Power Output of a Fully Furled Bergey Excel-s Manufactured by Bergey Windpower Company (BWC).

by

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Introduction

The original intent of this study was to examine the power output of a quarter-furled Bergey Excel-s (10 kW) turbine. Matt Tritt (?) told me that folks out west (the Dakotas and Montana) often quarter-furl their turbine to avoid the shut-down of the GridTek10 inverter. When unfurled, the turbine produces too much power of the GridTek10 inverter and as a consequence spends lots of time off line (due to power overloads) and hence looses about 20% of the potential annual production (see R#40 thru R#42 on SWIEP http://www.ualberta.ca/~mtyree/SWIEP/Publications.html). So I thought I should try this out, but I am usually located 2,400 miles NW of my turbine so I asked my neighbor to give me a hand. I assumed that ¼-furled means that you turn the tail until it is about 23^o out of alignment with the body of the turbine.

I tried my best to explain to my neighbor what I thought ¼-furled means and he did this while I talked to him on the phone. So I started collecting data which looked reasonable, i.e., about a 16% drop in power production. But when I got home for my holiday-break I noticed that he misunderstood me and the turbine was fully furled! You furl the BWC turbine by cranking in a cable at the base of the tower. So now I was surprised that a fully furled turbine produced so much power AND I noticed that it could still overload my GridTek10 inverter.

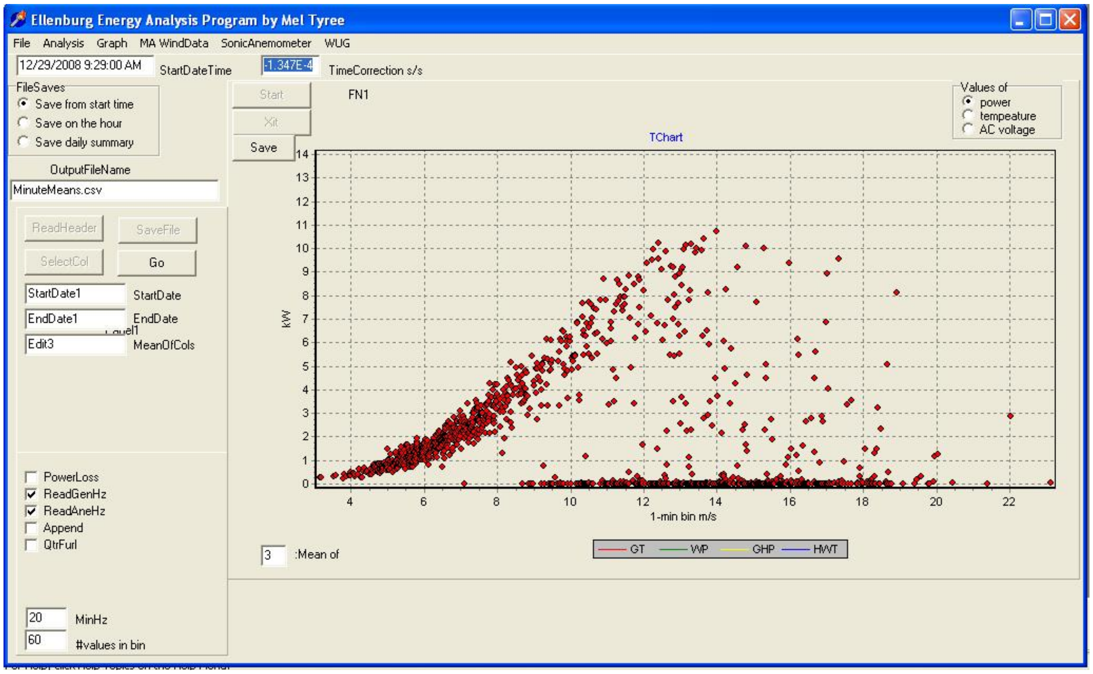
Methods

See R#40 thru R#42 for details of the methods I use. Briefly I monitor AC voltages on my service panel so I can tell when there are power outages caused by my power company (NYSEG). I also monitor voltage and current into the GridTek10 (= output of the Excel-s), voltage and current output (from which power in kW is calculated), I measure turbine RPM, and wind velocity at 102 ft (which is about 20 ft below hub height). With this setup, I cannot measure a true power-curve rather I measure what I call a power correlation curve (PCC). The PCC differs from a power-curve in that the mean wind velocity 20 ft below the hub is likely to be below that at hub height by 7% or less. I use the PCC curve or RPM to estimate how much power (kW) or energy (kWh) I loose whenever the GridTek10 has a fault. There are three common faults which I define as:

- Fault 0 = power-company's grid is down so the GridTek10 has disconnected.
- Fault 1 = the GridTek10 was overloaded by exceeding a power of about 12.4 kW and has gone off-line for 5 minutes.
- Fault 2 = the GridTek10 has experienced a bus voltage overload and remains off-line until I manually push a reset button (see R#39).

