deviation for Maglev / low-noise rooftop

HH (m)	SA (m^2)	AEP (kWh per year)	Cut-in wind speed (m/s)	Rated wind speed (m/s)	d_H	d_S	d_E	d_C	d_R	D_t
10	2.619	3421.76	2	12	0.077	0.379	0.317	0.524	0.400	1.697
15	2.619	3476.16	2	12	0.462	0.379	0.299	0.524	0.400	2.064
20	2.619	3496.59	2	12	0.846	0.379	0.293	0.524	0.400	2.442

Table 19. Goal programming deviation for Qingdao Greef / Rose-600W rooftop

HH (m)	SA (m^2)	AEP (kWh per year)	Cut-in wind speed (m/s)	Rated wind speed (m/s)	d_H	d_S	d_E	d_C	d_R	D_t
10	1.8	3078.27	2.8	12	0.077	0.241	0.428	0.905	0.400	2.051
15	1.8	3152.76	2.8	12	0.462	0.241	0.404	0.905	0.400	2.412
20	1.8	3187.77	2.8	12	0.846	0.241	0.393	0.905	0.400	2.785

Table 20. Ranking of turbines with respect to the three MCDM methods.

Turbine	HH (m)	SA (m^2)	AEP (kWh per year)	Cut-in wind speed (m/s)	Rated wind speed (m/s)	Fuzzy Logic		Weighted Sum		Goal Progamming	
						OM	Rank	W_t	Rank	D_t	Rank
ATO-VAWT-X5-600	10	0.413	1464.24	2	12	0.608	3	0.484	2	1.960	3
Generic Alibaba Savonius	10	0.48	1631.24	2.5	10	0.622	2	0.480	3	1.888	2

HICORPWELL Darrieus–Savonius hybrid	10	5.75	3994.96	1	15	0.607	4	0.460	4	1.963	4
Maglev / low-noise rooftop	10	2.619	3421.76	2	12	0.661	1	0.503	1	1.697	1
Qingdao Greef / Rose-600W rooftop	10	1.8	3078.27	2.8	12	0.590	5	0.460	4	2.051	5

5.5 Comparison of Methods

The comparison of the fuzzy logic approach with weighted sum and goal progamming techniques was done in the context of the five turbines. The objective of the analysis was to investigate whether the trends obtained using the fuzzy logic approach match with the trends observed using the other two aforementioned MCDM approaches. For this purpose, an approach similar to the ranking approach proposed by Lee et al. [46] and used by Rehman et al. [26] was adopted in this study and works as follows. First, the best $OM(x)$ for each turbine was taken from Tables 10 to 14. Then, the best $OM(x)$ values were ranked based on their merit, as shown in Table 20. Precisely, columns 7 and 8 of the table indicate the $OM(x)$ of the turbine and its corresponding relative rank, respectively. According to this ranking, Maglev / low-noise rooftop ranks first (best) with $OM(x)$ = 0.661, whereas Qingdao Greef / Rose-600W rooftop ranks the worst (having the 5th position) with $OM(x)$ = 0.590. Other turbines are ranked according to their $OM(x)$ values.

To validate the results obtained by the fuzzy logic methodology, ranking was also done for the weighted sum and goal programming methods. Table 20 also shows the ranking results for the two methods. As far as the weighted sum is concerned, results in columns 9 and 10 indicate that the highest W_t was achieved by Maglev / low-noise rooftop with W_t = 0.503, and thus ranking first. With regard to the worst option, a competition is observed between Qingdao Greef/Rose-600W rooftop and HICORPWELL Darrieus–Savonius hybrid. For both these turbines, W_t = 0.460 was obtained. Therefore, both were ranked equally at the 4th position. With regard to the goal proramming, results in the last two columns of Table 20 indicate that Maglev / low-noise rooftop showed the minimum deviation (D_t = 1.697) and therefore was ranked 1st, whereas Qingdao Greef / Rose-600W rooftop stood last with maximum deviation (D_t = 2.051).

To sum up, the results obtained by the three methods were almost identical. All methods delcared Maglev / low-noise rooftop as the best choice, whereas Qingdao Greef / Rose-600W rooftop turned out to be the worst option.

5.6 Discussion

The results in Sections 4.1 to 4.4 highlight some impor–tant trends. First, with the use of fuzzy logic, the impact of swept area on the overall membership highlighted that very small and very large swept areas did not pro–duce appealing results. The best performance was observed with the turbine with swept area in the me–dium range (i.e. 2.619 m^2). As a preliminary analysis, this indicates that while higher swept areas generally produce better results for bigger turbines as may have been pointed out in many other studies, low capacity turbines (such as the ones with 600W rated power con–sidered in this study) perform better with low swept areas. Another factor to be considered here could be the shape of the turbine, though this needs further empirical investigation.

When it comes to the hub height, the fuzzy logic results obtained were quite clear. The best results were obtained when the turbine height was kept at 10 meters. Logically, better power is absorbed at higher altitude. However, note that we are dealing with a multi-criteria problem, where the impact of turbine swept area also plays a role. Therefore, it could be a fair argument that the height was somewhat correlated with the swept area as well. However, this could be a preliminary obser–vation, and requires an in-depth analysis. With regard to the cut-in speed and rated speed, it was observed that these parameters did not seem to have a notable impact on the overall membership values. However, while high AEP values were more favorable and were observed at higher altitude, the best $OM(x)$ values were obtained at lower altitudes (and thus lower AEP values), which indicate that AEP did not have a very strong impact on the overall $OM(x)$ values.

