Assessments regarding the performances of wind turbines from the roofs of buildings

Sanda Budea*

Department of Hydraulics, Hydraulic Machines and Environmental Engineering, University Politehnica of Bucharest, Romania

Abstract. In the current energy context, wind energy remains the main renewable energy source. Greater attention should be paid to small-sized wind turbines, mounted on the roofs of buildings, for their many advantages: easy to construct, do not require additional space, easy maintenance, eliminate losses from the system and transport costs, can provide alone or in addition to energy solar, the entire energy need of buildings, etc. The present paper analyzes three models of wind turbines that can be placed on the roofs of buildings: crossflow wind turbine Banki, ridge blade turbine and aeroMINE model. The analysis refers to their constructive solutions, the working principle, the optimal design for a good power coefficient and the energy that can be obtained with these small turbines for urban applications and not only.

1 Introduction

In the current energy context, there is a need for the accelerated development of energy production from renewable sources. Wind power remains the leading non-hydro renewable source, generating 1870 TWh in 2021, almost as much as all others combined. The amount of electricity generated by wind increased by almost 273 TWh in 2021, a 55% increase over that achieved in 2020 and the largest among all power generation technologies. Wind power generation increase by a record amount in 2021, but even faster growth is needed to get on the Net Zero Scenario trajectory. Wind power generation in the Net Zero Scenario, for 2030, could reach 8000 TWh [1].

An estimation of the increase in onshore wind power capacity by region can be found in Figure 1. In July 2021 the European Commission proposed to increase the bloc's renewable energy target for 2030 from 32% to 40%. The proposed target was further increased to 45% in May 2022. Many European countries have already expanded their renewables support mechanisms to accelerate capacity growth with a view to 2030 targets and in response to the energy crisis caused by Russia's invasion of Ukraine [1].

Recently, more attention has been paid to small-sized wind turbines, mounted on the roofs of residential or office buildings, having many advantages: they are small, light in construction and stand-alone, energy transport costs are eliminated, and the losses generated by the system. They can be mounted both horizontally and vertically, they do not

* Corresponding author: sanda.budea@upb.ro

require orientation in the direction of the wind, but the dominant direction of the wind is chosen. They have applications in urban areas by integrating them into the architecture of buildings or by retrofitting existing buildings. Low noise, good stability, and a cut-in velocity lower than 2 m/s, low maintenance costs, small area allocated compared to photovoltaic solar panels, are another advantages. There are also disadvantages: power coefficient below 0.3, the angle of the blades cannot be adjusted, inappropriate for multi-directional winds.

The present paper analyses three models of wind turbines that can be placed on the roofs of buildings: crossflow wind turbine Banki, ridge blade turbine and aeroMINE model. The horizontal mounting of these turbines is preferable for better stability and easier construction. The analysis refers to the constructive solutions, their working principle, the optimal design for a good power coefficient and especially the energy that can be obtained with these small turbines.

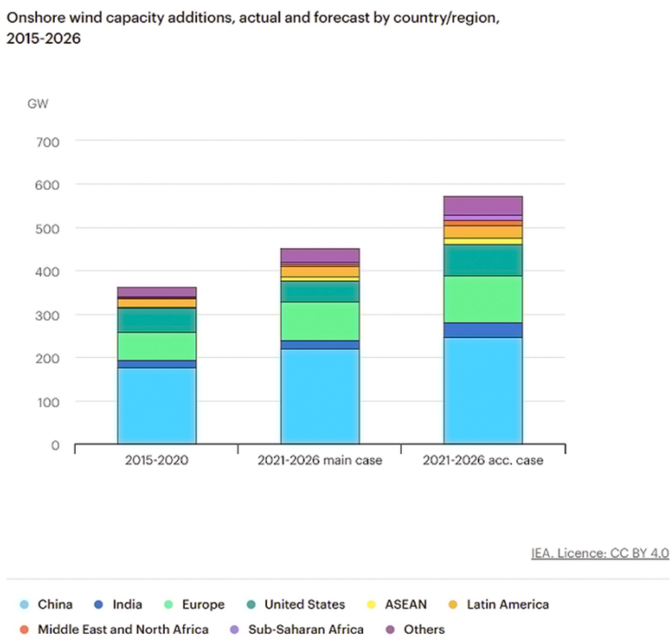


Fig. 1. Forecast by region regarding onshore wind turbine capacity additions [1].

