

Response to Reviewer 1 comments:

General comments: This manuscript quantitatively (statistically) analyzes the influence of different stability classes and turbulence regimes (obtained through the bulk Richardson number, turbulence intensity, etc.) on the wind turbine nacelle transfer functions. The authors analyzed data from one wind turbine and two sets of data from an upwind position from the wind turbine (mast and wind scanner data). The paper is well written and within the scope of Wind Energy Science.

The authors thank the reviewer for their kind comments.

The manuscript addresses an interesting subject that might have both practical and scientific applications in wind energy sector. However, the manuscript requires a number of clarifications throughout the text. Most of my questions are regarding the methodology and data, but I don't ask additional analyses to be conducted at this point. Namely, it is not clear how the authors calculated some of the atmospheric quantities (e.g. bulk Richardson number). Interpretation of the results could also be better. Please see my specific comments below.

I recommend minor to moderate revisions for this manuscript before it can meet the publishing standards of Wind Energy Science.

Specific comments:

1. Anemometer and wind vane are not visible in Figure 1. The purpose of this figure (according to the text) is to show these instruments, but they are not visible. I advise the authors to add Figure 1b in which the anemometer and wind vane will be zoomed in (i.e. visible). The current Figure 1 can be Figure 1a.

We thank the reviewer for pointing this out, and we have found another picture in which the nacelle anemometer is more visible. We have replaced the current Figure 1 with the following:



Figure 1. GE-1.5/77 sle turbine at the National Wind Technology Center. Photo credit: Dennis Schroeder/NREL (image gallery number 29611).

2. The last paragraph in Introduction contains too many “as well as” phrases. Please reformulate these sentences in order to increase the readability of the text.

We have changed to the following (changes are represented by the bold text):

“In this study, we quantify the effect of NTF-corrected nacelle anemometer measurements on the AEP and investigate the influence of different atmospheric stability and turbulence regimes on these NTFs. In Sect. 2, we briefly summarize our data set, which includes upwind **and** nacelle-based measurements, **as well as** our data analysis methods which include filtering based on turbine operation, and definitions of the stability and turbulence regimes. We present results of AEP calculations **together with results of** separate NTFs for different stability and turbulence regimes in Sect. 3. **In** Sect. 4 we summarize conclusions about the effect of the NTF on the AEP **in addition to** the effects of atmospheric stability and inflow turbulence on the NTFs.”

3. The last paragraph in Sect. 2.1 starts with “Further”. I would suggest starting it with “Lastly.”

We thank the reviewer for the suggestion and we have changed to “Lastly.”

4. Line 112. What do you mean by “simple, built-in transfer function” and how would this function modify the measured data? Please clarify as this might have importance for your results.

We agree that this statement is not clear, and have revised the paragraph as such:

“Lastly, the nacelle-reported wind speeds used in this analysis have been subjected to a simple, linear regression transfer function before the retrieval from the SCADA system of the DOE GE 1.5 sle turbine. This linear regression function, built into the SCADA system by the turbine manufacturer, effectively translates the raw signal from the cup anemometer to wind speed and is not unlike a transfer function provided by an anemometer manufacturer. We see the uncertainty of this built-in transfer function as an advantage to our analysis as a typical wind plant operator would only have access to similar data.”

5. Lines 120-125. You estimated Weibull distribution parameters from the 2.5 months of data and then assumed that these parameters are representative for the whole year; am I right? Assuming that, you calculated the annual energy production. Can you please compare these calculated parameters against the parameters obtained from the data that actually cover one full year at that site, so we can see the uncertainty of your assumption and analysis?

Yes, we calculated Weibull parameters based on the 2.5 months of hub-height wind speed data, filtered by wind direction sector, wind speed, and curtailment. These Weibull parameters were then used to calculate sample wind distributions for the AEP estimates. We then extrapolate the AEP estimates to one year so the AEP values are more characteristic of typical AEP numbers at sites suitable for wind development. We have clarified this reasoning and have added the following in bold to the end of Sect. 2.2:

“A sample wind distribution using Weibull distribution parameters representative of the data set (scale parameter: $\lambda = 10.04 \text{ m s}^{-1}$, shape parameter: $k = 2.63$, figure not shown) is used in these calculations as suggested by IEC 61400 12-1 (2015) for a site-specific AEP. **We note that these parameters, based on 2.5 months in the “high” wind season at this site, are not actually representative of the entire year. However, as noted in other analyses of this test site (Clifton and Lundquist, 2012; Clifton et al., 2013), this site would not be chosen for wind development given the long summer season with little or no wind. We emphasize that this approach is not meant to suggest actual AEPs for this site, but to explore the sensitivity of AEP calculations at sites reasonable for wind development. ”**

Because of the additional text, the following references have been added:

Clifton,A.and Lundquist,J.K.:Data clustering reveals climate impacts on local phenomena, J. Appl. Meteorol. Clim., 51, 1547– 1557, doi:10.1175/JAMC-D-11-0227.1, 2012.

Clifton, A., Schreck, S., Scott, G., and Lundquist, J. K.: Turbine inflow characterization at the National Wind Technology Center, J. Sol. Energ.-T. ASME, 135, 031017, doi:10.1115/1.4024068, 2013.

6. Line 130. You are talking about near-surface flux measurements at 15 m and humidity measurements interpolated to 15m, but in Sect. 2.1 (Meteorological and turbine data) you didn't mention any flux and/or relative humidity measurements. How/from where did you obtain this data? Also, what kind of interpolation did you apply to get relative humidity at 15 m?

A 3-D sonic anemometer mounted at 15 m on the tower as described in Sect. 2.1 provides measurements of the vertical component of the wind as well as sonic temperature. To make this clear, we have added the following in bold:

“On the met tower, cup anemometers placed at 3, 10, 30, 38, 55, 80, 87, 105, 122, and 130 m measure wind speed and vanes placed at 3, 10, 38, 87, and 122 m measure wind direction. Three-dimensional (3-D) sonic anemometers placed at 15, 41, 61, 74, 100, and 119 m **measure all three components of the wind as well as sonic temperature which are used to calculate momentum and heat fluxes.**”

As for humidity measurements, we have added the following in bold:

“Barometric pressure and precipitation amounts are measured at 3 m, temperature is measured at 3, 38, and 87 m **and dew point temperature is measured at 3, 38, 87, and 122 m.**”

As well as:

Using near-surface flux measurements at 15 m (within the surface layer) as well as surface temperature and humidity measurements **linearly** interpolated to 15 m, we calculate 30-min values of L to estimate the height at which the buoyant production of turbulence dominates the mechanical production of turbulence.”

We have also added the following table to make it easier to visualize the tower configuration:

Instrument	Mounting heights (m)
Cup anemometer	3, 10, 30, 38, 55, 80, 87, 105, 122, 130
Wind vane	3, 10, 38, 87, 122
3-D sonic anemometer	15, 41, 61, 74, 100, 119
Barometric pressure sensor	3
Precipitation sensor	3
Temperature sensor	3, 38, 87
Dew point temperature sensor	3, 38, 87, 122

7. Similar to the previous comment, how did you calculate the virtual temperatures (absolute and potential) in order to obtain the bulk Richardson number values? That is, did you

measure/calculate specific humidity or the mixing ration or the wet-bulb temperature? Please clarify.

We thank the reviewer for pointing out that we did not explain in full our Bulk Richardson number calculations. We have added the following equation and reference to Stull (1988):

$$R_B = \frac{g\Delta T\Delta z}{\bar{T}\Delta U^2}$$

where g is the gravitational constant, ΔT is the change in temperature across Δz , \bar{T} is the mean temperature across Δz , and ΔU is the change in horizontal wind speed across Δz . Humidity is not considered in this formulation of the bulk Richardson number.

8. I suggest you merge the last paragraph in Sect. 2.3 (Line 149) with the previous paragraph.

We thank the reviewer for this suggestion and have merged the last paragraph in Sect. 2.3 with the previous paragraph.

9. The caption for Fig. 3 can be simplified. You can say it's the same as Fig.2, but using second-order polynomial fit.

We have simplified the caption for Fig. 3 from:

“Comparison of upwind wind speeds with nacelle anemometer wind speeds. (a) Scatter is the upwind tower 80-m wind speed versus nacelle wind speed. Red line is the second-order polynomial fit and empirical transfer function between the tower 80-m observations and the nacelle-mounted anemometer observations; gray line is the fifth-order polynomial fit. Dashed line is 1:1. (b) Average deviation in the second-order polynomial NTF-corrected nacelle-mounted anemometer wind speed from tower 80-m wind speed versus tower 80-m wind speed is shown. Dashed line indicates a 0 m s^{-1} change. Includes data filtered for tower 80-m wind speeds between 3.5 and 25.0 m s^{-1} , 87-m wind directions between 235° and 315° , and for normal turbine operation.”

to:

“Comparison of upwind wind speeds with nacelle anemometer wind speeds. The red line in (a) is the second-order polynomial fit and empirical transfer function between the tower 80-m observations and the nacelle-mounted anemometer observations and the gray line in (a) is the fifth-order polynomial fit. (b) Average deviation in the second-order polynomial NTF-corrected nacelle-mounted anemometer wind speed from tower 80-m wind speed versus tower 80-m wind speed is shown.”

10. Line 220. If the nacelle anemometer underestimates the upwind winds, how is it possible that AEP based on the data from this anemometer is higher than using the upwind data? You provided an explanation, but I do not understand it. Please clarify.

If the nacelle anemometer underestimates the wind speed, the power curve is essentially shifted to the left. This is because the turbine appears to produce more power at lower wind speeds. For example, if the turbine is producing 400 kW, the corresponding wind speed according to the manufacturer power curve is 7 m s^{-1} , however, the anemometer may be reading 6 m s^{-1} , so it seems like the turbine is producing more power at lower wind speeds, moving the power curve over and increasing the AEP. Additional text indicated by the bold font has been added to the following to make this more clear:

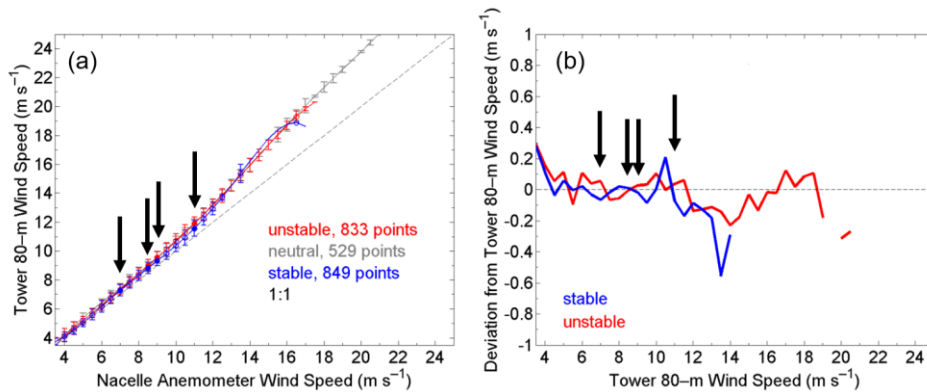
“This overestimation of AEP is expected as the nacelle anemometer consistently underestimates the upwind wind speed, which leads to the misrepresentation of higher power output at lower wind speeds, **effectively shifting the entire power curve to the left**, and therefore **leading to a higher AEP**.”

11. The bottom row in Table 2 says “% difference from tower winds.” If that’s the name you choose, then the values are not accurately corresponding to that name. It indicates that AEP_{upwind} is 100% different from itself. Please simplify/rename and clarify.

Thank you for pointing this out, and we have corrected the label to “% of tower winds”.

12. The size of error bars and circles in Fig. 6 are not (very well) visible at 100% zoom. Please try to make these figures bigger as the interested reader is not able to actually estimate the errors from this graph.

