Chapter

Thermodynamic Analysis of Wind Energy Systems

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Abstract

This chapter studies the efficiency performance of wind energy systems evaluated by energy and exergy analyses. The theories of energy and exergy analyses along with efficiency calculation for horizontal-axis wind turbines (WTs) are provided by a lucid explanation. A 1.5 MW WT is selected for the thermodynamic analysis using reanalyzed meteorological data retrieved from the National Aeronautics and Space Administration's (NASA) Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), data set. Matlab scripts are developed to calculate the energy and exergy efficiencies using the MERRA-2 data set. The energy efficiency presents higher magnitude than the exergy efficiency based on the theoretical derivation and the calculated time series of efficiencies. Comparison of impacts of four meteorological variables (wind speed, pressure, temperature, and humidity ratio) on WT efficiencies shows that although wind speed dominates the turbine's efficiency performance, other meteorological variables also play important roles. In addition, uncertainties of the meteorological variables are represented by the best-fit distributions, which are critically important for evaluating the reliability of wind power performance considering realistic meteorological uncertainty.

Keywords: wind energy, thermodynamic analysis, energy efficiency, exergy efficiency, meteorological uncertainty, wind speed, pressure, temperature, humidity

1. Introduction

Global installed wind power capacity has been tremendously increased over the last 15 years from 23,900 MW in 2001 to 486,790 MW in 2016 [1]. More than 314,000 WTs are now operating around the world, which accounts for more than 4.3% of 2015 global electricity demand. Yet it is still far from ambitious targets, e.g., increasing wind energy's contribution to 20% of US electricity supply by 2030 [2]. To approach that, it is of critical importance to accurately evaluate the WT performance considering realistic environmental conditions.

The most common factors that are considered when planning a wind farm include substantial wind resources, landowner and community support, feasible permitting, compatible land use, nearby access to electrical grid, appropriate site conditions for access during construction and operations, aviation compatibility, and favorable electricity market [3]. However, the influences of meteorological variables (e.g., pressure, temperature, and humidity) are often neglected which could cause inaccurate evaluation of WT performance. For example, a dry air assumption (i.e., constant air density) does not really consider the moisture changeability. Baskut et al. discussed the effects of several meteorological variables including air density, pressure difference, humidity, and ambient temperature on exergy efficiency and suggested that neglecting these meteorological variables while planning wind farms could cause important errors in energy calculations [3].

The efficiency performance of a WT can be studied in two aspects, energy and exergy efficiencies. The former is calculated as the ratio of produced electricity to the total wind potential within the swept area of the rotor. Thus, only the kinetic energy of the air flow is considered in the energy efficiency calculation, while other meteorological variables such as pressure and temperature are often neglected. The latter considers the maximum useful work that can be obtained by a system interacting with an environment in thermodynamic equilibrium state [4]. The exergy efficiency along with availability and capacity factor of a small WT (rated power 1.5 kW) has been studied in Izmir, Turkey, to assess the WT system performance [5]. Sahin et al. developed an improved approach for the thermodynamic analysis of wind energy using energy and exergy, which provided a physical basis for understanding, refining, and predicting the wind energy variations [6]. According to [7], exergies are suggested as the most appropriate link between the second law of thermodynamics and the environmental impact, in part because it measures the deviation between the states of the system and the environment.

This brief précis thus illustrates the importance of energy and exergy analyses for wind energy systems considering meteorological variables and provides a motivation for the thermodynamic analysis conducted herein. The chapter presents the methods and results of thermodynamic analysis of a 1.5 MW WT, which is assumed to be deployed in the northeastern United States, experiencing meteorological reanalysis data retrieved from the NASA's MERRA-2 data set. Matlab scripts are developed to calculate the energy and exergy efficiencies using the MERRA-2 data set. Section 2 provides the fundamental theory of thermodynamic analysis, particularly in derivations of energy and exergy efficiencies. The studied site, meteorological data, and the selected WT are explained in Section 3, which is followed by results and discussion in Section 4. Concluding remarks are provided in Section 5.

2. Theory

A WT converts kinetic energy from air flow to electrical energy through subassemblies including rotor blades, drivetrain, generator, and electronic control systems, as well as other auxiliary components. As the kinetic energy is extracted, the air flow that passes through the turbine rotor must slow down. Assuming there is a boundary surface that contains the affected air flow inside, a long stream tube extended far from the upstream and to the downstream with varied cross sections is often used to study the thermodynamics of horizontal-axis WTs [6, 7] (**Figure 1**). The wind speed, pressure, and temperature at the inlet of the stream tube are represented by V_1, P_1, and T_1, respectively. Their counterparts at the outlet are V_2, P_2, and T_2 and at the rotor are V_{ave}, P_{ave}, and T_{ave}. Here a constant specific humidity ratio is assumed in the stream tube for a short-period time (e.g., 10 minutes or 1 hour). The following sections explain the theory of WT thermodynamics in two aspects, energy analysis and exergy analysis, which both apply the meteorological variables such as wind speed, air density, atmospheric pressure, temperature, and humidity. The use of energy and exergy efficiencies considering a comprehensive set of meteorological variables can enable us to accurately evaluate the efficiency performance of WTs.

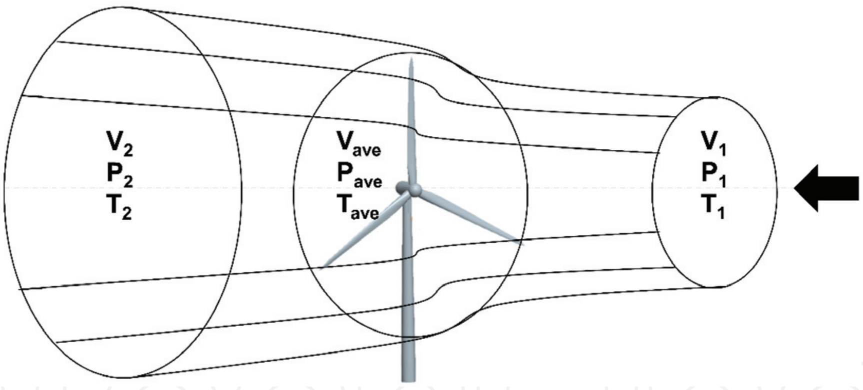

Figure 1.
A schematic plot of WT stream tube for thermodynamic analysis.

