THERMODYNAMIC AND ENVIRONMENTAL ASSESSMENT OF A WIND TURBINE SYSTEM

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Abstract

The wind turbine system is one of the most competitive sources in the field of renewable energy technologies. In many possible applications, a small power plant based on a renewable energy can be a good solution under both the environmental and economic point of view. Vertical axis wind turbine types have an important role in small-scale power development. This wind power plant would allow the reduction of electric energy consumption from the grid and the increase of the amount of renewable energy use. The large wind turbine market is mature and it is the product of several extensive researches. Wind turbine market is being developed to improve the efficiency, performance, and cost effectiveness of the turbines. The end goal of this development is to gain a position for wind power as a competitive alternative to fossil fuels. Among all renewable energy technology of different kinds, wind energy technology has many advantages such as extensive distribution, high efficiency, low cost, low maintenance, environmental friendliness, economic improvement and environmental characteristic that it stands for the most popularized and potentially applicable type of green energy. In many applications, wind is already competitive with conventional options for generating electricity. In this paper, thermodynamic analysis consisting of energy and exergy terminology and environmental impact factors for wind turbine systems are investigated, and parametric studies for efficiency of wind turbine system are given for different ambient conditions such as wind speed and huge tower high. The relationship between the actual energy generated from the wind turbine and the wind speed characteristics are investigated for sustainability of wind turbine system. Also, important outputs for wind turbine system, such as maximum relative output useful energy and optimal rotational speed corresponding to different wind speeds, are estimated to improve the system performance. By multiplying normalized power by maximum relative output power for the wind turbine system, the relative output power is calculated.

Keywords: Renewable energy, wind energy, thermodynamic analysis, environmental analysis, efficiency.

1. Introduction

It is expected that by 2050 the world energy demand will be significantly increased. In addition, due to global problems caused by greenhouse gas emissions, the world also needs low emission and low-carbon energy suppliers to eliminate air pollution. Therefore, a lot of countries in the world have expressed their views on alternative energy resources, such as sustainable solar energy, safe nuclear energy, clean hydrogen economy, ground source heat pumps and geothermal energy, bio-energy, wind energy, hydro-power and wave energy. Suitable renewable energy policies need to be developed for effective use of available alternative sources. Wind energy is a prime example of a sustainable energy resource. Because it is a non-polluting source of energy during power generation, it has no emissions or residues to burden society.

The dominant type of modern wind turbine is the upwind, horizontal, 3-blade turbine variety, where the rotor axis is parallel to the wind direction and the blades are arranged perpendicular into the wind direction [Manwell et al., 2011]. The wind turbine system consists of a foundation, a tower, nacelle and three rotors attached to a hub. The three blades are attached to the hub, which is attached to the shaft, which is eventually connected to the generator. The blades are shaped like aircraft propellers, but are considerably larger, and hollow; an absolute premium is placed on the strength to weight ratio and flexing properties of the blades [Veers et al, 2003]. The type of wind turbine selected for installation at the sites examined should be designed for moderate wind speeds, have as tall a tower is as practical, and as large a blade diameter as is possible.

Entropy production based on design and exergy analysis of the wind turbine system is shown to identify the maximum theoretical capability of system performance in power production applications. Exergy analysis is very useful for improving a wide range of energy conversion systems. Exergy analysis also provides a design tool for increased accuracy and more efficient performance.

However, there are few examples in past literature [Sahin et al., 2006(a); Sahin et al. 2006(b); Ozturk, 2011] that pertain to wind exergy. Through an energy and exergy analysis of the characteristics of wind energy, it was found that differences between energy and exergy efficiencies are approximately 20-24% at low wind speeds and approximately 10 - 15% at high wind speeds [Sahin et al., 2006(a)]. Sahin et al. [Sahin et al., 2006(b)] have developed a useful exergetic analysis technique for determining the exergetic efficiency of a wind turbine. The technique utilizes the wind chill temperature associated with wind velocity to predict the entropy generation of the process. Better turbine design and location selection can be achieved with the aid of such exergy analysis. Ozturk [2011] have estimated wind power potential for Turkey, and provided suitable data for evaluating potential wind power production by using the wind data collected at 23 different wind-monitoring stations in Turkey. The author has used the energy and exergy analyses of wind power for estimating of the wind power potential in these areas. Exergy analysis of wind power has been investigated according to air temperature and pressure at inlet and outlet of wind turbine; energy generated and heat loss from wind turbine. Also, energy and exergy analyses of wind power and capacity factor, energy and exergy efficiencies at 10, 25 and 50 m have been calculated for these wind-monitoring stations.