Based on your comment, we have decided to split this figure up to enlarge the individual panels. So we have taken Fig. 6 and shown (a) and (d) as one figure, (b) and (e) as another, and (c) and (f) as a third figure. This way the reader will be able to more clearly see bins where regimes are statistically distinct from one another. Example:



13. The size and scaling of Fig 6. (bars, lines, points, etc.) are inadequate to develop the discussion that starts at Line 235 and ends at Line 247. Looking at Fig. 6a, I am not able to see

any difference between the stable and unstable conditions and the arrows don't help much. Some discrepancies between the lines are visible at around 400% zoom.

Our answer to the above comment will make it easier for the reader to see these statistical differences. In addition, we have moved the discussion starting at line 243 to a new section after showing turbulence results in an additional section 3.5 titled "Discussion", in which we have expanded to include more explanation on a physical reasoning behind these results.

14. Line 244. You believe that unstable conditions amplify the blockage effect and you carefully used the words "we speculate", "might be", "could be", etc., which I like. However, can you provide some physical reasoning behind this speculation? Namely, why would the interaction between turbulent eddies and turbine augment the blockage effect and not diminish it? Your results show an augmentation (not very visible in Fig. 6 as it is now, but nevertheless show it), but what is the physics behind it?

We have added the following in bold and moved to a new discussion section 3.5:

"We speculate that at wind speeds below rated, mixing in the atmosphere during more convective conditions, as well as the turbine interaction with these turbulent eddies, may result in additional motion that exaggerates blockage effects by the rotor and nacelle and causes underestimation by the nacelle-mounted anemometer. We suspect that rotor response is lagging in more convective and turbulent conditions as the turbine responds more quickly to drops in wind speed. Therefore, during more turbulent conditions, it is possible that lower rotor efficiency influences flow induction and thus the wind speeds measured on the back of the nacelle. If turbine and rotor efficiencies are lower during periods with convective and more turbulent conditions, it may be surmised then, that less momentum passes through the rotor and along the nacelle. In addition, power curve results from the same dataset discussed here (St. Martin et al., 2016) show that during less stable and more turbulent conditions at wind speeds within the ramp-up region of the power curve, more power is produced than during periods of more stable and less turbulent conditions. Power production will also affect the flow induction (Frandsen et al., 2009) and thus the wind speed directly behind the rotor disk: if more energy is extracted by the rotor, the nacelle-mounted anemometer will likely measure lower winds."

15. References. Sometimes you used abbreviations for journal names and sometimes full names. Please be consistent.

We thank the reviewer for pointing this out and have made sure we use journal abbreviations consistently throughout our reference list.

Response to Reviewer 2 comments:

General comments: This paper demonstrates a nacelle transfer function for "decontaminating" wind measurements mounted on the nacelle of an operating wind turbine. They also explore the impacts of thermal stability and turbulence regimes. The paper is fairly well written, but the Introduction and Data and Methods sections require some clarification, and would benefit from concision.

I am not entirely convinced of the practical application of this technique. Your technique requires contemporaneous measurements from an "upwind" tower, but in practice such measurements often are not available. You even acknowledge this in the introduction: "However, it is not feasible to erect "site calibration" met towers after the turbine has been erected. And, even if "site calibration" is not required because a site is in simple terrain, tower erection is time consuming and unrealistic to complete for every turbine at a given park." Perhaps I am missing important details, but I do not understand how this technique could be applied in the absence of an upwind measurement(s). And those measurements need to be representative of the site. In regions such as Europe, these kind measurements are exceeding rare at operating projects, and it is not clear how applicable this approach is in practice.

As stated in Sect. 1:

"Nacelle measurements could also be used to help improve turbine or park efficiency. For example, power performance verifications for individual turbines can now be based on the nacelle anemometer with suitable nacelle transfer functions (NTFs) (International Electrotechnical Commission [IEC] 61400-12-2 2013). Nacelle measurements can also provide critical input for wind farm production optimization (Fleming et al., 2016). With sufficiently accurate NTFs, these data can provide a valuable, extensive, and continuous source of turbine-specific performance information."

The analysis presented in this work is motivated by the application of power performance testing as stated in the above excerpt. Typically, power performance testing is performed using measurements from some upwind tower or remote sensing instrument, however, IEC standards released in 2013 (IEC 61400-12-2) titled "Power performance of electricity-producing wind turbines based on nacelle anemometry" describe how nacelle anemometer measurements can be used for this application if based on transfer functions. Quantifying these transfer functions require upwind measurements be available at some point post-construction. However, once transfer functions are calculated for a site, the tower can be taken down and the transfer functions used to correct the nacelle measurements for future performance testing. The IEC standards (IEC 61400-12-2, 2013) even allow the use of these transfer functions at other, similar sites as stated within the standard:

“The procedure can be used for power performance evaluation of specific turbines at specific locations, but equally the methodology can be used to make generic comparisons between different turbine models or different turbine settings.”

...

“If during an NPC [nacelle power curve] measurement an NTF is used that has previously been measured in another park it may only be applied to turbines with a terrain classification that is the same as the terrain class during the NTF measurements; the terrain must also have the same sign of terrain slope in the measurement sector.”

This work focuses on the effect of atmospheric conditions on these transfer functions, so that when operators perform these calculations for future power performance testing, they will be aware of some of the factors these transfer functions are sensitive to. The manuscript ends with the following:

“Several atmospheric and operational conditions and how they affect the transfer functions should be investigated and perhaps combined to provide an algorithm for manufacturers and wind plant operators to use in power performance validation.”

To further clarify the practicality of the NTF, we have added the following to Sect. 1 when introducing NTFs:

“Quantifying these transfer functions require upwind measurements be available at some point post-construction. However, once transfer functions are calculated for a site, the tower can be taken down and the transfer functions used to correct the nacelle measurements for future performance testing.”

Specific comments:

(1) There is insufficient information about the methods and rationale. The reader is frequently referred other papers for these important details. For example, lines 149-151 of the paper state that: "Regimes or classifications for these stability and turbulence parameters are defined in Table 1 and described in detail in St. Martin et al. (2016), along with more detailed descriptions of the data from the lidar, tower and turbine, as well as filtering methods." A scientific paper should be entirely self-contained, and provide enough information for the reader to readily understand what you have done and how you have done it. We should not be forced to locate and dig through other papers for the details of your methods. (2) The classifications in Table 1 seem arbitrary, particularly for the TI and TKE "high", "medium", and "low". Without context and understanding of how you arrived at these classifications, they seem very subjective.

We understand, and have added equations for each stability metric with definitions of each parameter as well as the following:

“Regimes of TI, TKE, and α are determined by splitting the distributions of each parameter roughly into thirds. Regimes of R_B are similarly determined, as in Aitken et al. (2014) and St. Martin et al. (2016), and uncertainty in the R_B values calculated from propagation of instrument accuracy ensures the regimes are wide enough. Stability regimes based on L are similar to those defined by Muñoz-Esparza (2012).”

Because of the additional text, the following reference has been added:

Muñoz-Esparza, D., Cañadillas, B., Neumann, T., and vanBeech, J.: Turbulent fluxes, stability and shear in the offshore environment: mesoscale modelling and field observations at FINO1, J. Renew. Sustain. Energy, 4, 1–16, doi:10.1063/1.4769201, 2012.

(3) There are a number of confusion passages in the Introduction and Data and Methods sections. For example, the paragraph starting on line 58 is very hard to follow, and could be greatly shortened without losing the salient information. Here is my humble attempt, which combines the two paragraphs spanning lines 57-77):

"The relationship between UHWS measurements and NAWS measurements used for generating NTFs has been found to depend on a number of factors, including: nacelle height, wind inflow angle, blade pitch angle, yaw misalignment, the position of the anemometer on the nacelle, the anemometer calibration, and the characteristics of the surrounding terrain (References). However, the impacts of inflow turbulence and atmospheric stability on NTFs have not yet been explored, even though it has been recognized that they may play an important role (References)."

Thank you for the suggestion. To be more concise, we have changed the text in the Introduction from:

“In previous work, the relationship between UHWS measurements and NAWS measurements has been found to depend on multiple factors. Antoniou and Pedersen (1997) found that relations between the UHWS and the NAWS were dependent on rotor settings such as blade pitch angle and the use of vortex generators, yaw error, anemometer position, and terrain. They concluded that if these factors were kept constant, the relation could be used for all wind turbines of the same make and type. Frandsen et al. (2009) found a dependence on flow induction caused by the rotor. Dahlberg et al. (1999) discovered that pitch angle affects the relation. Dahlberg et al. (1999), Smith et al. (2002), and Frandsen et al. (2009) also stressed the importance of the correct calibration of the nacelle anemometers and that this calibration has an effect on the error measured in the relation. Zahle and Sørensen (2011) found that the inflow angle to the rotor and yaw misalignment influences the relationship. Smith et al. (2002) concluded the relation may depend on turbine controls, topography, and nacelle height and position. Smaïli and Masson (2004) implemented a numerical model and concluded that a relation should account for rotor-nacelle interactions and hypothesized that wakes, topography, and nacelle misalignment would all have some effect on the relation. To summarize, the factors found to be relevant in NTFs are:

rotor settings, yaw error, anemometer position, terrain, flow induction (decrease in wind speed just in front of or just behind the rotor), nacelle anemometer calibration, and inflow angle.”

To:

“In previous work, the relationship between UHWS measurements and NAWS measurements has been found to depend on multiple factors, including rotor and turbine control settings such as blade pitch angle and inflow angle, the use of vortex generators, yaw error, terrain, flow induction, calibration of the anemometer, and nacelle height and position (Antoniou and Pedersen, 1997; Dahlberg et al., 1999; Smith et al., 2002; Smaili and Masson, 2004; Frandsen et al., 2009; Zahle and Sørensen, 2011).”

(4) Lines 95 and 96: Change "(2.7 D upwind)" and "(2.0 D upwind)" to "(2.7 rotor diameters upwind; AND STATE THE PHYSICAL DISTANCE!)" and "(2.0 rotor diameters upwind)".

We agree and have made the following changes in bold:

“Upwind data include 1-Hz measurements of wind speed and direction averaged to 10 min from a Renewable NRG Systems (NRG)/LEOSPHERE WINDCUBE v1 vertically profiling Doppler lidar (**2.7 rotor diameters (D) upwind; 208 m**) and 10- and 30-min averages from a 135-m met tower (**2.0 D upwind, 154 m**).”

(5) Lines 100-104: This is really hard to follow, and keep the figures straight. I strongly suggest that you put this into a Table, which will be much easier to digest. This is also one of many places you refer the reader to some other paper for more details—in this case the configuration of met tower. Very frustrating!