2.1 Energy analysis

The energy analysis of WT systems stems from the air flow's kinetic energy E_k that is calculated as

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

where m and V are the mass and speed of the air flow, respectively. The mass m can be further expressed as

$$m = \rho A V t \tag{2}$$

where ρ is the air density, A is the rotor swept area perpendicular to the flow, and t is the time that the flow passing through the swept area with speed V. By applying the simple momentum theory, the rate of momentum change is equal to the overall change of velocity times the mass flow rate $\dot{m}$, i.e.,

$$\dot{M} = \dot{m}(V_1 - V_2) \tag{3}$$

where V_1 and V_2 are the wind speeds at the inlet and outlet, respectively, of the stream tube (**Figure 1**). The rate of momentum change is also equal to the resulting thrust force. Thus, the power absorbed by the WT is calculated as

$$P = \dot{m}(V_1 - V_2) V_{ave} \tag{4}$$

where V_{ave} is the average flow speed at rotor. On the other hand, the rate of kinetic energy change of the flow can be calculated as

$$\dot{E}_k = \frac{1}{2} \dot{m} \left(V_1^2 - V_2^2 \right) \tag{5}$$

Based on the conservation of energy, Eqs. (4) and (5) should be equal which results in

$$V_{ave} = \frac{1}{2}(V_1 + V_2) \tag{6}$$

Hence, the retardation of the wind before the rotor $(V_1 - V_{ave})$ is equal to the retardation of the wind after the rotor $(V_{ave} - V_2)$. By Eqs. (2), (4), and (6), the rotor power can be calculated as

$$P = \frac{1}{4}\rho A (V_1 + V_2)^2 (V_1 - V_2) \tag{7}$$

Let $a = \frac{V_2}{V_1}$; Eq. (7) can be reformulated as

$$P = \frac{1}{4}\rho A V_1^3 (1 + a)^2 (1 - a) \tag{8}$$

In order to obtain the maximum power, equate 0 to the differentiation of Eq. (8) with respect to a resulting in $a = \frac{1}{3}$. Thus, the maximum power $P_{max} = \frac{8}{27}\rho A V_1^3$ is achieved, when the outlet wind speed is equal to one-third of the inlet wind speed. Defining the power coefficient as

$$C_p = \frac{P}{\frac{1}{2}\rho A V_1^3} \tag{9}$$

the maximum power coefficient is calculated $C_{P_{max}} = \frac{16}{27} \approx 0.593$. This maximum power coefficient, known as the Lanchester-Betz limit (or Betz limit) [8, 9], explains the maximum power that can be extracted from the air flow and can also be easily derived by other theories (e.g., the rotor disc theory and blade element momentum theory [10]).

Despite the simplicity of Eq. (9) when calculating power coefficient, the total input power in the denominator does not take account of the impacts from pressure, temperature, and humidity. Actually the air density changes as the ambient pressure, temperature, and humidity change, which can be expressed as

$$\rho = \frac{1 + \omega}{R_a + \omega R_v}\frac{p}{T} \tag{10}$$

where ω (−) is the humidity ratio of air, gas constant R_a = 287.1 J/kg K, water vapor constant R_v = 461.5 J/kg K, and T is the absolute temperature (unit: K). In order to distinguish wind power P, the small letter p is used to represent the pressure (unit: Pa) in the humid air hereafter. Combining Eqs. (9) and (10), the power coefficient of a WT considering a comprehensive set of meteorological variables can be expressed as

$$C_p = \frac{2(R_a + \omega R_v)}{1 + \omega}\frac{TP}{pAV_1^3} \tag{11}$$

The above derivations provide the fundamentals of the theoretically available energy/power that a WT can extract from the air flow. However, various effects could have influence on the real power output, e.g., vortices shed from the blade tip and hub could significantly affect the rotor lift force and power output [11]. Power losses also occur during the energy transformation through rotor to mechanical shaft and to generator that converts angular kinetic energy to electrical energy. In addition, sustained high wind speeds could cause strong fatigue and extreme loads on WT systems without proper turbine control or safety protection. Thus, wind power is intended to be constrained, when the inflow wind speed is beyond a rated value (i.e., rated wind speed), through different strategies commonly including stall regulation, pitch regulation, and yaw control [12]. As a result, the output power P_{out} of a WT is corresponding to four operating stages: (1) zero power when the inflow wind speed is smaller than a cut-in wind speed, (2) exponentially increased power as the wind speed increases between the cut-in wind speed and the rated wind speed, (3) rated output power when the wind speed is between the rated wind

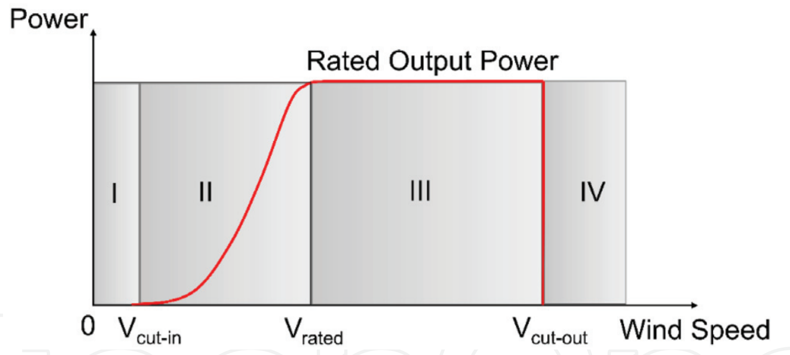

Figure 2.
A typical power curve of WTs with four operational stages I–IV.

speed and a cutout wind speed, and (4) zero power when the inflow wind speed is larger than the cutout wind speed (**Figure 2**).

2.2 Exergy analysis

In thermodynamics, the exergy of a system is defined as the maximum amount of useful work during a process that can bring the system into equilibrium with a reference environment [13]. Based on the second law of thermodynamics, exergy analysis is an alternative useful tool for analysis, evaluation, and design of many power and energy systems, e.g., renewable and traditional energy systems. The significant difference between energy and exergy analyses may be characterized as [6]:

1. In real irreversible process, exergy is always consumed; thus it is not subjected to a conservation law. In contrast, energy is neither created nor destroyed, but changing from one form to another, during a process. Thus, it is subjected to the conservation of energy law.

2. Although from a theoretical point of view exergy may be defined without a reference environment, it is often defined as a quantity relative to a specified reference environment and is equal to zero when it is in equilibrium with the reference environment.

The total exergy Ex of a flow with unit mass generally consists of four parts, which can be expressed as

$$Ex = Ex_{ki} + Ex_{po} + Ex_{ph} + Ex_{ch} \tag{12}$$

where Ex_{ki}, Ex_{po}, Ex_{ph}, and Ex_{ch} represent the kinetic, potential, physical, and chemical exergies, respectively. For thermodynamic analysis of WT systems, the potential exergy and chemical exergy are negligible in the total exergy. Thus, the total exergy for a WT can be reduced as

$$Ex = Ex_{ki} + Ex_{ph} \tag{13}$$

where the kinetic exergy is defined herein as the maximum possible available kinetic energy that the air flow can produce from a wind speed to a complete stop and the physical exergy includes the enthalpy and entropy changes related to the turbine operation. The physical exergy can be calculated as [6, 7].

