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CLIMATE REFERENCE NETWORK SOLAR POWERED SITE ANALYSIS

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ABSTRACT

The work presented here is a more formal continuation of past efforts to improve the quality and continuity of the measurements recorded at solar powered Climate Reference Network sites. In this study solar-powered Climate Reference Network sites that experienced power-limited periods were identified based on their 2008 and 2009 performance. The conditions under which the sites failed or neared failure were analyzed, and solutions were proposed. One of the relatively new components of the work presented here is an analysis of the potential for power production using small wind generators. Based on wind speed data recorded at individual sites during the periods when battery voltage approached critically low levels, it was apparent that many of the problematic sites would benefit from the addition of a wind generator. At a small number of sites, where wind speeds were insufficient to justify the installation of a wind generator, augmentation of the existing solar array and/or battery bank was recommended.

1. INTRODUCTION

Where line power was not available, Climate Reference Network (NOAA/NESDIS, 2002) sites were installed using solar panels and batteries to provide power for their sensors and data acquisitions systems. Historically, at some of the solar powered sites where data transmissions failed with an appreciable frequency the solar power systems were subsequently augmented with more batteries and/or solar panels. The work presented here includes a review of the solar powered site performance after these improvements were made. In addition, suggestions and metrics for use in guiding future improvements to existing solar-powered sites are presented.

2. METHODS

2.1 Background and Assumptions

In order to evaluate the primary causes of power failures and propose solutions, the load, storage capacity and power generated at individual Climate Reference Network (CRN) sites should be quantified. However power consumption and production were not monitored at CRN sites, and this analysis was based on best estimates. The estimates of power use that were formed during the design of the CRN system are given as follows: a CRN system with temperature probe aspiration fans on continuously draws 2 Amperes at 12 VDC; with the precipitation gauge (Model T-200B, Geonor A.S, Oslo, Norway) heaters on it draws 8 Amperes. To prevent the accumulation of frozen precipitation on the Geonor inlet and minimize power use, the Geonor heaters are activated when the battery voltage is above 12 V, temperature is between 5 C and -5 C, and the wetness sensor is activated. In this analysis, when all of these conditions were met the Geonor heaters were assumed to be on for the entire hour. In addition, hourly statistics were chosen to simplify the analysis and create a common measurement frequency for all variables analyzed.

In addition to the variable load, the changing capacity of the batteries potentially contributed to the loss of power experienced at some sites. Low temperatures are known to reduce the capacity of batteries. The degree to which this occurs is described by a ‘design factor’, which is a function of temperature and describes the amount by which the rated capacity of the battery bank must be multiplied in order to achieve the desired capacity. For the batteries used at CRN sites, this design factor was 1.6 at 0 to 9 deg. C, and 2.23 at -20 to -11 deg. C. In this analysis, the daily average data logger panel temperature was used as the best available proxy for the temperature of the batteries.

Horizontal wind speed (*u*) was measured at a height of 1.5 m AGL at all sites by a cup anemometer (Model 014A, Met One Instruments Inc, Grants Pass, OR, USA). These measured data were used to estimate wind speed at the planned wind generator installation height of 5 m AGL. Roughness length (z_0) was conservatively estimated from available site photos as 1/10 of the apparent canopy height, and when photos from multiple site visits were available the lowest canopy height was used. The logarithmic wind profile (Thom, 1975) was used to estimate the wind speed at z = 5 m:

$$\bar{u} = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right) \tag{1}$$

where *u* is the horizontal wind speed, *w* is the vertical wind speed, overbars represent block averaging, and u_* is the friction velocity ($\sqrt{-\overline{u'w'}}$). Assuming that u_* was equal at both heights, the wind speed at z = 5 m was estimated from:

$$u_{z=5m} = \left(\bar{u}_{z=1.5m}\right) \frac{\ln\left(\frac{5m}{z_0}\right)}{\ln\left(\frac{1.5m}{z_0}\right)} \tag{2}$$

A 4th order polynomial was fit to wind speed and power data provided by the manufacturer of one of the prospective wind generators (Model AIR X, Southwest Wind Power, Flagstaff, AZ, USA), and potential output from this wind generator was thereby estimated for every hour of data using mean wind speed estimated at z = 5 m.

3. RESULTS

3.1 Site Statistics

Statistics were generated for individual sites from hourly winter (1 November 2008 – 1 February 2009) data. These statistics, presented in Table 1, were used to guide decisions regarding augmentation of the solar and wind power infrastructure during the annual CRN site maintenance trips performed during the spring and summer of 2009.

'Data online' indicates the percentage of data available on the NCDC CRN website on 20 May 2009. The percent of time that battery voltage was less than 12 V (BV <12 V) indicates the amount of time that data quality transmission and quality was compromised due to low power. When battery voltage is below 11.4 V, the solar charge controller automatically disconnects the power to aspiration fans and the data transmitter to prevent damage to the batteries. In the statistics generated, the percentage of time with battery voltage below 11.5 V therefore indicates the amount of time that power levels were near or below critically-low levels. At Holly Springs, for example, the battery voltage was frequently <12 V, but never fell low enough to affect the temperature sensor aspiration or prevent data transmission.

The average incoming solar radiation indicates the gross potential for solar power, and although there is a trend for stations with more available solar energy to perform better during the winter, there are also notable deviations from this trend. Montrose, CO for example, had on average the most potential solar power, but nevertheless had critically low battery voltages for 14% of the winter. The cause of this is addressed in more detail in the site by site examples, but it demonstrates the effects of synoptic scale variability on power generation. Like average solar inputs, mean wind speed and mean estimated wind power (Wind Amp) indicate the gross potential for power production. They can be used to evaluate which sites are windiest, but do not describe the variability in potential power production. As the load at CRN sites is constant and storage capacity is limited, the availability of wind power during times when solar inputs are low is equally or more important than the average potential for wind power. The site by site examples include this more detailed analysis.

