EAI Endorsed Transactions
on Energy Web

Research Article EAI.EU

Comparative investigation of Savonius and hybrid H-Savonius wind rotor- an energy and exergy analysis

Shikha Bhuyan[1], Agnimitra Biswas[2,*]

[1]Mechanical Engineering Department, Tezpur University, Tezpur, Assam, India-784028
[2]Mechanical Engineering Department, National Institute of Technology, Silchar, Assam, India-788010

Abstract

Exergy analysis is a vital tool for wind power development apart from energy analysis. The present study is based on a comparative energy and exergy analysis of Savonius wind rotor and hybrid H-Savonius wind rotor based on the parameters- power coefficient, power output and exergy efficiency, by using an experimental approach. For this the performances of a two-bladed Savonius rotor, a three bladed Savonius rotor, and a hybrid two-bladed Savonius and three-bladed H-rotor (H-Savonius rotor) are analyzed at four different wind velocities (7.5, 8.5, 10.5 and 12.5 m/s). The results show that power coefficient for the two-bladed Savonius rotor is higher than the three-bladed Savonius rotor with a maximum power coefficient of 0.18 at 10m/s wind velocity. The two-bladed Savonius rotor is then attached with the H-rotor having unsymmetrical S818 airfoil blades for which the maximum power coefficient of the hybrid turbine is creased to 0.197. The exergy efficiency of the H-Savonius rotor is found higher than any other rotor, which is increased by 8.5% compared to the two-bladed Savonius rotor and which is also higher than published result. The novelty of the present study is that it analyses the work potential of some prominent vertical axis wind turbines under varying wind speed conditions.

Keywords: Savonius rotor, H-Savonius rotor, power coefficient, exergy efficiency.

Received on 24 March 2020, accepted on 16 September 2020, published on 25 September 2020

doi: 10.4108/eai.25-9-2020.166362

*Corresponding author. Email: agnibis@yahoo.co.in

1. Introduction

The gradual extinction of conventional energy sources has dragged the research orientation towards renewable energy with probable reasons being the rising scales of global warming due to greenhouse gases. The cleanest and promising candidate amongst all alternative energy sources, and increasing demand for renewables over conventional energy aroused a keen interest in wind energy technology. It has an inherited quality of being freely available in abundance. Attempts to introduce cost-effective and reliable conversion systems encouraged the scientists to conduct in-depth studies to come up with reliable designs and configurations of wind turbines in order to extract the maximum amount of energy [1].

The rotating wind machines make use of kinetic energy of wind converted into mechanical energy for its power extraction and based on the axis of turbine rotation the wind machines can be classified mainly into two types. One is horizontal axis wind turbine (HAWT) and the other is vertical axis wind turbine (VAWT) [2,3]. However, the later one has proved to be more meritorious in terms of safety, compact design, cost and operation in urban environments. Also, better robust power output can be achieved even at low blade tip speed ratios [4]. The common vertical axis wind turbines (VAWT) are shown below in figure 1.

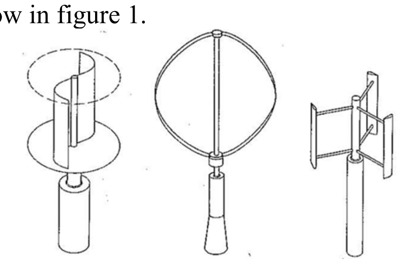


Fig 1. (a) Savonius rotor; (b) Darrieus rotor; (c) H-rotor [4]

