Thermodynamic Wind Energy Analysis: Bonneville Power Administration

Cal Abel
Skylane Engineering crabel@skylaneengineering.com

Abstract

Failure to incorporate statistical information into electrical grid analysis and energy policy hinders development. Using a thermodynamic approach, we show how renewable energy can be successfully integrated into the grid, and that the consequence of not properly curtailing wind generation is grid instability.

Introduction

Assessing various energy sources has been primarily done through looking at the average capacity factor over a year. From this basis and the stated policy objectives of providing carbon free electricity, renewable energy seems to be an attractive alternative. The problem with this approach is that it ignores the inherent unpredictability of wind energy and the need to balance electricity supply and electricity demand.

This motivated the search for an appropriate metric to quantify the unpredictability of renewable energy sources. First efforts focused on adapting the Effective Forced Outage Rate (EFOR) to assess reliability but this had little applicability outside of an arbitrary measure with little to no meaning in this application. The main effort shifted to adapting the methods of statistical mechanics to our application. We felt using the insights of Lienhard and Davis [1] were justified enough to explore this issue. To make the adaptation we used the methods of Gibbs [2].

Assumptions

Gibbs approach has two main components, first is the idea of the conservation of the density in phase. This is the first law balance. It states that the information contained cannot be created or destroyed. This holds for a frictionless system where there are no losses. In our application, we assumed that there were no line losses; any power produced has to be consumed. This is the condition of balancing the grid. If the grid is to maintain constant voltage and frequency it must produce and consume exactly the same net quantity of power for any given period of time.

The grid operators use either a 1-minute or a 5-minute average power to balance the grid. Over that integration period the average power delivered has to equal the average power produced. By using the same integrating interval as grid operators, we are able to make comparisons directly with the decisions they face.

We used the online data for the Bonneville Power Administration (BPA) from January 1, 2007 to February, 28 2011.[3] The study period was broken into several segments based upon the increases in wind capacity of the BPA grid, Table 1. Again, in order to make direct comparisons, each interval that we did analysis of wind was exactly the same interval that we used to analyze the service area load.

Unfortunately, we could not obtain generator level data. Such data is needed to do a formal aggregation of the various generators. Because of the lack of information, we treated wind as an aggregate that changed its density as generation capacity increased. As a result, we lost some of the information that would be contained in the covariance matrix of the power output from each generator. More detailed generator level information is needed to correct this assumption.

Table 1 Change in BPA Wind Generating Capacity

Total Capacity (MW)	Date Online
722	Oct. 4, 2006
922	Oct. 10, 2007
1148	Oct. 15, 2007
1274	Nov. 17, 2007
1301	Nov. 26, 2007
1397	Apr. 29, 2008
1421	May 10, 2008
1496	Jun. 6, 2008
1599	Dec. 7, 2008
1671	Jan. 1, 2009
1771	Jan. 27, 2009
1871	Feb. 12, 2009
1968	Mar. 22, 2009
2105	May 1, 2009
2254	Aug. 6, 2009
2284	Sep. 21, 2009
2517	Nov. 30, 2009
2617	Dec. 16, 2009
2680	Jan. 1, 2010
2780	Jan. 15, 2010
2830	Jun. 6, 2010
2836	Jun. 30 2010
2850	Aug. 11, 2010
3011	Aug. 11, 2010
3061	Oct. 8, 2010
3152	Oct. 24, 2010
3253	Nov. 15, 2010
3263	Nov. 29, 2010
3372	Dec. 1, 2010
3522	Feb. 11, 2011

Methodology and Results

We divided each day into three parts consisting of 96 5-minute increments. The raw data contained 437,760 data points for the five vectors we studied, wind, thermal and hydro generation, BPA service area load, and total power produced. In each of the 4,560 8-hour study periods, we computed an empirical cumulative distribution function, equation (1.1).

$$F_j(x) = \frac{1}{N_j} \sum_{i}^{N_j} \mathrm{Boole}\left[x_i \le x\right] \tag{1.1}$$

This was then used to estimate the probability density function and compute the probability for each data point, excluding missing data. We used Mathematica v9 for the analysis.[1] By breaking the problem up into the distinct sets and analyzing each individually, we were able to treat the problem as a series of 4,560 one-dimensional problems.