In this paper, some results of the application methods of the thermodynamic analysis based on the second law of thermodynamics for reducing the exergy losses in the wind turbine system are investigated for better system design. In addition that, some parametric studies for produced energy, exergy destruction, energy efficiency and exergy efficiency of the wind turbine system are investigated for varying wind speeds. The other outputs of this paper should be given as follows;

- To develop an advanced Engineering Equation Solver (EES) software code and carry out parametric studies for wind energy system components.
- To calculate the exergy content of the proses including the physical or flow exergy for the system.
- To determine the exergy destruction rate and exergy efficiency of each system component.
- To perform a complete parametric study and the performance assessment of the system.

2. Thermodynamic Analysis

General thermodynamic assessments involving the energy and exergy balance equations, and energy and exergy efficiencies are given to analyze wind turbine improvement potentials. In the most general viewpoint, a balance equation for a given quantity in a process should be written as follows;

$$\text{Input} + \text{Generation} - \text{Output} - \text{Consumption} = \text{Accumulation} \quad (1)$$

Eq. (1) is supposed to as the quantity balance for the process, and should be given as quantity accumulated in a process is equal to the difference between the net quantity transfer through the system boundary plus the quantity generated and the quantity consumed within the system boundaries.

2.1 Energy Analysis

Wind turbine blades capture a fraction of the kinetic energy from the air passing the turbine blades and convert this into electric energy [Manwell et al., 2002]. The mass flow of air moving past the blades should be given as follows;

$$\dot{m} = \rho A_{wt} V_a \quad (2)$$

where ρ is density of the air (kg/m^3), A is the swept rotor area (m^2) and V_a is the velocity of the air flowing past the rotor disk (m/s). The air density changes with both ambient temperature and altitude, and should be calculated by the specific air gravity viewpoint as follows;

$$\rho = \rho_s \left(\frac{T_R}{T_S}\right)\frac{(P_S)}{(P_R)} \quad (3)$$

where ρ_s is the standard air density, and taken as 1.225 kg/m^3 for ambient temperature and pressure at 15 °C and 1 atm, respectively, T_R and T_S are the absolute reference temperature (15 °C) and space average air temperature, respectively, P_R and P_S are the absolute reference pressure (1 atm) and space average air pressure, respectively. The space average air pressure varies inversely with height above the sea level, and should be calculated as follows for altitudes less than 5000m [Manwell et al., 2002];

$$P_s = 101.29 - 0.11837z + (4.793x10^{-7})z^2 \tag{4}$$

The kinetic energy of flowing air can be calculated as;

$$E_k = \frac{1}{2} m V_a^2 \tag{5}$$

The kinetic energy per unit time through the rotor disk is the power of the air flow, and should be given as;

$$P = \frac{1}{2} \dot{m} V_a^2 \tag{6}$$

Also, it can be calculated as follows using the Eq. (2);

$$P = \frac{1}{2} \rho A_{wt} V_a^3 \tag{7}$$

This is the basic law that applies to extracting power from moving air. Also, Eq. (7) should be given in terms of the rotor radius (R).

$$P = \frac{1}{2} \rho \pi R^2 V_a^3 \tag{8}$$

Air is a compressible fluid. Therefore, all of the kinetic energy cannot be extracted from the air passing the turbine blades. The maximum quantity of the produced energy which can be extracted through a wind turbine system from moving air is represented using the Betz limit, which has a value of 16/27 or nearly 59.26% [Spera, 1994]. But in practical application, the best that the most blade designs can achieve is nearly 50%, and this performance usually changes with wind speeds [Walker and Jenkins, 1997]. Also, this performance indicator is given as the rotor power coefficient (C_p). Eq. (7) can be written as follows by incorporating C_p;

$$P = \frac{1}{2} \rho \pi R^2 V_a^3 C_p \tag{9}$$

At high wind speeds, the effect of C_p usually is determined by changing the pitch of the turbine blades. Therefore, the turbine blades become less performance at converting moving air into rotary motion. When the wind speeds are too high, the turbine rotation is stopped by adjusting the blade angles to an aerodynamic braking position. Capacity factor (CF) can also easily be found as the ratio of the annual average power generated and the rated power of a turbine as follows;