The blades of H-Darrieus rotor are much easier to manufacture than that of an eggbeater Darrieus turbine or HAWT. Visual aesthetics, lower noise are the good attributes of using three bladed designs [5]. The major disadvantageous factor possessed by H-Darrieus rotor is its non-ability to self-start, which can be overcome by Savonius rotor. An extensive research was conducted to risen up the performance of a Savonius rotor as they have the brilliant competence to self-start even at lower speeds. Based on various geometries of Savonius rotor Mahmoud et al. [6] determined the most effective operational parameters experimentally and concluded that aluminum-based two-bladed rotors are more efficient than three and four ones. Works on staging and orientation of the rotor blades have also been of keen interests to the researchers. Rosmin et al. [7] employed the concept of multi-staging for a rain water harvesting system and examined the performance of the double-stage and single- stage two bladed micro-sized Savonius turbine for it. The aspect ratio taken for the study was 1.8. They came up with the findings that single staged turbines generate double the power than the double-staged ones. Bachant et al. [8] performed power and drag measurements for two different helical cross flow devices- a cylindrical Gorlov helical turbine and a lucid spherical turbine and compared the performance in terms of power and drag coefficients. They found the former turbine outperform the spherical lucid turbine due to the higher blockage factor of the later one. Kargic at al. [9] designed a workflow which can synthesize shapes of both classical Darrieus and Savonius rotors. The developed workflow can invent new generic shapes for custom operating conditions and consists of efficient geometry parametrization. The work demonstrated the developed framework for generating custom-designed shapes for maximum energy production at a specific location. Mohamed et al. [10] worked on optimizing blade shape of a modified Savonius turbine using an obstacle shielding the returning blade in order to increase the output power of a classical Savonius turbine. The size and position of the obstacle have been optimized using evolutionary algorithms, which caused an improved performance compared to standard Savonius turbine, leading particular to a relative increase of the power output coefficient by 38.9% at a tip speed ratio of 0.7.

Over the decades, many types of research have successfully been done to merge and extract the combined effects of Darrieus and Savonius rotor and are found to be much effective than the individual ones. Much more parametric studies based on computational and experimental works [11,12] are done in terms of aspect ratios, overlap ratios, stages thus enhancing the performance or efficiency of the combined rotor.

The extensive literature study depicts the research based on optimal parametric design and it is also believed that exergy analysis can play a prominent role in the optimum designing of wind rotors as the analysis is capable of determining the amount of useful lost work [13]. Energy and exergy analysis for wind energy storage system was done by Mohammadi et al. [14] where they studied the system performance based on the effect of key parameters. Their study revealed that the components of the system such as a wind turbine, combustion chamber, and compress air storage system are having the highest amount of exergy destruction [14]. Pope et al. [15] conducted the study of exergy and energy efficiencies for different geometries, design parameters, and operating conditions. Based on their study they compared the performances of horizontal and vertical axis wind turbines. They found the second law to be a useful design tool for wind power development. Boroumandjazi et al. [16] focused on the technical characteristics and performance analysis of the wind energy systems. In their energetic and exergetic analysis of the system, they found a 20-40% difference between energy and exergy efficiencies for low wind speeds while the same changes to 10-15% for high speed condition and hence advocated for better reliability of analysis using exergy analysis.

Thus, the exergy analysis is found to be at a nascent stage as very little work has been done in this area and need attention as a significant tool for obtaining qualitative results for wind power development. The present study is experimentally performed using a subsonic wind tunnel at various wind velocities. An analysis based on H-rotor and H-Savonius rotor have been done by Bhuyan et al. [12] and the present work is an extension of the work given in reference [12]. A comparative study between a two-bladed Savonius, a three-bladed Savonius, and a hybrid H-Savonius wind rotor based on energy and exergy efficiency is made. The novelty of the present study is that it analyses the work potential of some prominent vertical axis wind turbines under varying wind speed conditions.

2. Technical details of the wind rotors

The detailed specifications of the wind rotors (shown in figure 2) are considered keeping the dimensions of reference [9] in mind. As can be seen from figure 2(a), the blades are made of wood as it has good stiffness and high strength to weight ratio. The blades of the Savonius turbine are semicircular in profile and the blades of the H-rotor are of NREL S818 airfoil profile. The overall dimensions of the Savonius rotor and the H-rotor can be found from figure 2(b), which shows the design of hybrid H-Savonius rotor. As can be seen the two-bladed Savonius rotor is mounted inside the three-bladed H-rotor to implement self-starting of the hybrid rotor.