$$Ex_{ph} = c_p(T_2 - T_1) + T_0\left(c_p \ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{P_2}{P_1}\right) - \frac{c_p(T_0 - T_{ave})}{T_0}\right) \tag{14}$$

where the first term and the second term on the right side of Eq. (14) are the enthalpy and entropy contributions, respectively. c_p is the specific heat of the flow; $T_0, T_1, T_2, T_{\text{ave}}$ are the reference temperature, inlet temperature, outlet temperate, and average temperature, respectively; P_1 and P_2 are the inlet pressure and outlet pressure, respectively (see **Figure 1**); and R is a constant related to the gas and water vapor constants. Ideally, temperature and pressure at both inlet and outlet are needed to calculate the physical exergy. However, it is cumbersome to measure the temperatures and pressures at both inlet and outlet for the WT stream tube in real applications, not to mention the situation when evaluating the wind energy resource and/or WT efficiency performance before deploying WTs. In addition, the meteorological variable humidity is not considered in Eq. (14). To handle this difficulty, other studies have provided another formula to calculate the physical exergy for wind energy [3, 5, 14, 15]:

$$\begin{aligned} Ex_{ph} = {} & \left(c_{p,a} + \omega c_{p,v}\right)(T - T_0) \\ & - T_0\left[\left(c_{p,a} + \omega c_{p,v}\right)\ln\left(\frac{T}{T_0}\right) - (R_a + \omega R_v)\ln\left(\frac{p}{P_0}\right)\right] \\ & + T_0\left[(R_a + \omega R_v)\ln\left(\frac{1 + 1.6078\omega_0}{1 + 1.6078\omega}\right) + 1.6078\omega R_a \ln\left(\frac{\omega}{\omega_0}\right)\right] \end{aligned} \tag{15}$$

where $c_{p,a}$ and $c_{p,v}$ are specific heat of air and water vapor, respectively; ω_0 and ω are the humidity ratio of air at the reference state and at the current state, respectively; R_a and R_v are the gas constant and the water vapor constant, respectively; T_0 and P_0 are the reference temperature and atmospheric pressure, respectively; and T and p are measured temperature and pressure in this study.

2.3 Energy and exergy efficiencies

The efficiency for wind energy systems is explained by using energy efficiency η and exergy efficiency ψ. The former is obtained as the ratio of useful energy produced by a WT to the total input wind energy, while the latter is defined as the useful exergy created by a WT to the total exergy of the air flow. These general definitions of energy and exergy efficiencies have been introduced in several literature (e.g., [3, 5–7, 16]). However, the specific definitions of useful energy/exergy for wind energy systems are often not very clearly explained in the literature. In order to avoid confusion, here we define that both the useful energy and useful exergy are equal to the rate of electricity output E_{out} that a WT can produce under a wind speed (i.e., E_{out} equals to actual output power P_{out}). Thus, the energy efficiency and exergy efficiency are calculated as, respectively,

$$\eta = \frac{E_{out}}{W_{wind}} \tag{16}$$

$$\psi = \frac{E_{out}}{Ex} \tag{17}$$

where W_{wind} is the total input wind energy equal to the total kinetic energy given in Eq. (1) and Ex is the total exergy given in Eq. (13). By incorporating the meteorological variables and referring Eqs. (9)–(11), the energy efficiency can be expressed as

$$\eta = \frac{2(R_a + \omega R_v)}{1+\omega}\frac{TP_{out}}{pAV_1^3} \tag{18}$$

where P_{out} is the output power defined by the power curve (see **Figure 2**). By Eqs. (13), (15), and (17), the exergy efficiency can be reorganized as

$$\psi = \frac{P_{out}}{\left\{\begin{array}{l} \dfrac{(1+\omega)pAV_1^3}{2(R_a+\omega R_v)T} + \left(c_{p,a} + \omega c_{p,v}\right)(T - T_0) \\ -T_0\left[\left(c_{p,a} + \omega c_{p,v}\right)\ln\left(\dfrac{T}{T_0}\right) - (R_a + \omega R_v)\ln\left(\dfrac{p}{P_0}\right)\right] \\ +T_0\left[(R_a + \omega R_v)\ln\left(\dfrac{1+1.6078\omega_0}{1+1.6078\omega}\right) + 1.6078\omega R_a \ln\left(\dfrac{\omega}{\omega_0}\right)\right] \end{array}\right\}} \tag{19}$$

Eqs. (18) and (19) derive the energy and exergy efficiencies given various meteorological variables, which can offer a straightforward evaluation of WT efficiency performance in a perspective of energy and exergy before deploying WTs. Hence, it will be beneficial in wind resource evaluation, wind farm site selection, and new WT design.

3. Case study

Using the presented thermodynamic analysis methods for wind energy systems, the wind energy potential is evaluated by investigating the energy and exergy efficiencies of a Goldwind 1.5 MW WT (model GW82/1500) [17], which is assumed to be deployed at Ithaca, New York, where 18-year reanalysis meteorological data are obtained from the Modern-Era Retrospective analysis for Research and Application, version 2 (MERRA-2), the latest atmospheric reanalysis of the modern satellite era produced by NASA's Global Modeling and Assimilation Office [18]. This section explains the site; the meteorological data including wind speed, pressure, temperature, and humidity; and the characteristics of the WT used for thermodynamic analysis.

3.1 Site and data

The wind energy potential is evaluated at Ithaca, which has moderately complex terrain in a landscape dominated by patches of forest, crop fields, hills, waterfalls, and lakes in the Upstate New York (at approximately 42.44° N, 76.50° W, **Figure 3**). Experiencing a moderate continental climate, Ithaca has long, cold, and snowy winters and warm and humid summers with a dominance of westerly wind flows. The meteorological data are obtained from the MERRA-2 (a meteorological reanalysis data set created by NASA), which has a resolution of 0.5° latitude × 0.625° longitude [19]. Although it does not provide measured data in fields, the meteorological reanalysis is thought as a valuable tool to estimate the long-term variables, such as wind speed and temperature, for subsequent meteorological, climatological, energy, and environmental studies. By specifying the latitude and longitude of Ithaca, five types of meteorological data are retrieved from the

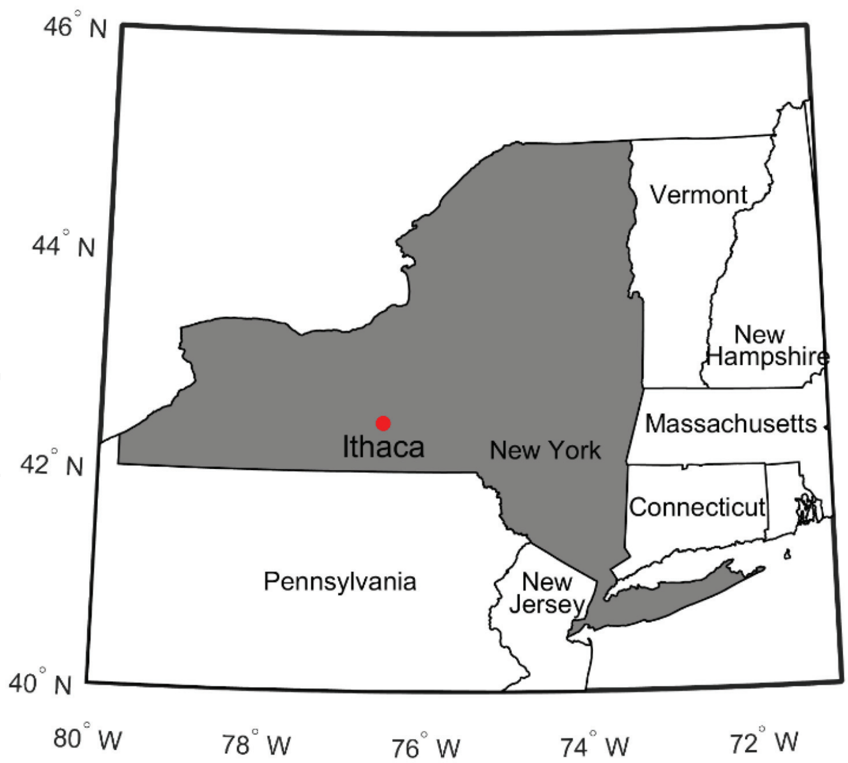

Figure 3.
Location of Ithaca, New York, where thermodynamic analysis of a 1.5 WM WT is investigated.