Results

It is normally not as windy in my NY home as in the Great Planes States, but occasionally we get a good wind-storm. I had one from about 2 PM on 28 December 2008 until the next morning. Figure 1 shows the PCC based on consecutive 1-min bin wind speeds.


Ellenburg Energy Analysis Program by Mel Tyree

12/29/2008 9:29:00 AM StartDateTime
-1.347E-4 TimeCorrection s/s

FileSaves
● Save from start time
○ Save on the hour
○ Save daily summary

OutputFileName
MinuteMeans.csv

StartDate1 StartDate
EndDate1 EndDate
Edit3 MeanOfCols

☐ PowerLoss
☑ ReadGenHz
☑ ReadAneHz
☐ Append
☐ QtrFurl

20 MinHz
60 #values in bin

3 :Mean of

Values of
● power
○ tempeature
○ AC voltage

Figure 1: I illustrate here the output of a program I wrote to analyze the data I am collecting. Above is an analysis of the data I collected for 14 hours starting at 2 PM December 28, 2008. In this case I computed consecutive 1-min bins of mean wind speed (x-axis) versus bin mean power (kW). This is similar to the way power-curves are measured by AWEA and IEC standards except that hub-height measurements of wind speed are usually made, but in this case wind speed is measured on the turbine tower 20 ft below the hub.

In the case of BWC's Excel-s turbine, the PCC does not look very good, because there are many high-wind-speeds with zero kW output power, i.e., during periods when there is a Fault 1 or 2 condition. The 'snow-fall' of values below the PCC corresponds to 1-min periods during which the turbine produced power for only part of the 1-min bin. To get an idea of what an 'ideal' PCC might look like without outages, we need to selectively collect a PCC for bins when there are no Fault conditions (0, 1 or 2). This is illustrated in Figure 2 for both fully-furled and unfurled turbines collected on different dates.