Fig 2 (a) Fabricated Darrieus and Savonius blades

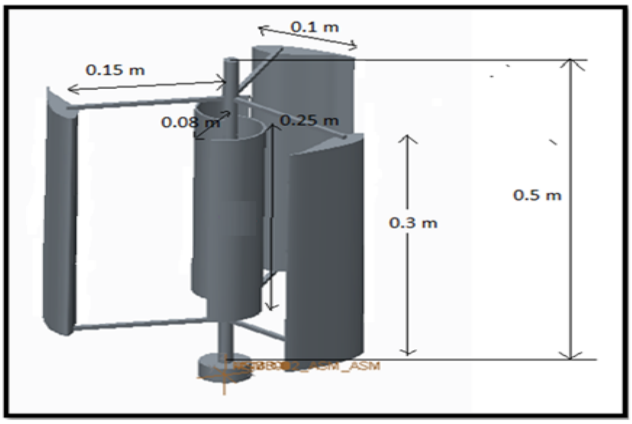


Figure 2(b) Theoretical CAD model of Hybrid H-Savonius rotor.

3. Experimental setup and methodology

Experiments are performed at the exit of wind tunnel which is an open circuit subsonic tunnel whose succinct description is mentioned in reference [17]. The tunnel is run by a 20 horsepower motor and its turbulence intensity is within the permissible limit i.e. ±1%. Further, the flow is made uniform through the experimental test rig by placing it at a distance of more than 6 meters from the exit of the wind tunnel as shown in figure 3. The wind velocity is measured by digital anemometer having calibrated accuracy of +/2% with measuring a range of 2-20 m/s. A non-contact type digital tachometer was employed to record the rotational speed of the rotors. The tachometer is having an accuracy of +/0.05% and least count of 1 rpm.

Experimental set-up consists of required components as shown in figure 3 for conducting the experiments. The washers and nuts are used properly to hold the iron plate intact. The apparent and easy positioning of the rotor center and its replacement is smoothly executed with the operation of nuts and bolts. For minimizing the frictional losses, the bearings are applied with grease and hence lubricated periodically.

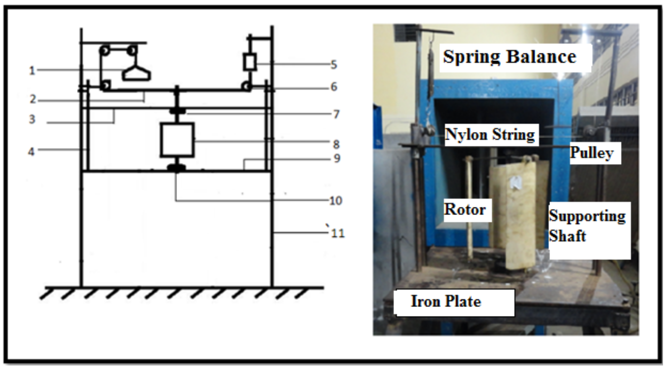


Fig 3. Pictorial view of the experimental set-up: (1) Base frame; (2) Nylon-string; (3) Supporting shaft; (4) Pulley; (5) Spring balance; (6) Upper bearing; (7) Iron plate; (8) Position of rotor; (9) Base bearing; (10) Weighing pan.

The experiments are conducted at four different wind velocities of 7.5, 8.5, 10.5 and 12.5 m/s. The rotor is loaded gradually by putting weights (initially started from the no-load condition) which is constantly monitored with the help of a spring balance readings. The rotor rpm is recorded with the help of a digital tachometer. The reference angle is in anticlockwise direction for measuring coefficient of static torque.

The following equations are followed for generating the experimental results [18]:

(a) Torque (T) :

The mechanical torque produced by the rotor shaft has been calculated from the given formula:

$$T = (N - S)(r_{sh} + d_n)g \qquad (1)$$

Where, N is given load, S is the spring balance load, r_{sh} is the shaft radius, d_n and is the diameter of the nylon string, g is the acceleration due to gravity. All the parameters are taken in SI units.