As far as the weighted sum and goal programming methods are concerned, the results indicated trends si–milar to the ones obtained by fuzzy logic. The results of both methods indicated that the best values of W_t and D_t were obtained at hub heights of 10m and swept area of 2.619m^2. Again, the impact of AEP, cut-in speed, and rated speed was not clearly reflected in the results.

The validation of results carried out with the three methods while using the ranking approach provided almost identical results. All three methods identified the same best and worst solution.

One perception at looking towards the results is with regard to the turbine shape. Interestingly, both the best (Maglev / low-noise rooftop) and the worst (Qingdao Greef / Rose-600W) performers were Helix type. This somewhat indicates that the shape of the turbine had a little correlations with the performance, particularly in a multi-criteria decision scenario. However, this obser–vation is preliminary and solicits further investigation.

6. CONCLUSION AND FUTURE DIRECTIONS

In an urban setting, small scale wind turbines can play an effective role in generating necessary energy in regions where energy shortfall is high or the area is not connected to power grids. Focusing on this aspect, this study presented a preliminary analysis of the effectiveness of several small scale turbines having rated capacity of 600 Watts. The problem was modelled as a multi-criteria decision-making problem using fuzzy logic. Five criteria, namely, hub height, turbine swept area, annual energy production, cut-in speed, and rated speed were considered as the decision criteria. The results suggest that small scale VAWTs can be effective in harnessing power effectively at smaller hub heights with swept areas at a reasonably medium range. This range was around 2.619m^2 as far as the present study is concerned. Compared to turbines with higher swept areas, VAWTs with medium swept area are suitable for small sized homes, as could typically be expected in a densely populated urban settings. Furthermore, more favorable results were obtained with lower hub height (10m) than higher altitudes (15m or 20m). In addition, it was also found that cut-in speed and rated speed did not have a notable impact on the overall performance of the turbine.

The study can be expanded in several directions as future work. A more comprehensive study can be carried out with a large number of variety of VAWTs, while considering more hub heights. Furthermore, more decision criteria can be added to the multi-criteria decision-making model considered in this study. Another direction is to consider other MCDM techniques to analyze their performance. In addition, more wind conditions can be added to the wind model. While the study used the arithmetic mean operator, attention should also be paid to the use of other fuzzy operators and their impact on the decision should be assessed.

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NOMENCLATURE

$\mu_H(x)$	Membership for hub height
$\mu_S(x)$	Membership for swept area
$\mu_E(x)$	Membership for energy
$OM(x)$	Overall membership

ρ	Air density
C_p	Power coefficient
η	Drivetrain efficiency
α	Wind shear exponent
MnH	Minimum hub height
MxH	Maximum hub height
MnE	Minimum energy
MxE	Maximum energy
MnS	Minimum swept area
MxS	Maximum swept area
MCDM	Multi-criteria decision-making
VAWT	Vertical axis wind turbine
HAWT	Horizontal axis wind turbine
HH	Hub height of turbine
SA	Swept area of turbine
AEP	Annual energy production
W_t	Weighted sum of turbine t
D_t	Overall deviation of turbine t

ПРИСТУП ДОНОШЕЊА ОДЛУКА ЗАСНОВАН НА ВИШЕ КРИТЕРИЈУМА ЗАСНОВАН НА ФАЗИ ЛОГИЦИ ЗА ИЗБОР МАЛИХ ВЕТРОТУРБИНА СА ВЕРТИКАЛНОМ ОСОМ У УРБАНОМ ОКРУЖЕЊУ

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Енергија ветра се појавила као ефикасна алтер–натива фосилним горивима. На комерцијалном нивоу, енергија ветра се користи кроз ветроелек–тране. Међутим, у урбаном окружењу, мале ветро–турбине могу се инсталирати и ефикасно користити за производњу енергије без потребе за огромном инфраструктуром. Ова студија има за циљ да процени број ветротурбина са вертикалном осом номиналног капацитета од 600 вати. Развијен је приступ доношења одлука заснован на више критеријума (MCDM) заснован на фази логици, узимајући у обзир висину главчине, површину зах–вата турбине, годишњу производњу енергије, бр–зину укључивања и номиналну брзину као крите–ријуме одлучивања.

Процена је урађена на основу података прикуп–љених за град Карачи који се налази у јужном Пакистану. Процене су урађене коришћењем пет ветротурбина са вертикалном осом са различитим површинама захвата у распону од 0,413 м^2 до 5,75 м^2, узимајући у обзир висине глав–чине од 10 м, 15 м и 20 м. Предложена метода је такође упоређена са две друге MCDM методе, наиме, методом понде–рисане суме и циљним прог–рамирањем. Резултати показују да су све три методе произвеле мање-више исте одлуке. Утврђено је да је кров са маглевом/ниским нивоом шума са повр–шином захваћеном 2,619 м^2 произвео најбоље укуп–но фази чланство од 0,661, док је кров са кровом Qingdao Greef/Rose-600W показао најгоре са укуп–ним чланством од 0,590. Штавише, повољнији резултати су добијени на висини од 10 м у поређењу са висинама од 15 м и 20 м.