MERRA-2 including 10-m eastward wind U10M (in ms^{-1}), 10-m northward wind V10M (in ms^{-1}), surface pressure PS (in Pa), 10-m air temperature T10M (in K), 10-m specific humidity QV10M (in kg kg^{-1}), as well as their hourly time stamps from January 2000 to December 2017. The 10-m horizontal wind speed U is calculated as $U = \sqrt{U10M^2 + V10M^2}$, and the humidity ratio ω is calculated from the specific humidity as $\omega = QV10M/(1 - QV10M)$. In total, there are 18 years of hourly meteorological data used for the thermodynamic analysis of the WT, which is assumed to be deployed in Ithaca, New York.

3.2 Wind turbine

The expected wind energy that can be harvested at a location is highly related to the WT characteristics, e.g., power curve and the available wind resources. Herein a Goldwind 1.5 MW permanent magnet direct-drive (PMDD) WT (GW85/1500) is assumed to be deployed at Ithaca area and used for evaluating the WT's energy and exergy efficiencies. **Table 1** provides a summary of technical specifications of the WT. Since this study investigates the WT efficiency performance before real deployment, measured output power data are not available. It is assumed that the WT is performing perfectly according to its power curve, which consists of four operational stages (**Figure 2**). The WT starts to produce electricity at its cut-in wind speed of 3 ms^{-1}, and the produced power is increased to the rated one of 1.5 MW at the rated wind speed of 10.3 ms^{-1}. In order to mitigate the fatigue and structural loadings under sustained high wind, WT control systems (e.g., the active blade pitch control) are operated to maintain the aerodynamic loads applied on blades and control the output power to be constant at the rated power. The WT is stopped, when wind speed is larger than the cut-out wind speed of 22 ms^{-1}, to keep the whole turbine safe under extreme wind conditions. In this study, the power curve is represented by a six-order polynomial equation of wind speed during the cut-in and rated speeds, which is expressed as

IEC wind class	IIIA
Rated power (kW)	15,000
Cut-in wind speed (ms^{-1})	3
Rated wind speed (ms^{-1})	10.3
Cutout wind speed (ms^{-1})	22
Swept area (m^2)	5325
Number of blades	3
Hub height (m)	90
Power control	Active blade pitch control
Generator	PMDD synchronous generator
Rated voltage (V)	690
Yaw system	3 induction motors with hydraulic brakes
Tower	Tubular steel tower
Foundation	Flat foundation
Converter	Full-power convert modular system
Control system	Microprocessor controlled with remote monitoring

Table 1.
Technical specifications of the Goldwind 1.5 MW PMDD WT [17].

$$P_{out} = \begin{cases} 0, \quad V_1 < 3\ \text{ms}^{-1} \text{ or } V_1 > 22\ \text{ms}^{-1} \\ 0.0184V_1^6 - 1.3507V_1^5 + 30.8477V_1^4 - 320.8737V_1^3 + 1699.2172V_1^2 \\ \qquad - 4366.5508V_1 + 4287.3549\ \text{kW}, \quad 3\ \text{ms}^{-1} \le V_1 \le 10.3\ \text{ms}^{-1} \\ 1500\ \text{kW}, \quad 10.3\ \text{ms}^{-1} < V_1 \le 22\ \text{ms}^{-1} \end{cases} \tag{20}$$

4. Results and discussion

With the available meteorological data and the selected WT properties, assumptions are made for calculating the energy and exergy efficiencies: (1) the air pressure, temperature, and humidity are not significantly changed in the swept area of the WT. Thus, the surface pressure data, 10-m air temperature, and 10-m specific humidity obtained from the MERRA-2 data are directly used for the thermodynamic analyses. (2) Due to the wind shear effect in the atmospheric boundary layer, the normal wind profile model with a power law exponent of 0.2 is used to convert the 10-m horizontal wind speed to the hub-height (90 m) wind speed according to the IEC standard [20]. It takes about 0.5 hour to convert six channels (five meteorological channels and one channel for time stamps) from the MERRA-2 netCDF4 data to Matlab data and then to calculate 18 years' hourly energy and exergy efficiencies using the developed Matlab scripts. Results and discussion are elaborated in three aspects: (1) WT efficiency variation in time domain, (2) meteorological variables impact on the efficiencies, and (3) uncertainty of meteorological variables represented by the best-fit distributions.

4.1 Variation of energy and exergy efficiencies in time domain

The energy and exergy efficiencies of the Goldwind WT are calculated by Eqs. (18) and (19), respectively, using the Ithaca meteorological data (wind speed, pressure, temperature, and humidity) retrieved from the MERRA-2 data set. As demonstrated in **Figure 4**, the variation of energy and exergy efficiencies is more closely following the variation of wind speed comparing with the other three meteorological variables, as wind power is proportional to the cubic of wind speed. Both efficiencies become 0 when the wind speed is less than the cut-in wind speed due to the WT being in idling status at the very low wind speed. As the WT is stopped when wind speed is larger than the cutout wind speed, the efficiencies are also equal to 0. In addition, the energy efficiency present a higher magnitude than that of exergy efficiency, which is consistent with the theoretical derivations (Eqs. (18) and (19)) and previous findings (e.g., [6, 7]). The difference between the two efficiencies is due to exergy destruction caused by irreversibility [7]. The concurrent low temperature and humidity ratio also demonstrate the cold and dry weather in winter of Ithaca.

Figure 5 shows the mean and standard deviation of energy and exergy efficiencies in different years and months. Annual means of energy and exergy efficiencies are smaller than the corresponding standard deviations, which indicates a significant variation of WT efficiency performance in 1 year as also demonstrated in **Figure 4(e)**. Neither energy efficiency nor exergy efficiency exhibits clear trend from 2000 to 2017, even though relatively small and large means are observed in 2005 and 2014, respectively (**Figure 5(a)**). However, both mean and standard deviation of energy and exergy efficiencies present smaller values in summer than those in winter (**Figure 5(b)**). This seasonal change of efficiencies is likely related to the fact that high sustained wind speeds with strong variation more frequently occur in winter than in summer at the Ithaca area.