(b) Tip speed ratio (γ):

$$\gamma = \frac{\omega D}{2U} \qquad (2)$$

Where ω is angular velocity of rotor, U is free stream velocity, D is rotor diameter.

(c) Coefficient of torque(C_t) and coefficient of power(C_p) :

The coefficient of torque (C_t) and coefficient of power (C_p) is calculated by using following formula:

$$C_t = \frac{4T}{\rho U^2 D^2 H} \qquad (3)$$

$$C_p = \gamma \times C_t \qquad (4)$$

(d) Power of the rotor:

The power of rotor can be expressed by the equation (5):

$P_{rotor}= C_p \times \frac{1}{2}\rho A U^3$ (5)

Where, P_{rotor} = Power available at the rotor; C_p = maximum coefficient pf power of the rotor at particular Reynolds number, A is the frontal area of the rotor.

(e) Exergy efficiency (Ψ):

The ratio of useful work to the exergy of the wind energy is known as exergy efficiency, Ψ [19] and is given by the equation (6):

$$\Psi= \frac{\dot{W_{out}}}{\dot{Ex_{flow}}} \quad (6)$$

$$\dot{Ex_{flow}}= \dot{Ex_{ph}} + \dot{Ex_{ke}} \quad (7)$$

Where, $\dot{Ex_{ph}}$ and $\dot{Ex_{ke}}$ are the physical and kinetic exergies.

Generally, the energy balance equation for a wind turbine can be represented by equation (8):

$(\text{kinetic energy})_1= \dot{W_{out}} +(\text{kinetic energy})_2$ (8)

The right hand side of equation (8) is calculated by the following relation:

$P= 0.5\rho A^{/} V^3$ (9)

Where P stands for the magnitude of wind stream kinetic power, ρ stands for the density of fluid (air in our case), $A^{/}$ stands for the rotor swept area and is perpendicular to the wind and V is the velocity of wind. This expression is employed to calculate the kinetic exergy.

On the other hand, physical exergy [20] comprises of the enthalpy and entropy changes associated with the turbine operation and can be calculated using the given equation (10):

$$\dot{Ex_{ph}}=\dot{m}\left(c_p\left(T_2 - T_1\right) + T_0\left(c_p \ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{p_2}{p_1}\right)\right) - \frac{c_p(T_0 - T_{avg})}{T_0}\right) \quad (10)$$

Where, $\dot{m}$ is the mass flow rate of wind. T_1 and T_2 are determined based on a model developed by Zecher [21] through wind chill temperature. c_p is the specific heat at constant pressure (J/kgK), R is the universal gas constant,$p_i = p_0 \pm (\frac{\rho}{2})V^2$.The first term in the above equation gives the magnitude for the enthalpy change associated with the turbine actions while the later terms designate the irreversibilities of the flow associated with the system, which is determined by the following equation (11):

$$I= T_0\left(c_p \ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{p_2}{p_1}\right)\right) - \frac{c_p(T_0 - T_{avg})}{T_0}) \quad (11)$$