2 Crossflow wind turbine

The multi-blade crossflow turbine has gained attention due to its high torque and low cut-in speed characteristics. This turbine is usually called the Banki wind turbine due to its similarity to the Banki water turbine [2]. The wind passes two times through the rotor blades, ensuring a better twisting moment. Moreover, the large number of blades gives the turbine the ability to have a low cut-in speed and a high operating torque.

The components of absolute wind speeds v, transport u and relative w for the first passage of the wind through the rotor are indicated in Figure 2. A good design assumes that the relative velocity w_2 passes through the center of the rotor, like in Figure 2, optimal angles are α_1=22°, β_1 between (38-45°), and β_2 = 90° [2]. Regarding the number of blades usually there are 6 to 24 blades, cylindrical shapes in single or multi-stages model. This number of blades depends on the rotor diameter ratio, and influence the efficiency, cut-in, and cut-off of the turbine.

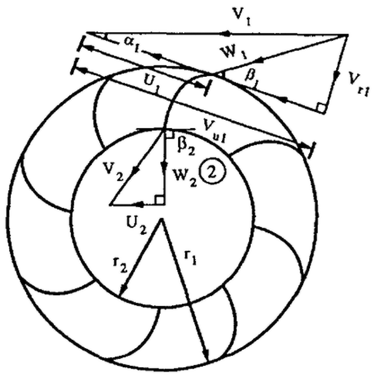


Fig. 2. Velocities triangles in section through the crossflow wind turbine.

Regarding the number of blades, numerical analysis and multiple experiments were done, and the conclusion was according to some authors [3] that 12 blades ensure a good power coefficient. According to other authors [4] [5], 16 blades with an angular extension of 60°, or 22 blades ensure good performances. Crossflow turbine for water has many blades 30-35 [6] for a good efficiency. An important parameter in the analysis of wind turbines is tip speed ratio *TSR*, like in relation (1), with *R* inlet radius, ω angular velocity, v wind velocity, *n* rotational speed:

$$TSR = \frac{R\omega}{v}; \tag{1}$$

$$\omega = \frac{\pi n}{30}. \tag{2}$$

The power extracted from the wind is:

$$P_w = \frac{\rho_{air}}{2} \cdot A \cdot v^3, \tag{3}$$

where *A* is the rotor area with diameter *D* and length *L*, as relation (4):

$$A = D \cdot L. \tag{4}$$

The turbine power is

$$P_t = c_p . \frac{\rho_{air}}{2} \cdot A \cdot v^3. \tag{5}$$

So, the power coefficient depending on the wind direction (α) and *TSR* is:

$$c_p = \frac{P_t}{P_w}. \tag{6}$$

The torque coefficient is c_T and between the two coefficient that define the turbine performance is the *TSR*:

$$c_T = \frac{c_p}{TSR}. \tag{7}$$

Both the number of blades, as well as the profile of the blade and the characteristic angles are important. The TSR for this type of wind turbine is small, between 0.3-0.8. Good performances are obtained if guide vanes, casing and deflector are used, as in Figure 3 and Figure 4. These can lead to a c_{pmax}=0.265, or even 0.3. A complete analysis in this sense can be found in the paper [7].

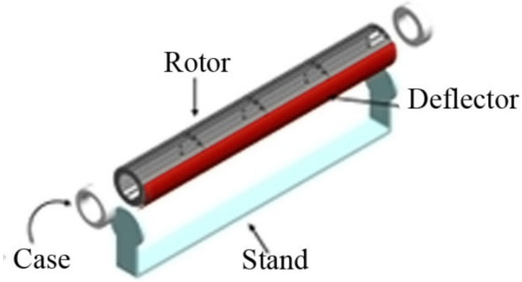


Fig. 3. Deflector for crossflow turbine.