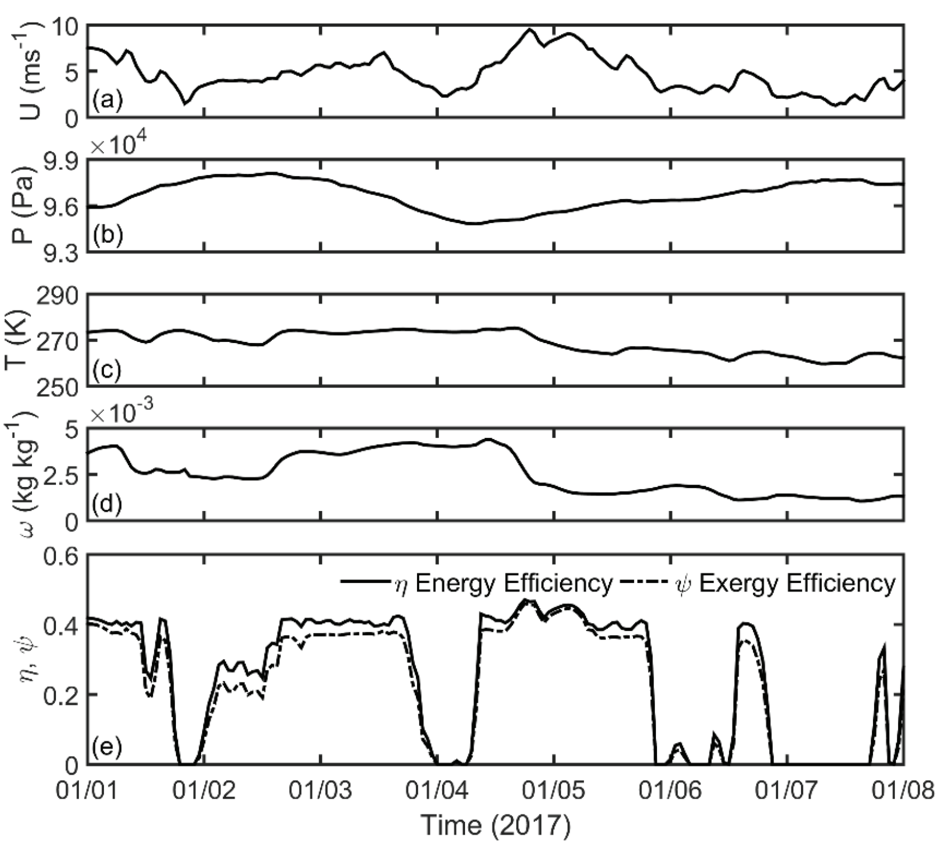

Figure 4.
Time series of hourly concurrent (a) wind speed U, (b) pressure P, (c) temperature T, (d) humidity ratio ω, and (e) energy efficiency η and exergy efficiency ψ during January 1–7, 2017.

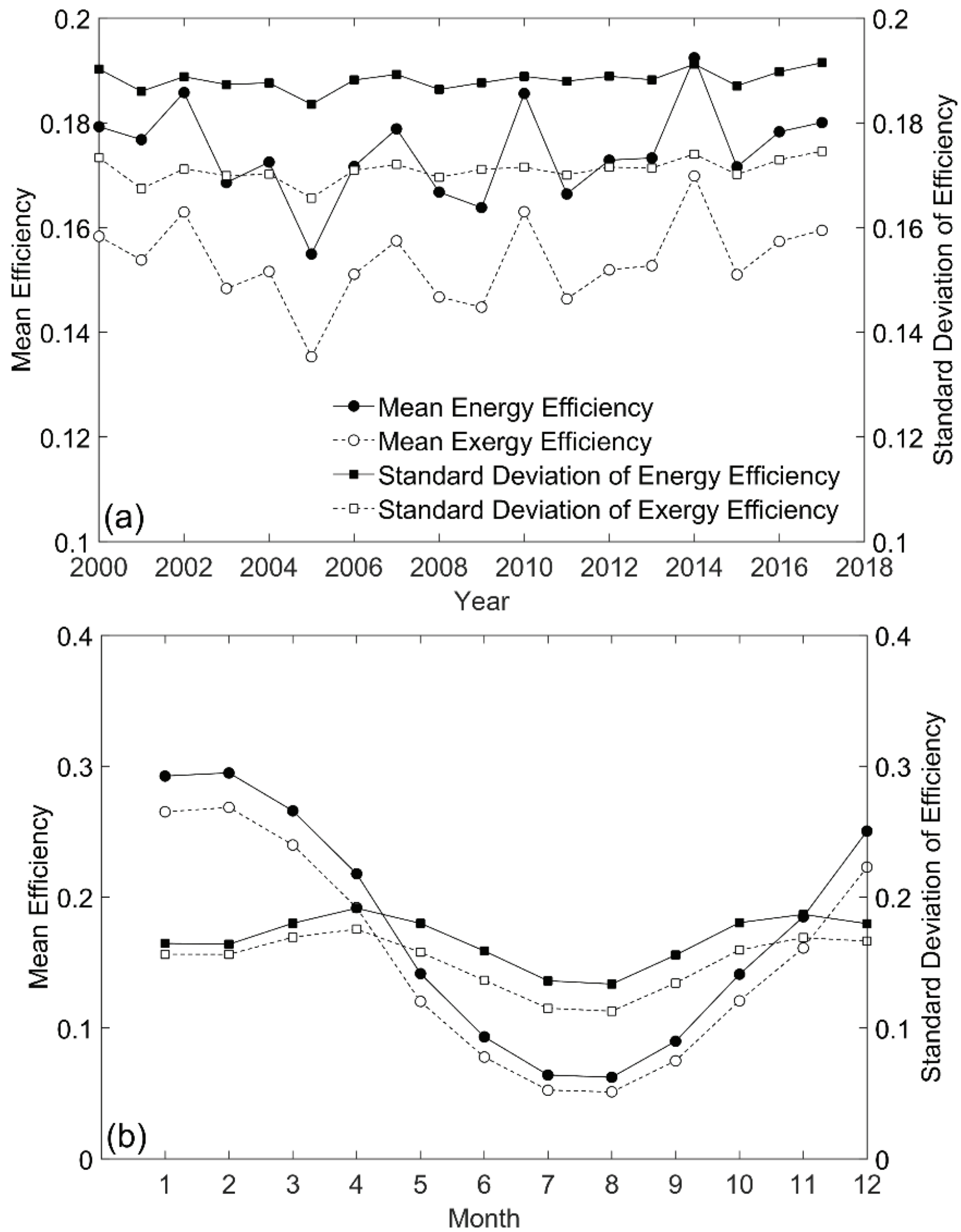

Figure 5.
Mean and standard deviation of energy and exergy efficiencies in different (a) years and (b) months.

4.2 Impact of meteorological variables on energy and exergy efficiencies

Relationships between the WT efficiencies and meteorological variables offer the trends of WT efficiency performance as meteorological variables change. **Figure 6** shows the scatter diagrams of energy and exergy efficiencies versus the four meteorological variables (wind speed, pressure, temperature, and humidity ratio), as well as their relationships represented by different metrics. A bimodal relationship between the efficiencies and wind speed is observed due to the nonlinearity of the efficiency function with respect to wind speed (**Figure 6(a)**). The mean curves in **Figure 6(a)** show that the maximum means of energy and exergy efficiencies are 46.2% and 45.2%, respectively, at the high peaks when the wind speed is equal to $\sim$9.2 ms^{-1}, while the counterparts at the low peaks are 42.7% and 38.1% when the wind speed is equal to $\sim$5 ms^{-1}. Despite the large variation, the efficiencies are linearly proportional to temperature and to the inverse of pressure (**Figure 6(b** and **c)**). **Figure 6(d)** shows that both the energy and exergy

