Exergy analysis of Wind energy in Iran

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Abstract — Life is directly affected by energy and its consumption. Wind energy is among the world's most significant and rapidly developing renewable energy resources. Wind energy is one of the renewable energies that have attracted great attention. The objective of this paper is to develop an improved approach for the thermodynamic analysis of wind energy using energy and exergy analysis. Such a formulation can provide a physical basis for understanding, refining and predicting the variations in wind energy calculations. Manjil, one of the wind farms in Iran that generates 25 MW, is studied and energy and exergy analysis is performed. The exergy analysis of the wind energy shows that there are significant differences between energy and exergy analysis results. Thus, the energy and exergy efficiency are presented as a function of wind speed. The results show that output power of wind turbine changes rapidly when the wind speed is less than 15m/s and it does not change after this wind speed.

Keywords — wind turbine, energy analysis, exergy analysis

1 Introduction

The demand for the new types of energy has been grown in the recent years. The renewable energies can be good substitutes for the conventional energies. In fact, the increase in the population, industrial development, the growing demand for the energy and the environmental pollution are the crucial reasons for using the renewable energy recourses [1]. Moreover, life is directly affected by energy and its consumption. Therefore, the research about energy and its different aspects are very important. The application of wind energy in Iran goes back to 200 years B.C. The Persian windmills with wind-catching surfaces as long as 5 m and as high as 10 m were used for grinding grain in the area known as Nehbandan in the western part of Iran up to a few years ago [2]. Recent technological developments, concerns over fossil fuel demands and the corresponding environmental effects and the continuous increase in the consumption of conventional energy resources have reduced wind energy costs to economically acceptable levels in many locations.

Wind energy like other renewable energies is available in some areas over the world. Therefore, meteorological variables such as temperature, pressure and moisture play important role in the occurrence of wind. The pressure force in each area leads to kinetic energy of wind. It should be noted that wind occurs due to the fact that when there is a difference cooling and heating phenomena within the lower atmosphere and over the earth's surface [3]. Moreover, wind energy has an alternative behavior and it is not continuous. As a meteorological variable, wind energy refers to the energy content of wind. In electricity generation wind takes the same role as water does for hydraulic generation, and based on this fact, the wind variables should be analyzed. Wind velocity variation depends on time and position. The knowledge of such characteristics is the subject of wind velocity modeling. The state of the atmosphere is well described by seven variables: pressure, temperature, density, moisture, two horizontal velocity components, and the vertical velocity. All of them are functions of time and location. The behavior of these seven variables is governed by seven equations: the equation of state, the first law of thermodynamics, three components of Newton's second law, and the continuity equations for mass and water substance in air. These equations are mathematical relations between each atmospheric variable and their temporal and spatial derivatives. Mathematical models of the atmosphere can be obtained by integrating the relevant equations with special initial and boundary conditions. As it was mentioned, the determination of wind energy potential depends very much on the meteorological measurements of the wind direction, velocity, and solar irradiation. Unfortunately, in many parts of the world, it is difficult to obtain such data.

The physical behavior of wind shows great temporal and spatial variability. The horizontal movement of air parallel to the earth's surface is a measure of the wind in both direction and magnitude. However, wind prediction is very difficult due to random changes both in wind direction and speed magnitude. Wind energy is directly related to wind speed and other meteorological factors. The studies concerned with the production of electricity by wind turbines have been done with practical electricity production expectations. For this purpose, convenient area-selection for greater efficiency is important and necessary. The sources of wind speed and energy changes with time are not continuous at the same

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area during the entire year. In addition to these changes, solar irradiation with astronomical features and short times, topography, pressure, temperature and moisture conditions cause rather unpredictable changes in wind speed. In any energy system, a source of raw material availability and efficiency are the most important issues. If efficiency is not taken into account carefully and correctly, then the energy plants that are built, will not function properly.

