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Measuring the Power Curve of a Small-scale Wind Turbine: A Practical Example

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Abstract: We show that the measurement of the power curve of a small-scale wind turbine system following the IEC 61400-12-1 standard might lack consistency. This is due to characteristics specific to small-scale wind turbines. We give recommendations to ensure consistency, accuracy and reproducibility of the measurements. Besides, in the hope of making the standard more accessible, we clarify the impact of various parameters such as generator heating, battery voltage, controller settings, and anemometer position. Our Matlab code used for data processing is included.

Keywords: Small-scale wind turbine; Wind energy conversion system; Power curve; Testing.

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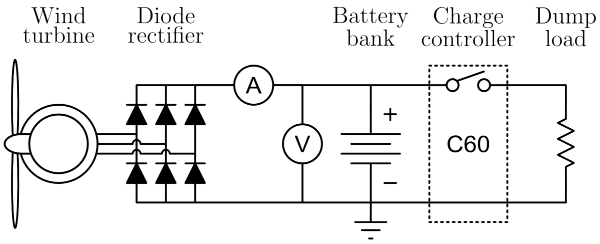
1. Introduction

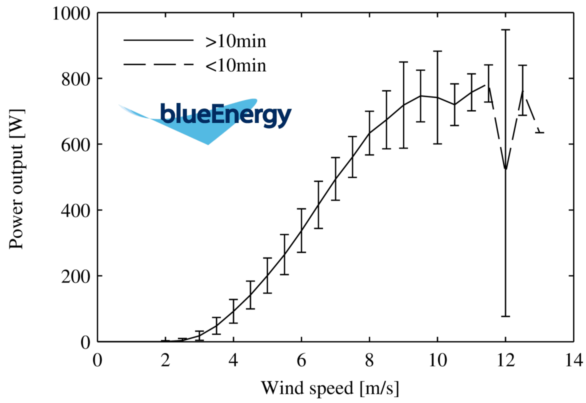
The small-scale wind turbine (SWT) industry has experienced strong global growth, with a cumulative total of over 730,000 installed units, and a 27% increase in installed capacity in 2010 [2]. While grid-connected SWT represent a large market share (82% in 2009 [1]), off-grid SWT can economically solve power supply problems in rural areas where there are strong wind resources.

The power curve of a wind energy conversion system, whether a stand-alone system with a battery bank or a grid-connected system, is an important characteristic. Along with local wind statistics, it enables the estimation of annual energy production, allowing for cost comparison with different energy generation options such as photovoltaic, diesel, or grid connection. It is also a metric for wind turbine

Figure 1. (a) Overview of blueEnergy's small-scale wind turbine system. (b) Power curve of blueEnergy's blueDiamond3-TSR6. The error bar represents the power output standard deviation in each bin. (c) Tilt-up test tower. (d) Wind turbine generator with anemometer boom.



(a)



(b)

(c)

(d)

designers, allowing them to evaluate the impact of design changes. It is crucial to have a standard to measure the power curve of a SWT. Not having a uniform procedure could make comparisons between turbines difficult and create an avenue for fly-by-night vendors to introduce unreliable machines into developing markets. This can both damage public perceptions of the technology as well as lead to economic losses. In this context, USA, Canada and the UK have been developing testing standards for SWT [4–6]. These standards are largely derived from the International Electrotechnical Commission (IEC) 61400-12-1 standard [3] and its annex H for SWT.

The standard should ensure consistency, accuracy and reproducibility in the measurement and analysis of power performance of small-scale wind turbines. We show here that the measurement of the power curve of a 3.6 meter diameter, horizontal-axis battery-connected wind turbine system following the IEC 61400-12-1 standard might lack consistency. This is due to characteristics specific to SWT. Besides, the IEC standard is well detailed but comes without a practical example that could help to make it more accessible. This article fills in the gap. The Matlab code for processing the measured data is included in the appendix.

Table 1. Device references

Device	Model
Voltage transducer	Ohio Semitronics VTU-003X5Y
Current transducer	Ohio Semitronics CTH-101LSX5Y
Anemometer	NRG Maximum ♯40H
Wind vane	NRG ♯200P
Datalogger	Campbell CR10X

Table 2. Datalogger parameters

Measure	Location	Freq	Recording
Wind speed	boom on test tower (20 m high)	1 Hz	1 min ave
Output current	after rectifier (DC)	1 Hz	1 min ave
Output voltage	battery bank (DC)	1 Hz	1 min ave

2. Experimental Setup

The power curve is a graph that represents the system electrical power output as a function of the wind speed. It is obtained from field measurements. An anemometer is placed close to the wind turbine and the wind speed is recorded. At the same time, the electrical power output from the generator is recorded. Fig.1(b) shows the measured power curve of blueEnergy's "blueDiamond3-TSR6" wind turbine. blueEnergy is a non-profit that has manufactured small wind turbines in Nicaragua. In this section, we describe the experimental setup used to obtain this power curve.