We computed the entropy in the standard manner for the j^{th} group, equation (1.2).

$$\left\langle S_j \right\rangle = -\sum_{i}^{N_j} p_{ji} \ln p_{ji} \tag{1.2}$$

Similarly we computed other expectations as,

$$\left\langle x_j \right\rangle = \sum_{i}^{N_j} p_{ji} x_{ji} \tag{1.3}$$

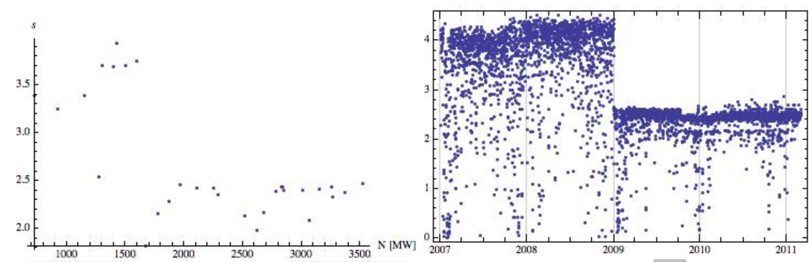


Figure 1 (a & b) Change in wind entropy in generation capacity and time.

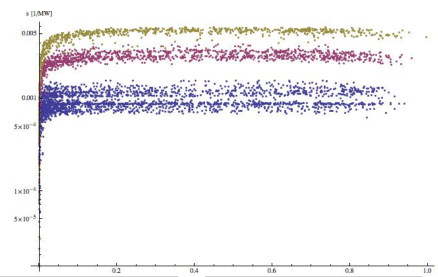
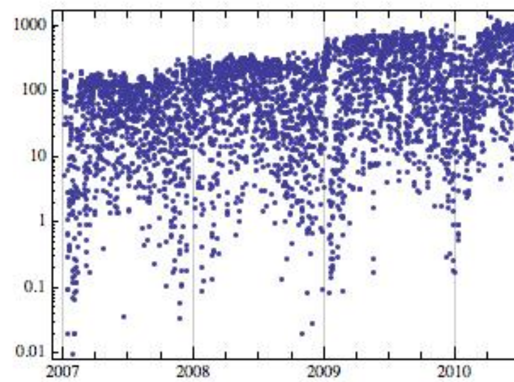


Figure 2 Wind specific entropy vs capacity factor.

Figure 1 shows the initial plot of the entropy as a function of installed capacity of the wind turbines. There is a shift in the entropy from 3.7 to 2.4 in the first period of January 1, 2009. While there was a capacity increase of 72 MW on that day, it is not sufficient to explain the entropy shift. Additionally, Figure 2, plot of the specific entropy to the capacity factor for each period, shows three specific operational regimes that are of sufficient differences that capacity changes cannot explain them. Additionally, in the first two periods shown in Figure 2, the specific entropy decreases as capacity increases. In the period, in question the BPA had a wind curtailment procedure when wind capacity reached 90% of installed balancing load.[4] Changes in the procedural and structural conditions of the BPA grid could help explain these abnormalities. Later, we will evaluate these differences and develop a simple and effective equation of state.

---

[1] The PDF's were not properly normalized under this software package. We verified that the computation of the PDF's was done properly by checking the expectations for each period against the simple arithmetic mean.