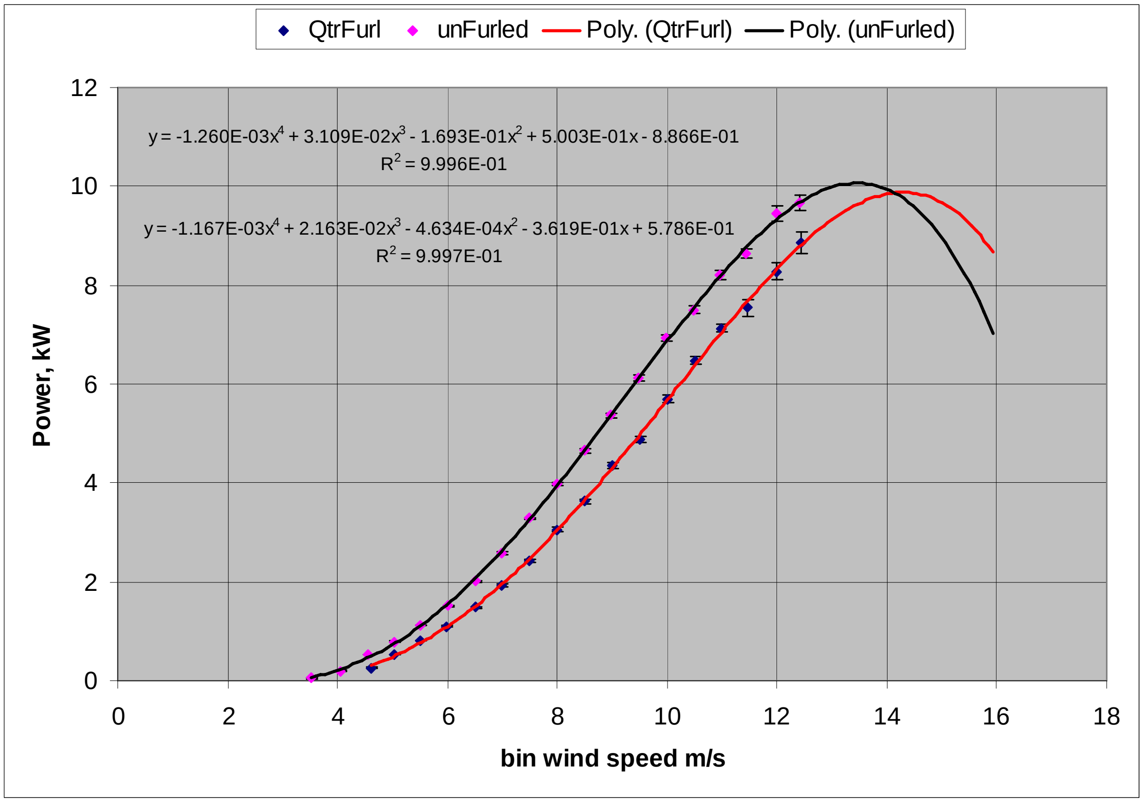


Figure 2: The PCC collected by selectively removing bin wind-speeds where the GridTek10 inverter is off line due to Faults 0, 1 or 2 (see Methods). Points are mean values and error bars, when visible, are the standard error of the mean (SEM). When SEMs are too small they are fully covered by the size of the points.

The PCCs in Figure 2 have no points for wind-speeds > 12.5 m/s because the probability is so small for the GridTek10 to remain online for 60 s when the mean wind-speeds equal or exceed 13 m/s. See Appendix 1 for more details. A well designed turbine will remain on-line producing power near the peak value up to wind-speeds exceeding 20 m/s. As an example look at the recent power-curve measured by ASU on Southwest

Windpower's Skystream turbine (R#43). The Excel-s turbine is clearly 'too big' for the GridTek10. An ideally-designed inverter for the Excel-s might follow the trend of the extrapolated polynomial curve in Fig 2 up to about 14 m/s then level out remaining at a constant output of 10 kW. The original intent of BWC & Xantrex was to make an ideal inverter, because on page 4-1 of their manual they write: **"If the available generator power is above the maximum allowable power level of the [GridTek10], the control circuit will maintain maximum power."** From Figures 1 and 2 it can been seem that BWC fell well-short of the design goal!

Furthermore, the design goal does not even work for a fully-furled turbine. Furling does reduce the power output but not nearly as much as I might have guessed. Figure 3A shows power loss as a percentage of the unfurled power

= 100%(FP-unFP)/unFP, where unFP = the unfurled power at any given wind-speed and FP = the furled power at the same wind speed. And Figure 3B shows a plot of furled power versus unfurled power.