2.1. Overview of the system

The systems considered here consists of: horizontal-axis wind turbine (3.6 m diameter), permanent magnet axial flux generator [9–12], test tower (hub 24.4 m high), 3-phase diode rectifier, 24 V battery bank (3x4 Trojan 6 V, deep cycle), and charge controller (Xantrex C60) with a resistive dump load.

2.2. Data measurement

The rectifier output current is measured with a shunt. The battery bank voltage is measured with a voltage transducer. The wind speed is measured with an anemometer installed on a boom on the same tower as the wind turbine (Fig.1(d)). Following IEC standard, datalogger parameters are set as summarized in Table 2. Data were recorded during 20 days (480 hours).

2.3. Data rejection

We apply three filters to take into account external factors such as the stopping of the turbine for maintenance. First, we remove the data with wind speed under 0 m/s. Second, we remove the data with current under 0 A. Third, we remove the data with battery voltage under 21.66 V (22.8 V -5%) or above 30.24 V (28.8 V +5%).

2.4. Additional correction factors

The anemometer boom is several meters below the wind turbine hub. The wind speed at hub height is estimated using a power law wind shear model [13],

$$\frac{v(h_{hub})}{v(h_{boom})} = \left(\frac{h_{hub}}{h_{boom}}\right)^{\alpha} \tag{1}$$

where v is the wind speed, h_{hub} is the wind turbine hub height, h_{boom} is the anemometer boom height, and α is the wind shear factor.

In order to avoid the effect of air density on the measurements, the IEC standard require output power data to be normalized to an ISO standard atmospheric pressure. The normalization is applied using [3],

$$\frac{P_{norm}}{P_{meas}} = \frac{\rho_0}{\rho_{meas}} \tag{2}$$

where P_{norm} is the normalized power output, P_{meas} is the measured power output, ρ_0 is the reference air density, and ρ_{meas} is the measured air density.

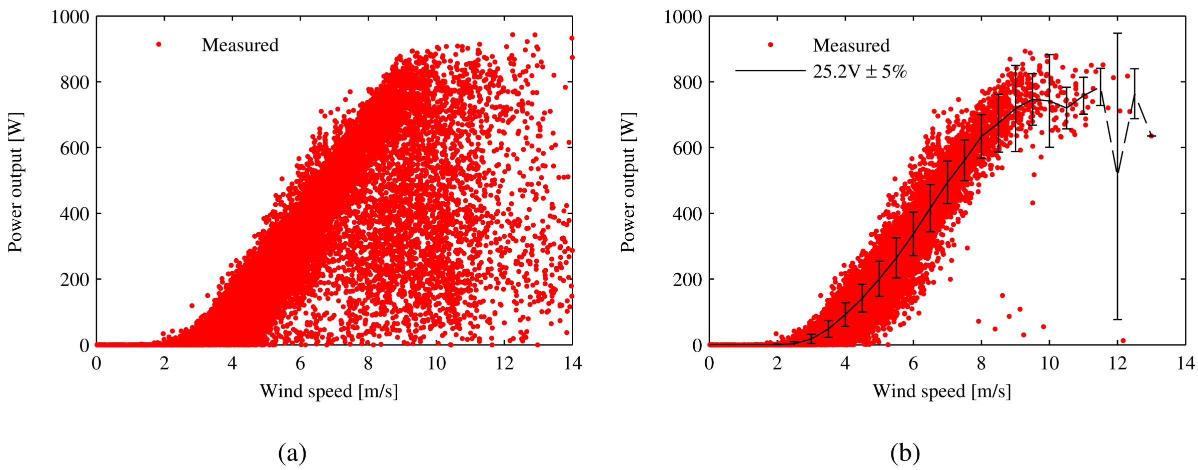
3. Power curve characterization

The measured data set, after data rejection and application of the additional correction factors, is shown in Fig.2(a). In this section, we show how to obtain the power curve from it.

As recommended by the standard [4, section 2.1.7], we select only the data with a battery voltage of $25.2\ V \pm 5\%$ (see section 5.2). The resulting dataset is shown in Fig.2(b).