We have placed the following table to make it easier for the reader to absorb and retain the information:

Instrument	Mounting heights (m)
Cup anemometer	3, 10, 30, 38, 55, 80, 87, 105, 122, 130
Wind vane	3, 10, 38, 87, 122
3-D sonic anemometer	15, 41, 61, 74, 100, 119
Barometric pressure sensor	3
Precipitation sensor	3
Temperature sensor	3, 38, 87
Dew point temperature sensor	3, 38, 87, 122

Atmospheric turbulence affects wind turbine nacelle transfer functions

Clara M. St. Martin,¹ Julie K. Lundquist,^{1,2} Andrew Clifton,² Gregory S. Poulos,³ and Scott J. Schreck²

¹ Department of Atmospheric and Oceanic Sciences (ATOC), University of Colorado at Boulder, 311 UCB, Boulder, CO, 80309

² National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO, 80401

³ V-Bar, LLC, 1301 Arapahoe Street, Suite 105, Golden, CO, 80401

Correspondence to: Clara M. St. Martin (clara.st.martin@colorado.edu)

5 **Abstract.** Despite their potential as a valuable source of individual turbine power performance and turbine array
energy production optimization information, nacelle-mounted anemometers have often been neglected because
complex flows around the blades and nacelle interfere with their measurements. This work quantitatively explores
the accuracy of and potential corrections to nacelle anemometer measurements to determine the degree to which
they may be useful when corrected for these complex flows, particularly for calculating annual energy production
10 (AEP) in the absence of other meteorological data. Using upwind meteorological tower measurements along with
nacelle-based measurements from a General Electric (GE) 1.5sle model, we calculate empirical nacelle transfer
functions (NTFs) and explore how they are impacted by different atmospheric and turbulence parameters. This work
provides guidelines for the use of NTFs for deriving useful wind measurements from nacelle-mounted anemometers.
Corrections to the nacelle anemometer wind speed measurements can be made with NTFs and used to calculate an
15 AEP that comes within 1 % of an AEP calculated with upwind measurements. We also calculate unique NTFs for
different atmospheric conditions defined by temperature stratification as well as turbulence intensity, turbulence
kinetic energy, and wind shear. During periods of low stability as defined by the Bulk Richardson number (R_B), the
nacelle-mounted anemometer underestimates the upwind wind speed more than during periods of high stability at
some wind speed bins below rated speed, leading to a more steep NTF during periods of low stability. Similarly,
20 during periods of high turbulence, the nacelle-mounted anemometer underestimates the upwind wind speed more
than during periods of low turbulence at most wind bins between cut-in and rated wind speed. Based on these
results, we suggest different NTFs be calculated for different regimes of atmospheric stability and turbulence for
power performance validation purposes.

Keywords

25 nacelle anemometry, nacelle transfer function, atmospheric stability, turbulence

Copyright statement

The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S.
Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published
form of this work, or allow others to do so, for U.S. Government purposes.

30

1 Introduction

Traditionally, each wind turbine has an anemometer and wind vane mounted on its nacelle, behind the hub (Fig.2).

Measurements collected from these instruments are used for yaw control and turbine cut-in/cut-out procedures.

Nacelle measurements could also be used to help improve turbine or park efficiency. For example, power

35 performance verifications for individual turbines can now be based on the nacelle anemometer with suitable nacelle transfer functions (NTFs) (International Electrotechnical Commission [IEC] 61400-12-2 2013). Nacelle measurements can also provide critical input for wind farm production optimization (Fleming et al., 2016). With sufficiently accurate NTFs, these data can provide a valuable, extensive, and continuous source of turbine-specific performance information.

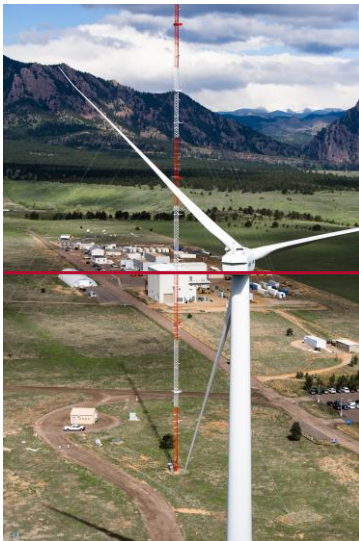


Figure 2. GE-1.5/77 sle turbine at the National Wind Technology Center. Photo credit: Dennis Schroeder/NREL (image gallery number [2961125872](#)).

Power performance validation has traditionally relied on hub-height wind speed observations from a meteorological (met) tower upwind of a turbine (Link and Santos, 2004; IEC 61400-12-1, 2015). The IEC 61400-12-1 (2015) standards require a met tower to be placed at the turbine location prior to turbine erection (the so-called “site calibration” procedure) for a power performance test to be considered valid (of sufficiently low total uncertainty) in complex terrain. However, it is not feasible to erect “site calibration” met towers after the turbine has been erected. And, even if “site calibration” is not required because a site is in simple terrain, tower erection is time-consuming and unrealistic to complete for every turbine at a given park. These factors motivate exploration of the use of nacelle-mounted anemometers to provide wind speed data for power performance validation.

Several studies have found that nacelle anemometer measurements can be adjusted by the use of transfer functions between some upwind hub-height measurement and the nacelle-mounted anemometer measurement (Antoniou and Pedersen, 1997; Hunter et al., 2001, Smith et al., 2002; Smaili and Masson, 2004). The IEC 61400-12-2 (2013) standard now allows the use of nacelle-mounted anemometers to verify power curves based on these transfer functions, or fitted functions of correction factors between upwind hub-height wind speed (UHWS) measurements and nacelle-mounted anemometer wind speed (NAWS) measurements. Quantifying these transfer functions require upwind measurements be available at some point post-construction. However, once transfer functions are calculated for a site, the tower can be taken down and the transfer functions used to correct the nacelle measurements for future performance testing.

An empirical NTF may not result in a linear relationship between the UHWS and NAWS. In fact, Antoniou and Pedersen (1997) found that the transfer functions fit well with a fifth-order polynomial curve. Hunter et al. (2001) similarly found a non-linear relationship and that a linear regression would overestimate the wind speed between 6 and 11 m s⁻¹ and underestimate the wind speed at wind speeds less than 4 m s⁻¹ and greater than 16 m s⁻¹. Smith et al. (2002) found a linear relationship with the exception of wind speeds below cut-in and wind speeds about 15 m s⁻¹.

In previous work, the relationship between UHWS measurements and NAWS measurements has been found to depend on multiple factors, including rotor and turbine control settings such as blade pitch angle and inflow

angle, the use of vortex generators, yaw error, terrain, flow induction, calibration of the anemometer, and nacelle height and position (Antoniou and Pedersen, 1997; Dahlberg et al., 1999; Smith et al., 2002; Smaïli and Masson, 2004; Frandsen et al., 2009; Zahle and Sørensen, 2011). In previous work, the relationship between UHWS measurements and NAWS measurements has been found to depend on multiple factors. Antoniou and Pedersen (1997) found that relations between the UHWS and the NAWS were dependent on rotor settings such as blade pitch angle and the use of vortex generators, yaw error, anemometer position, and terrain. They concluded that if these factors were kept constant, the relation could be used for all wind turbines of the same make and type. Frandsen et al. (2009) found a dependence on flow induction caused by the rotor. Dahlberg et al. (1999) discovered that pitch angle affects the relation. Dahlberg et al. (1999), Smith et al. (2002), and Frandsen et al. (2009) also stressed the importance of the correct calibration of the nacelle anemometers and that this calibration has an effect on the error measured in the relation. Zahle and Sørensen (2011) found that the inflow angle to the rotor and yaw misalignment influences the relationship. Smith et al. (2002) concluded the relation may depend on turbine controls, topography, and nacelle height and position. Smaïli and Masson (2004) implemented a numerical model and concluded that a relation should account for rotor-nacelle interactions and hypothesized that wakes, topography, and nacelle misalignment would all have some effect on the relation. To summarize, the factors found to be relevant in NTFs are: rotor settings, yaw error, anemometer position, terrain, flow induction (decrease in wind speed just in front of or just behind the rotor), nacelle anemometer calibration, and inflow angle.

The roles of inflow turbulence and atmospheric stability on NTFs have not yet been explored. However, previous work on power performance and annual energy production (AEP) does acknowledge the role of atmospheric stability, wind shear, and turbulence intensity (TI) in inducing deviations of power from the manufacturer power curve (MPC) (e.g., Sumner and Masson, 2006; Antoniou et al., 2009; Rareshide et al., 2009; Wagenaar and Eecen, 2011; Wharton and Lundquist, 2012; Vanderwende and Lundquist, 2012; St. Martin et al., 2016).

In this study, we quantify the effect of NTF-corrected nacelle anemometer measurements on the AEP and investigate the influence of different atmospheric stability and turbulence regimes on these NTFs. In Sect. 2, we briefly summarize our data set, which includes upwind as well as nacelle-based measurements, as well as our data analysis methods which include filtering based on turbine operation, and definitions of the stability and

turbulence regimes. We present results of AEP calculations ~~together with results of as well as~~ separate NTFs for different stability and turbulence regimes in Sect. 3. ~~and in~~ Sect. 4 we summarize conclusions about the effect of the NTF on the AEP ~~in addition to as well as~~ the effects of atmospheric stability and inflow turbulence on the NTFs.

2 Data and methods

2.1 Meteorological and turbine data

For this analysis, we use 2.5 months of data collected at the U.S. Department of Energy (DOE) National Wind Technology Center (NWTC) at the National Renewable Energy Laboratory (NREL) during the wintertime (29 November 2012–14 February 2013). Ten-minute-averaged turbine supervisory control and data acquisition (SCADA) data used in this study are from a General Electric (GE)-1.5-MW turbine (GE-1.5/77 sle, Fig.2), with a cut-in wind speed of 3.5 m s^{-1} , rated wind speed of 14 m s^{-1} , and cut-out wind speed of 25 m s^{-1} . A map of the site can be found in St. Martin et al. (2016) (Fig. 1). See Mendoza et al. (2015) for power performance test results from the DOE GE-1.5 along with instrument and site calibration information.

Upwind data include 1-Hz measurements of wind speed and direction averaged to 10 min from a Renewable NRG Systems (NRG)/LEOSPHERE WINDCUBE v1 vertically profiling Doppler lidar (2.7 ~~rotor diameters (-D)~~ upwind; ~~208 m~~) and 10- and 30-min averages from a 135-m met tower (2.0 D upwind; ~~154 m~~). Volumetric-averaged wind speeds and directions are measured by the lidar every 20 m, from 40 m to 220 m. Comparison of the lidar wind profiles to those from the met tower suggest that the lidar data at this site suffered from inhomogeneities as a result of complex flows (Bingöl et al., 2009; Rhodes and Lundquist, 2013; Lundquist et al., 2015), and so the majority of this paper will focus on the results of the analysis using the tower data. On the met tower, cup anemometers placed at 3, 10, 30, 38, 55, 80, 87, 105, 122, and 130 m measure wind speed, vanes placed at 3, 10, 38, 87, and 122 m measure wind direction, and three-dimensional (3-D) sonic anemometers placed at 15, 41, 61, 74, 100, and 119 m measure ~~all three~~ the components of the wind ~~as well as sonic temperature which are used to calculate momentum and heat fluxes (Table 1)~~. Barometric pressure and precipitation amounts are measured at 3 m, ~~and~~ temperature is measured at 3, 38, and 87 m, ~~and dew point temperature is measured at 3, 38, 87, 122 m (Table 1)~~. See Fig. 2 in St. Martin et al. (2016) for a schematic of the tower.

Table 1. 135-m met tower instrument mounting heights.

Instrument	Mounting heights (m)
Cup anemometer	3, 10, 30, 38, 55, 80, 87, 105, 122, 130
Wind vane	3, 10, 38, 87, 122
3-D sonic anemometer	15, 41, 61, 74, 100, 119
Barometric pressure sensor	3
Precipitation sensor	3
Temperature sensor	3, 38, 87
Dew point temperature sensor	3, 38, 87, 122

Formatted: Font: 9 pt, Bold, Not Italic

Formatted: Font: 9 pt

Formatted: Caption, Keep with next

Formatted: Font: 9 pt, Not Italic

Formatted: Font: Bold

120 As discussed in St. Martin et al. (2016), meteorological and turbine data are filtered for quality assurance. Data are only considered during time periods when the turbine is operating and wind direction indicates the turbine is located downwind of the lidar and met tower (235°–315°). As the turbine data from the SCADA system is available in 10-min increments, variability of the turbine parameters on a shorter timescale cannot be discerned. However, we filter for “normal turbine operation” based on curtailment using generator speed set point for wind speeds greater than 5.5 m s⁻¹, whereas for wind speeds less than 5.5 m s⁻¹, we discard data when the turbine is not grid-connected and is faulted (Fig. 6 in St. Martin et al., 2016).