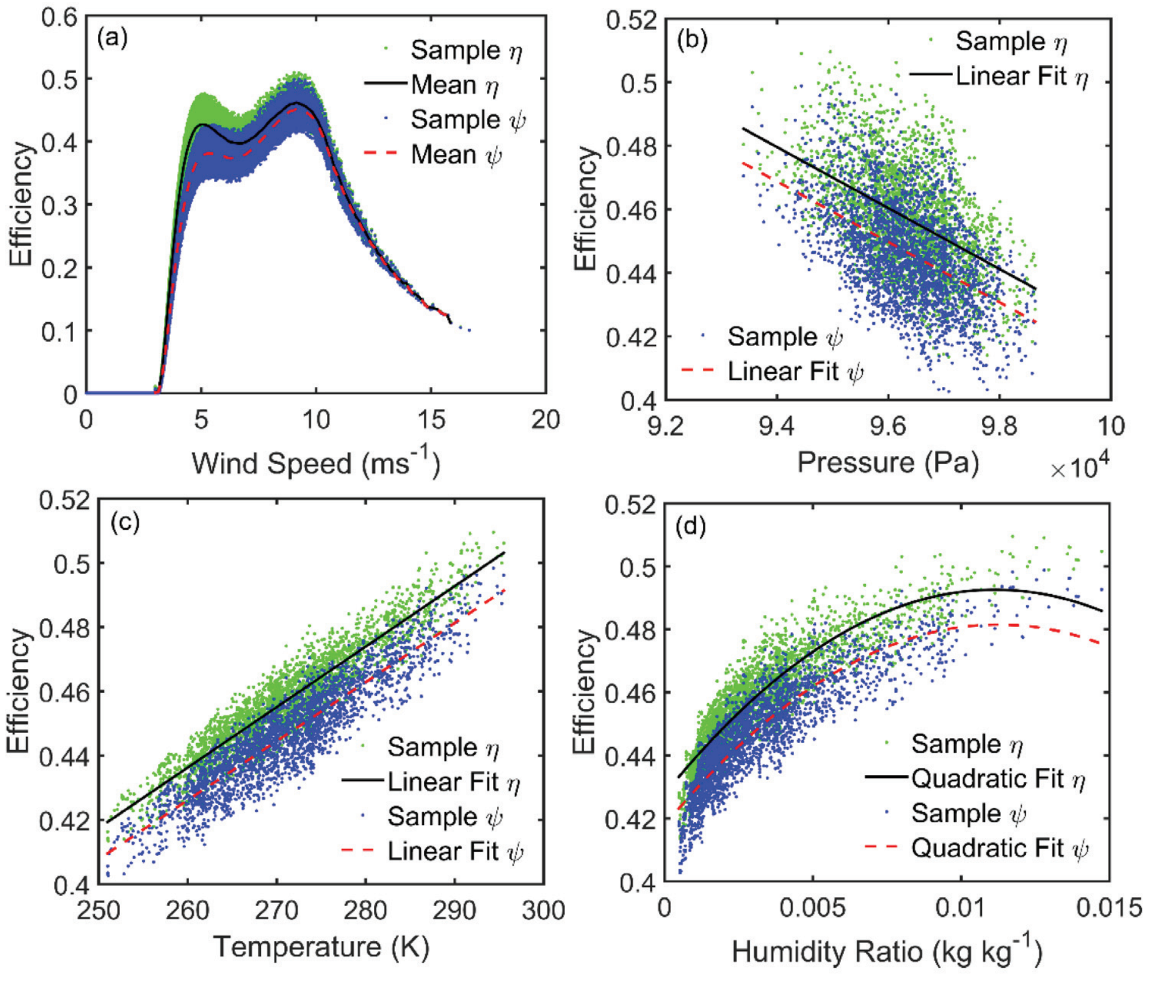

Figure 6.
Relationships between the WT efficiency (energy efficiency η and exergy efficiency ψ) and meteorological variables including (a) wind speed, (b) pressure, (c) temperature, and (d) humidity ratio. All 18-year samples of hourly η and ψ versus wind speed are used in (a). For demonstration, samples in (b), (c), and (d) are conditionally sampled under a wind speed bin of 9 ms^{-1} (bin width 1 ms^{-1}).

efficiencies are increased by ∼8% as the humidity ratio is increased from 0.001 to 0.015 kg kg^{-1}, which indicates humidity plays an important role in affecting the WT efficiency performance.

4.3 Uncertainties of meteorological variables and WT efficiencies

Variation of meteorological variables could have significant impact on not only energy and exergy efficiencies as explained in Section 4.2 but also many other aspects, e.g., fatigue and structural reliability. Although Weibull distribution is often used to represent the uncertainty of mean wind speed in long term [21, 22], few previous studies have sought to address which parent distribution best represents other meteorological variables, e.g., pressure, temperature, and humidity for WT analyses. This is an important omission since these meteorological variables could have critical roles, but maybe indirectly, to WT performance. For example, high air humidity, low wind speed, and temperature above ∼10°C are preferred by insects that will increasingly foul the leading edges of WT blades and contaminate the blade surface eventually decreasing the aerodynamic performance [23]. Since both the wind speed and pressure considered herein are zero bounded, four positive-valued distribution types (Weibull, lognormal, gamma, and log-logistic; see **Figure 7(a** and **b)**) are fitted to wind speed and pressure using maximum likelihood estimation (MLE). Due to the clear two-peak histograms observed for