The power curve shown in Fig.2(b) is obtained by applying the binning method. The binning method consists of grouping output power measurements into wind speed bins so that an average output power is obtained for each bin. The IEC standard calls for ”0.5 m/s contiguous bins centered on multiple of 0.5 m/s”. The more data, the greater the certainty will be for the averaged value in the power curve.

Figure 2. Power curve characterization. (a) Measured data set. (b) Measured data set at $25.2\ V \pm 5\%$ and power curve. The error bar represents the output power standard deviation in each bin.



Following IEC 61400-12-1 annex H, the data set shall be considered complete when it has met the following criteria:

(i) Each wind speed bin between 1 m/s below cut-in and 14 m/s shall contain a minimum of 10 min of recorded data (ie. 10 points per bin).

(ii) The total database contains at least 60 hours of data (ie. 3600 points) with the wind turbine within the speed range and the battery voltage within $25.2\ V \pm 5\%$.

(iii) In the case of furling turbines, the database should include completed wind speed bins characterizing performance when the turbine is furled.

Our dataset meets (i) and (ii) for wind speed under 11 m/s, but (iii) could not be satisfied because of the typical low wind regime at the test site (see Table 3).

4. Consistency

The procedure should be consistent and reproducible. To test it, we extract 3 subsets from the main dataset (Table.3). In compliance with the standard, each subset meets requirement (ii). The bins that satisfy (i) are used to plot the power curves shown in Fig.3(a). We observe a lack of consistency and reproducibility: at 8 m/s, the average power output varies between 610 W and 680 W.

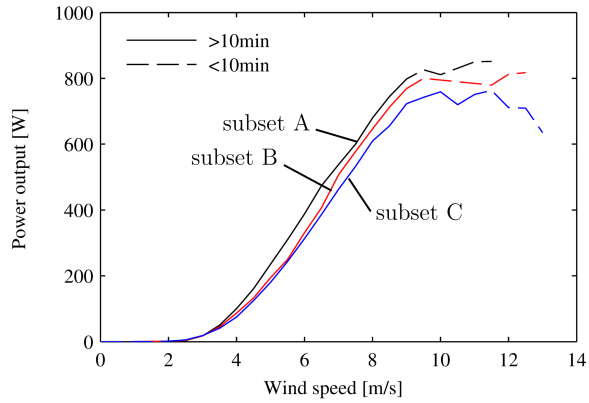
The wind characteristics corresponding to the 3 subsets is shown in Fig.3(b). The power output variation is clearly not due to the wind direction because it is almost constant. But it can be a consequence of the different wind speed distributions: subset A has mainly low and moderate winds, subset B has mainly low winds, subset C has mainly moderate and strong winds. At high speed, the SWT generator typically tends to heat up, the battery voltage tends to rise and the charge controller tends to connect the dump load. A combination of these effects could explain the lack of consistency.