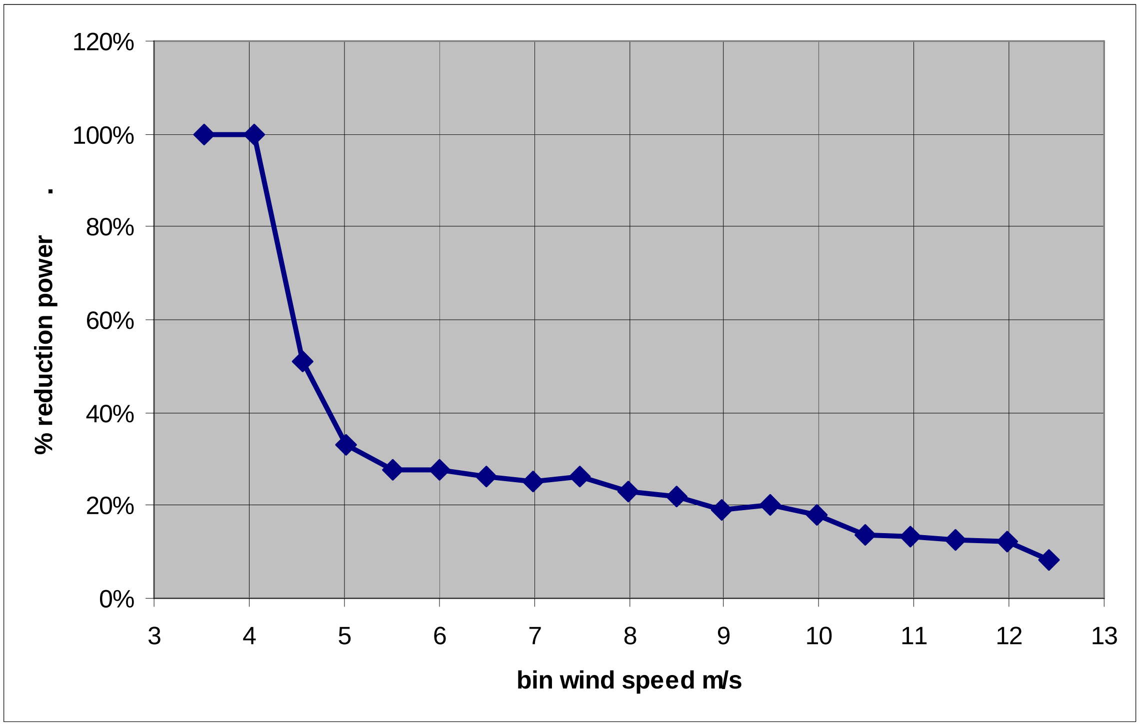


Figure 3A: Percentage reduction in power of a furled Excel-s as a percentage of the unfurled power output versus wind speed measured at 102 ft (20 ft below hub height).

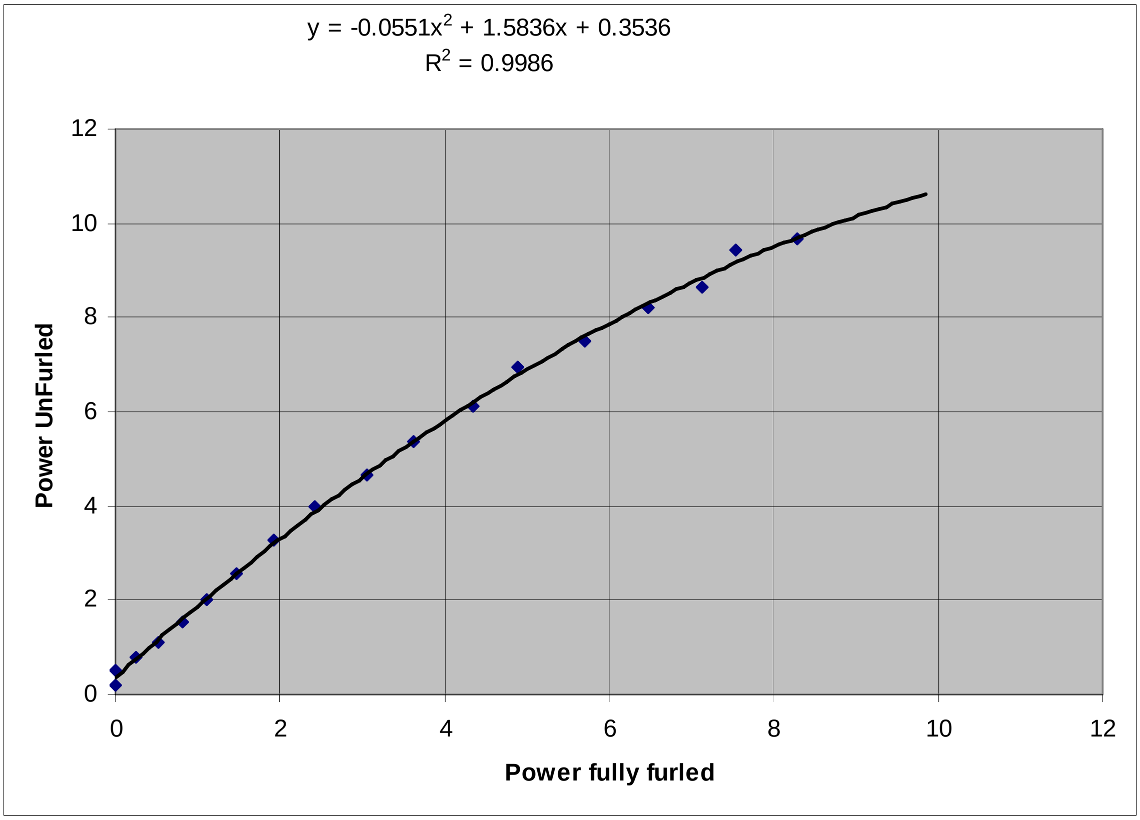


Figure 3B. A parametric plot of UnFurled power output versus Furled power output derived from Figure 2. This plot was used to estimate how much power might have been produced during a wind storm when power was measured from a fully-furled turbine.