4. Results and Discussion

The performance of all the three designed rotors is analyzed in terms of coefficient of power (Cp), power output (P) and exergy efficiencies at four different wind velocities i.e 7.5, 8.5, 10.5 and 12.5 m/s. The dynamic response of the rotors is depicted graphically in figure 4. It can be seen that with an increase in wind velocity (Reynolds number, Re), there is an increment in power coefficient attaining its maximum value at 10.5 m/s after which it decreases with further increase of wind velocity to 12.5 m/s. This is due to the low value of TSR obtained in case of 12.5 m/s. The reason for such low TSR values is because of high wind velocity values which are inversely proportional to it. Further, it can be observed that Savonius rotor with 3-blades is the poorest performer when it comes to power coefficient followed by Savonius rotor with two-blades. The hybrid H-Savonius rotor gives higher power coefficient at all wind velocities due to the inclusion of cambered profiled H-Darrieus rotor and lift attribution of H-Darrieus airfoils thus enhancing its power producing ability. The maximum Cp obtained is from H-Savonius rotor and is 0.19 at wind velocity 10.5 m/s. Figure 5 shows the comparative behavior of the three wind rotor in terms of power output. In fig 5 it is observed that the power extracted by the turbine shows an increasing trend with an increase in free stream velocity while operating in an inspected free stream velocity the power output of the turbine is found to be proportional to its angular velocity. Similar to the variation of Cp, a positive effect of H-Savonius rotor has been also observed in terms of power. Hence, it can be inferred that the hybrid H-Savonius rotor has the highest capacity of producing power amongst the three rotors.

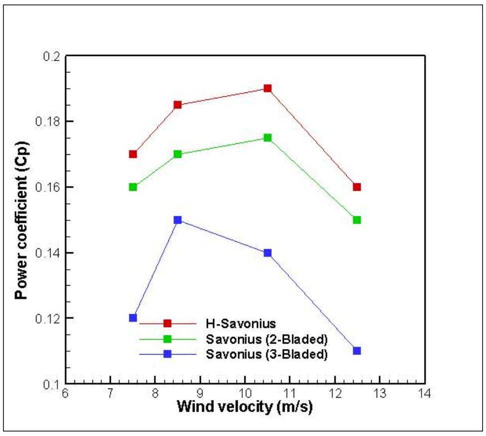


Fig 4. Comparison of power coefficient (Cp) at four different wind velocities.

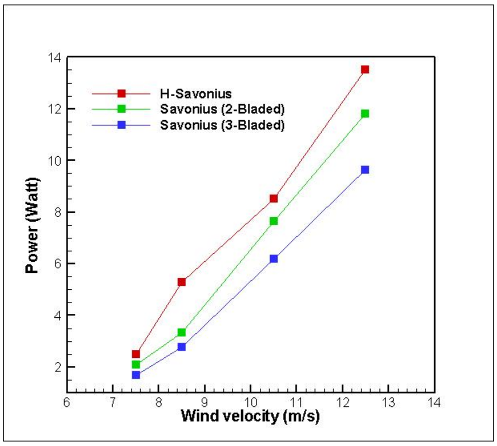
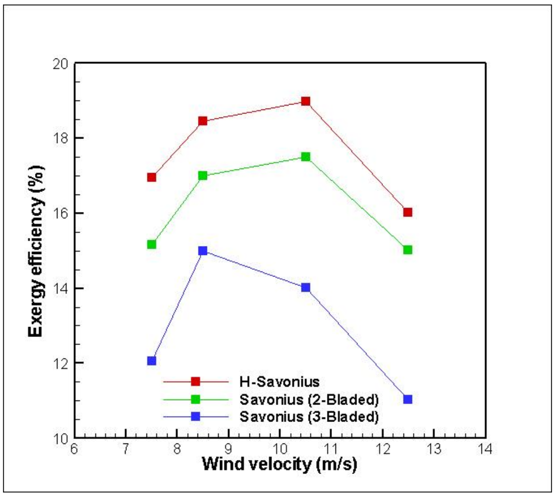
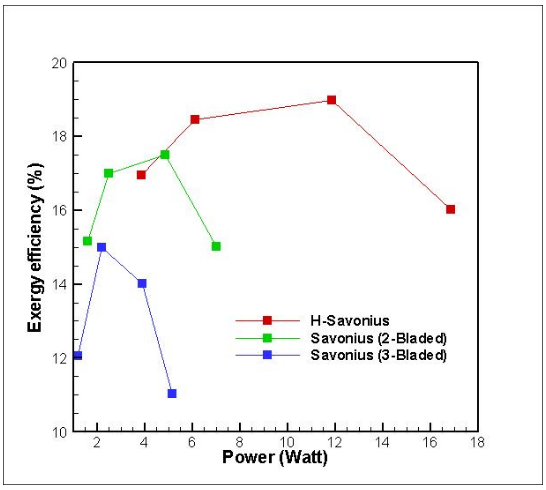


Fig 5. Comparison of power output at four different wind velocities.