130 ~~Lastly~~Further, ~~it is possible that~~ the nacelle-reported wind speeds used in this analysis have been subjected to a simple, ~~linear regression~~~~built-in~~ transfer function before the retrieval from the SCADA system of the DOE GE 1.5 sle turbine. ~~This linear regression function, built into the SCADA system by the turbine manufacturer,~~ effectively translates the raw signal from the cup anemometer to wind speed and is not unlike a transfer function provided by an anemometer manufacturer. We see the ~~is~~ uncertainty of this built-in transfer function as an advantage to our analysis as a typical wind plant operator would only have access to similar data.

2.2 AEP calculations

135 To simulate a scenario in which a wind plant operator only has nacelle-based measurements and no upwind tower or remote-sensing measurements, we calculate an AEP (as described in Sect. 9.3 of IEC 61400-12-2, 2013) using only

nacelle winds to compare to an AEP calculated with upwind met tower 80-m winds. We then correct the nacelle-based measurements with NTFs and calculate AEP based on these results for comparison as well. Although data for this analysis only spans 2.5 months in the wintertime at the NWTC during the 2012–2013 season, we calculate AEPs using the total amount of hours in an entire year to show values close to a representative AEP value. A sample wind distribution using Weibull distribution parameters representative of the data set (scale parameter: $\lambda = 10.04 \text{ m s}^{-1}$, shape parameter: $k = 2.63$, figure not shown) is used in these calculations as suggested by IEC 61400 12-1 (2015) for a site-specific AEP. We note that these parameters, based on 2.5 months in the “high” wind season at this site, are not actually representative of the entire year. However, as noted in other analyses of this test site (Clifton and Lundquist, 2012; Clifton et al., 2013), this site would not be chosen for wind development given the long summer season with little or no wind. We emphasize that this approach is not meant to suggest actual AEPs for this site, but to explore the sensitivity of AEP calculations at sites reasonable for wind development.

2.3 Stability metrics

We calculate Bulk Richardson number (R_B), Obukhov length (L), and the power law exponent (α) and use these as stability metrics for these data. Using wind speed and temperature differences between surface and upper tip (3 m and 122 m, respectively) tower measurements, we calculate 10-min values of R_B to compare the buoyant production of turbulence to the mechanical production of turbulence (Stull, 1988) as

$$R_B = \frac{g\Delta T\Delta z}{T\Delta U^2}, \quad (1)$$

where g is the gravitational constant, ΔT is the change in temperature across Δz , \bar{T} is the mean temperature across Δz , and ΔU is the change in horizontal wind speed across Δz . Humidity is not considered in this formulation of the bulk Richardson number.

Using near-surface flux measurements at 15 m (within the surface layer) as well as surface temperature and humidity measurements linearly interpolated to 15 m, we calculate 30-min values of L to estimate the height at which the buoyant production of turbulence dominates the mechanical production of turbulence (Stull, 1988) as:

$$L = -\frac{u_*^3}{kg} \frac{T_p}{wT_s}, \quad (2)$$

Formatted: Indent: First line: 0.5"

where u_* is the friction velocity, k is the von Kármán constant, T_v is the virtual temperature, w' is the vertical wind speed fluctuation, and T_s' is the sonic temperature fluctuation.

Formatted: Font: Italic

Using horizontal wind speeds as measured by cup anemometers at 38 m and 122 m (lower tip and upper tip of the rotor disk), we calculate 10-min values of α to quantify the wind speed vertical profile across the rotor disk as:

Formatted: Indent: First line: 0.5"

$$\alpha = \frac{\log \frac{U_2}{U_1}}{\log \frac{z_2}{z_1}} \quad (3)$$

where U_2 is the wind speed at height z_2 and U_1 is the wind speed at height z_1 .

Though some previous studies combine metrics to define stability (Vanderwende and Lundquist, 2012), the three atmospheric stability metrics discussed here are treated separately with regard to the NTFs because of slight differences between their definitions of unstable and stable conditions (see Fig. 11 in St. Martin et al., 2016). These differences may be attributed to distinctions between each approach in defining atmospheric stability, a difference in averaging period, heights of the measurements used in the calculations, or how R_B and L use wind speed and temperature measurements to define stability, whereas α uses only wind speed measurements.

Formatted: Indent: First line: 0.5"

Further, we calculate TI and turbulence kinetic energy (TKE) to provide turbulence metrics and estimate the effect of hub-height inflow turbulence on the NTFs. Using 80-m wind speed measurements from the met tower, we calculate 10-min values of TI, or the standard deviation of the horizontal wind speed normalized by the average horizontal wind speed at hub height. Using 74-m wind measurements from a 3-D sonic anemometer on the tower, we calculate 30-min values of TKE per unit mass, or the sum of the variances of the components of the wind divided by two. Note that after filtering out spikes in the raw 74-m sonic anemometer data, only about 367 thirty-min TKE values remain (183.5 h) and the fewer number of data points likely affects the statistical significance of the NTFs for different TKE regimes.

Regimes of TI, TKE, and α are determined by splitting the distributions of each parameter roughly into thirds. Regimes of R_B are similarly determined, as in Aitken et al. (2014) and St. Martin et al. (2016), and uncertainty in the R_B values calculated from propagation of instrument accuracy ensures the regimes are wide enough. Stability regimes based on L are similar to those defined by Muñoz-Esparza (2012). Regimes or classifications for these

Formatted: Indent: First line: 0"

Formatted: Font: Italic

Formatted: Font: Italic

stability and turbulence parameters are defined in Table 42 and described in detail in St. Martin et al. (2016), along with more detailed descriptions of the data from the lidar, tower and turbine, as well as filtering methods.

Table 21. Defined stability and turbulence regimes.

Regime	R_B	L (m)	α	TI (%)	TKE ($\text{m}^2 \text{s}^{-2}$)
Low	$R_B < -0.03$	$-1,000 < L \leq 0$	$\alpha < 0.11$	$TI < 15$	$TKE < 3.0$
Medium	$-0.03 < R_B < 0.03$	$0 \leq L < 1,000$	$0.11 < \alpha < 0.17$	$15 < TI < 20$	$3.0 < TKE < 6.5$
High	$R_B > 0.03$	$ L \geq 1,000$	$\alpha > 0.17$	$TI > 20$	$TKE > 6.5$

3 Results

To explore the variability of the NTF, we calculate specific NTFs filtered by atmospheric stability metrics, TI, and TKE. We investigate filters that have either previously been found to affect the transfer function or are suspected to have an effect on the transfer functions based on power curve studies (e.g., St. Martin et al., 2016). Additionally, we explore the effects of yaw error and wind veer and distributions of these variables, but, as in St. Martin et al. (2016), yaw error and wind veer do not seem to impact either the power curves or the NTFs at this site and therefore are not shown.

3.1 Preliminary NTFs

A general NTF (Fig. 3a) compares the tower 80-m wind speed to the nacelle-reported wind speed using all data that pass the wind speed, wind direction, and normal operation criteria defined in Sect. 2.1 and in more detail in Sect. 3.2 and 3.3 in St. Martin et al. (2016). As a fifth-order polynomial fit was found to be suitable for power curve assessment in previous work by Antoniou and Pedersen (1997) and Hunter et al. (2001), we also apply this type of fit to the wind speeds in this work to estimate an empirical transfer function between 80-m tower wind speed measurements and nacelle-mounted anemometer wind speed measurements (Fig. 3a). The r-squared value of the fifth-order polynomial fit to the data is 0.9912, which means the fit line predicts 99.12% of the variance in the tower data. The root-mean-square error (RMSE) of the fifth-order polynomial fit is 0.3615 m s^{-1} . After correcting the nacelle-measured wind speeds using this NTF, deviations between the corrected nacelle wind speed and the tower

80-m wind speeds (Fig. 3b) vary between -0.2 and 0.2 m s⁻¹ throughout all wind speed bins between cut-in and cut-out wind speed.

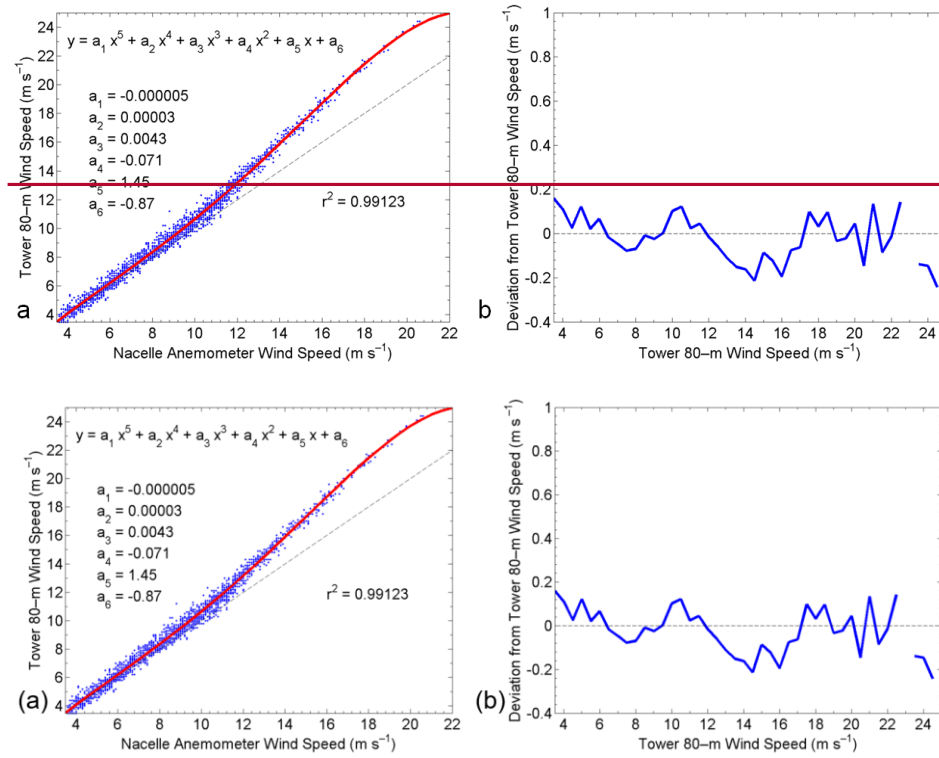


Figure 3. Comparison of upwind wind speeds with nacelle anemometer wind speeds: (a) Scatter is the upwind tower 80-meter (m) wind speed versus nacelle wind speed. Red line is the fifth-order polynomial fit and empirical transfer function between the tower 80-m observations and the nacelle-mounted anemometer observations. Dashed line is 1:1. (b) Average deviation in fifth-order polynomial nacelle transfer function (NTF)-corrected nacelle-mounted anemometer wind speed from tower 80-m wind speed versus tower 80-m wind speed. The dashed line indicates a 0 m s⁻¹ change. The figure includes data filtered for the tower 80-m wind speeds between 3.5 and 25.0 m s⁻¹, 87-m wind directions between 235° and 315°, and for normal turbine operation.

Based on the small coefficients of the third-, fourth-, and fifth-order of the fit in Fig. 3a, a fifth-order polynomial may be unnecessarily complex. Therefore, a second-order polynomial fit is also calculated to estimate an empirical transfer function. The r-squared value of the second-order polynomial fit with the data is also very high, 0.9909 (Fig. 4a). The RMSE of the second-order polynomial fit is 0.3680 m s^{-1} . After correcting the nacelle-measured wind speeds using this NTF, deviations between the corrected nacelle wind speed and the tower 80-m wind speeds, shown in Fig. 4b, vary from about -0.3 to 0.2 m s^{-1} at wind speed less than about 22 m s^{-1} but grow to about 0.8 m s^{-1} at higher wind speeds. Though there are fewer data points at these higher wind speed bins, this larger deviation of the second-order NTF-corrected wind speeds from the upwind wind speeds at higher wind speeds suggests that a fifth-order polynomial NTF is unnecessary until high wind speeds are considered.