Discussion & more Results

Figure 4: My turbine fully furled

A fully furled Bergey Excel-s produces a lot of power! Why? Part of the answer comes from just watching the turbine when it is windy. I have a quantitative measure of the wind direction using my wind-vain, but I have no quantitative measure of the direction the Excel-s points at any given wind direction. Qualitatively, however, visual inspection can assess the direction within ± 12^o, e.g., I think I can tell NW from WNW etc. My visual assessment is that the fully-furled tail directs the turbine only about 35^o ± 12^o from the wind direction (on average). At the time I observed this the wind direction was rapidly changing from WNW to S so the direction of the turbine was changing rapidly to keep up with the wind direction. I had expected a deflection closer to 90^o. So just based on a cosine law, it appears that about 70% of the sweep-area of the blades is still presented to the wind when the turbine is fully furled.

So how much power might be lost by a furled versus unfurled Excel-s during a windy event? I recorded power production and wind speed for a 20 h period from 2PM Dec 28th 2008. It was quite windy for the first 8 h and the GridTek10 went off-line many times during the storm AND needed a manual reset 6 times. So furling does not prevent this problem on my Excel-s with SH3055 blades. Maybe furling will work better on older type blades which produce less power (see R#23). Anyway, during this storm the turbulence intensity was higher than average (0.23 versus my ‘normal’ 0.15) and the 1-min bin wind-speeds were within the normal range for an AWEA or IEC power-curve (see Figure 5A and 5B).

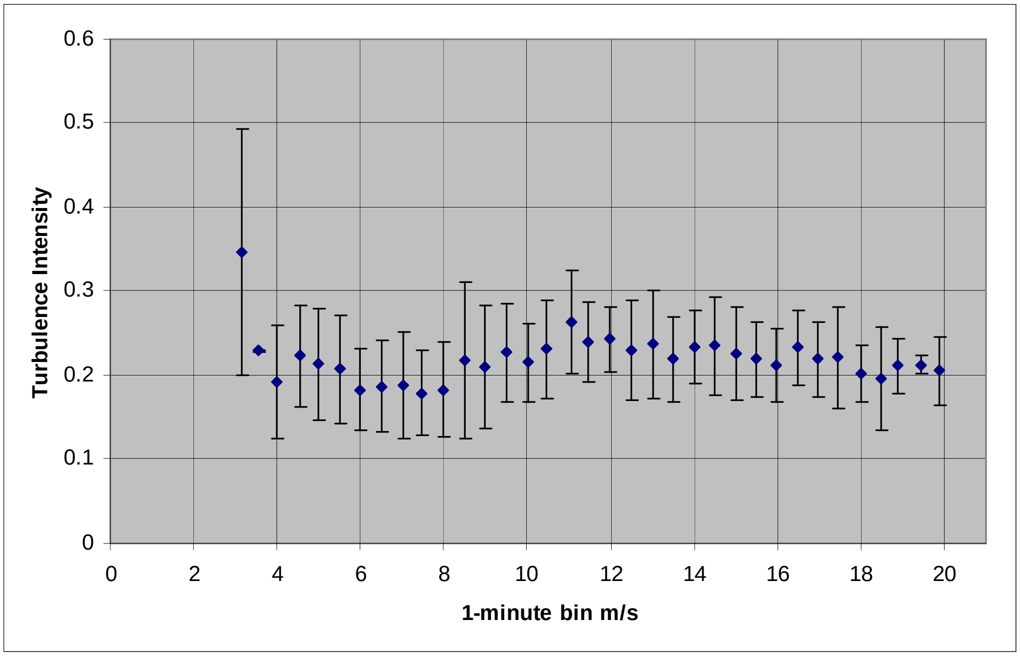


Figure 5A: Turbulence intensity (TI = standard deviation of wind speed/wind speed) versus 1-min bin wind speeds. The error bars are the standard deviation of the TI.