Exergy represents the second law efficiency carrying the significance of obtaining best power producing rotor amongst the three in the present study. The figure 6 gives a comparative analysis of exergy efficiencies for the wind rotors at all the four velocities.



(a)



(b)

Fig 6. Comparative exergy efficiencies of the rotors

From the above data, it is observed that the Savonius rotor with three-blades has got the lowest exergy efficiency as compared to the two-bladed Savonius rotor and H-Savonius wind rotor. Employing the cambered profile H-rotor to the two-bladed Savonius rotor, the maximum exergy efficiency (at 10 m/s) increases by 8.5 %. From figure 6(b), it can also be inferred that the H-Savonius rotor has the capacity of producing a wide range of useful work over a given span of wind velocities which is not the case for the single Savonius rotor. Finally figure 7 depicts the comparative exergy efficiency of hybrid H-Darrieus Savonius rotor from the present study and the already available Savonius rotor with respect to same range of wind velocity. It is found to have higher work potential for hybrid rotor as compared to the earlier established work.

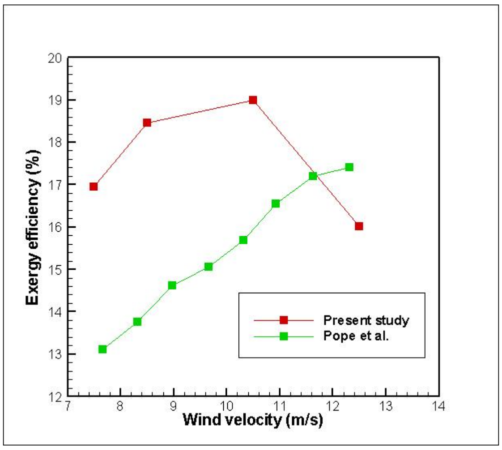


Fig 7. Comparative exergy efficiency of present study with established result [19]

5. Conclusions

The present experimental study shows a comparative analysis of the performance of Savonius rotor (2-bladed and 3-bladed) and H-Savonius rotor at 4 different wind conditions i.e at 7.5, 8.5, 10.5 and 12.5 m/s. The following conclusions can be made from the current work:
a) For all wind rotors, with an increase in wind velocity, there is an increment in power coefficient attaining its maximum value at 10.5 m/s after which it decreases when the wind velocity is increased further to 12.5 m/s.

b) For all wind rotors, power extracted by the turbine is found to follow an increasing trend with increasing free stream velocity as the output turbine power is proportional to the angular velocity of the turbine. And, hybrid H-Savonius rotor has the highest capacity of producing power at all wind velocities with a maximum power coefficient of 0.197.

c) Employing the cambered profile H-rotor to the two-bladed Savonius rotor the maximum exergy efficiency (at 10 m/s) increases by 8.5 %, which is also higher than published work.

d) A wide range of useful work can be obtained by employing hybrid H-Savonius rotor at all wind velocities making it superior to two-bladed and three bladed Savonius rotor.

References

[1] Herbert Inhaber , “Why wind power does not deliver the expected emissions reductions”, Renewable and Sustainable Energy Reviews, Vol 15 (2011), 2557–2562.

[2] Janet Sawin. Wind Power Continues Rapid Rise. Worldwatch Institute, April 2008

[3] “Wind as a renewable source of energy”, A report, National Institute of Technology Rourkela, Rourkela-769008, Orissa, (2009).

[4] J. Yen and N. Ahmed, “Improving safety and performance of small-scale vertical axis wind turbines”, Procedia Engineering, Vol 49 (2012), 99- 106.