5. Influence of external parameters

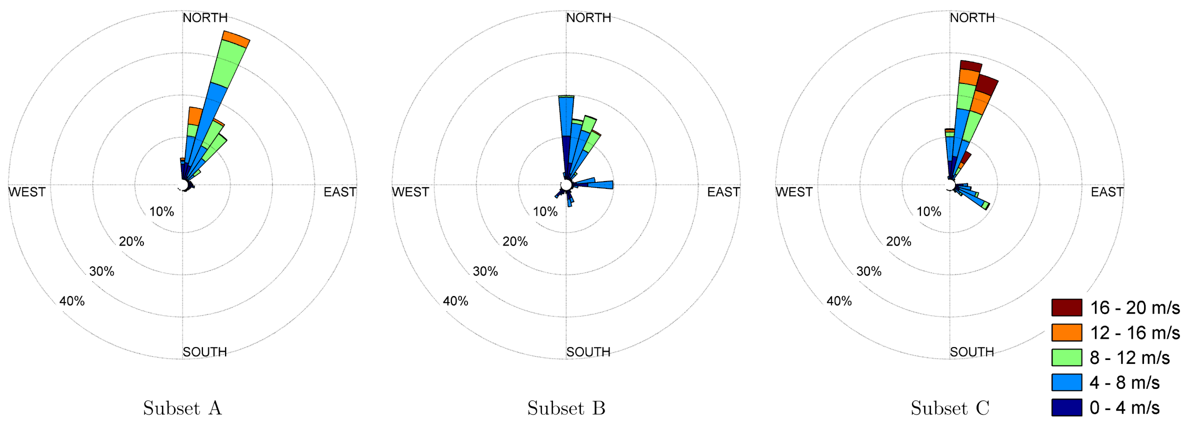
5.1. Generator heating

Small-scale axial flux generators can have important localized heating because of (1) their high power density, and (2) their poor thermal design in comparison with large-scale machines. To illustrate the potential impact of generator heating on electrical output power, we carried out test bench measurements. We measured the output power as a function of the rotor speed. Results are shown in Fig.4(a). The battery voltage was regulated to 27 V. The ”no heating” curve was obtained from standstill and room temperature, by increasing the rotor velocity by 10 RPM every 15 s. The final temperature of the generator was under 60^{o}C. The ”with heating” curve was obtained from steady-state temperature for a rotor velocity of 250 RPM, by decreasing the rotor velocity by 10 RPM every 15 s. The initial and final temperatures of the generator were over 100^{o}C and 90^{o}C, respectively. The scattering caused by generator heating can reach 50 W at 175 RPM. This gives us an upper bound on power loss due to machine heating.

Figure 3. (a) Power curves obtained with the 3 subsets. (b) Subset windroses. The length of each "spoke" shows the frequency that the wind blows from a particular direction over the specified period. Each spoke is broken down into color-coded bands that show wind speed ranges.

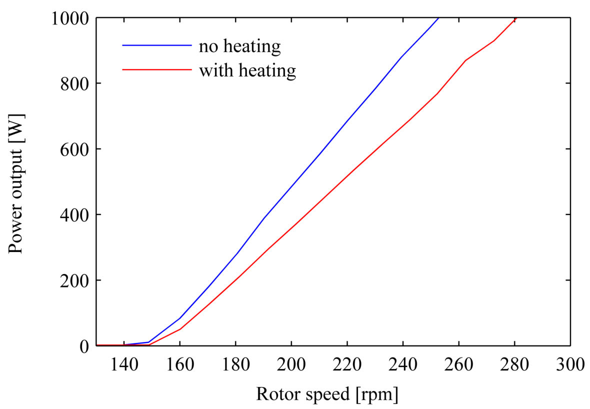


(a)

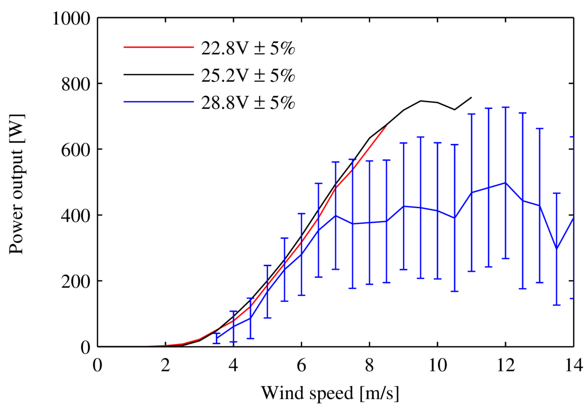


(b)

Figure 4. (a) Influence of generator heating. (b) Influence of battery voltage.



(a)



(b)

Table 3. Measured power curve for the data set and the three subsets.

Hub height wind speed (m/s)	data set Power output (W)	data set No. of data sets (1 min ave)	subset A Power output (W)	subset A No. of data sets (1 min ave)	subset B Power output (W)	subset B No. of data sets (1 min ave)	subset C Power output (W)	subset C No. of data sets (1 min ave)
0	0	71	0	4	-	0	-	0
0.5	0	94	0	4	0	1	-	0
1.0	0	128	0	14	-	0	-	0
1.5	0	251	0	40	0.8	13	0	1
2.0	0.4	495	0.7	106	1.7	24	1.6	11
2.5	3.6	1023	3.5	235	4.2	150	5.2	68
3.0	18.0	1753	16.8	360	17.0	335	18.1	207
3.5	47.9	2249	49.9	355	44.8	448	40.5	317
4.0	92.1	2227	100.3	333	86.5	417	75.0	236
4.5	141.7	2327	160.3	363	132.5	430	124.5	279
5.0	200.8	2185	234.6	406	193.8	439	179.5	336
5.5	264.6	1990	309.6	375	249.6	412	243.6	417
6.0	337.4	1595	388.3	347	331.0	295	312.7	449
6.5	415.7	1155	473.9	263	406.4	240	386.3	365
7.0	494.3	786	537.9	189	506.9	174	463.1	291
7.5	561.2	471	600.4	99	577.9	111	532.6	210
8.0	633.8	263	679.6	64	645.9	60	609.5	123
8.5	674.0	167	744.9	25	712.6	30	655.5	101
9.0	718.7	96	798.3	10	769.1	14	722.9	66
9.5	746.5	59	825.7	4	799.9	4	742.2	50
10.0	741.6	34	811.0	2	-	0	759.3	31
10.5	719.9	22	-	0	-	0	719.9	22
11.0	757.7	15	850.3	1	-	0	751.1	14
11.5	784.3	5	851.3	1	779.4	1	763.6	3
12.0	512.1	3	-	0	812.5	1	711.0	1
12.5	763.5	2	-	0	817.3	1	709.7	1
13.0	635.1	1	-	0	-	0	635.1	1
13.5	-	0	-	0	-	0	-	0
14.0	-	0	-	0	-	0	-	0
total		19467		3600		3600		3600