Average temperature was included to help discern if low temperatures affected battery capacity and to thereby guide increases in the number of batteries installed. The amount of time that the precipitation sensor heaters were on was also included in the site statistics in order to estimate the contribution of the additional load on the batteries caused by the heaters. This statistic indicated that the heaters did not contribute significantly to power usage at any of the sites over the course of the entire winter.

Name	Data online (%)	BV < 12 V (%)	BV < 11.5 V (%)	Solar (Wm^{-2})	Wind speed (ms^{-1})	Wind Amp (Amp)	T (C)	Heater time (%)	z_o (m)
Holly Springs, MS	100	23	0	100	1.8	0.7	6	0.8	0.03
Avondale, PA	100	15	1	86	2.1	1.4	1.8	0.3	0.03
Elkins, WV	100	13	2	76	2.3	1.1	-1.2	5.6	0.03
Coshocton, OH	100	11	2	75	3	2	-0.5	3.3	0.03
Salem, MO	100	7	1	98	2.5	1.6	2.3	0.8	0.03
Charlottesville, VA	100	3	0	103	2	0.5	4.6	0.7	0.03
Joplin, MO	100	2	0	107	2.7	2.5	3.3	0.5	0.03
Cape Charles, VA	100	0	0	102	2.9	1.1	6.3	1.4	0.03
Lewistown, MT	100	0	0	72	3.8	4.7	-2.6	3	0.03
Dillon, MT	100	3	0	82	2.3	2	-5.2	1	0.03
Pierre, SD	100	5	1	82	4.2	2.5	-3.9	0.9	0.03
Sundance, WY	98	20	2	81	2.9	3.2	-3.9	1.8	0.08
Sandstone, MN	98	10	2	69	1.4	0.2	-9	0.7	0.08
Lander, WY	97	3	3	99	2	1.1	-0.6	1.6	0.08
Aberdeen, SD	95	17	6	86	4.8	6.6	-8.5	0.6	0.03
Northgate, ND	95	12	6	73	3.7	4.6	-10.8	1	0.03
Spokane, WA	93	22	7	52	1.6	1.1	-0.6	2.1	0.3
Montrose, CO	92	14	8	123	1.8	1.6	-1.3	3.5	0.3

Table 1: Average hourly winter (11/01/08 – 2/01/09) statistics from all sites identified for review. 'Data online' is the amount of data available from the NCDC CRN website on May 20, 2009, and was calculated as the number of hours downloaded divided by the total number of hours in the 4-month period. Battery voltage (BV) < 12 V or < 11.5 V is the percent of time that the recorded battery voltage was not above 12 V or 11.5 V. 'Solar' is the average incoming solar radiation measured on site. 'Wind speed' is the mean measured wind speed at z = 1.5 m. 'Wind Amp' is the mean estimated wind generator output and was calculated based on the measured wind speed and the roughness length. 'T' is the average panel temperature. 'Heater time' indicates the number of hours in the record that the Geonor heaters were activated. z_o is the estimated roughness length.

3.2 Effects of Roughness Length

Reliance upon some assumptions and simplifications was required in order to estimate the potential for wind energy production. The logarithmic wind profile used is strictly valid only in neutrally stratified atmospheric conditions. In addition, the photos from which z_0 was estimated were only available annually. The vegetation present at the sites can undergo annual cycles of growth and senescence, and in addition some sites are periodically mowed. It was beyond the scope of this study to estimate the effects of this variability on the potential for wind energy, and estimates of wind speed were therefore made conservatively. As an example of the effects of z_0, given a z_0 of .03 m, estimated wind speed at 5 m was 1.3 times stronger than wind speed at 1.5 m. A z_0 of 0.3 m resulted in an estimated wind speed at z = 5 m that was 1.75 times greater than the z = 1.5 m wind speed. As the generator model used for the wind energy evaluation did not produce any energy below 3.5 ms^{-1} and its output increased exponentially with wind speed, at some sites the potential for wind energy production was sensitive to small changes in the estimated wind speed.

3.3 Site by Site Examples

Solar powered CRN sites that failed to transmit data 1% or more of the days during the 2008/2009 winter were chosen for more detailed analysis. For these sites, key variables were plotted vs. time. Based on this analysis, specific recommendations were made for augmentation of the installed power generation and storage infrastructure. Some of these recommendations have already been implemented during 2009 annual site visits.

3.3.1 Aberdeen, SD

Aberdeen requires more power production than was available during the analysis period. The battery voltage was below 12 V for 17% of the time during the winter months. Low battery voltages occurred during several periods throughout the winter, some of them occurring as early as November (Fig. 1). Solar inputs were low for periods lasting 10-20 days due to clouds (Fig. 1 and 2). The station latitude is 45.5 deg N. Periods when solar power was low often coincided with strong winds, and throughout the winter months winds were frequently strong enough to generate electricity (Fig. 1). Therefore, a wind generator was installed on 27 August 2009. Additional batteries would also help the system store available wind energy and last through overcast and windless periods. Without the heaters running, one fully charged 100 amp-hour battery can power a typical Climate Reference Network system for ~2 days. Approximately 10 batteries are required to power the system for 20 days with no sun or wind. Given the prevalence of windy conditions at this site, 20 days of battery power would be unnecessary with a wind generator installed, but augmentation of the current size of the battery bank from its current size of 4 may be warranted; this is especially true considering the effect of the low wintertime temperature on the batteries at the site, which reduced the capacity of the battery bank by ~50% during the coldest periods of the winter.