[5] M. Islam, V.Esfahanian, D.S-K Ting, A.Fartaj, “Applications of Vertical Axis Wind Turbines for Remote Areas”, In: Proceedings of 5th Iran National Energy Conference, Tehran, (2005).

[6] N.H.Mahmoud, A.A.El-Haroun, E.Wahba, M.H.Nasef, “An experimental study on improvement of Savonius rotor performance”, Alexandria Engineering Journal, Vol 51, Issue 1 (2012), 19-25.

[7] N.Rosmina, A.S.Jauharib, A.H. Mustaamalc, F.Husind, M.Y.Hassane, “Experimental study for the single-stage and double-stage two-bladed Savonius micro-sized turbine for rain water harvesting (RWH) system”, Energy Procedia, Vol 68 (2015), 274 – 281.

[8] Peter Bachanta, Martin Wosnik, “Performance measurements of cylindrical- and spherical-helical cross-flow marine hydrokinetic turbines, with estimates of exergy efficiency”, Renewable energy, Vol 74 (2015), 318-325.

[9] Ivo Marinic Kragic, Damir Vucina, Zoran Milas, “Numerical workflow for 3D shape optimization and synthesis of vertical-axis wind turbines for specified operating regimes”, Renewable energy, Vol 115 (2018), 113-127.

[10] M.H. Mohamed, G. Janiga, E. Pap, D. Thévenin, “Optimal blade shape of a modified Savonius turbine using an obstacle shielding the returning blade”, Energy Conversion and Management, Vol 52 (2011), 236–242.

[11] R. Gupta and A. Biswas, “CFD analysis of flow physics and aerodynamic performance of a combined three-bucket Savonius and three-bladed Darrieus turbine”, International Journal of Green Energy, Vol 8 (2011), 209–233.

[12] S.Bhuyan, A.Biswas, “Investigations on self-starting and performance characteristics of simple H and hybrid H-Savonius vertical axis wind rotors”, Energy Conversion and Management, Vol 87 (2014), 859-867.

[13] S. Mehdi Mortazavi, M.RezaSoltani, H. Motieyan, “A Pareto optimal multi-objective optimization for a horizontal axis wind turbine blade airfoil sections utilizing exergy analysis and neural networks, Journal of Wind Engineering and Industrial Aerodynamics”, Vol 136, (2015), 62-72.

[14] A. Mohammadi, M.H.Ahmadi, M. Bidi, F.Joda, A. Valero, “Exergy analysis of a Combined Cooling, Heating and Power system integrated with wind turbine and compressed air energy storage system”, Energy Conversion and Management, Vol 131, (2017), 69-78.

[15] K.Pope, Dincer, G.F.Naterer, “Energy and exergy efficiency comparison of horizontal and vertical axis wind turbines”, Renewable Energy, Volume 35, Issue 9, (2010), 2102-2113.

[16] G. BoroumandJazi, B. Rismanchi , R. Saidur, “Technical characteristic analysis of wind energy conversion systems for sustainable development”, Energy Conversion and Management, Vol 69 (2013), 87–94.

[17] R. Gupta, R. Das, K.K. Sharma, “Experimental study of a Savonius–Darrieus wind machine”, In: Proceedings of the international conference on renewable energy for developing countries. University of Columbia; (2006).

[18] K. Golecha, TI Eldho, S.V. Prabhu, “Performance study of modified Savonius water turbine with two deflector plates”, Int. J. Rotating Mach (2012).

[19] K.Pope, I.Dincer, G.F.Naterer, “Energy and exergy efficiency comparison of horizontal and vertical axis wind turbines ”, Renewable Energy, Vol 35, Issue 9 (2010), 2102-2113.

[20] A.D. Sahin, I. Dincer, M.A. Rosen, “Thermodynamic analysis of wind energy”, International Journal of Energy Research, Vol 30 (2006), 553-566

[21] J.B. Zecher, “A new approach to an accurate wind chill factor, Bulletin of the American Meteorology Society”, Vol 80, Issue 9 (1999), 1893-1899.