$$CF = \frac{E_{real}}{E_{rated}} \tag{10}$$

where E_{real} and E_{rated} are total energy generated and maximum annual rated energy by the wind farm, respectively, and they can be given as follows;

$$E_{real} = P x N_{turbine} x t_{total} \tag{11}$$

and

$$E_{rated} = P_{rated} x N_{turbine} x t_{total} \quad (12)$$

where P_{rated} is maximum rated power of a turbine, $N_{turbine}$ is number of turbines in the farm and t_{total} is number of operational hours in a year.

2.2 Exergy Analysis

Exergy analysis based on the second law of the thermodynamics can support to create the strategies and managements for more economical and effective use of energy sources, and is utilized to study wind energy system. The sources of the irreversibility and proposed approaches to increase the whole efficiency of the given system should be considered by using exergy analysis. Exergy content of matter is generally divided into four parts which are physical exergy (ex_{ph}), chemical exergy (ex_{ch}), kinetic exergy (ex_k) and potential exergy (ex_p). Therefore, general exergy balance equation per unit mass should be given as follows;

$$ex = ex_{ke} + ex_{pe} + ex_{ph} + ex_{ch} \quad (13)$$

where ex_{ke}, ex_{pe}, ex_{ph} and ex_{ch} are the kinetic, potential, physical and chemical exergy, respectively. In this paper, kinetic, potential and chemical exergies are negligible, as the elevation differences are low, speeds in the process are small and there is no chemical reaction. In general, physical exergy is represented the maximum effective work available as a process interacts with the environment. Any substance of which the temperature, pressure or composition is different from the thermodynamic equilibrium with the surroundings (thermal, mechanical and chemical) has the possibility to produce a change. The physical exergy or general flow exergy of the i_{th} flow is given as;

$$ex_{ph,i} = (h_i - h_o) - T_o(s_i - s_o) \quad (14)$$

where subscripts i and o show the i^{th} flow rate and reference condition flow rate, respectively, h is the specific enthalpy and s is the specific entropy, respectively. Enthalpy difference can be given as follows;

$$\Delta h = C_{p,a}(T_2 - T_1) \quad (15)$$

where $C_{p,a}$ is the air specific heat in (kJ/kgK), T_1 and T_2 are the wind chill temperature at the input and output to the wind turbine blades, respectively. Wind chill temperature for the turbine can be given as follows [Nelson et al., 2002];

$$T_{i,wind-ct} = 13.12 + 0.06215T_a - 11.37V_i^{0.16} + 0.3965T_aV_i^{0.16} \quad (16)$$

where $T_{i,wind\text{-}ct}$ is the wind chill temperature °C and V is the wind speed in km/h at 10 m elevation from the ground level. Output wind speed (V_2) should be calculated as follows [Abed, 1994];

$$V_2 = \sqrt[3]{\frac{2(E_{potential} - E_{generated})}{\rho At}} \quad (17)$$

The entropy changes for the wind turbine system are consisting of the total entropy of the system and surround entropy difference [Szargut, et al., 1988].

$$\Delta s = \Delta s_{system} + \Delta s_{surround} \tag{18}$$

or

$$\Delta s = T_a \left[C_{p,a} ln\left(\frac{T_2}{T_1}\right) - R ln\left(\frac{P_2}{P_1}\right)\right] - \frac{\dot{Q}_{loss}}{T_a} \tag{19}$$

Heat losses per unit mass from the rotor blade of the turbine system should be given as follows;

$$\dot{Q}_{loss} = C_{p,a}\left(T_a - \frac{T_1 - T_2}{2}\right) \tag{20}$$

From Eq. (15), the total exergy of wind power can be expressed as;

$$ex_{wt} = \dot{E}_{generated} + C_{p,a}(T_2 - T_1) + T_a\left[C_p ln\left(\frac{T_2}{T_1}\right) - Rln\left(\frac{P_2}{P_1}\right) - \frac{\dot{Q}_{loss}}{T_a}\right] \tag{21}$$

Total exergy of the wind turbine system should be written as follows;

$$\dot{E}x_{wt} = \dot{m}ex_{wt} \tag{22}$$

Also, exergy destruction rate for the wind turbine system can be given as;

$$\dot{E}x_D = \dot{W}_u - \dot{W}_e \tag{23}$$

2.3 Thermodynamic Efficiencies

The thermodynamic efficiencies of the design system should be considered through the first law of thermodynamics (energy efficiency) and both the first and second laws of thermodynamics (exergy efficiency). Energy and exergy efficiencies of the system components and whole system should be given for detailed thermodynamic analysis.