Both transfer functions for this dataset (Fig. 3a, Fig. 4a) are close to linear at low wind speeds but non-linear just before rated speed (14 m s^{-1}), hence the higher-order polynomial fits. This behavior suggests that at wind speeds below about 9 m s^{-1} , the nacelle anemometer measurement closely corresponds to the upwind wind speed. Above this wind speed threshold, however, the nacelle anemometer underestimates the upwind wind speed by almost 2 m s^{-1} around rated speed to about 4 m s^{-1} at upwind wind speeds near 20 m s^{-1} ; higher ambient wind speeds are associated with more significant slow-downs around the nacelle.

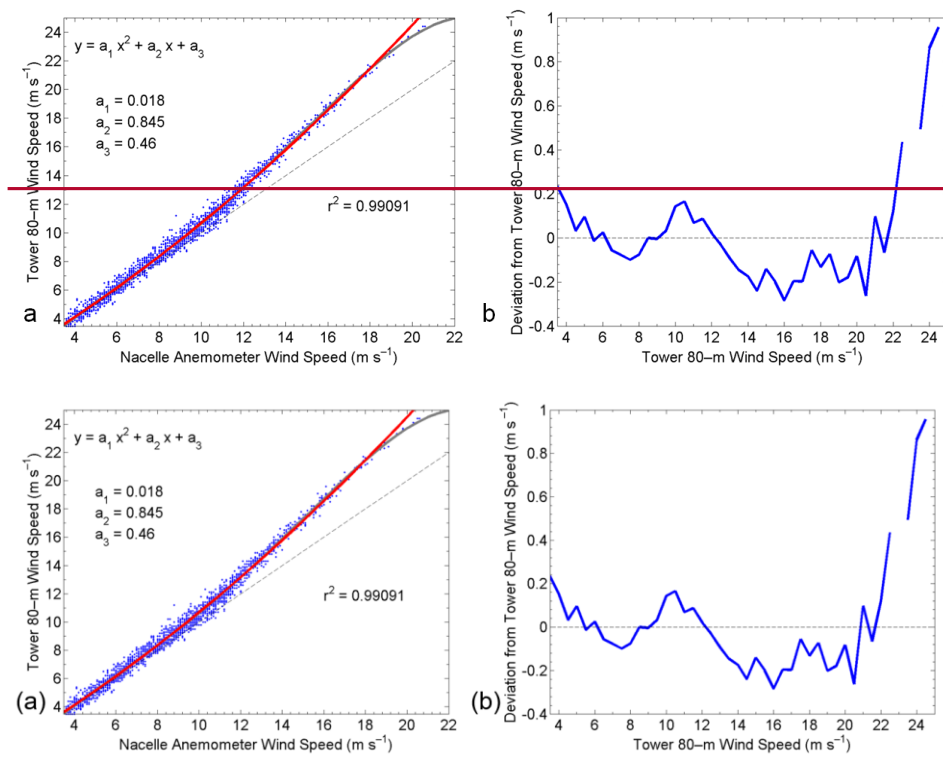


Figure 4. Comparison of upwind wind speeds with nacelle anemometer wind speeds. The red line in (a) Scatter is the upwind tower 80-m wind speed versus nacelle wind speed. Red line is the second-order polynomial fit and empirical transfer function between the tower 80-m observations and the nacelle-mounted anemometer observations and the gray line in (a) is the fifth-order polynomial fit. Dashed line is 1:1. (b) Average deviation in the second-order polynomial NTF-corrected nacelle-mounted anemometer wind speed from tower 80-m wind speed versus tower 80-m wind speed is shown. Dashed line indicates a 0 m s^{-1} change. Includes data filtered for tower 80-m wind speeds between 3.5 and 25.0 m s^{-1} , 87-m wind directions between 235° and 315°, and for normal turbine operation.

Comparison of the NTF developed from the upwind tower measurements and the NTF developed from the upwind lidar measurements (Fig. 5a) emphasizes that the lidar measurements exhibit greater variability ranging over all relevant wind speeds. The variability in the lidar measurements caused by the inhomogeneity of the flow

suggests that the tower measurements are more reliable for calculating power curves and transfer functions at this particular site, which is known to experience complex and inhomogeneous flow (Aitken et al., 2014). Despite the larger variability in the lidar data set for both the transfer function (Fig. 5a) and deviations between the corrected nacelle wind speed and the upwind wind speeds (Fig. 5b), both transfer functions in Fig. 5a show linearity at lower wind speeds and non-linearity at higher wind speeds.

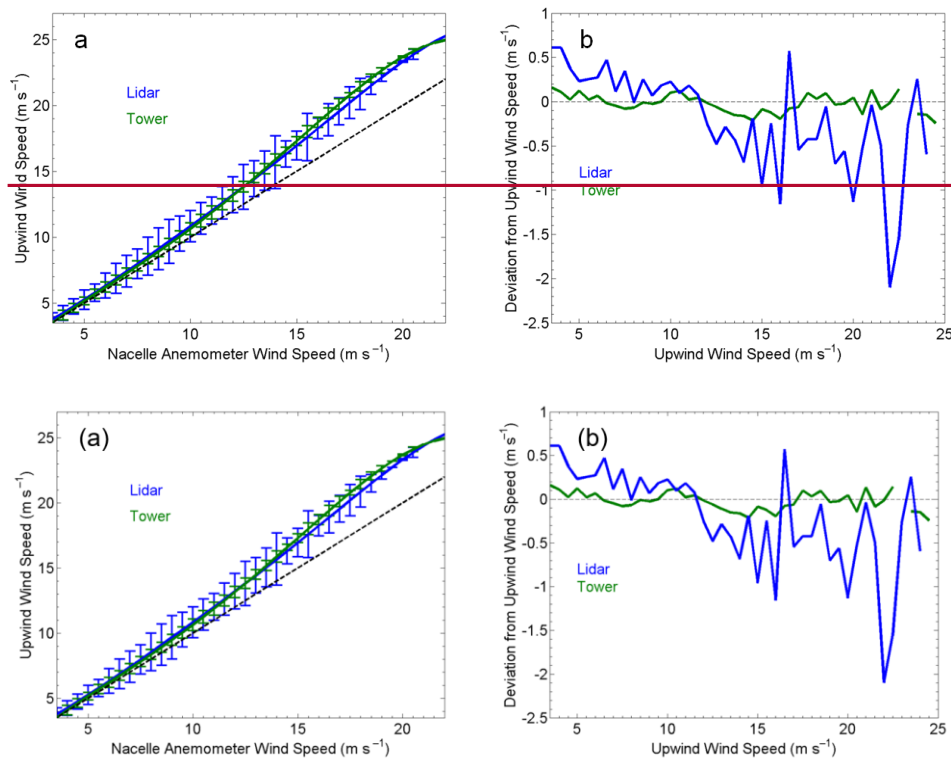


Figure 5. (a) NTFs calculated employing fifth-order polynomial fits using tower hub-height data (green) and lidar hub-height data (blue). Envelopes represent $\pm \sigma$ of the data within the same bins as the bins the NTFs are calculated with. Includes data filtered for tower 80-m wind speeds between 3.5 and 25.0 m s⁻¹, 87-m wind directions between 235° and 315°, and for normal turbine operation. Dashed line is 1:1; (b) shows the average deviation in NTF-corrected nacelle-mounted anemometer wind speed from tower 80-m wind speed (green) and lidar 80-m wind speed (blue) versus tower 80-m wind speed. Dashed line indicates a 0 m s⁻¹ change.

To try to quantitatively explain this change in the transfer function from linear to non-linear and to connect with possible flow blockage behind the rotor and along the nacelle, the non-dimensional Froude number (Stull, 1988) for flow around the nacelle is calculated. Froude numbers are investigated during stable conditions using measurements from the tower at the surface and around hub height and using a range of length scales from 1–10 m to represent the length and width of the nacelle. However, distinctions between these two wind speed regions could not be seen in these calculations as Froude numbers were found to be positive and increase with increasing wind speed.

Additionally, because the transfer functions become non-linear between cut-in wind speed and rated speed, the transfer function may be impacted by turbine operations in that region of the power curve possibly because of root vortices (Whale et al., 2000). Just below rated speed, the blades begin to pitch forward to maintain rated generator speed, thus allowing power production to remain near rated power (Fig.6). This “feathering” of the blades changes the flow around the blades and therefore the wind that affects the nacelle-mounted anemometer measurement. Though this hypothesis cannot be further investigated within this campaign as higher resolution data from the SCADA system are unavailable, this does make a compelling argument for installing 3-D sonic anemometers on nacelles so vertical velocity can be measured to further understand the 3-D wind structures behind the rotor and along the nacelle, and how these flow structures change as inflow wind speed increases.

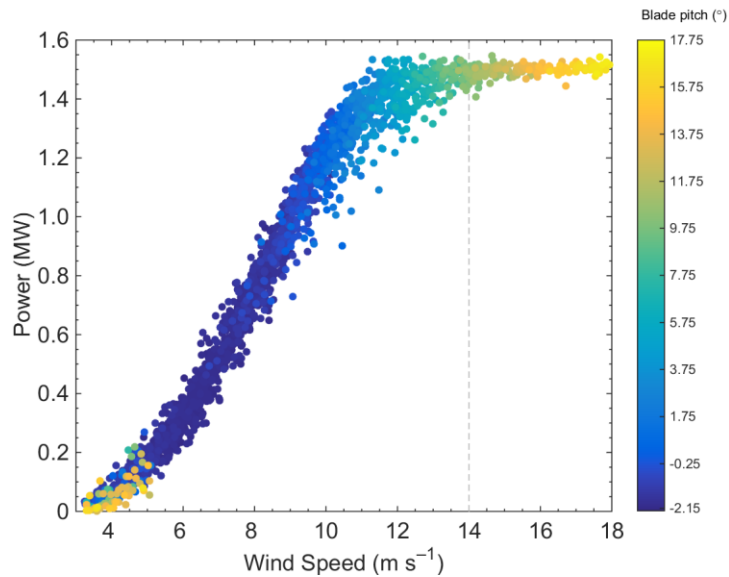


Figure 6. Scatter power curve using 80-m tower winds after filtering for wind speeds between 3.5 and 25 m s⁻¹, wind directions between 235° and 315°, and for normal turbine operation. Colors of the scatter points correspond to blade pitch angles. The grey dashed line marks rated speed.

3.2 Annual energy production and NTFs

250 It is important to understand the characteristics of the NTF and how it changes with wind speed, as this under-estimation of the ambient wind speed, especially at wind speeds in which the growth in power production with wind speed is the most significant, could result in a significant overestimation of AEP in power performance verification.

255 With no NTF correction applied (aside from the transfer function that is built into the SCADA system by the manufacturer), the AEP calculated with nacelle winds (AEP_{nacelle}) overestimates the AEP calculated with 80-m tower winds (AEP_{upwind}) by 5.96 % (Table 32). This overestimation of AEP is expected as the nacelle anemometer consistently underestimates the upwind wind speed, which leads to the misrepresentation of higher power output at lower wind speeds, effectively shifting the entire power curve to the left, and therefore leading to a higher AEP.