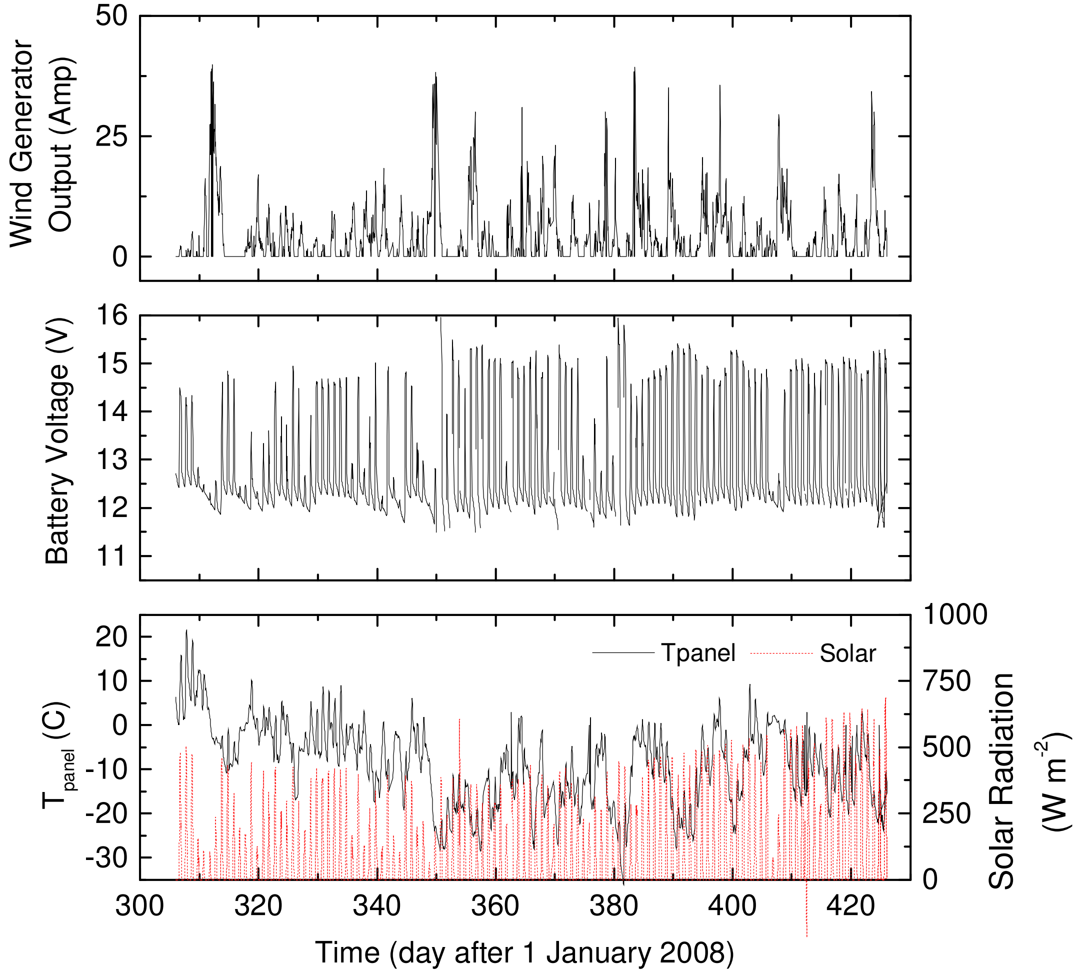

Figure 1. Estimated wind generator output and measured battery voltage, datalogger panel temperature (T_{panel}), and solar radiation from Aberdeen throughout the winter of 2008-2009. Wind generator output was estimated from measured wind speed and wind generator manufacturer specifications.