The energy efficiency (η) of the system should be given as the ratio of useful energy produced by the system to the total energy input. The useful produced energy represents the desired results produced by the system components. The energy efficiency for the single production should be written as follows:

$$\eta = \frac{useful\ energy\ output\ rate\ with\ products}{total\ energy\ input\ rate} = \frac{\dot{E}_{out,useful}}{\sum \dot{E}_{in,total}} \tag{24}$$

The exergy efficiency (ψ) of the process should be defined as the divided of exergy output rate ($\dot{E}x_{out,useful}$) that is created by the considered system to the overall exergy inlet rate ($\sum \dot{E}x_{in,total}$) that is cross the boundaries of the system, as follows;

$$\psi = \frac{total\ useful\ exergy\ output\ rate\ with\ products}{total\ exergy\ input\ rate} = \frac{\sum \dot{E}x_{out,total}}{\sum \dot{E}x_{in,total}} \tag{25}$$

The exergy efficiency for the process should also be given in terms of exergy destruction rate as the following;

$$\psi = \frac{\sum Ex_{out}}{\sum Ex_{in}} = \frac{\sum Ex_{in} - Ex_D}{\sum Ex_{in}} = 1 - \frac{Ex_D}{\sum Ex_{in}} \qquad (26)$$

Using the derived equations, a model is generated by using Engineering Equation Solver (EES). With the help of this model, the system performance and emissions are investigated by varying a series of input conditions.

3. Results and discussion

The main production characteristics of the wind turbine system are given in Table 1. In this paper, the ambient temperature and pressure are given as 25 °C and 1 atm, respectively. For the useful energy production from the chosen wind turbine system, wind speeds from 10 m to 50 m above the ground level are from 5 to 12 m/s. Higher wind speeds create axial forces which are liable to damage the wheel, the transmission and support of the machine. This is very important to take special protective measures in the design of the wind wheel sub-system.

Table 1. ENERCON E-40/6.44 product specifications

Wind Turbine Product Specifications	
Model	**ENERCON E-40/6.44**
Rated Power	600 kW
Hub height	46 m on tabular steel tower
Rotor	
Diameter	44 m
Type	Upwind
Direction of rotation	Clockwise
Number of blades	3
Rotor swept areas	1662 m^2
Blade materials	Fiberglass (reinforced epoxy) with light protection
Rotor speed	Variable, 18-34 rpm
Generator	
Generator	Gearless-no oil required
Braking system	3 independent systems with emergency supply Rotor brake Rotor lock for service and maintenance
Cut-in speed	2.5 m/s
Rated wind speed	13.0 m/s

Thermodynamic analysis and environmental assessment of the wind turbine system are very important in terms of the view for sustainable developments. To achieve for these aims, measured and calculated parameters according to the average values of the wind turbine system are shown in Table 2. These design parameters are measured wind speed (ms^{-1}), measured time in a year ($hyear^{-1}$), wind speed percent (%), capacity factor (C_p), mass flow rate (kgs^{-1}), available power (kW), useful power (kW) and produced power (kWh/year). For this paper, using the energy analysis which given in this paper, available power and useful power for the wind turbine system are calculated as 1364 and 1603 kW respectively for 11.5 ms^{-1} wind speed. But, produced maximum power from the wind turbine system is calculated as 47739 kWh/year at 6.5 ms^{-1} wind speed. The maximum and minimum capacity factors of the wind turbine system are obtained as 0.35 for 7.5 ms^{-1} and 0.18 for 2.5 ms^{-1} wind speed, respectively. This indicates that capacity factor is depended on the measured time in a year and wind speed. Also, high mass flow rate for the wind system produces high available power and useful power, respectively. The electricity produced is zero below the 2.5 ms^{-1} cut-in wind velocity.