The atmosphere contains motions with scales varying from about 1 mm to thousands of kilometers. Ideally, mathematical models should be constructed from observations with one millimeter spatial and with a fraction of a second temporal resolution. Clearly, this is impossible in practice, and models are constructed separately for systems on different scales. Thus, for example, there are models for local circulations such as sea breezes, for flow over mountains, for weather developments over Europe, or for the entire globe. Depending on the system that is modeled, the equations can be simplified and for the development of wind power meteorology the starting point is the simplest model for motion in the atmosphere: steady winds over very extensive plains under an overcast sky or, in other words: a stationary wind field over an infinite at plane of uniform roughness with neutral stratification. The only quantity of interest is the variation of wind speed with height. Straightforward physical considerations lead to the well-known logarithmic wind profile, which is determined solely by three variables: the height above ground, the roughness length and the friction velocity. The roughness length parameterizes the roughness of the surface and the friction velocity parameterizes the frictional force between the moving air and the ground. The power output from the wind turbine is also governed by the design features of wind turbine such as cut-in speed, which is the minimum wind speed required for the wind turbine to start delivering useful power, rated wind speed, which is the wind speed above which the machine delivers the rated power output, and cut-out speed, which is the maximum wind speed the machine is allowed to deliver power. The purpose of this paper is to develop an improved approach for the thermodynamic analysis of wind energy using energy and exergy. Such a formulation can provide a physical basis for understanding and predicting the variations in wind energy estimations. Wind energy among renewable energy source is one of the economical generation electricity methods, which has no pollution and no limit. It is estimated that generation of 1-Kilowatt hour of wind energy electricity leads to decrease pollution agents as it is described:

CO_2=200 gr , SO_2=2.9 gr, NO_x=2.6 gr, Soil= 0.1 gr, Ash = 55 gr

Generally, by substituting the electricity from fossil fuel power plant with electricity from wind energy the greenhouse gases can be decreased.

Iran geographical latitude is 25.2-39.5 degree northern hemisphere and its longitude is 44-63.6 degree east. Iran is exposed to the continental streams from Asia, Europe, Africa, Indian and Atlantic Pacific. The Ministry of Energy has serious programs for the evaluation of the wind energy potential in the country [1]. At the first stage, the country's wind energy potential evaluation is performed for a wide range of the country. At the second stage, after the exact investigation on the wind potential, the Iran's wind atlas is prepared. It must be noted that the preparation of the wind atlas and the assessment of the country wind potential is the first step that should be taken in order to perform the economical evaluation. In table (1), the potential of wind farms in Iran is shown. It shows that in recent years the importance of wind energy in Iran is increased.

Table 1. Wind farm projects in Iran based on province proportion

Province	Installed		Under construction		Under study	total	
	Number	Capacity (kW)	Number	Capacity (kW)	Capacity (kW)	Number	Capacity (kW)
Guillan	70	34120	1	10	60000	71	94130
Ghazvin	--	--	40	26400	--	40	26400
Khorasan	22	13460	24	15260	--	46	
Azerbaijan sharghi	--	--	1	10	--	1	28720
Total	92	47580	66	41680	60000	158	149260

In table (2), the specifications of wind energy in Iranian farms are listed. It is shown that from 2003 to 2009 the out put power produced by wind energy in Iran is increased rapidly.

Table 2. Specification of wind energy under study and construction

Project name	Geographical position	Start date	Finish	Capacity (kW)	Annual ability of electricity generation (10^6KW)
Sahand wind Turbine 10 kW	Azerbaijan Sharghi	1996	2007	10	0.25
Binaloud Wind Power Plant	Khorasan	2001	2005	28400	124
Vahidi Turbine	Bojnord	2003	2007	60	(1)
Moahed turbine	Guilamn-Manjil	2003	2007	10	(1)
60MW wind farm	Guilamn-Manjil	2005	2009	60000	190

In particular, the objective of the present study is composed of three important parts. At the first part of this paper a model for providing improved wind energy and its energy components are discussed. At the second part, exergy analysis is applied to wind, and the exergy is formulated for wind energy. Finally, energy and exergy efficiencies for one of the wind farms in Iran (i.e. Manjil Power Plant) will be carried out.

2. Energy and exergy analysis of wind energy

People sense whether air is warm or cool based not only on air temperature, but also on wind speed and humidity. During cold weather, faster wind makes the air feel colder, because it removes heat from our bodies faster. Wind chill is a measure of this effect, and is the hypothetical air temperature in calm conditions (air speed, $V = 0$) that would cause the same heat flux from the skin as occurs for the actual air speed and temperature. The heat transfer for an air flow over a surface is slightly modified in some versions of the wind chill expression [4]. The present wind chill expression is based on the approaches of Osczevski [5] and Zecher [6].In addition, clinical trials have been conducted and the results have been used to verify and improve the accuracy of the expression, which is given as

$$T_{winch} = 35.74 + 0.6215 T_{air} - 35.74(V^{0.16}) + 0:4274 T_{air}(V^{0:16}) \quad (1)$$

where the wind chill temperature T_{windch} is in $^{\circ}F$ and wind speed V is in mph.