Table 23. Top row: Annual energy production (AEP) in megawatt-hours/year calculated using upwind tower measurements (AEP_upwind), nacelle winds (AEP_nacelle), corrected nacelle winds using the NTF calculated with a fifth-order polynomial (AEP_NTF5th), and corrected nacelle winds using the NTF calculated with a second-order polynomial (AEP_NTF2nd). Bottom row: AEP in percentage calculated as ~~the difference from~~ percentage of AEP_upwind.

	AEP_upwind	AEP_nacelle	AEP_NTF5 th	AEP_NTF2 nd
AEP (MWh/y)	7,479.3	7,924.7	7,479.1	7,465.8
% difference from tower winds	100.00	105.96	100.00	99.82

The use of the general NTF to correct the nacelle anemometer measurements reduces the AEP error significantly (Table 32). With the application of the fifth-order polynomial NTF (AEP_NTF5th), AEP_NTF5th underestimates AEP_upwind by only 0.003 %, whereas with the application of the second-order polynomial NTF (AEP_NTF2nd), AEP_NTF2nd underestimates AEP_upwind by 0.18 %. Therefore, using either the fifth-order polynomial or the second-order polynomial for the NTF results in an AEP similar to that of an AEP calculated with upwind hub-height winds; though both lead to a slight underestimation.

3.3 Atmospheric stability effects of NTFs

The value of atmospheric-stability segregation for NTFs seems to depend on how stability is defined. Some statistically significant distinctions in the NTFs for R_p -defined unstable and stable cases do emerge (Fig. a, Table 43), particularly for wind speeds between 7 and 11 m s⁻¹. Closed circles in Fig. a-e represent statistically distinct wind speed bins between the stability classes and are determined by the Wilcoxon rank sum test with a 1 % significance level. Stable cases follow a linear relationship more closely for low and moderate wind speeds (less than 11 m s⁻¹), whereas unstable cases show more deviation from the 1:1 line at wind speeds greater than 8 m s⁻¹. This behavior shown by NTFs segregated by R_p suggests that below rated speed in convective conditions, the nacelle anemometer underestimates the ambient wind speed more than in stable conditions. Conversely, no statistically significant distinctions emerge in the NTFs for L -defined stability classes for this site using our dataset (Fig. 7a, Table 4). Distinctions in the NTFs for α -defined cases (Fig. 8a, Table 5) emerge only around 13.5 m s⁻¹—much closer to rated speed—and stable cases underestimate the upwind wind speed more than unstable cases.

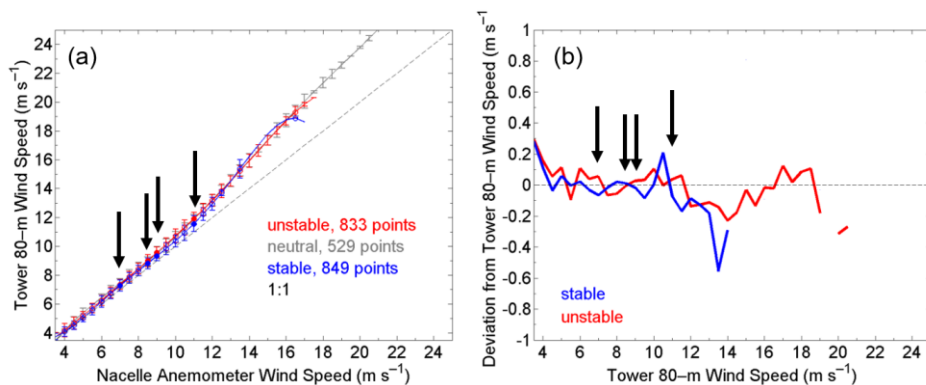


Figure 7. (a) Tower 80-m NTFs calculated using fifth-order polynomial fits with stability regimes based on R_p . Error bars represent $\pm \sigma$ of the data within the same bins as the bins with which the NTFs are calculated. Statistically distinct differences within each wind speed bin between the stability classes are determined by the Wilcoxon rank sum test with a 1 % significance level and denoted by closed circles. Black arrows point towards statistically distinct bins. The figures include data filtered for tower 80-m wind speeds between 3.5 and 25.0 m s⁻¹, 87-m wind directions between 235° and 315°, and for normal turbine operation. (b) Average deviation in NTF-corrected nacelle-mounted anemometer wind speed from tower 80-m wind speed is shown during stable conditions (blue) and during unstable conditions (red) versus tower 80-m wind speed with stability regimes based on R_p . Dashed line indicates a 0 m s⁻¹ change

Conversely, no statistically significant distinctions emerge in the NTFs for L -defined stability classes for this site using our dataset (Fig. 6b, Table 3).

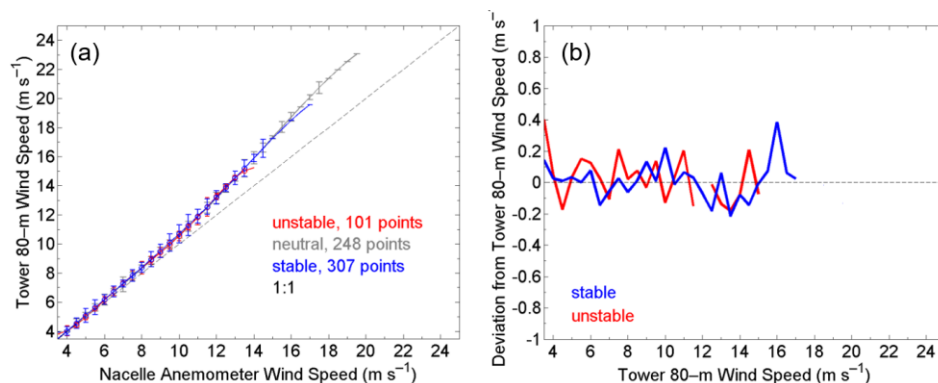


Figure 8. (a) Tower 80-m NTFs calculated using fifth-order polynomial fits with stability regimes based on L . Error bars represent $\pm \sigma$ of the data within the same bins as the bins with which the NTFs are calculated. Statistically distinct differences within each wind speed bin between the stability classes are determined by the Wilcoxon rank sum test with a 1 % significance level and denoted by closed circles. The figures include data filtered for tower 80-m wind speeds between 3.5 and 25.0 m s⁻¹, 87-

m wind directions between 235° and 315°, and for normal turbine operation. (b) Average deviation in NTF-corrected nacelle-mounted anemometer wind speed from tower 80-m wind speed is shown during stable conditions (blue) and during unstable conditions (red) versus tower 80-m wind speed with stability regimes based on L . Dashed line indicates a 0 m s⁻¹ change.

Distinctions in the NTFs for α defined cases (Fig. 6c, Table 4) emerge only around 13.5 m s⁻¹—much closer to rated speed—and stable cases underestimate the upwind wind speed more than unstable cases.

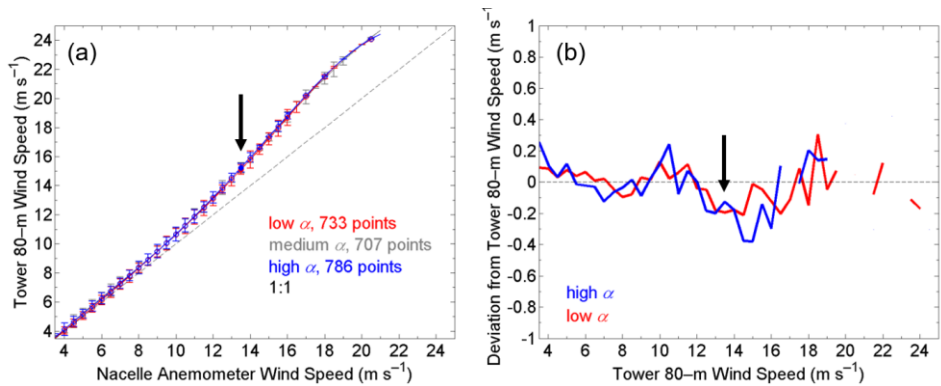


Figure 9. (a) Tower 80-m NTFs calculated using fifth-order polynomial fits with stability regimes based on α . Error bars represent $\pm \sigma$ of the data within the same bins as the bins with which the NTFs are calculated. Statistically distinct differences within each wind speed bin between the stability classes are determined by the Wilcoxon rank sum test with a 1 % significance level and denoted by closed circles. Black arrows point towards statistically distinct bins. The figures include data filtered for tower 80-m wind speeds between 3.5 and 25.0 m s⁻¹, 87-m wind directions between 235° and 315°, and for normal turbine operation. (b) Average deviation in NTF-corrected nacelle-mounted anemometer wind speed from tower 80-m wind speed is shown during stable conditions (blue) and during unstable conditions (red) versus tower 80-m wind speed with stability regimes based on α . Dashed line indicates a 0 m s⁻¹ change.

Formatted: Keep with next

Formatted: Font: Bold

Formatted: Font: Bold

Formatted: Font: 9 pt, Bold

Formatted: Font: 9 pt, Bold

Formatted: Font: 9 pt

Formatted: Font: Not Italic

Formatted: Font: Not Italic

Formatted: Font: Not Italic

Formatted: Caption, Line spacing: single

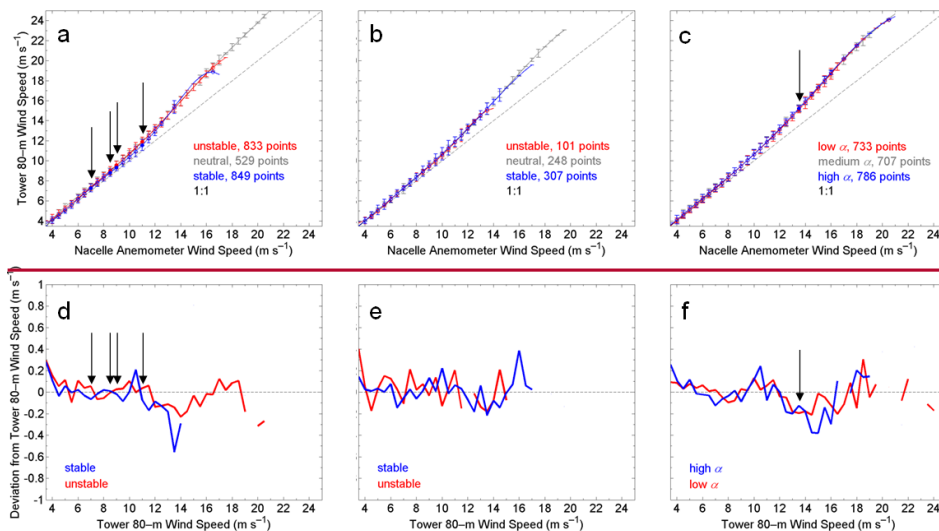


Figure 6. Tower 80-m NTFs calculated using fifth-order polynomial fits with stability regimes based on (a) R_B , (b) L , and (c) α . Error bars represent $\pm \sigma$ of the data within the same bins as the bins with which the NTFs are calculated. Statistically distinct differences within each wind speed bin between the stability classes are determined by the Wilcoxon-rank sum test with a 1 % significance level and denoted by closed circles. Black arrows point towards statistically distinct bins. The figures include data filtered for tower 80-m wind speeds between 3.5 and 25.0 m s^{-1} , 87-m wind directions between 235° and 315° , and for normal turbine operation. Average deviation in NTF-corrected nacelle-mounted anemometer wind speed from tower 80-m wind speed is shown during stable conditions (blue) and during unstable conditions (red) versus tower 80-m wind speed with stability regimes based on (d) R_B , (e) L , and (f) α . Dashed line indicates a 0 m s^{-1} change.

Table 43. Coefficients for fifth-order polynomial NTFs for stability metrics.