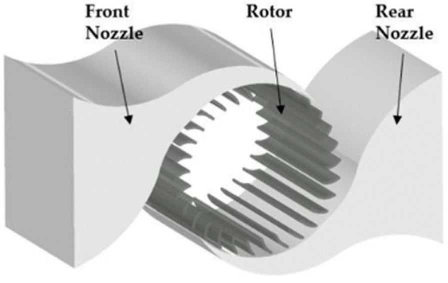


Fig. 4. Double nozzle [7].

New manufacturing technology involves 3D printing solutions for laboratory experimental models with 0.13 m diameter and 0.16 m lenght, easy to make, as in Figure 5. But be careful, the scale factor can greatly influence the performance of the turbines. With this small turbine can obtain a power of 7.35W assuming a wind speed of 6 m/s and a roof inclined at 45°.

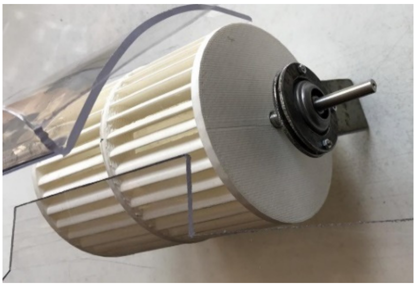


Fig. 5. Small scale experimental wind turbine with 0.13 m diameter and 0.16 m length.

3 Wind turbines on the ridge of the roof

A new solution, patented in 2010 by Raymond E. Paggi [10], refers to the mounting of small wind turbines, with a horizontal axis, on the ridge of sloping roofs. The rotor design is similar to a paddle wheel, with many blades on a horizontal shaft and a housing that includes air guide elements. Through the impact of the wind with the sloping surface of the roof, an important increase in the speed of the air reaching the turbines is obtained. The effect is like an airfoil, low pressure favors high speed according to Bernoulli's relation.

The horizontal mounting of these wind turbines on roofs is relatively easy. Figure 6 represents the effect of the sloping roof on the wind speed and in Figure 7 is presented a residential application. The system can be retrofitted to an existing sloped roof, mounted directly to the roof, or it can be included into the roof of a new building to improve wind energy capture.

The wind speed at the ridge of the roof increases significantly. The American specialists have shown that the optimal angle of inclination of the roof for a good multiplication of the speed, respectively the energy is 45° (Table 1). At a roof inclination of 30 °, the speed multiplication is 1.5 times [9].

Table 1. Wind velocity multiplier [9].

Roof pitch angle	**0°**	**8°**	**15°**	**30°**	**45°**	**60°**
Multiple of wind velocity	X 1.0	X 1.1	X 1.2	X 1.5	X 2.2	X 1.3

In terms of performance, turbines mounted on the ridge of sloping roofs can provide 5 to 8 times more energy compared to similar turbines mounted on a flat surface. According to [10], with a rotor with a diameter of 1.5 m and a length of 6 m (from 5 rotors x 1.2 m), swept area is 1.8 m2, a power of 100 W is obtained at 4.5 m/s wind speed for a flat location. Due to the mounting on the slope, there is an important factor of multiplying the wind speed by 1.5-2.2 times (6.75-10 m/s), resulting in powers up to 1500 W. See Table 2 adapted from paper [10].

Table 2. The effect of the ridge montage of the wind turbine adapted from [10].

Diameter 1.5 m	**Wind velocity (m/s)**	**Area (m2)**	**Roof effect factor**	**Wind energy available (W)**
Roof ridge WT	4.5	1.8	1.0	100
Roof ridge WT	4.5	1.8	1.5	337
Roof ridge WT	4.5	1.8	2.0	800
Roof ridge WT	4.5	1.8	2.2	1065

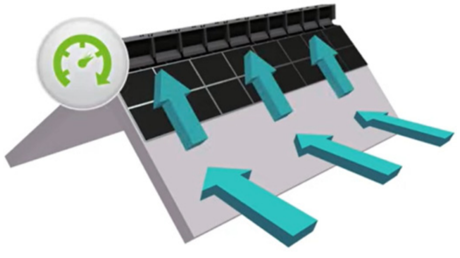


Fig. 6. The effect of the sloping roof on the wind speed [9].

Fig. 7. Ridge blade applicatins on house [8].

Small wind turbines, with an horizontal axis, are often located on the roofs of houses in the UK, Figure 7 or in industrial applications, like in Figure 8 [9].