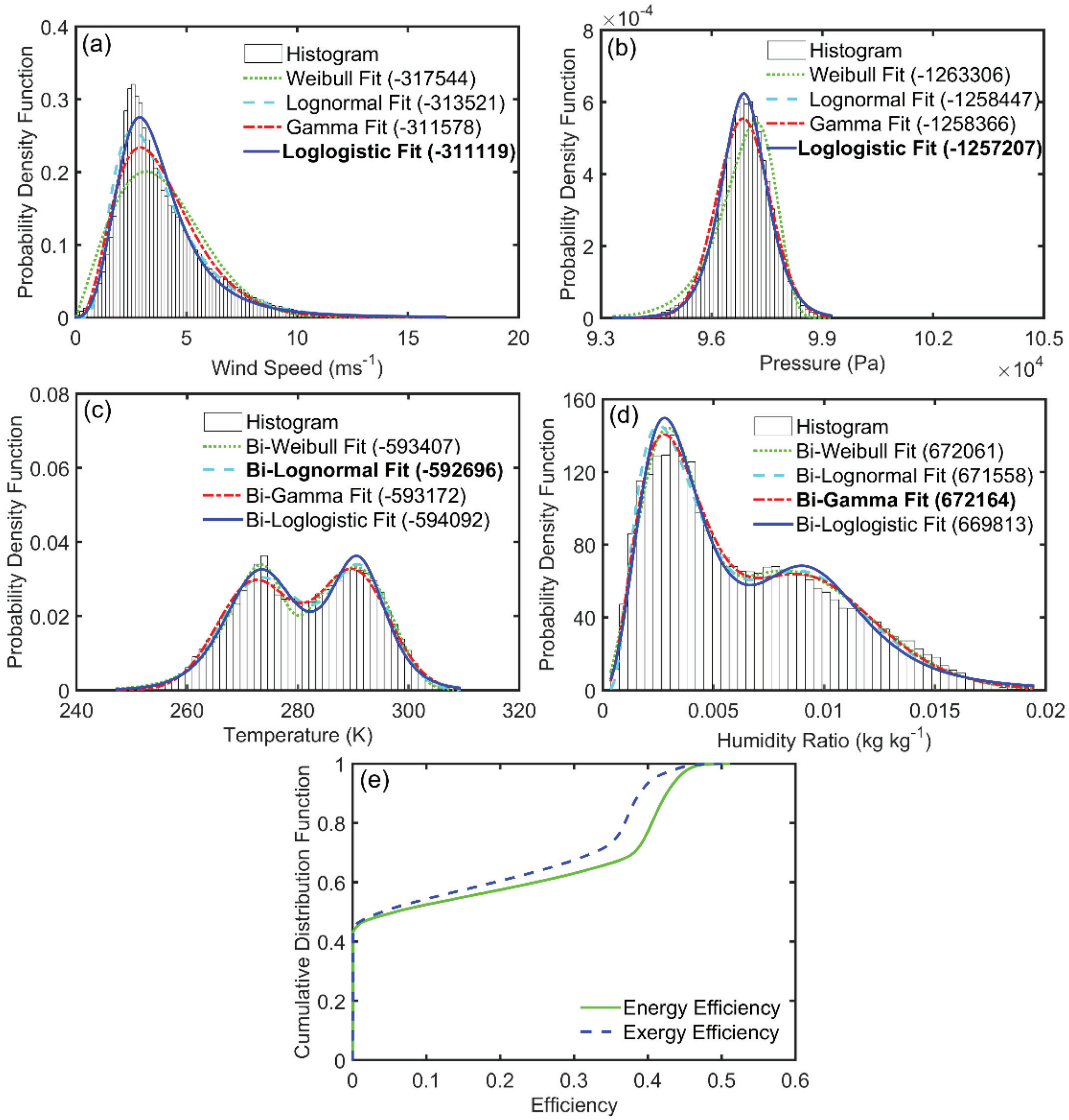

Figure 7.
Histograms and distribution fits for (a) wind speed, (b) pressure, (c) temperature, and (d) humidity ratio; and (e) empirical cumulative distribution function of energy and exergy efficiencies. In the legends, the log-likelihood values are in parentheses. The bolded distribution with the largest log-likelihood value is selected as the best-fit distribution and is summarized in **Table 2**. *Recall all 18-year samples of hourly meteorological data, and the calculated WT energy and exergy efficiencies are used in* **Figure 7**.

temperature and humidity ratio, four positive-valued bimodal distributions (bi-Weibull, bi-lognormal, bi-gamma, and bi-log-logistic) are fitted to temperature and humidity ratio (**Figure 7(c** and **d)**). The probability density function (PDF) of a bimodal distribution consists of two PDFs with the same distributional type, which is expressed as

$$f(x|w, a_1, b_1, a_2, b_2) = wf(x|a_1, b_1) + (1-w)f(x|a_2, b_2) \tag{21}$$

where x represents a meteorological variable; (a_1, b_1) and (a_2, b_2) are the parameters of the first and the second constituent PDFs, respectively; and w is the weight for the constituent distributions $f(x|a_1, b_1)$ in the bimodal distribution form. The candidate distribution with the largest log-likelihood value is selected as the best-fit distribution [24].

Figure 7 and **Table 2** summarize the distributional fits for the four meteorological variables. It is found that the log-logistic distribution is best fit for wind speed

Meteorological variables	Best-fit distribution type	Probability density function
Wind speed (ms^{-1})	Log-logistic distribution	$f(x\|a,b) = \frac{1}{b}\frac{1}{x}\frac{\exp(z)}{[1+\exp(z)]^2}$, where $z = \frac{\ln(x)-a}{b}$, $a = 1.2307$, $b = 0.2887$
Pressure (Pa)	Log-logistic distribution	$f(x\|a,b) = \frac{1}{b}\frac{1}{x}\frac{\exp(z)}{[1+\exp(z)]^2}$, where $z = \frac{\ln(x)-a}{b}$, $a = 11.4812$, $b = 0.0041$
Temperature (K)	Bi-lognormal distribution	$f(x\|w,a_1,b_1,a_2,b_2) = w\frac{1}{xb_1\sqrt{2\pi}}\exp\left[\frac{-(\ln x - a_1)^2}{2b_1^2}\right] + (1-w)\frac{1}{xb_2\sqrt{2\pi}}\exp\left[\frac{-(\ln x - a_2)^2}{2b_2^2}\right]$, $w = 0.5824$, $a_1 = 5.6125$, $b_1 = 0.0280$, $a_2 = 5.6752$, $b_2 = 0.0182$
Humidity ratio ($kg\ kg^{-1}$)	Bi-gamma distribution	$f(x\|w,a_1,b_1,a_2,b_2) = w\frac{1}{b_1^{a_1}\Gamma(a_1)}x^{a_1-1}\exp\left(-\frac{x}{b_1}\right) + (1-w)\frac{1}{b_2^{a_2}\Gamma(a_2)}x^{a_2-1}\exp\left(-\frac{x}{b_2}\right)$, $w = 0.5970$, $a_1 = 3.8190$, $b_1 = 0.0010$, $a_2 = 12.6287$, $b_2 = 0.0008$

*The distributional fits and empirical histograms are shown in **Figure 7**.*

Table 2.
The best-fit distribution form and distribution parameters for the four meteorological variables.

and pressure (**Figure** 7(**a** and **b**)), despite the commonly used Weibull distribution for mean wind speed. The bi-lognormal and bi-gamma distributions are best fit for temperature and humidity ratio, respectively. The existence of bimodal shape of the distributions of temperature is likely related to the very distinguished high and low temperature corresponding to the summer and winter seasons, respectively, in Ithaca. The same reason explains the bimodal shape for humidity. The obtained specific distributions for the meteorological parameters, provided in **Table 2**, are readily applicable for WT performance analyses, i.e., fatigue, structure, aerodynamics, and thermodynamics, in moderately complex terrain of the northeastern United States. **Figure 7(e)** presents the empirical cumulative distribution function (CDF) of energy and exergy efficiencies calculated herein. Due to the large amount of 0 energy and exergy efficiencies when wind speed is below the cut-in wind speed, the CDF curves show that there is a probability of ~43% that the efficiencies are equal to 0. The largest discrepancy between CDF of energy and exergy efficiencies occurs at efficiencies equal to 0.4. The presented CDF could be used to evaluate the reliability of wind power performance considering realistic meteorological uncertainty.

5. Conclusions

This chapter presents methods and results for thermodynamic analysis of wind energy systems considering four types of meteorological variables, i.e., wind speed, pressure, temperature, and humidity. An improved understanding of WT efficiencies is critically important and necessary before launching any wind projects. The evaluation of WT efficiencies considering thermodynamics, conducted here for an

1.5 MW WT (Goldwind GW82/1500) potentially deployed at Ithaca, New York, is beneficial to WT design, siting, and operation in moderately complex terrain in the northeastern United States. The key concluding remarks are the following:

- The chapter offers the fundamental derivations of energy and exergy efficiencies of WTs considering wind speed, pressure, temperature, and humidity, which lay a foundation for the thermodynamic analysis of wind energy systems.

- The WT energy efficiency presents higher magnitude than exergy efficiency based on the theoretical derivation and the calculated time series of efficiencies. There is no clear trend of annual variations of mean and standard deviation of both energy and exergy efficiencies. However, a clear seasonal change is found that energy and exergy efficiencies studied herein have smaller values in summer than those in winter.