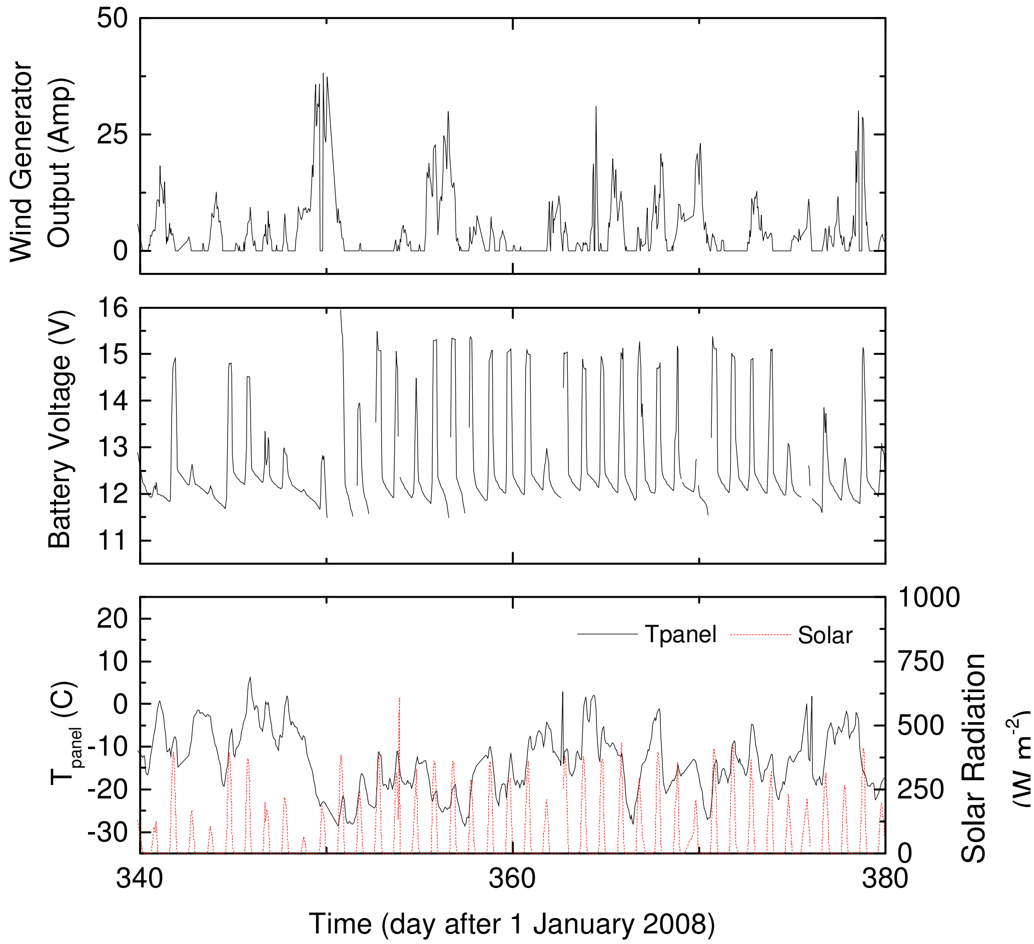

Figure 2. Estimated wind generator output and measured battery voltage, datalogger panel temperature (T_{panel}), and solar radiation from Aberdeen throughout a selected period of low battery voltage. Wind generator output was estimated from measured wind speed and wind generator manufacturer specifications.

3.3.2 Lander, WY

Although battery voltage was only below 12 VDC for 3% of the winter, this site failed to transmit data for 3% of the winter. Possible improvements to the system include adding batteries to help power the system through potential periods of low incoming solar radiation. Low levels of sunlight for only 3 days sent the batteries into decline (Fig. 4). Currently only 4 batteries are on site, and additional batteries are recommended. Estimated wind generated power was insignificant during this event, and the Geonor heaters were not on. Throughout the rest of the winter however, the potential for wind energy here was good (Fig. 3).

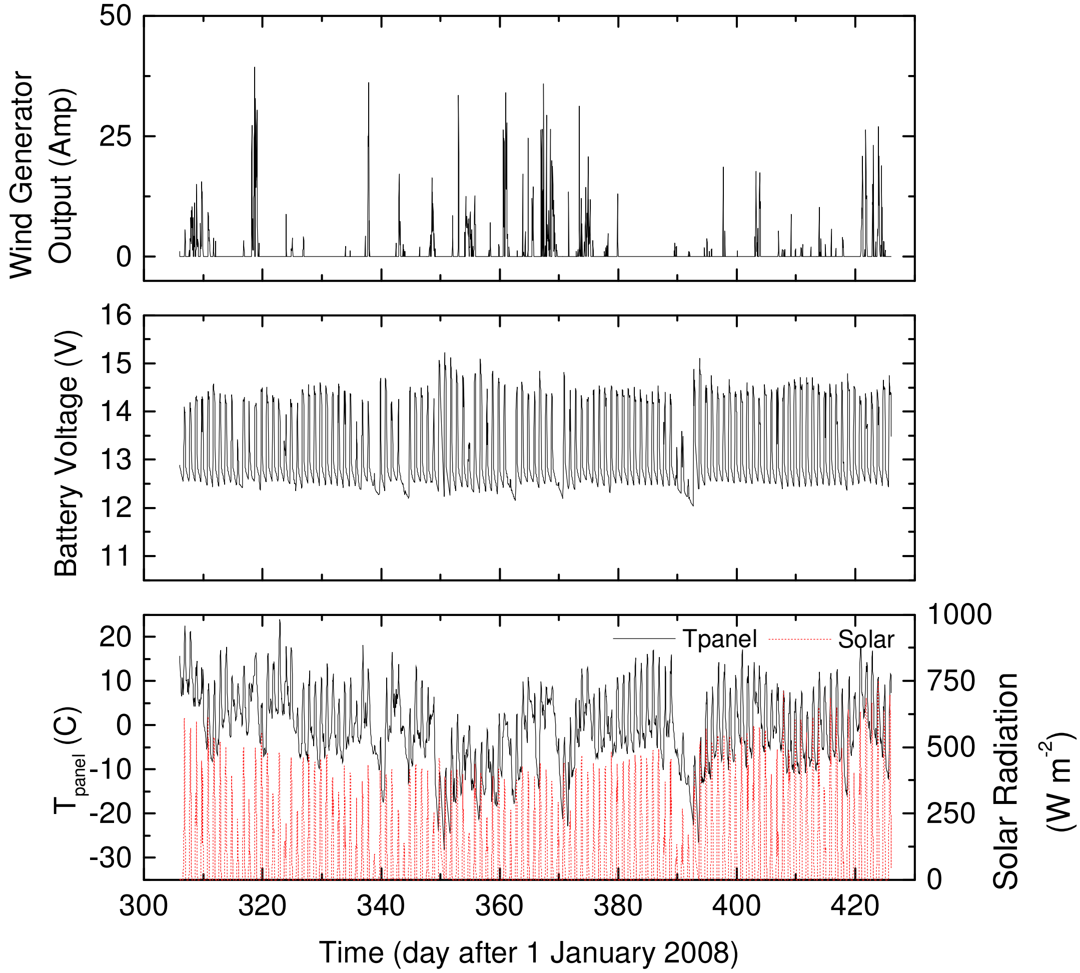

Figure 3. Estimated wind generator output and measured battery voltage, datalogger panel temperature (T_{panel}), and solar radiation from Lander throughout the winter of 2008-2009. Wind generator output was estimated from measured wind speed and wind generator manufacturer specifications.