Fig. 8. The ridge blade wind turbine industrial application [9].

If the rotor is placed on dominant wind direction, Ridge roof wind turbine has advantages likes: -works well even in turbulent regime, - works at optimal parameters from low wind speeds of 4.5 m/s - they are silent in operation - they are self-autoregulating - works well even in storm conditions. The blades are symmetrical, designed as a bi-directional turbine system and generate energy even if the wind changes direction.
When operating in conditions of a 40° inclined roof, wind speed of 6 m/s, with 5 rotors of 1.2 m length (6 m) and 1.5 m diameter, a power of 1 185 W results, i.e. a monthly energy of 425 kWh /month, more than 5 MW/year, if the wind blows half the time.

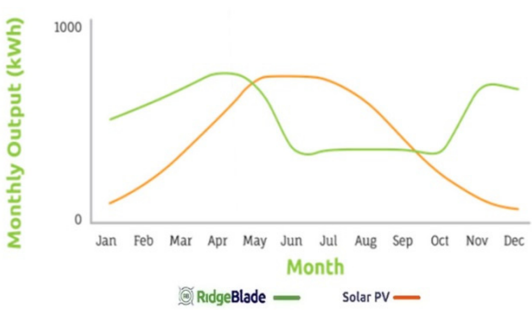


Fig. 9. Complementary of solar and wind energies [9].

Due to the fact that wind energy and solar energy are relatively complementary, the wind blows stronger at night, we have sun during the day, wind-solar hybrid projects have been implemented on the model of ridge blade turbine, like in Figure 9.

Such a project is carried out for a commercial building in Parc del Forum, Barcelona, with 20 ridge roof wind turbines, which at an average wind speed of 4.3 m/s, produce 14,000 kWh/year, and a solar PV installation of 20 kW, which at the average solar radiation of 185 W/m2 would annually produce 26,000 kWh/year [9].

4 Aeromine model bladeless wind turbines

A relatively recent model of wind turbines, small in size, without blades, mounted on the roofs of residential or office buildings, is the third comparative option that I propose in this study. The constructive solution of these wind turbines that can be placed on roofs, not in the ridge area like a ridge blade, but at the bottom edge of the roofs, is based on the principle of the Venturi channel: when fluids flow in a narrowed section, a baffle is formed between two profiles, increasing the speed of air flow. The depression created sucks the air up.

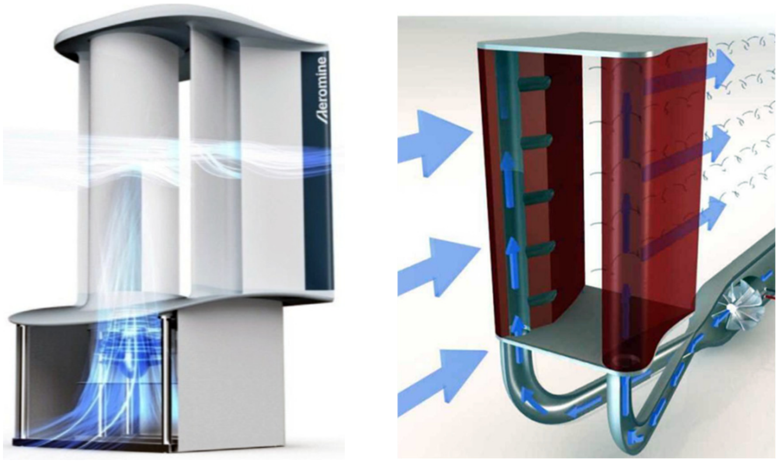


Fig. 10. The working principle of aeromines [11].