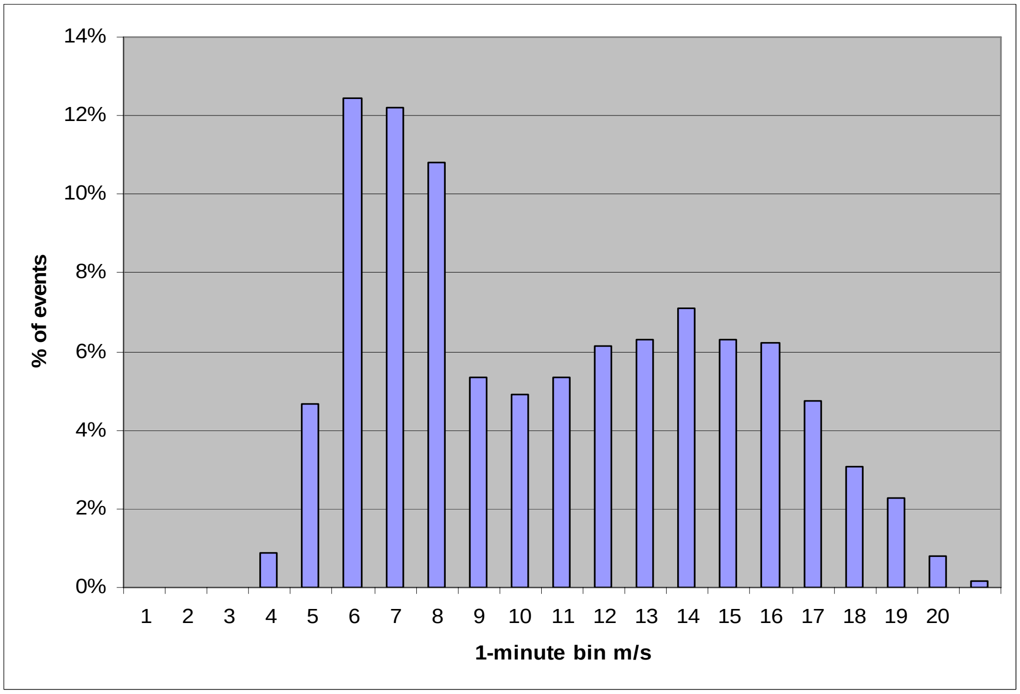


Figure 5B: % of 1-min bin mean wind speeds observed over a 20 h period starting at 2 PM Dec 28th 2008. The main storm lasted 12 h and produced most of the speeds above 13 m/s. The more frequent lower wind speeds occurred in the last 8 h.

However, during the windiest period wind gusts did go up to 27 m/s as evidenced by the 1-s readings during one h of the storm shown in Fig. 6 which is representative of other hours of the storm.

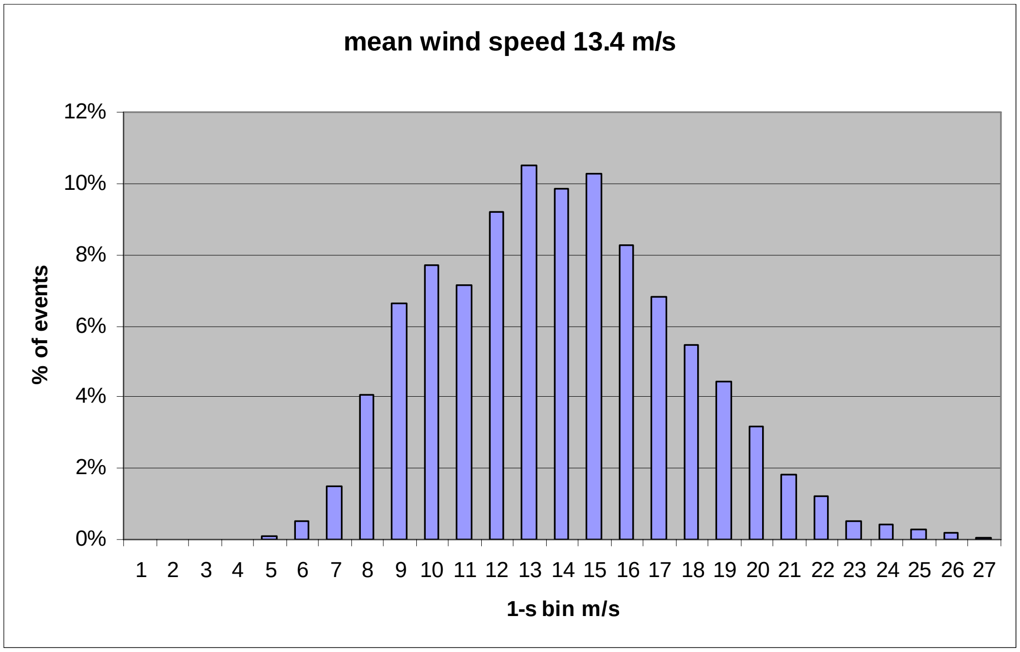


Figure 6: Wind speeds were sampled at 1 Hz. The figure above is a histogram of 1-s readings. Y-axis = the % of seconds in one hour versus X-axis = the wind speeds in 1 m/s bins.