- Although wind speed has a dominating influence, other meteorological variables (i.e., pressure, temperature, and humidity) do have a considerable impact on the WT efficiency performance. The WT efficiencies are linearly associated with pressure and temperature, while it has highly nonlinear relationships with wind speed and humidity ratio.

- Log-logistic distributions are most appropriate for the wind speed and pressure data retrieved from the MERRA-2 data set at Ithaca, New York. A bi-lognormal distribution and a bi-gamma distribution are most appropriate for the temperature and humidity ratio, respectively. The obtained PDFs of meteorological variables and CDFs of energy and exergy efficiencies could be beneficial for evaluating the reliability of wind power performance considering realistic meteorological uncertainty in the northeastern United States.

Naturally the specific findings are based on reanalysis meteorological data and the assumed WT deployment; the methodologies of thermodynamic analysis presented here are applicable for real measured meteorological data and recorded WT performance somewhere else if available. In addition, although the thermodynamic analysis of wind energy systems in this chapter focuses on energy and exergy efficiencies, other variables, e.g., dynamic response, fatigue damage, structural deformation, etc., of the PMDD WT are also potentially affected by the meteorological variables, which could be investigated in the future.

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Conflict of interest

The authors certify that this work has no conflict of interest with any organization or entity in the subject matter or materials discussed in this chapter.

Nomenclature

A	rotor swept area
C_P	power coefficient
c_p, $c_{p,a}$, $c_{p,v}$	specific heat of flow, specific heat of air, specific heat of water vapor
E_k	kinetic energy
Ex	exergy
Ex_{ki}	kinetic exergy
Ex_{po}	potential exergy
Ex_{ph}	physical exergy
Ex_{ch}	chemical exergy
f	PDF of meteorological variables
m	mass
P	wind power/wind pressure
P_0, P_1, P_2, P_{ave}, p	reference pressure, inlet pressure, outlet pressure, average pressure, and wind pressure in humid air, respectively
PS	surface pressure retrieved from the MERRA-2 data set
QV10M	10-m specific humidity retrieved from the MERRA-2 data set
R_a, R_v	gas constant and water vapor constant, respectively
T_0, T_1, T_2, T_{ave}	reference temperature, inlet temperature, outlet temperature, and average temperature, respectively
T10M	10-m air temperature retrieved from the MERRA-2 data set
U	10-m horizontal wind speed
U10M	10-m eastward wind speed retrieved from the MERRA-2 data set
V10M	10-m northward wind speed retrieved from the MERRA-2 data set
V	wind speed
W_{wind}	total input wind energy
η	energy efficiency
ψ	exergy efficiency
ρ	air density [kgm^{-3}]
ω_0/ω	humidity ratio of air at the reference state/at the current state
MERRA-2	Modern-Era Retrospective Analysis for Research and Applications, Version 2
NASA	National Aeronautics and Space Administration
PMDD	permanent magnet direct-drive
WTs/WT	wind turbines/wind turbine

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References

[1] Global Wind Energy Council. Global Wind Statistics. 2016. Available from: http://www.gwec.net/wp-content/uploads/vip/GWEC_PRstats2016_EN_WEB.pdf [Accessed: June 1, 2018]

[2] U.S. Department of Energy. 20% Wind Energy by 2030–Increasing Wind Energy's Contribution to U.S. Electricity Supply. U.S. Department of Energy, Office of Scientific and Technical Information: Oak Ridge, TN; 2008

[3] Baskut O, Ozgener O, Ozgener L. Effects of meteorological variables on exergetic efficiency of wind turbine power plants. Renewable and Sustainable Energy Reviews. 2010;**14**: 3237-3241

[4] Krakow KI. Exergy analysis: Dead-state definition. ASHRAE Transactions. 1991;**97**:328-336

[5] Ozgener O, Ozgener L. Exergy and reliability analysis of wind turbine systems: A case study. Renewable and Sustainable Energy Reviews. 2007;**11**: 1811-1826

[6] Şahin AD, Dincer I, Rosen MA. Thermodynamic analysis of wind energy. International Journal of Energy Research. 2006;**30**:553-566

[7] Redha AM, Dincer I, Gadalla M. Thermodynamic performance assessment of wind energy systems: An application. Energy. 2011;**36**:4002-4010

[8] Lanchester FW. A contribution to the theory of propulsion and the screw propeller. Journal of the American Society for Naval Engineers. 1915;**27**: 509-510

[9] Betz A. Schraubenpropeller mit geringstem Energieverlust. Gottinger Nachrichten. 1919:193-213

[10] Burton T, Jenkins N, Sharpe D, Bossanyi E. Aerodynamics of horizontal axis wind turbine. In: Burton T, Jenkins N, Sharpe D, Bossanyi E, editors. Wind Energy Handbook. 2nd ed. John Wiley & Sons; 2011. pp. 39-136

[11] Moriarty PJ, Hansen AC. AeroDyn Theory Manual: National Renewable Energy Laboratory Golden. Colorado: USA; 2005. pp. 2-10

[12] Hansen MO. Aerodynamics of Wind Turbines. London: Routledge; 2015. pp. 63-77

[13] Rant Z. Exergie, ein neues wort fur 'technische arbeitsfaehigkeit'(exergy, a new word for technical availability). Forschung auf dem Gebiet des Ingenieurwesens A. 1956;**22**:36-37

[14] Wepfer W. Proper evaluation of available energy for HVAC. ASHRAE Transactions. 1979;**85**:214-230

[15] Dincer I, Sahin AZ. A new model for thermodynamic analysis of a drying process. International Journal of Heat and Mass Transfer. 2004;**47**:645-652

[16] Pope K, Dincer I, Naterer GF. Energy and exergy efficiency comparison of horizontal and vertical axis wind turbines. Renewable Energy. 2010;**35**:2102-2113

[17] Goldwind. 1.5 MW Permanent Magnet Direct-Drive (PMDD) Wind Turbine. Available from: https://www.goldwindamericas.com/15-mw-pmdd [Accessed: August 15, 2018]

[18] Gelaro R, McCarty W, Suárez MJ, Todling R, Molod A, Takacs L, et al. The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). Journal of Climate. 2017; **30**:5419-5454

[19] NASA. MERRA-2: File specification. Greenbelt, Maryland: Global Modeling and Assimilation Office, Earth Sciences Division, NASA Goddard Space Flight Center; 2016

[20] International Electrotechnical Commission. Wind turbines—part I: Design requirements. IEC standard 61400–1. 3rd ed; 2005

[21] Hu W, Choi K, Zhupanska O, Buchholz JH. Integrating variable wind load, aerodynamic, and structural analyses towards accurate fatigue life prediction in composite wind turbine blades. Structural and Multidisciplinary Optimization. 2016;**53**:375-394

[22] Hu W, Choi K, Cho H. Reliability-based design optimization of wind turbine blades for fatigue life under dynamic wind load uncertainty. Structural and Multidisciplinary Optimization. 2016;**54**:953-970

[23] Dalili N, Edrisy A, Carriveau R. A review of surface engineering issues critical to wind turbine performance. Renewable and Sustainable Energy Reviews. 2009;**13**:428-438

[24] Hogg RV, Craig AT, McKean JW. Introduction to Mathematical Statistics. 6th ed. Upper Saddle River, New Jersey: Pearson Prentice Hall; 2005. pp. 311-317