	R_B			L		
Regime	Convective	Neutral	Stable	Convective	Neutral	Stable
a_1	-6.4141×10^{-5}	3.7809×10^{-5}	-3.0593×10^{-4}	-6.7085×10^{-4}	2.9071×10^{-6}	-3.8242×10^{-5}
a_2	0.0030	-0.0025	0.0142	0.0287	-4.4810×10^{-4}	0.0016
a_3	-0.0539	0.0621	-0.2473	-0.4721	0.0153	-0.0245
a_4	0.4628	-0.6843	2.0334	3.7194	-0.1881	0.1789
a_5	-0.8555	4.4391	-6.8356	-12.9316	2.0185	0.4534

a_6	2.9265	-5.9942	11.3853	19.7947	-1.9273	0.5361
-------	--------	---------	---------	---------	---------	--------

Table 54. Coefficients for fifth-order polynomial NTFs for the shear exponent.

	α		
Regime	Convective	Neutral	Stable
a_1	-2.3643×10^{-5}	1.4220×10^{-5}	-5.9409×10^{-6}
a_2	0.0011	-0.0011	7.3499×10^{-5}
a_3	-0.0202	0.0301	0.0038
a_4	0.1781	-0.3451	-0.0689
a_5	0.2889	2.7912	1.4373
a_6	1.0387	-3.2175	-0.7869

~~This behavior shown by NTFs segregated by R_g suggests that below rated speed in convective conditions, the nacelle anemometer underestimates the ambient wind speed more than in stable conditions. We speculate that at wind speeds below rated, mixing in the atmosphere during more convective conditions, as well as the turbine interaction with these turbulent eddies, may result in additional motion that exaggerates blockage effects by the rotor and nacelle and causes underestimation by the nacelle-mounted anemometer.~~

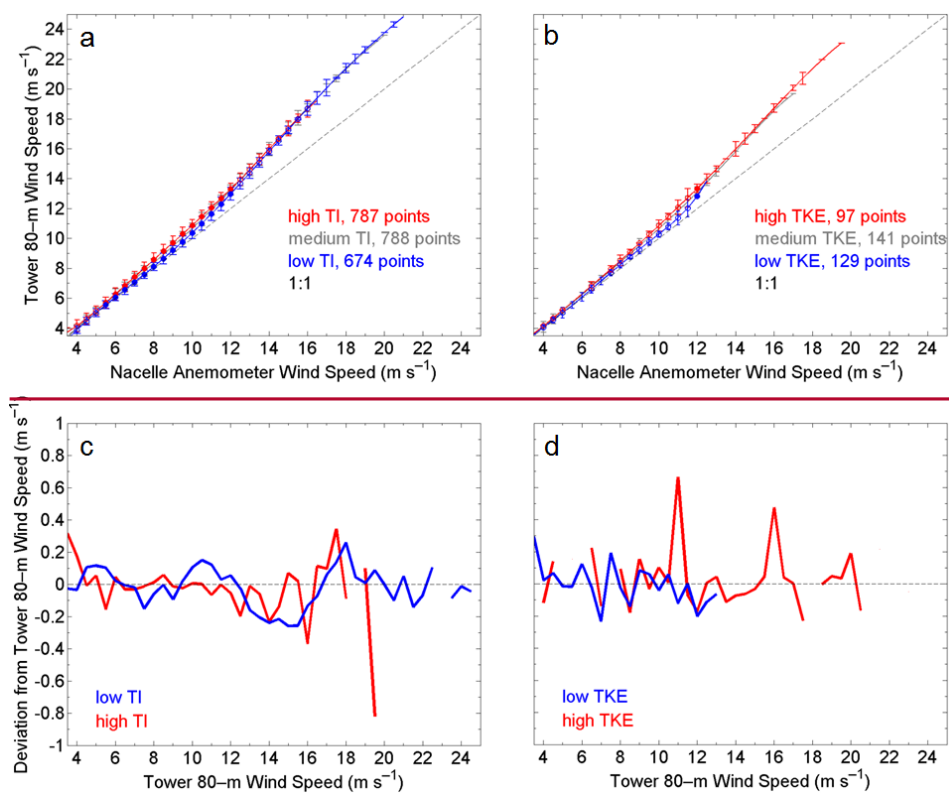
We apply the NTFs to the nacelle anemometer measurements to evaluate the deviations from the upwind met tower data (Figs. 6d-f6b, 7b, 8b); however, the results show no consistency or systematic distinctions between stability metrics, stability classes, or wind speed.

3.4 Turbulence effects on NTFs

The hypothesis that convectively-driven mixing and turbulence causes underestimation by the nacelle-mounted anemometer is further supported in the NTFs segregated by TI (Fig. 7a9a, Table 56) and TKE classes (Fig. 7b9b, Table 56). Distinctions between unstable and stable cases in the transfer functions for wind speeds between 5.5 and 12 m s⁻¹ are also apparent when the transfer functions are segregated by TI class (Fig. 7a9a) and for wind speeds around 12 m s⁻¹ when the transfer functions are segregated by TKE class (Fig. 7b9b). Periods of relatively high TI

and TKE result in greater underestimations of the wind speed by the nacelle anemometer from just above cut-in wind speed to about 12 m s^{-1} .

330 Corrections to the nacelle wind speeds using NTFs based on atmospheric turbulence show lower deviations from the ambient wind speed below rated speed and larger deviations from the ambient wind speed after rated speed for high TI cases. However, similar to the results in Figs. [b](#), [7b](#), and [8bd-f](#), Fig. [7e9c](#)-d also show inconsistencies between deviations from the upwind speed for the different turbulence metrics and regimes.



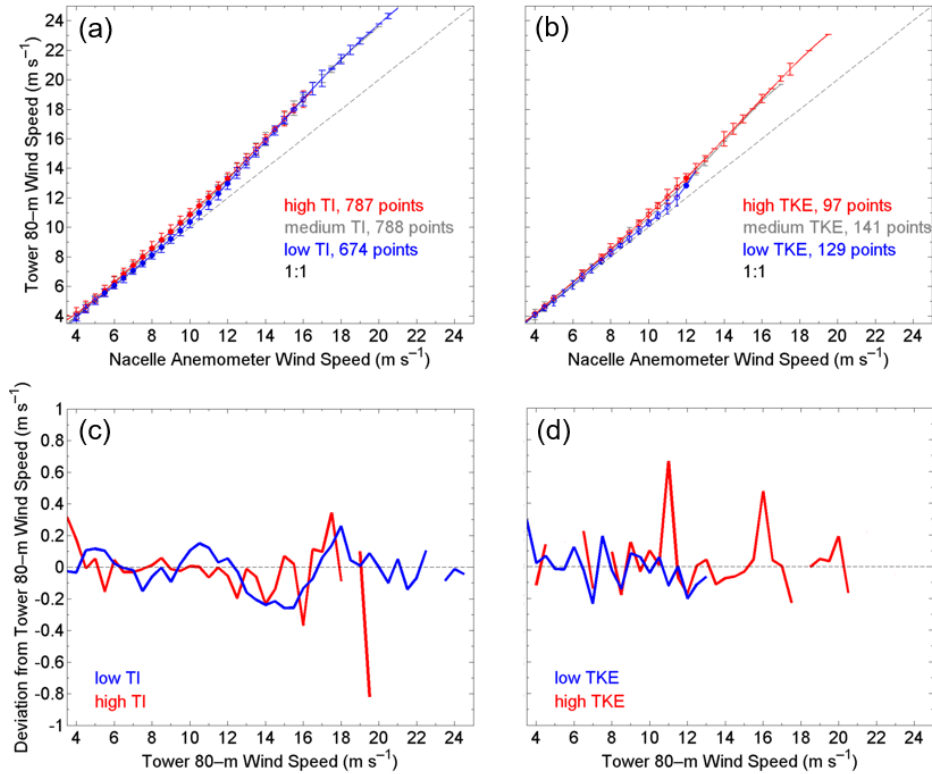


Figure 10. Tower 80-m NTFs calculated using fifth-order polynomial fits with turbulence regimes based on (a) turbulence intensity (TI) and (b) turbulence kinetic energy (TKE). Error bars represent $\pm \sigma$ of the data within the same bins as the bins with which the NTFs are calculated. Statistically distinct differences within each wind speed bin between the stability classes are denoted by closed circles. Figures include data filtered for tower 80-m wind speeds between 3.5 and 25.0 m s^{-1} , 87-m wind directions between 235° and 315°, and for normal turbine operation. Average deviation in NTF-corrected nacelle-mounted anemometer wind speed from tower 80-m wind speed is shown during stable conditions (blue) and during unstable conditions (red) versus tower 80-m wind speed with turbulence regimes based on (c) TI and (d) TKE. Dashed line indicates a 0 m s^{-1} change.

Table 65. Coefficients for fifth-order polynomial NTFs for turbulence metrics.

	TI			TKE		
Regime	High	Med	Low	High	Med	Low
a_1	-9.0463×10^{-5}	1.5534×10^{-5}	2.3161×10^{-5}	-1.3295×10^{-5}	-6.7464×10^{-5}	4.5266×10^{-4}
a_2	0.0045	-0.0012	-0.0017	6.0813×10^{-4}	0.0031	-0.0156
a_3	-0.0842	0.0305	0.0428	-0.0103	-0.0539	0.2048
a_4	0.7602	-0.3409	-0.4763	0.0949	0.4418	-1.2609
a_5	-2.1704	2.7552	3.3911	0.6268	-0.6458	4.6488
a_6	5.0077	-3.2307	-4.4045	0.6460	2.3183	-3.9372

3.5 Discussion

We speculate that at wind speeds below rated, mixing in the atmosphere during more convective conditions, as well as the turbine interaction with these turbulent eddies, may result in additional motion that exaggerates blockage effects by the rotor and nacelle and causes underestimation by the nacelle-mounted anemometer. We suspect that rotor response is lagging in more convective and turbulent conditions as the turbine responds more quickly to drops in wind speed. Therefore, during more turbulent conditions, it is possible that lower rotor efficiency influences flow induction and thus the wind speeds measured on the back of the nacelle. If turbine and rotor efficiencies are lower during periods with convective and more turbulent conditions, it may be surmised then, that less momentum passes through the rotor and along the nacelle. In addition, power curve results from the same dataset discussed here (St. Martin et al., 2016) show that during less stable and more turbulent conditions at wind speeds within the ramp-up region of the power curve, more power is produced than during periods of more stable and less turbulent conditions. Power production will also affect the flow induction (Frandsen et al., 2009) and thus the wind speed directly behind the rotor disk: if more energy is extracted by the rotor, the nacelle-mounted anemometer will likely measure lower winds.

Formatted: Font: Not Bold

4 Conclusions

Over two months of data from both upwind instruments and nacelle-based instruments are used to quantify general nacelle transfer functions (NTFs) as well as NTFs that vary with atmospheric stability and turbulence parameters.

We show that correcting nacelle winds using these NTFs results in more accurate annual energy production (AEP) estimates that are similar to estimates obtained using upwind meteorological (met) tower-based wind speeds. Further, multiple factors have been investigated for their influence on NTFs, including both parameters known to influence wind power production and parameters never before investigated in the context of transfer functions.

We find that fitting the data to a fifth-order polynomial to estimate the NTF results in a slightly higher r-squared value and smaller root-mean-square error (RMSE) than fitting to a second-order polynomial. The small differences in the uncertainties between the two methods seem insignificant, as the r-squared value of 0.9909 using the second-order polynomial is comparable to the 0.9912 value using the fifth-order fit. However, though the r-squared value of the second-order fit is high, after correcting the nacelle winds with the second-order NTF, larger deviations from the upwind tower winds occur than if a fifth-order NTF is used, especially at higher wind speeds.