How much power was produced by the fully-furled turbine and how much was potentially lost? This is illustrated in Figure 7 below. The amount of power produced by the fully furled turbine was about 37.4 kWh during the storm, but the amount of energy that might have been captured by an unfurled turbine with an ‘ideal’ inverter is given in the solid pink line (109.2 kWh). This line was computed from the unfurled PCC in Figure 2 assuming the inverter performed according to the design goals in the quote on page 4 (bold quote). If I had left the turbine unfurled and check for Fault 2 only twice a day at 7 AM and 7 PM I would have lost almost all the power production (see thin blue line, see also R#40). See Appendix 2 for how I computed lost production. So completely furling the turbine is better than not furling at all. However, the amount of energy lost even while furled is surprisingly large. I have estimated this loss to be 77.5 kWh. Part of this loss is due to the lower PCC (See Figure 2 or Figure 3B) but most of the loss (about 50 kWh) was due to the time the GridTek10 spent off line due to Fault 1 and Fault 2 events. I stayed up late on the night of the 28th to keep the period in Fault 2 condition at a minimum. Fault 1 conditions occurred 65 times and Fault 2 occurred 6 times in 8 hours! Had I NOT reset the turbine 6 times I would have lost most of the power produced, i.e., all but about 5 kWh.

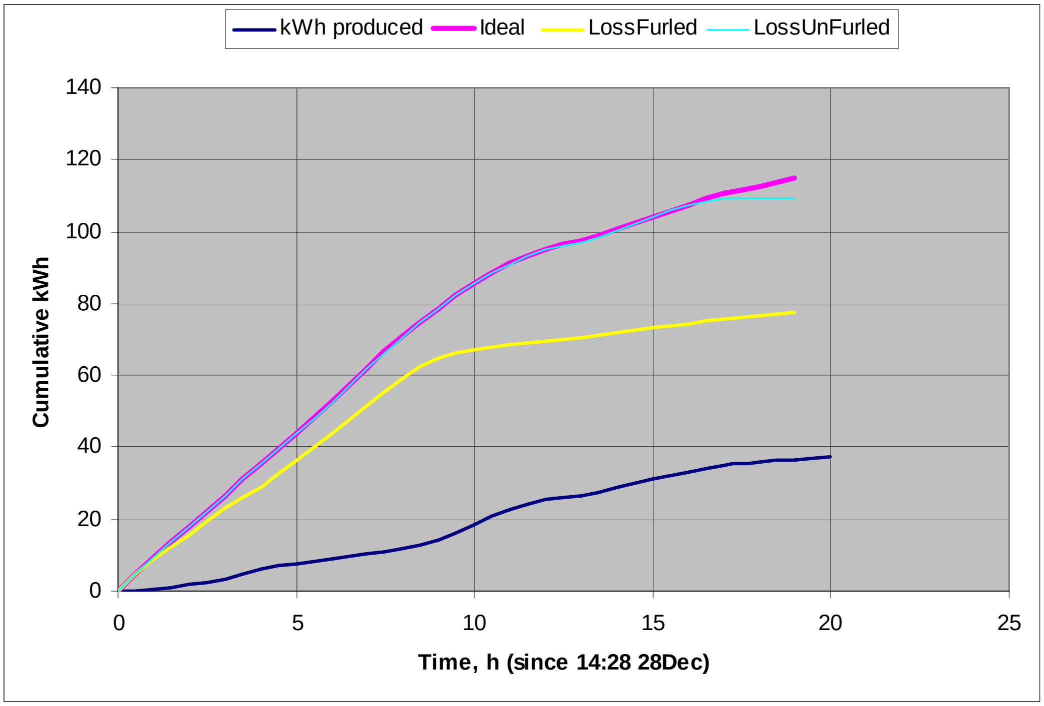


Figure 7: The blue line is the cumulative amount of power produced by a fully-furled Bergey Excel-s turbine, which I had to reset 6 times in the first 8 hours to keep power production going. See text for more details.

Conclusion

There is potentially a lot of energy to be gained by owners of a Bergey Excel-s who live in windy locations who wish to upgrade their systems. For maximum gains you will want to upgrade from the older blades to the SH3055 blades and from the GridTek10 to new PowerSync II inverter PROVIDED the new BWC inverter has an ideal behavior. I hope to evaluate the PowerSync II as soon as BWC is willing to sell me one! For an example of an ideal inverter see the Skystream (R#43). Without bothering with an upgrade the potential exists that 2 Skystream turbines might produce as much energy as one older-style Bergey Excel-s system. I will evaluate this in more detail in the future and let you know if my guess is correct.

Comments and suggestions for correction and improvement of what I write above are most welcome. I will revise this report as needed.