According to Berboulli's relation of conservation of energy, the decrease in pressure leads to the increase in speed, which favors the more accelerated movement of air upwards, through the two profiles, mounted face to face, like a Venturi channel. The turbine has double suction, the fluid flow in the internal circuit stimulates the external flow, between the 2 profiles in the form of a Venturi channel. The air flow passes through a turbine / propeller located at the bottom of the installation, generating energy [11], like in Figure 10. System named Aeromine begins operating around a wind velocity of 2.5 m/s. With wind velocity of 9-10 m/s and greater generated by Venturi channel effect, results an efficiency of 25%.
The equations are conformed [12]. The drop pressure from in to out of the foils is:

$$\Delta p = \frac{\rho}{2} \cdot c_{pres} \cdot U_{\infty}^2. \quad (8)$$

The mechanical / pneumatical power can be calculated with:

$$P = \Delta p \cdot A_d \cdot u_d \quad (9)$$

The wind power is:

$$P_w = \frac{\rho}{2} \cdot A \cdot U_{\infty}^3; \quad (10)$$

$$c_p = \frac{P}{P_w}. \quad (11)$$

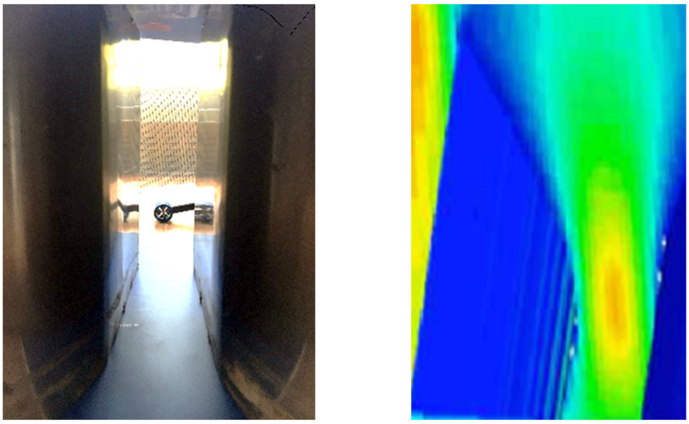
The notations are: U_{∞} - wind velocity, c_{pres} – pressure coefficient, ρ – air density, A_d - area of the internal ducts, u_d – velocity in ducts, A – area of the rectangular section from the foils.

So, in experimental research from [13], the power coefficient for a wind turbine at 1/3 scale is 0.18 and from the real turbine with 3 m tall and 1 m profile chord, power coefficient is maxim 0.25 for wind velocity in channel 9 m/s [12]. The experimental tests were made with a foil profile S1210.

The operation of the system starts from wind speeds of 2.5 m/s, but in Venturi channel increases to 9 m/s . The internal propeller is not really a wind turbine, it is like a fan in reverse operating. Placed on the dominant direction of the wind, 1.5-2 kW can be obtained with a single wind turbine. The technical solution is relatively recent, other experimental studies follow to confirm the results. Aeromine is a bladeless wind energy solution which occupies only 10% of the area occupied by PV solar panels that provide similar power and can be integrated in residential or office buildings. Also in this case, solar PV-aeromine hybrid solutions are suitable.

5 Experimental results

A model of an aeromine turbine - with 2 profiles simulating a venturi channel for air I built in the laboratory. The profile is 0.5 m high and the chord of the profile 0.52 m, the inlet section 0.5 x 0.15 m, and in the narrowed area 0.5 x 0.05 m. With an anemometer with ±2% accuracy I measured the velocities of the air current in the reduced area and represented the values with the Sigmaplot 14 application, as in Figures 11a, b.



(a) (b)

Fig. 11. The experimental stand with aeromine profiles a) with anemometer, b) velocities spectrum.

Following the experimental measurements, it was observed that at relatively low velocities, below 4 m/s in the downstream area, in the narrowed area the velocity increases by a maximum of 3 times, but at speeds of 4.5-10 m/s downstream (Table 3), in the reduced area the speed increases less , 2.5-1.5 times, the current of air tends not to enter in the narrowed area, but to go around the outside of the profiles, see Figure 11b.