Another wind speed factor is wind pressure. When the wind approaches an obstacle, the air flows around it. However, one of the streamlines that hits the obstacle decelerates from the upstream velocity of v_s to a final velocity of zero (or to some lower velocity). The pressure (dynamic pressure) at this stagnation point is higher than the free stream pressure (static pressure) well away from the obstacle. The dynamic pressure is calculated from Bernoulli's equation. For flow at constant altitude, the only two terms that change in Bernoulli's equation are kinetic energy and pressure.

2.1 Energy Analysis

Wind energy E is the kinetic energy of a flow of air of mass m at a speed V. The mass m is difficult to measure and can be expressed in terms of volume υ through its density ($\rho = m/v$). The volume can be expressed as (V=AL) where A is the cross-sectional area perpendicular to the flow and L is the horizontal distance. Physically, L = V.t and wind energy can be expressed as [7]

$$E = 1/2\, \rho.A.t.V^3 \quad (2)$$

For a windmill, the retardation of wind passing through a windmill occurs in two stages: before and after its passage through the windmill rotor. Providing that a mass m is air passing through the rotor per unit time, the rate of momentum change is $\dot{m}.(V_1 - V_2)$ which is equal to the resulting thrust. In this study, V_1 and V_2, represent upwind and downwind speeds at a considerable distance from the rotor. The power absorbed P is expressed as:

$$P = \dot{m}(V_1 - V_2)\overline{V} \quad (3)$$

On the other hand, the rate of kinetic energy change in wind can be expressed as:

$$E_k = 1/2\, m(V_1^2 - V_2^2) \quad (4)$$

These two formulas represent the expressions in Equations (3) and (4) should be equal, so the retardation of the wind, $V_1 - \overline{V}$; before the rotor is equal to the retardation, $\overline{V} - V_2$; behind it, assuming that the direction of wind velocity through the rotor is axial and that the velocity is uniform over the area A. Finally, the power extracted by the rotor is

$$P = \rho A \overline{V}(V_1 - V_2)\overline{V} \quad (5)$$

Furthermore,

$$P = \rho A \overline{V}^2 (V_1 - V_2) = \rho A \left(\frac{V_1 + V_2}{2}\right)^2 (V_1 - V_2) \quad (6)$$

and

$$P = \rho \frac{A V_1^3}{4}\left[(1+\alpha)(1-\alpha^2)\right] \quad (7)$$

where $\alpha = \dfrac{V_2}{V_1}$

Differentiation shows that the power P is maximum when $\alpha = \frac{1}{3}$ i.e. when the final wind velocity V_2 is equal to one third of the upwind velocity V_1. Hence, the maximum power extracted is $\rho A V_1^3 \frac{8}{27}$.

2.2 Exergy analysis

Exergy is defined as the maximum amount of work, which can be produced, by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Unlike energy, exergy is not subject to a conservation law (except for ideal, or reversible, processes). Exergy is consumed or destroyed, due to irreversibilities in any real process [8]. Exergy analysis is a method that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the analysis, design and improvement of energy and other systems. Exergy consumption during a process is proportional to the entropy generated due to irreversibilities associated with the process. Exergy is a measure of the quality of energy that, in any real process, is not conserved but rather is in part destroyed or lost. For exergy analysis, the characteristics of a reference environment must be specified. This is commonly done by specifying the temperature, pressure and chemical composition of the reference environment. The results of exergy analyses, consequently, are relative to the specified reference environment, which in most applications is modeled after the actual local environment. The exergy of a system is zero when it is in equilibrium with the reference environment. Energy and exergy balances are expressed as follow [9]:

$$\dot{Q} - \dot{W} = \sum_{out} \dot{m}_{out}(h + pe + ke)_{out} - \sum_{in} \dot{m}_{in}(h + pe + ke)_{in}$$

$$\dot{E}_Q + \sum_{in} \dot{m}_{in} e_{in} = \sum_{out} \dot{m}_{out} e_{out} + \dot{E}_W + \dot{E}_D + \dot{E}_L$$

where subscripts i and e refer to streams entering and leaving the control volume, respectively. The exergy rate of a stream of substance (neglecting the potential and kinetic components) can be written in the form: In this equation, (e) is the total specific exergy and is the exergy destruction.