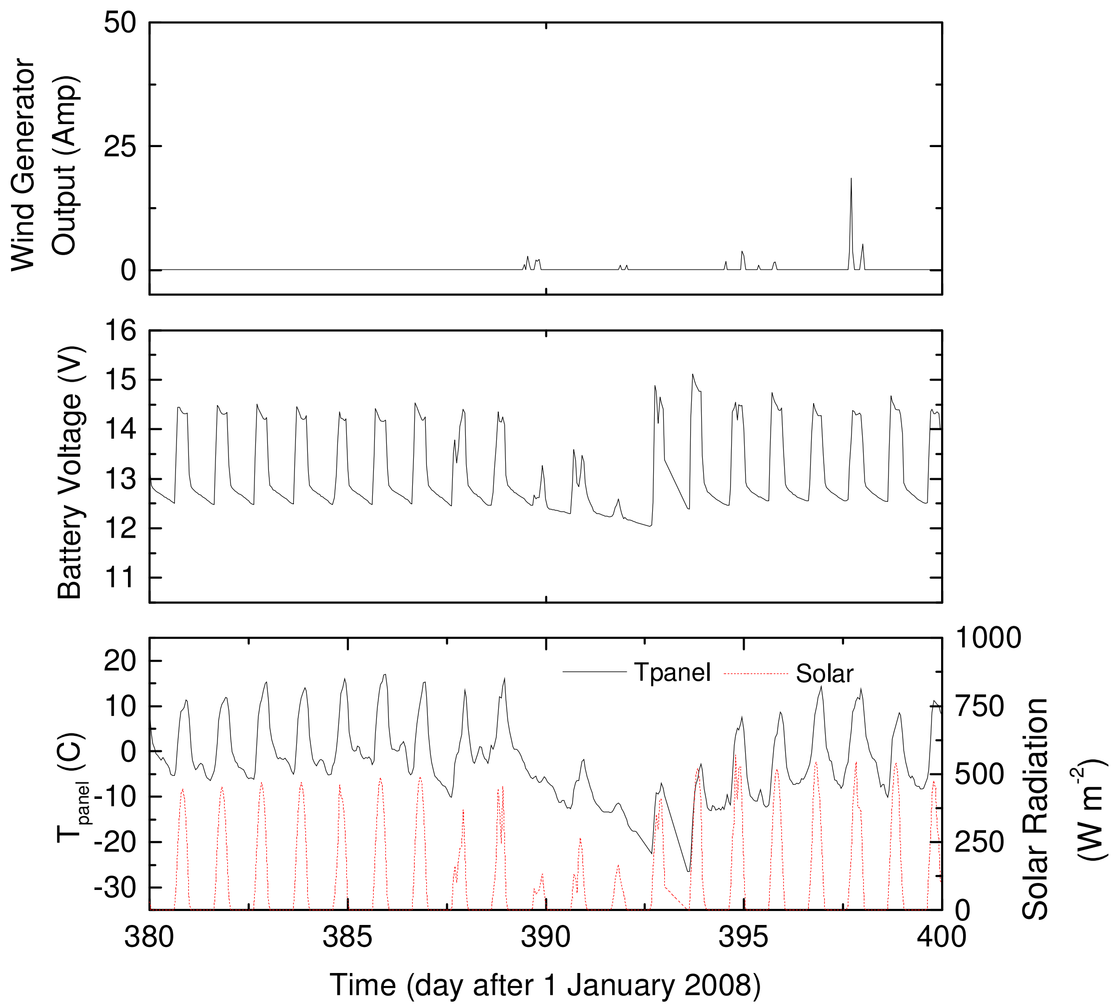

Figure 4. Estimated wind generator output and measured battery voltage, datalogger panel temperature (T_{panel}), and solar radiation from Lander throughout a selected period of low battery voltage. Wind generator output was estimated from measured wind speed and wind generator manufacturer specifications.

3.3.3 Montrose, CO

Throughout December the battery voltage at this site frequently dropped below 12 V (Fig. 5 and 6). During the period between day 330 and 365, the Geonor heaters were activated for 86 hours. This is 10% of this entire ‘trouble’ period. The resultant total increase in power requirements due to the heaters was 32%, and most of this extra demand occurred in the first half of the period. During the winter of 2008/2009 wind energy would have provided enough energy to considerably aid this site (Table 1 and Fig. 5). The site is hilly, with ~2 m tall shrubs surrounding the station. The wind speeds estimated at a height of 5 m winds therefore were considerably larger than wind speeds measured at z = 1.5 m, and were strong enough to generate electricity during some of the periods when it was needed.

Throughout most of the winter, levels of incoming solar radiation were high compared to the other sites included in this analysis. Increasing the size of the solar array would help supply the system with power through partially overcast periods. Incoming solar radiation during extended overcast periods was 1/3 of its clear-sky value. Increasing the solar power generating potential using solar tracking mounts or additional panels may be justified. In addition to increasing the power generating equipment, augmentation of the battery bank may be required.