Table 3. Elements of comparison

Tip of WT	Wind velocity (m/s)	Cp max	Mounting	Area (m2)	Wind energy available (W)	Specificity
Crossflow	4.5 to 9	0.265	Horizontal	6x1.5	1200	2 passing
Roof ridge	4.5x2.2	NA	Horizontal	1.8	1065	Good power ratio W/ m2
Aeromine	2.5 to 9	0.25	Vertical	3	1500	Double suction

6 Conclusions

From the analysis of the three models of wind turbines that can be placed on the roofs of buildings: crossflow wind turbine Banki, ridge blade turbine and aeroMINE model we can draw the following conclusions:

i) They have many advantages - They are the most suitable for urban layouts, not affecting additional spaces. - Horizontal mounting of these turbines is preferable for better stability and easier construction. Exceptions are aeroMINE that are mounted vertically. - they are stand-alone, eliminating energy transport expenses and losses generated in the system. - does not require orientation to the direction of the wind but are mounted on the dominant direction of the wind. - They can be integrated into the architecture of new or existing residential or office buildings. - Low noise, good stability, does not create visual discomfort. - the cut-in velocity lower than 2 m/s, low maintenance costs, - they can replace or supplement the PV solar energy, from the roofs of the buildings, in this case they can fully ensure the energy needs of the buildings.

ii) Disadvantages - Relatively low power coefficient, below 0.3 - The blades are not adjustable - The resulting power is low, 2-3 kW per module.

iii) Additional observations:

There is a need for greater promotion of these turbine models for a cheap source of energy, right at the point of consumption - residential and office or industrial buildings.

- additional studies are required for the aeromine variant.
- It is necessary to adopt solar PV-wind hybrid solutions for more energy, but also for the fact that the presence of wind turbines in the vicinity of the PV panels ensures a better operation for both
- it is known that cooling panels have better performance, at the same time concentrating the heat drives air movement towards the turbines.
- The scale factor between the model and the real turbine must be taken into account, in the analysis of their performances.

The analysis should be completed with experimental results, in future detailed research.

References

1. https://www.iea.org/topics/net-zero-emissions (2023)
2. Al-Maaitah, A. Ayman, *The design of the Banki wind turbine and its testing in real wind conditions*, Renewable Eneryy, **3**, No. **6**, 7, pp. 781-786, (1993)
3. I. Ushiyama, N. Isshiki, G. Z. Chai, *Experimentally evaluating the design and performance of cross-flow wind rotors.* Energy and the Environment in the 1990s, 1st Worm Renewable Energy Congress (Edited by A. A. Sayigh). Pergamon Press, Oxford (1990)
4. A. Wibowo,; D.D.D.P Tjahjana,. B. Santoso, M.R.C. Situmorang, *Study of turbine and guide vanes integration to enhance the performance of cross flow vertical axis wind turbine*. AIP Conf. Proc. 2018, **1931**, 030043 (2018) [CrossRef]
5. T. Pujol, A. Massaguer, E. Massaguer, L. Montoro, M. Comamala, *Net Power Coefficient of Vertical and Horizontal Wind Turbines with Crossflow Runners*. Energies **11**, 110 (2018)
6. R. Adhikari, D. Wood, *The Design of High Efficiency Crossflow Hydro Turbines: A Review and Extension* , *Energies* , **11** (2), 267, 1-18 (2018)

https://doi.org/10.1051/e3sconf/202340402005

7. Z. Sefidgar, A. Ahmadi Joneidi, A. Arabkoohsar, *A Comprehensive Review on Development and Applications of Cross-Flow Wind Turbines*. Sustainability, **15**, 4679, https://doi.org/10.3390/su15054679 (2023)
8. https://www.youtube.com/watch?v=eUv3Pt9LW7c (accessed April 2023)
9. The power collective, RB, https://www.switchontario.ca/resources/Documents/Managing%20Energy%202017/Managing%20Energy%202017%20-%20Business%20-%20RidgeBlade%20-%20Llion%20Rowlands.pdf Accessed April 2023
10. R. E. Paggi, *Roof ridge wind turbine*, United States Patent Application Publication Paggi, US 2010/0126086 A1, (accessed 27 May 2010)
11. https://www.aerominetechnologies.com/ (accessed in April 2023)
12. B. C. Houchens, D. V. Marian, S. Pol and C. H. Westergaard, *High Wind Speed Performance of AeroMINE at Pilot-Scale*, J. Phys.: Conf. Ser. **2265** 042065, IOP Publishing, (2022)
13. S. Pol, B. C. Houchens, D. V. Marian, C. H. Westergaard, *Performance of* AeroMINEs *for Distributed Wind Energy*, AIAA SciTech (2020)