$$\dot{E}_Q = \left(1 - \frac{T_\circ}{T_i}\right)\dot{Q}_i$$

$$\dot{E}_W = \dot{W}$$

$$e_{ph} = (h - h_\circ) - T_\circ(s - s_\circ)$$

where T is the absolute temperature (K) and subscripts (in),(out) and (0) refer to inlet, outlet and ambient conditions, respectively.

$$\dot{E} = \dot{E}_{ph} + \dot{E}_{ch}$$

where $\dot{E} = \dot{m}e$

Based on these definitions we could define energy and exergy efficiency. The expressions for energy (η) and exergy (ψ) efficiencies for the principal types of processes considered in the present study are based on the following definitions [10-11]:

$$\eta = \frac{energy\,in\ products}{total\ energy\,input}$$

$$\psi = \frac{exergy\,in\ products}{total\ exergy\,input}$$

Here, exergy efficiencies can often be written as a function of the corresponding energy efficiencies. It is worth mentioning that the exergy efficiency frequently gives a better understanding of performance than the energy efficiency. The exergy efficiency expresses that both external losses and internal irreversibilities that should be dealt with to improve efficiency [10]. In many cases, the internal irreversibilities are more significant and more difficult to deal with than external losses. Electric work production processes produce shaft work W and the efficiencies for shaft work production from electricity through a wind energy system are

$$\eta_{m,e} = W / W_e$$

$$\psi_{m,e} = E^W / E^{W_e} = W / W_e = \eta_{m,e}$$

Therefore, the exergy efficiencies for the electricity generation process can be taken as equivalent to the corresponding energy efficiencies. The efficiencies for the fossil fuel and wind driven kinetic energy production processes, which produces a change in kinetic energy Δke in a stream of matter are as follows [12]:

$$\eta_{ke,f} = m_s \Delta ke_s / m_f H_f$$

$$\eta_{ke,f} = m_s \Delta ke_s / m_f H_f$$

$$\psi_{ke,f} = m_s \Delta ke_s / m_f \gamma_f H_f \cong \eta_{ke,f}$$

The input and output variables are described in Figure 1. Output wind speed is estimated using the continuity equation. The total electricity generated is related to the decrease in wind potential. Subtracting the generated power from the total potential gives the wind turbine backside wind potential can be obtained based on Equation (2), (Figure 1):

$$V_2 = \sqrt[3]{\frac{2(E_{Potential} - E_{Generated})}{\rho A t}}$$

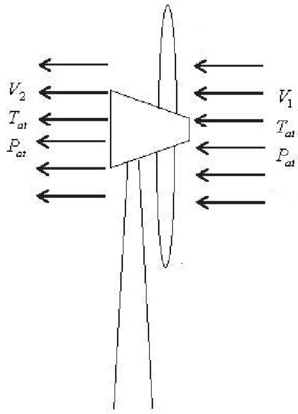


Fig. 1. Schematic diagram of wind turbine and inlet and outlet flow

3. Case study (Manjil Wind Power Plant)

For evaluation of wind potential in Iran, eight years ago a project was done in two phases. In the first phase of the project, software pack of wind turbine is developed and tested. In the second phase, location that could be utilized for electricity generation was found and electricity generation in these locations was estimated. Studies for determination of time and intensity of wind in the period of one year in these locations are done based on developed soft wares. In recent years, by installing two wind turbines in Manjil, a major project with the final capacity of 90 MW has been started. This project, which is not finished yet, produces 25 MW. Figure (2) shows the Manjil wind farms at the north part of Iran.

Fig (2): The Manjil Wind Farm

By considering the location, the potential for installation the wind turbine in north part of country has been started. It reveals that Safidroud have a good potential. Furthermore, the stability and high velocity of wind in this location is the main factor of this palace. Manjil wind farm is located at the southeastern of Sefidroud dam. The area of this site is around $2 \times 10^6 m^2$. Air flow in this location is known as Manjil wind. For evaluation of wind potential in this area, 10 stations installed. Obtained data was recorded in height of 10, 20 and 40 meter. For determination of wind direction in this study, collected data in 10 minutes interval were estimated. Table (3) shows the variation of wind velocity in 6 station in the Manjil area.