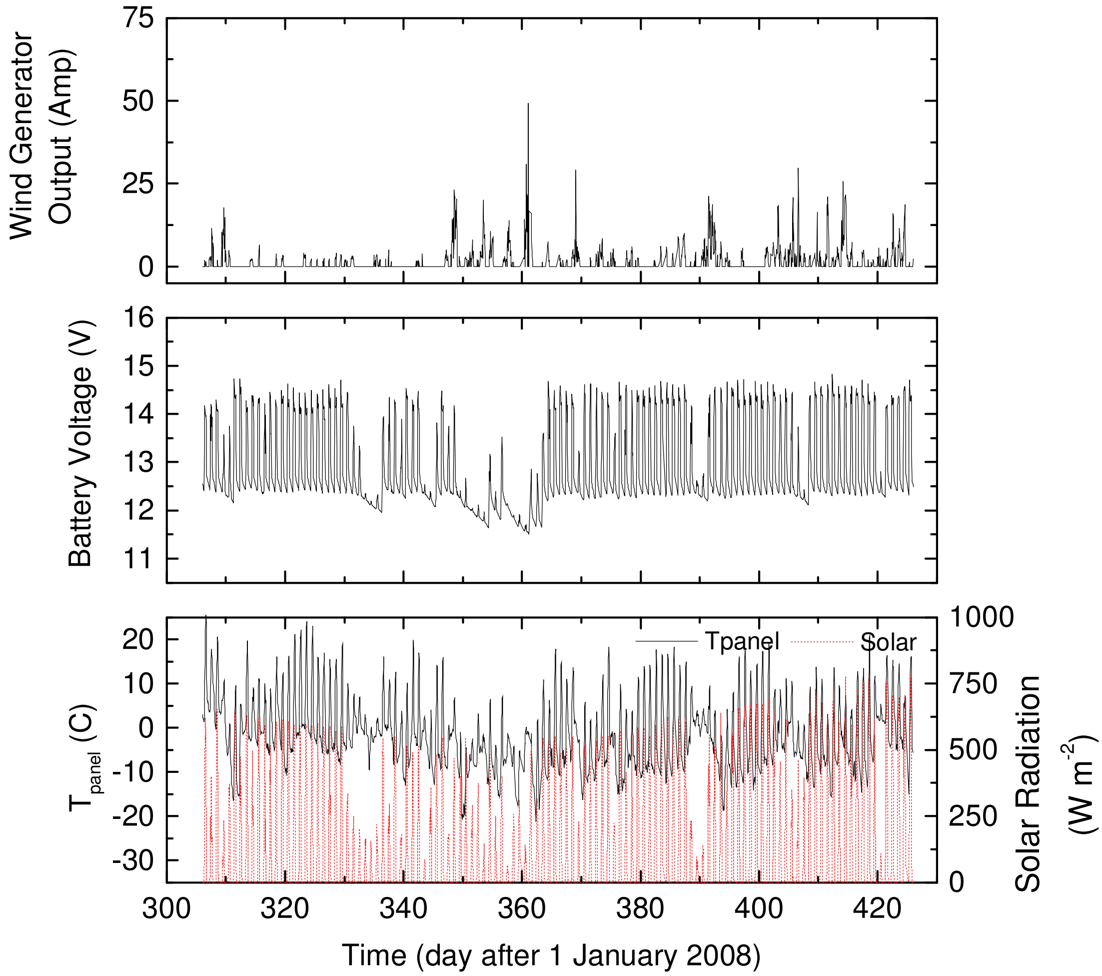

Figure 5. Estimated wind generator output and measured battery voltage, datalogger panel temperature (T_{panel}), and solar radiation from Montrose throughout the winter of 2008-2009. Wind generator output was estimated from measured wind speed and wind generator manufacturer specifications.