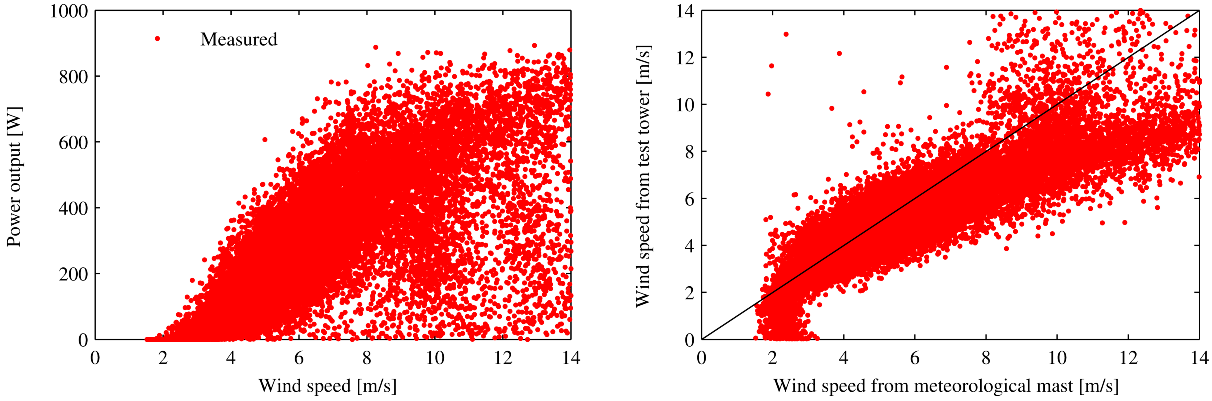
5.2. Battery voltage

At a given wind speed, the power output of a battery-connected wind turbine depends on the voltage of the batteries [8]. The power curve should be independent of the particular battery configuration. To this end, IEC standard requires to set the battery bank voltage to 25.2 V (for a 24 V nominal voltage system). Additional power curves should be obtained by setting the battery bank voltage to optional low (22.8 V) and high (28.8 V) settings. The scattering caused by a fluctuation of the battery voltage is 40 W for a wind speed of 7 m/s, as shown in Fig.4(b). The large standard deviation in the high voltage curve can likely be explained by the behavior of the charge controller.

5.3. Charge controller settings

Following IEC standard, the SWT systems includes the charge controller and the dump load. The charge controller is connected in parallel to the generator rectified output. It diverts the energy to the dump load when the battery voltage rises above a preset level (26.4 V here). This happens when the battery is fully charged or during wind gusts. The resulting effect can clearly be seen on the $28.8V \pm 5\%$

Figure 5. Wind speed comparison between anemometers. (a) Measured data set with anemometer on meteorological mast at hub height. (b) Comparison of wind speed measured between the test tower and the meteorological mast.



(a) (b)

power curve in Fig.4(b) : the output power has a large standard deviation and drops in average. The scattering linked to the charge controller settings during wind gusts is difficult to estimate.

5.4. Generator inertia

Due to the different inertia of the wind turbine and the anemometer, the output power at a given speed can be bigger or smaller than the steady-state output power. The assumption of the binning method is that the time lag for a downward step in wind speed is the same as the time lag for an upward step in wind speed, and that the occurrence of downward and upward steps within the binned data are the same. Then the binning method gives power curves of acceptable accuracy for practical purpose. But some errors arise from large wind gusts and from the SWT furling system that behaves differently between increases and decreases in wind speed.