Table 2. Measured and calculated parameters for the wind turbine system

Measured wind speed V_r (ms^{-1})	Measured time in a year t_{total} ($hyear^{-1}$)	Wind speed percent (%)	Capacity factor C_p	Mass flow rate $\dot{m}$ (kgs^{-1})	Available power P_a (kW)	Useful power P_u (kW)	Produced power P_o (kWh/year)
2.5	4028	45.99	0.18	4.486	14.02	16.24	0
3.5	1202	13.73	0.21	6.28	38.46	45.2	9229
4.5	1674	19.10	0.28	8.074	81.75	99.08	36425
5.5	1023	11.68	0.30	9.868	149.3	182.4	43544
6.5	637	7.28	0.32	11.66	246.4	303.4	47739
7.5	104	1.18	0.35	13.46	378.5	471.3	13096
8.5	72	0.83	0.33	15.25	550.9	681	12444
9.5	11	0.12	0.30	17.05	769.2	939.8	2413
10.5	7	0.07	0.25	18.84	1039	1243	1728
11.5	2	0.02	0.21	20.63	1364	1603	544.7

The results of the energy and exergy analysis, including the energy and exergy efficiency, and exergy destruction rate for the wind turbine system are reported. It is shown that, the inlet and outlet exergy flows of the system are mainly attributed to the wind speeds. Produced energy (kW) and energy efficiency of the wind turbine system based on the measured wind speeds are given in Figure 1. It is seen that, produced energy and energy efficiency for the system changes between 1364 to 7729 kW and 0 to 26.72%, respectively, at different measured wind speed, and maximum energy efficiency is obtained for 6.5 ms^{-1} wind speed, considering inlet and outlet pressure differences for the system.

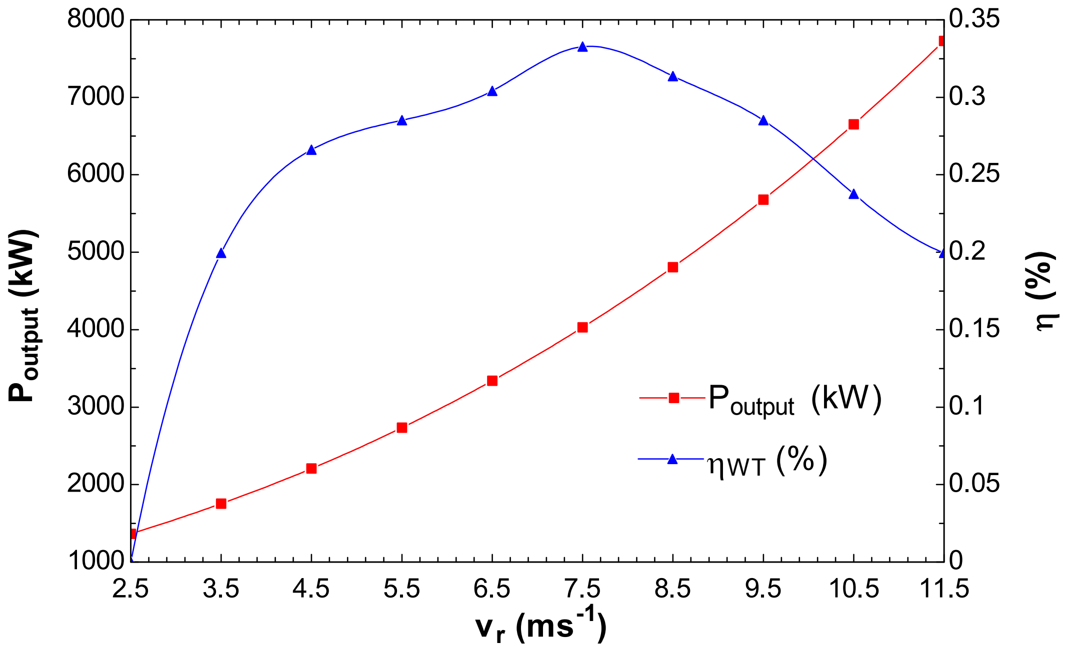

Figure 1. Variations with wind turbine of the produced energy (kW) and energy efficiency for the wind turbine

Exergy analysis of the system has an important role in evaluating wind energy technology. Also, the exergy destruction rate is another important matter to be emphasized because the study of irreversibility can help to identify where the work or energy lost during the operation. Various factors identified in the design section can influence both the energy and exergy efficiencies of the wind turbine system.