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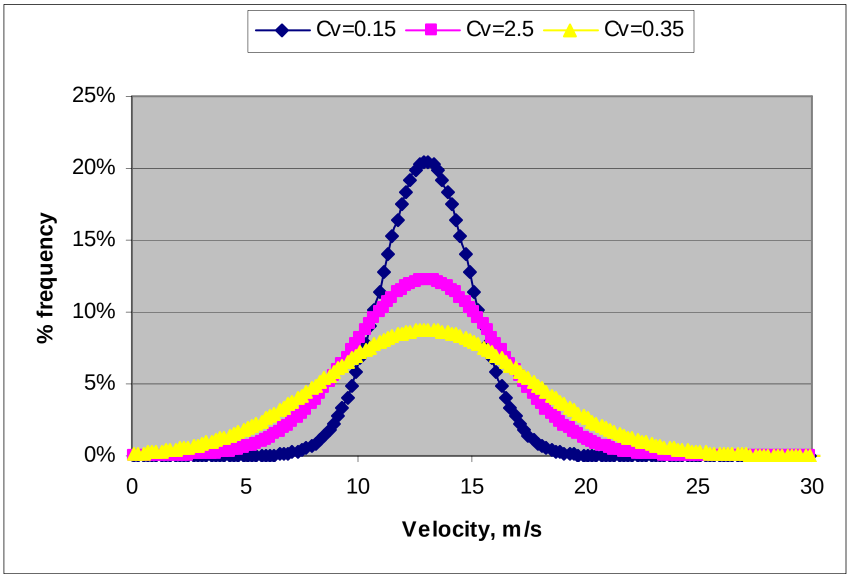
APPENDIX 1 (Why my Bergey goes offline at low mean wind-speeds)

The Bergey Excel-s will go offline (Fault 1) when the 3-s mean wind-speed exceeds about 17 m/s. So why can't I collect one minute's worth of power production data when the wind speed exceeds just 13 m/s? This is because wind speeds in any given 1-min interval have a Gaussian distribution determined by the mean and standard deviation (SD) of the 1 Hz wind-speed measurements. This issue is fully discussed in SWIEP posting R#30 but I reproduce below the probability density function for a mean wind-speed of 13 m/s. C_v = SD/mean = turbulence intensity. The C_v at my turbine-site is between 0.15 and 0.25. This Gaussian distribution of wind speeds means that there is a high probability of a 3-s wind gust exceeding 17 m/s, which would trigger a Fault 1 condition. This explains why there are no bin values above 12.5 m/s in Figure 2.



APPENDIX 2 (How I computed lost production).

During the wind-storm event the fully-furled Excel-s turbine frequently went offline because of Fault 1 or 2 events. During these events I still had wind velocity data sampled at 1 Hz. I computed running mean wind velocities based on 60 1-s values ($\overline{u}_{60}$). For every second the turbine was furled and in Fault 1 or 2 condition I used second equation in Fig 2 to compute lost power (kW = y_2) from $x = \overline{u}_{60}$ when $x < 14$ m/s. If $x \geq 14$ m/s I assumed a constant power production of 10 kW. The computed lost power (yellow line) was much more than the produced power (blue line). I added to the lost power under Fault 1 or 2 conditions, an additional amount equal to the difference between the first and second equations ($y_1 - y_2$) for every second of wind velocity data. However, I stayed up late resetting the GridTek10 inverter whenever Fault 2 was noted to keep the turbine producing as much as possible. Had I reset less frequently then more energy would have been lost and the net gain would have been just a few kWh versus a potential gain of 109 kWh.

For the unfurled state the computation was a little more complex. I had to estimate when the unfurled turbine would be offline because of Fault 1 or 2 conditions. To do this I computed the 3-s running mean wind velocity, $\overline{u}_3$, and when this value exceeded 17 m/s I then I noted a Fault 1 condition and used the first equation in Fig. 2 to compute lost power for the next 5 minutes (300 s), where power in kW = y_1 and $x = \overline{u}_{60}$. If at the end of 300 s of Fault 1 condition the value of $\overline{u}_3 > 19$ m/s I noted a Fault 2 condition and continued accumulating lost power as noted for Fault 1. In my simulation I assumed Fault 2 was cleared by manual rest only twice a day, i.e., at 7 AM or 7 PM. Hence almost all the potential power production was lost in Fig. 7. Had the 'simulated owner' stayed up all night resetting the inverter from Fault 2 conditions a few more kWh of energy might have been produced.