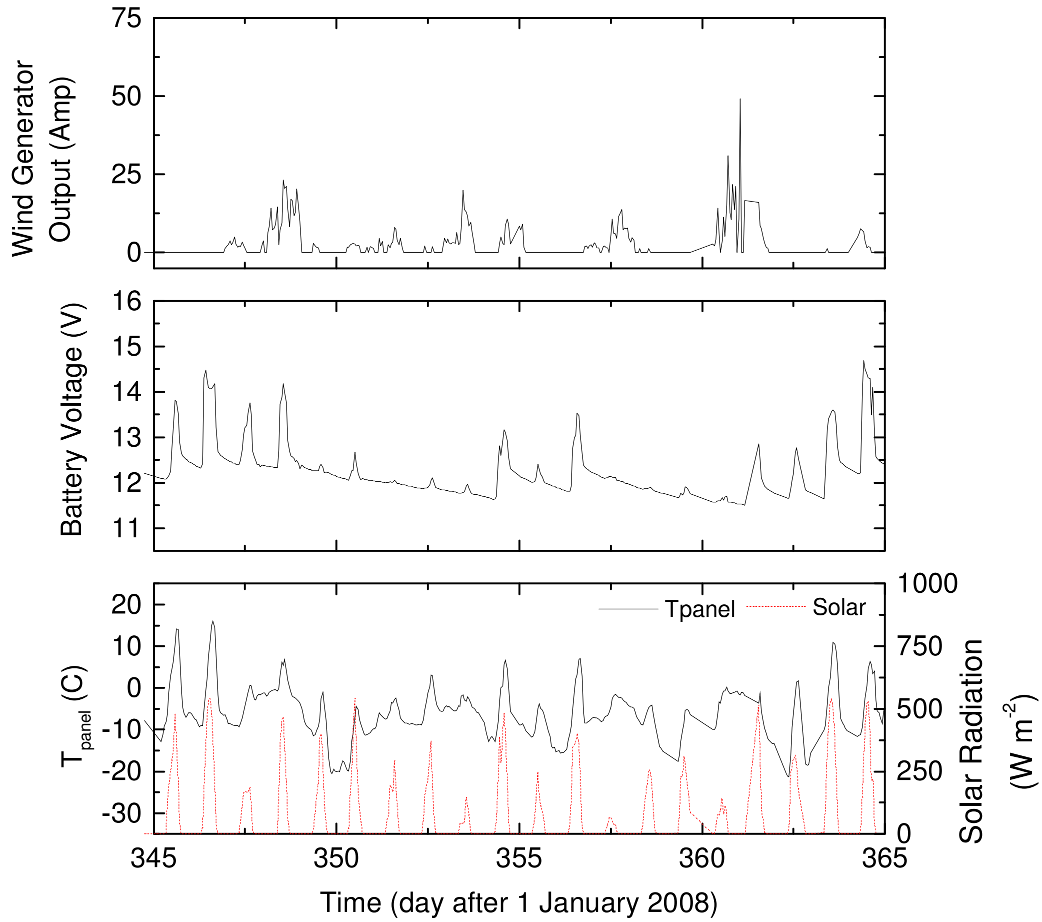

Figure 6. Estimated wind generator output and measured battery voltage, datalogger panel temperature (T_{panel}), and solar radiation from Montrose throughout a selected period of low battery voltage. Wind generator output was estimated from measured wind speed and wind generator manufacturer specifications.

3.3.4 Northgate, ND

Battery voltage <12 V for 12% of the winter indicates that this site requires more power production in addition to increased battery capacity. The most critical period at this site occurred near the winter solstice (Fig. 7). As the angle of the solar array is already optimized for winter sun angles, the shortage of power appears to have been caused primarily by the short length of the day (latitude = 49°) and was exacerbated by several 2-5 day overcast periods (Fig. 8). Wind energy production was recommended at this site, with estimated wind speeds frequently high enough to produce energy. Therefore, a wind generator was installed on 30 August 2009. An AirX generator would have produced an average of 2.3 Amps of power throughout the worst period of the winter (days 340 – 385). Additional solar panels would also help recharge the system more quickly during the short days, and should be considered if installation of a wind generator is not permissible. Cold temperatures significantly decreased the battery capacity during isolated periods, with a design factor of 2.84 calculated based on temperature. Therefore, the current number of batteries (6) could also be augmented.

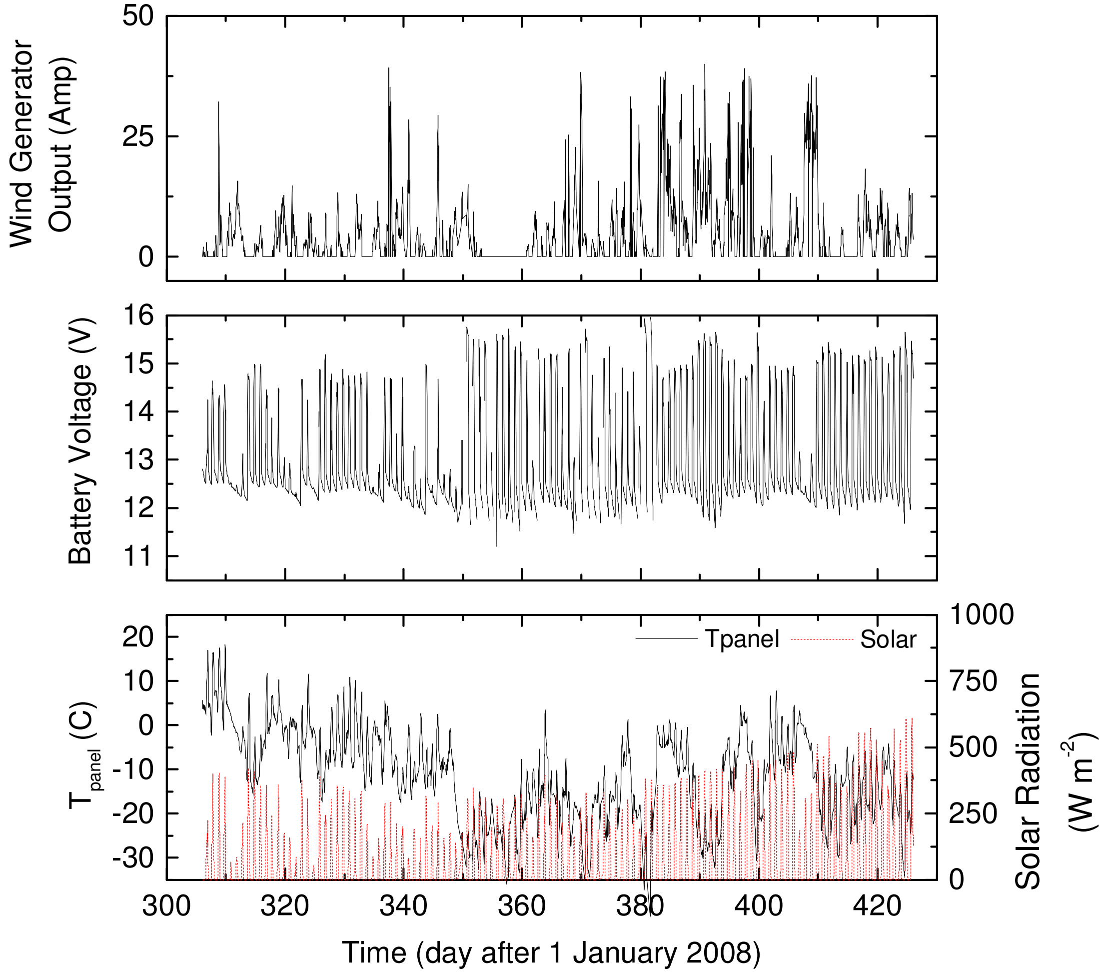

Figure 7. Estimated wind generator output and measured battery voltage, datalogger panel temperature (T_{panel}), and solar radiation from Northgate throughout the winter of 2008-2009. Wind generator output was estimated from measured wind speed and wind generator manufacturer specifications.