Station	Ali Abad	Babaeian	Esfestan
Heigh (m)	10	10	20
Average wind speed (m/s)	9.2	4.9	5.1

4. Result and discussion

In this paper wind potential for generation of power in Iran considered. Results show that Sefidroud has a good potential for generation of electricity. Moreover, Manjil wind power plant is located in this area. On the other hand, in the present study the energy and exergy analysis for this power plant has been done and results are as it follows:

Figure (3) shows the power generation versus wind speed. By examination of this figure, two different types of behavior are shown. At low wind speeds, increasing the wind speed leads to increase of the power. By using minimizing least square, it could be found a second degree polynomial curve for power curve. A curve is fitted between the cut-in and rated power wind speed and coefficient of determination (R^2) is estimated about 0.98. At high speed above (15.5m /s) by increasing the wind speed generation level, rated power decreases. Wind turbine performance point for Manjil Wind turbine is between 4 and 25 m/s. For the second type of this

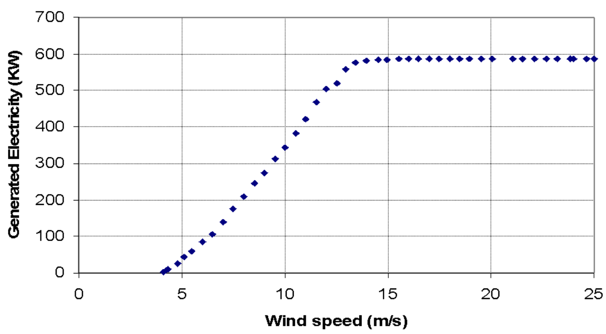
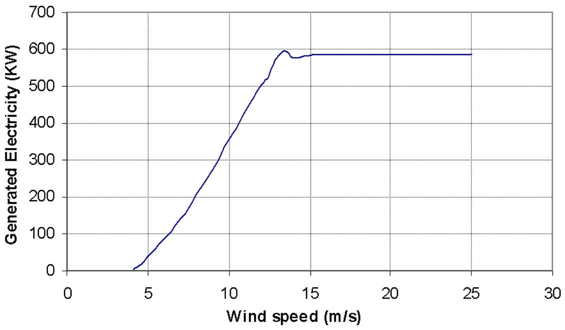


Figure (3): Electricity generated as a function of wind speed (Wind turbine power curve)



Figure(4):Generated electricity as a function of wind speed (regression curves for electricity).

Energy and exergy analysis show that there is significant difference between energy and exergy analysis. According to conventional energy efficiency analysis that examine capacity factor, result of wind energy is overestimated by this technique. The capacity factor defines as the percentage of nominal power that the wind turbine generates. The differences between exergy and energy efficiencies are shown in Figure (5). Below the cut-in wind speed (4.2.8m/s) and over the cutout wind speed (25.1 m/s) electricity generation is zero. As a result, energy and exergy efficiencies also are zero in those ranges. Since wind speed exhibits unstable behavior during the day, with greater fluctuations than all other meteorological parameters, the fluctuations in energy and exergy efficiency values are high.

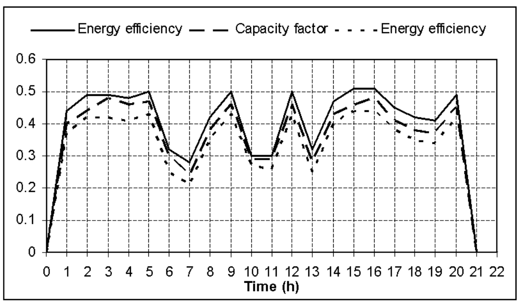


Figure (5): Variation of capacity factor, energy and exergy efficiency with set of wind data during a day in Manjil wind farm.

5. CONCLUSION

In this paper, the thermodynamic modeling of wind energy in one of the wind power plants in Iran was done. For having a good insight into this study exergy analysis was done as well. Moreover, results reveal that Safidroud have a good potential in Iran. Accordingly, the stability and high velocity of wind in this location is the main factor of this palace. Based on the formulations, differences are illustrated between energy and exergy efficiencies as a function of wind speed. It is thus suggested that exergy efficiency should be used for wind energy evaluations and assessments, so as to allow for more realistic modeling.

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