At wind speeds below 9 m s^{-1} , the nacelle anemometer measurement closely corresponds to the upwind wind speed measurement. Above this wind speed threshold, however, the nacelle anemometer underestimates the upwind wind speed, which could result in a significant underestimation of power production and could be perceived as turbine over-performance (or mask turbine under-performance) if not corrected for by a NTF. Additionally, the non-linear nature of the transfer functions above 9 m s^{-1} or so suggests that the transfer function may be impacted by turbine operations near rated speed and how they affect the flow behind the rotor disk and along the nacelle.

The use of NTFs in AEP calculations results in a less than 1 % difference from the AEP calculated with the upwind met tower wind speed. AEP calculations reveal that an AEP calculated using a fifth-order polynomial correction to the nacelle winds results in a 0.003 % underestimation of the AEP calculated with the upwind wind speed, whereas an AEP calculated using a second-order polynomial correction results in a 0.18 % underestimation of the AEP calculated with the upwind wind speed. Both are sizeable improvements over using the uncorrected nacelle wind speed, which leads to a 5.96 % overestimation when compared to the AEP calculated with the upwind wind speed.

Statistically significant distinctions emerge in the transfer functions for unstable and stable cases as defined by the Bulk Richardson number (R_B), particularly for wind speeds between 9 and 11 m s⁻¹. At these wind speeds before rated, in unstable conditions, the nacelle anemometer underestimates the ambient wind speed more often than in stable conditions. Similar but more prominent behavior is found in transfer functions separated by turbulence intensity (TI) and turbulence kinetic energy (TKE) classifications: during periods with relatively high TI and TKE, the nacelle anemometer underestimates the ambient wind speed more than during periods of relatively low TI and TKE, between about 6 and 12 m s⁻¹. We speculate that turbine interaction with the mixing in the atmosphere during more convective and turbulent conditions may result in additional motion, thereby exaggerating the blockage by the nacelle and thus underestimation by the nacelle-mounted anemometer.

Distinctions in power curves (Sumner and Masson, 2006; Antoniou et al., 2009; Vanderwende and Lundquist, 2012; Dörenkämper et al., 2014; St. Martin et al., 2016) can lead to a correlation between these and distinctions in NTFs as well as the idea of validating power performance data with similar atmospheric and operational characteristics with their corresponding power curve in an effort to decrease the amount of uncertainty in power performance testing.

NTFs have recently been accepted for power curve validation under certain circumstances (IEC 61400-12-2, 2013). They can also enable the use of nacelle-mounted anemometers for AEP estimates, turbine performance analysis, and data assimilation for improved forecasting (Draxl, 2012; Delle Monache et al., 2013).

Further work could explore how turbine controls and characteristics such as thrust affect the transfer functions. Simulations of flow around the nacelle such as those of Keck (2012) could be expanded to account for variations in atmospheric stability and could be coupled with control software simulators. As Bibor and Masson (2007) suggest, a single transfer function should not be used for every wind plant site and for every atmospheric and operating condition. Several atmospheric and operational conditions and how they affect the transfer functions should be investigated and perhaps combined to provide an algorithm for manufacturers and wind plant operators to use in power performance validation.

Acknowledgements

The authors express appreciation to the Center for Research and Education in Wind for supporting this work, to Thomas Fischetti and Peter Gregg at GE Renewable Energy for their assistance in turbine data collection and interpretation, and to the reviewers of a previous version of this work. This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory. Funding for the work was provided by the DOE Office of Energy Efficiency and Renewable Energy, Wind and Water Power Technologies Office.

References

- Aitken, M.L., Lundquist, J.K., Pichugina, Y.L., and Banta, R.M.: Quantifying wind turbine wake characteristics from scanning remote sensor data, *J. Atmos. Ocean. Tech.*, 31, 765–787, doi:10.1175/JTECH-D-13-00104.1, 2014.
- Antoniou, I., Pedersen, S.M., and Enevoldsen, P.B.: Wind shear and uncertainties in power curve measurement and wind resources, *Wind Engineering*, 33, 449–468, doi:10.1260/030952409790291208, 2009.
- Antoniou, I., and Pedersen, T.F.: Nacelle Anemometry on a 1MW Wind Turbine, Risø National Laboratory, Roskilde, Denmark, 37 pp., 1997.
- Bibor, E., and Masson, C.: Power Performance via Nacelle Anemometry on Complex Terrain, *Wind Energy*, Springer Berlin Heidelberg, 43–47, 2007.
- Bingöl, F., Mann, J., and Foussekis, D.: Conically scanning LIDAR error in complex terrain, *Meteorologische Zeitschrift*, 18, 189–195, doi:10.1127/0941-2948/2009/0368, 2009.
- Clifton, A. and Lundquist, J.K.: Data clustering reveals climate impacts on local phenomena, *J. Appl. Meteorol. Clim.*, 51, 1547–1557, doi:10.1175/JAMC-D-11-0227.1, 2012.
- Clifton, A., Schreck, S., Scott, G., and Lundquist, J. K.: Turbine inflow characterization at the National Wind Technology Center, *J. Sol. Energ.-T. ASME*, 135, 031017, doi:10.1115/1.4024068, 2013.
- Dahlberg, J.A., Frandsen, S., Madsen, H.A., Antoniou, I., Pedersen, T.F., Hunter, R., Klug, H., and Albers, A.: Is the nacelle mounted anemometer an acceptable option in performance testing, *Proceeding of the European Wind Energy Conference*, Nice, 624–637, 1999.
- Delle Monache, L., Eckel, F.A., Rife, D.L., Nagarajan, B., and Searight, K.: Probabilistic Weather Prediction with an Analog Ensemble, *Monthly Weather Review*, 141, 3498–3516, doi: 10.1175/MWR-D-12-00281.1, 2013.
- Dörenkämper, M., Tambke, J., Steinfield, G., Heinemann, D., and Kühn, M.: Atmospheric impacts on power curves of multi-megawatt offshore wind turbines, *Journal of Physics: Conference Series*, 555, 1–11, doi: 10.1088/1742-6596/555/1/012029, 2014.
- Draxl, C.: On the Predictability of Hub Height Winds, DTU Wind Energy PhD-Report, 104 pp., 2012.

- 435 Fleming, P.A., Ning, A., Gebraad, P.M.O., and Dykes, K.: Wind plant system engineering through optimization of layout and yaw control, *Wind Energy*, 19, 329-344, doi: 10.1002/we.1836, 2016.
- Frandsen, S., Sørensen, J.N., Mikkelsen, R., Pedersen, T.F., Antoniou, I., and Hansen, K.: The generics of wind turbine nacelle anemometry, *Proceedings of European Wind Energy Conference*, Marseille, France, 2009.
- 440 Hunter, R., Pedersen, T.F., Dunbabin, P., Antoniou, I., Frandsen, S., Klug, H., Albers, A., and Lee, W.K.: European wind turbine testing procedure developments: Task 1: measurement method to verify wind turbine performance characteristics, *Risø National Laboratory, Roskilde, Denmark*, 1–120, 2001.
- IEC 61400-12-1 Ed 2.0: Wind turbines – Part 12-1: power performance measurements of electricity producing wind turbines, IEC, Geneva, Switzerland, 2015.
- IEC 61400-12-2 Ed. 1.0: Wind turbines – Part 12-2: power performance of electricity producing wind turbines based on nacelle anemometry, IEC, Geneva, Switzerland, 2013.
- 445 Keck, R.E.: A numerical investigation of nacelle anemometry for a HAWT using actuator disc and line models in CFX, *Renewable Energy*, 48, 72-84, doi: 10.1016/j.renene.2012.04.004, 2012.
- Link, H.F., and Santos, R: International Energy Agency Wind Turbine Round-Robin Test Task: Final Report, NREL, Golden, CO, 31 pp, 2004, last access: 24 May 2016, <http://www.nrel.gov/docs/fy04osti/36238.pdf>.
- 450 Lundquist, J.K., Churchfield, M.J., Lee, S., and Clifton, A.: Quantifying error of lidar and sodar Doppler beam swinging measurements of wind turbine wakes using computational fluid dynamics, *Atmospheric Measurement Techniques*, 8, 907–920, doi: 10.5194/amt-8-907-2015, 2015.
- Mendoza, I., Hur, J., Thao, S., Curtis, A.: Power performance test report for the U.S. Department of Energy 1.5-megawatt wind turbine, NREL, Golden, CO, 1–55, 2015, last accessed: 8 May 2016, <http://www.nrel.gov/docs/fy15osti/63684.pdf>.
- 455 Muñoz-Esparza, D., Cañadillas, B., Neumann, T., and vanBeech, J.: Turbulent fluxes, stability and shear in the offshore environment: mesoscale modelling and field observations at FINO1, *J. Renew. Sustain. Energy*, 4, 1–16, doi:10.1063/1.4769201, 2012.
- Rareshide, E., Tindal, A., Johnson, C., Graves, A.M., Simpson, E., Bleeg, J., Harris, T., and Schoborg, D.: Effects of complex wind regimes on turbine performance, *AWEA Windpower 2009 meeting*, Chicago, IL, 2009.
- 460 Rhodes, M.E., and Lundquist, J.K.: The effect of wind-turbine wakes on summertime US Midwest atmospheric wind profiles as observed with ground-based Doppler LIDAR, *Boundary-Layer Meteorol.* 149, 85–103, doi:10.1007/s10546-013-9834-x, 2013.
- Smaïli, A., and Masson, C.: On the rotor effects upon nacelle anemometry for wind turbines, *Wind Energy*, 28, 695-714, doi: 10.1260/0309524043729958, 2004.
- 465 Smith, B., Link, H., Randall, G., and McCoy, T.: Applicability of Nacelle Anemometer Measurements for Use in Turbine Power Performance Tests, *AWEA Windpower*, Portland, OR, 2002.
- St. Martin, C. M., Lundquist, J. K., Clifton, A., Poulos, G. S., and Schreck, S. J.: Wind turbine power production and annual energy production depend on atmospheric stability and turbulence, *Wind Energ. Sci.*, 1, 221-236, doi:10.5194/wes-1-221-2016, 2016.
- 470 Stull, R.B.: *An Introduction to Boundary Layer Meteorology*, Kluwer Academic Publishers, Netherlands, 1988.

Sumner, J., and Masson, C.: Influence of atmospheric stability on wind turbine power performance curves, *J. Sol. Energ.-T ASME*, 128, 531–538, doi:10.1115/1.2347714, 2006.

Vanderwende, B., and Lundquist, J.K.: The modification of wind turbine performance by statistically distinct atmospheric regimes, *Environ. Res. Lett.*, 7, 1–7, doi:10.1088/1748-9326/7/3/034035, 2012.

- 475 Wagenaar, J.W., and Eecen, P.J.: Dependence of power performance on atmospheric conditions and possible corrections, European Wind Energy Association (EWEA) 2011 conference, Brussels, Belgium, 2011.
<http://www.ecn.nl/docs/library/report/2011/m11033.pdf>, last access: 9 May 2016.

Whale, J., Andersen, C.G., Bareiss, R., and Wagner, S.: An experimental and numerical study of the vortex structure in the wake of a wind turbine, *J. Wind Eng. Ind. Aerodyn.*, 84, 1-21, doi: 10.1016/S0167-6105(98)00201-3, 2000.

- 480 Wharton, S., and Lundquist, J.K.: Atmospheric stability affects wind turbine power collection, *Environ. Res. Lett.*, 7, 1–9, doi:10.1088/1748-9326/7/014005, 2012.

Zahle, F., and Sørensen, N.N.: Characterization of the unsteady flow in the nacelle region of a modern wind turbine, *Wind Energy*, 13, 271-283, doi: 10.1002/we.418, 2011.