5.5. Anemometer position

To illustrate the influence of the anemometer position, we recorded simultaneously the wind speed on a meteorological mast situated 40 m away from the test tower. Note that the maximum distance allowed by the IEC standard is 4 times the turbine diameter, ie. 14.4 m. The data set obtained (Fig.5(a)) shows a large scattering in comparison to Fig.2(a). The wind speed simultaneously measured by both anemometers is shown in Fig.5(b). The wind speed error between the two towers can stretch to 2 m/s.

5.6. Recommendations

Processing of the recorded data can correct for a number of uncertainties. Errors introduced by battery voltage are corrected by filtering out data recorded within the appropriate voltage range. The substantial variance introduced by the difference between the wind turbine inertia and that of the anemometer is smoothed using the binning method. However, in order for this form of averaging to reduce uncertainty, a minimum data set must be collected. (1) This may not always possible given time constraints, or the wind regime where testing is being carried out. We recommend to include the bins with insufficient number of data points but to mark this portion of the curve with dashes. (2) The minimum amount of data to be collected following the standard (10 points per bin) seems low to allow for the creation of a statistically probable power curve. This is even more critical considering the long time constant of generator heating, and the increase in the uncertainty linked to battery voltage and charge controller settings. We recommend that all power curves should display error bars, or at least have a note that the error for each bin is below a given percentage. (3) To address the consistency problem, we recommend increasing the size of the usable database when error bars are large. Further analysis needs to be done to look at the decreases in standard deviation if the database is increased to the requirements for large turbines, ie. 180 hours of data. (4) With the aim of reducing uncertainties linked with generator heating, and considering that manual start is not a ”normal” operating condition, we suggest to discard data recorded less than 1 hour after system startup. (5) It is critical that accurate wind measurements are made, correlating well to the wind experienced by the wind turbine. As we demonstrated, even small distances between the wind turbine and the anemometer can introduce significant errors. As allowed by the standard, we recommend to install the anemometer on a boom on the same tower as the wind turbine, ”at least 3 m away from any part of the rotor”.

6. Conclusions

Following the IEC 61400-12-1 standard, we measured the power curve of a stand-alone small-scale wind turbine with battery energy storage. We observed a lack of consistency when analyzing various data sets. We investigated the parameters that could be responsible for such a variation: generator heating, battery voltage, charge controller settings, generator inertia and anemometer position. We recommend including error bars with power curves, increasing the size of the usable database, rejecting system manual start data, and installing the anemometer on a boom on the same tower as the wind turbine.

7. Appendix - Matlab code

```
%% Parameters and data
bin = [0:0.5:14.5]; % 0.5m/s wind bins
load blueDiamond3-TSR6.mat % year,day,hour,spd,cur,volt

%% Data rejection and selection 24 V range
ind = find(spd>0 & cur>=0 & volt>=23.94 & volt<=26.46); % 25.2+-5%
spd = spd(ind); cur = cur(ind); volt = volt(ind);

%% Correction factors
spd = spd*(24.4/20)^0.31; % speed corrected with Eq.(1)
pwr = volt.*cur/0.95; % power correct with Eq.(2)

%% Binning method
for i = 1:length(bin)
    ind = find(spd>=(bin(i)-0.25) & spd<(bin(i)+0.25)); % 0.5m/s bins
```

```
    pts_bin(i) = length(ind); % bin nb of points
    if isempty(ind)
        pwr_bin(i) = NaN; vel_bin(i) = NaN; err_bin(i) = NaN;
    else
        pwr_bin(i) = mean(pwr(ind)); % bin average power
        vel_bin(i) = bin(i); % bin average speed
        err_bin(i) = std(pwr(ind)); % bin standard deviation
    end
end

%% Display Table 3
Table3 = [bin',pwr_bin',pts_bin']

%% Plot Figure 2(b)
ind10 = find(pts_bin>=10);  % >10 min
figure(); hold on , box on
    plot(spd,pwr,'.r');  % measured
    errorbar(vel_bin(ind10),pwr_bin(ind10),err_bin(ind10)); % >10 min
    errorbar(vel_bin,pwr_bin,err_bin,'--'); % <10 min
legend('Measured','25.2V \pm 5%',2), legend('boxoff')
xlabel('Wind speed [m/s]'), ylabel('Power output [W]'), axis([0 14 0 1000])
```

Acknowledgements

The data presented in this work was collected during 2008-2009, supporting design and testing work for the non-profit blueEnergy, on the Atlantic coast of Nicaragua [7]. The setup, testing, and data collection were made possible with the support of numerous volunteers and local employees working for blueEnergy. A large portion of the testing equipment was donated by DNV Energy and the University of California, Berkeley.

Conflicts of Interest

The authors declare no conflicts of interest.

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