Exergy destruction rate (kW) and exergy efficiency of the wind turbine system based on the measured wind speeds are given in Figure 2. Increasing of the measured wind velocity decreases the energy and exergy efficiencies because the net energy inlet to the wind turbine increases. Furthermore, maximum produced energy and exergy destruction rate are produced as 272.4 and 1331 kW, respectively, at 11.5 ms^{-1} wind speed. Higher exergy destruction refers high inefficiencies or irreversibilities occur in this system. Exergy efficiency of the system is more meaningful than the energy efficiency since it gives right magnitudes for the losses to be determined. It is suggested that exergy efficiency should be used for wind energy evaluations and assessments, so as to allow for more realistic modeling. In the general manner, the exergy efficiency of the wind turbine system is based on the turbine type, such as horizontal or vertical, rotor radius hub height and local wind speed.

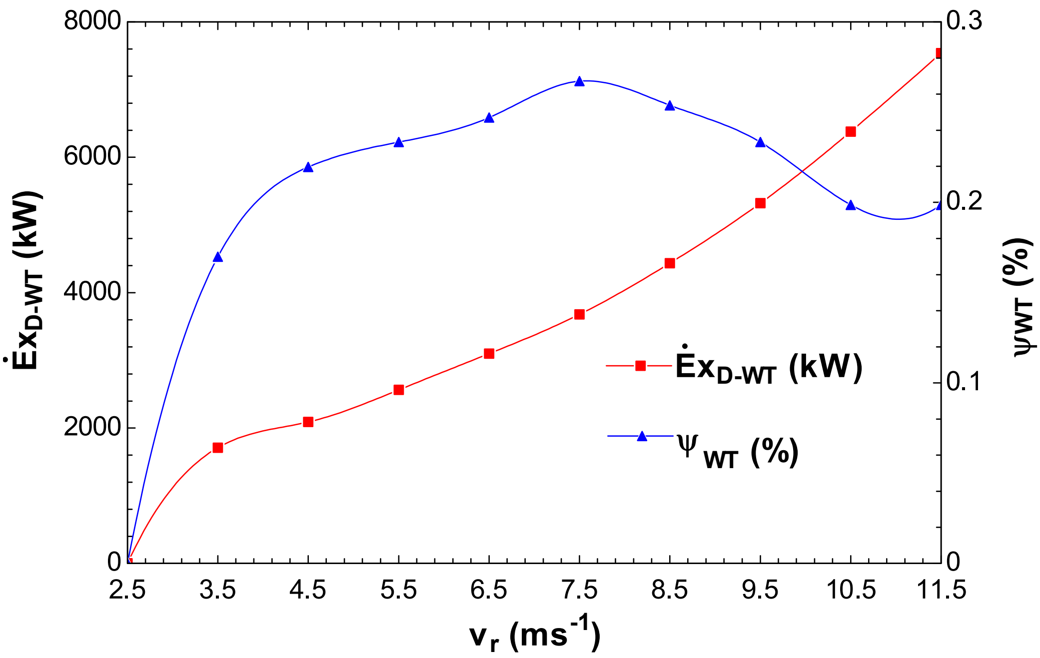

Figure 2. Variations with wind turbine of the exergy destruction rate (kW) and exergy efficiency for the wind turbine

4. Conclusions

Wind turbine system can make significant supports for energy production due to their potential for high efficiency as well as low operating costs and greenhouse gas and pollution emissions. Environmental problems such as fossil fuel depletion and climate change upgrade the advantages and significance of wind turbine system performance. In this study, energy and exergy analyses are carried out for the wind turbine system to evaluate the system performance and exergy destruction rates. Exergy analysis of a wind turbine system is given based on the thermodynamic quantities, such as enthalpy and entropy productions. Therefore, exergy analysis has a significant role in evaluating wind turbine system. The differences between the energy and exergy efficiency is very important for analyzing of the energy conversation. It is suggested that, exergy efficiencies can be used for wind energy evaluation and assessment, so as to allow for more realistic modeling, evaluation and planning for wind turbine system. Exergetic assessments of wind power system provide more meaningful and useful data than energetic assessments for engineers and wind energy companies before making decisions.

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