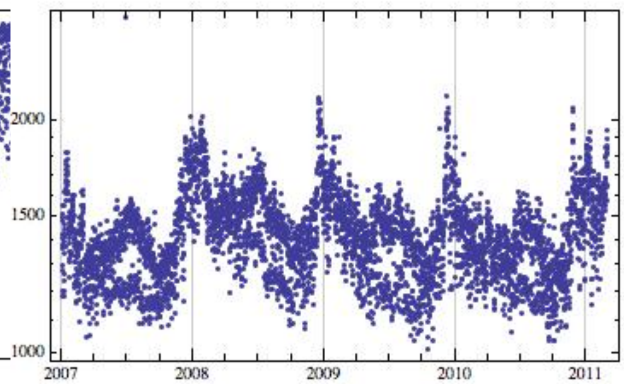


Figure 3 BPA wind temperature time series. Figure 4 BPA service area load temperature time series

If we were to account for changes in the installed turbines the Euler equation would be $U = TS + \mu N$. However, based off of the capacity factor for each turbine being independent of the number of turbines installed, $\mu = 0$ leaving $U = TS$. This assumption is valid because the turbines are placed at such an interval that the wake turbulence does not create mutual interference. This means that the entropy for the wind turbines does not depend on the installed capacity. Based on the information given it also provides a simple method for calculating the temperature of the wind as shown in Figure 3. Figures 3 and 4 show the time series plots of the wind and grid temperatures.

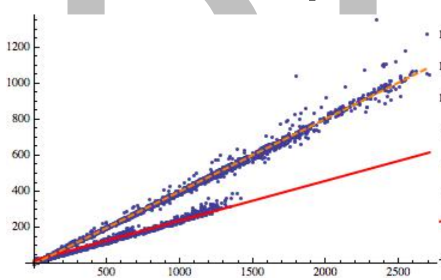


Figure 5 Wind T-U plot

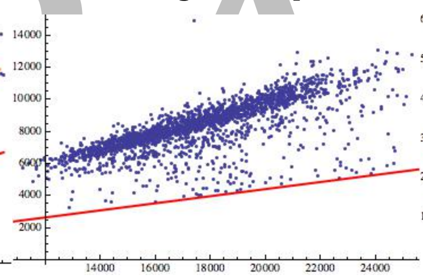


Figure 6 Dispatchable T-U plot

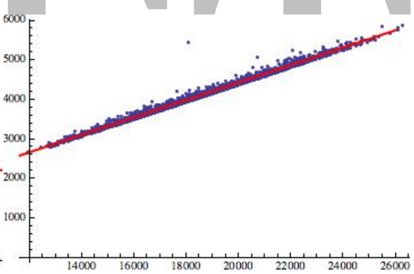


Figure 7 All generation T-U plot

When we shift to a $T - U$ representation, Figures 5, 6, and 7, we have a startling revelation, each generation source, the total load, and the sum of all generation is linear under a $T - U$. This is the same relationship that exists for ideal gases equation (1.4). The red lines in Figure's 5, 6, and 7 is the fit of the total generation over the range of generation for each source. The dashed orange line in Figure 5 is the fit of the data after the entropy shift noted in Figure 1b.

$$U = CT \tag{1.4}$$

Using a first law balance we have,

$$C_{total} T_{total} = C_{dispatch} T_{dispatch} + C_{wind} T_{wind} \tag{1.5}$$

We note that the grid has to be balanced with the generation, with their two temperatures and power produced balanced. This results in a relationship where the thermal generation has to produce more power at a higher temperature, Figure 6, and higher heat capacity.

$$C_{dispatch} = \frac{C_{total}T_{total} - C_{wind}T_{wind}}{T_{dispatch}} \tag{1.6}$$

Table 2 Regression Coefficients

(Post Jan. 2009)	C	T_0
All Gen	4.5	20
Wind Gen	2.5	0
Dispatchable Gen	2.1	0

We use the red line in Figure 6 as a counterfactual. We hypothesize that the temperatures corresponding with the power produced would be the case if there was no wind, and the remaining needed capacity was provided by another dispatchable generation source with the same heat capacity as the red line.

The actual data would then be a perturbation caused by the wind. Using equation (1.6), we have a distribution of heat capacity for the dispatchable generation, Figure 8. Where the mode of the distribution is 2.1. Please note that the heat capacity is dimensionless. Table 2 lists the fitted parameters for the total generation and the wind $U = C(T - T_0)$.

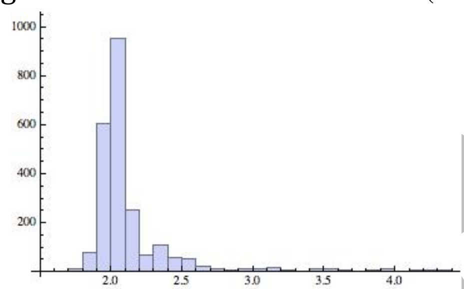


Figure 8 Histogram of dispatchable generation heat capacity

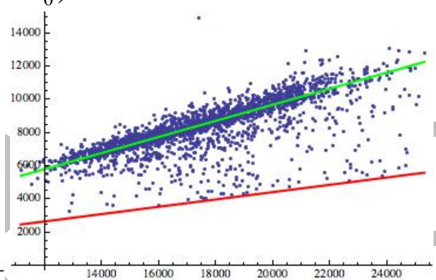


Figure 9 T-U plot of dispatchable generation with regressed equations of state

Figure 9 shows the result of the heat capacity for the dispatchable generation. There is a physical limitation for each of the generation sources where their continued operation is no longer economic. The reduction in the heat capacity is the same as a reduction in the system's entropy. From the standpoint of thermodynamic stability, a reduction in entropy over time, $\mathrm{d}S/\mathrm{d}t < 0$, is destabilizing. As we saw earlier, Figure 1b and Figure 5 it is possible to increase wind generation capacity in such a manner as not to reduce the entropy of other sources of generation. This mode of operation characterized the BPA prior to January 2009. Thus it is possible to have significant quantities of wind on the grid, however, it requires management of its entropy. If the grid operator is unable sufficiently to curtail wind generation, Figure 5, then the grid will be destabilized. The magnitude of the entropy loss determines the extent of destabilization. Operators can readily handle a small entropy loss, however, a large loss could cause a blackout.

As the penetration of wind energy in to the grid increases the heat capacity of the thermal generation sources is reduced. Rapid demand response needed in wind energy due to its elevated uncertainty/entropy, pushes the limits of what the other plants are capable of doing. It is not that renewables and distributed generation remove the need for baseload generation, they destroy baseload generation by destabilizing the gird.

Conclusion

We can see that entropy provides a very real measure for us to be able to assess the intermittency of wind energy and assess its impact to the overall grid. The temperature of the all generating capacity provides a means for us to assess the mix of generation capacity. It may even provide a better metric for assessing plant performance than other measures like EFOR. We can see too that there is a hidden cost to adding renewable energy into the grid. It can cause a loss of entropy, making other generation sources to have to work that much harder. As we see with the BPA, wind energy can be integrated into the grid if it is properly curtailed. If it is not managed, even relatively small penetration, <10%, can be destabilizing.

Grid entropy management is as important as ensuring that there are enough generation assets. As a tool the approach provided here hopefully demonstrates the importance of incorporating additional tools in our grid level analysis.

Future Work

The concepts here need to be further developed and tested. They need to be integrated with grid price data and economic modeling to be able to assess the costs of various policy alternatives.

References

1. Lienhard, J.H. and L.B. Davis, *An Extension of Statistical Mechanics to the Description of a Broad Class of Macroscopic Systems.* Journal of Applied Mathematics and Physics (ZAMP). **22**(1): p. 85-96.

2. Gibbs, J.W., *Elementary Principles in Statistical Mechanics Developed with Especial Reference to The Rational Foundation of Thermodynamics*1902, New York: Charles Scribner's Sons. 207.

3. *Data for BPA Balancing Authority Total Load, Wind Gen, Wind Forecast, Hydro, Thermal, and Net Interchange*, 2012, Bonneville Power Administration: http://transmission.bpa.gov/business/operations/wind/.

4. Fink, S., et al., *Wind Energy Curtailment Case Studies*, 2009, National Renewable Energy Laboratory: Golden, Colorado.