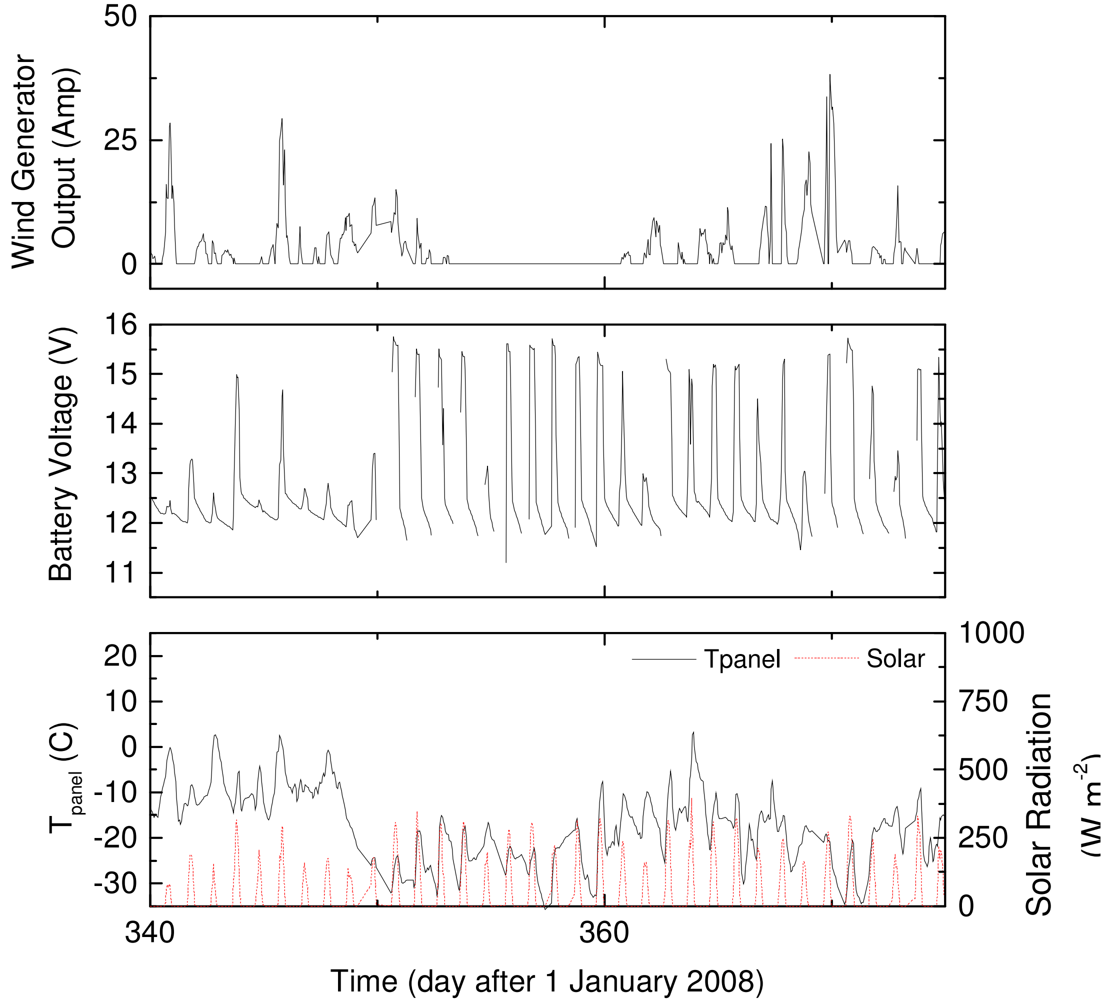

Figure 8. Estimated wind generator output and measured battery voltage, datalogger panel temperature (T_{panel}), and solar radiation from Northgate throughout a selected period of low battery voltage. Wind generator output was estimated from measured wind speed and wind generator manufacturer specifications.

3.3.5 Sandstone, MN

Increased power production is required at this site, with battery voltage below 12 V for 10% of the winter. The latitude is 46° N, and the most severe problems occurred near the winter solstice (Fig. 9 and 10). The site is in a clearing surrounded by forest. The trees are more than 100 m from the site, and the canopy height of the grasses within the clearing appears to vary from a few cm to almost 2 m depending upon how recently it was mown. All of these effects make it very difficult to accurately estimate the wind speed above the site from the locally measured wind speed. Locally measured winds were very low. Installing the wind generator on a 20 to 50 m tall tower might effectively place the generator in a region of the surface layer where stronger winds occur, but this is difficult to predict based on the data available. As the calculated potential for wind energy production is low at Sandstone, the size or efficiency of the solar array must be improved. The number of batteries installed at this site was increased from 6 to 8 during the 2009 maintenance visit.

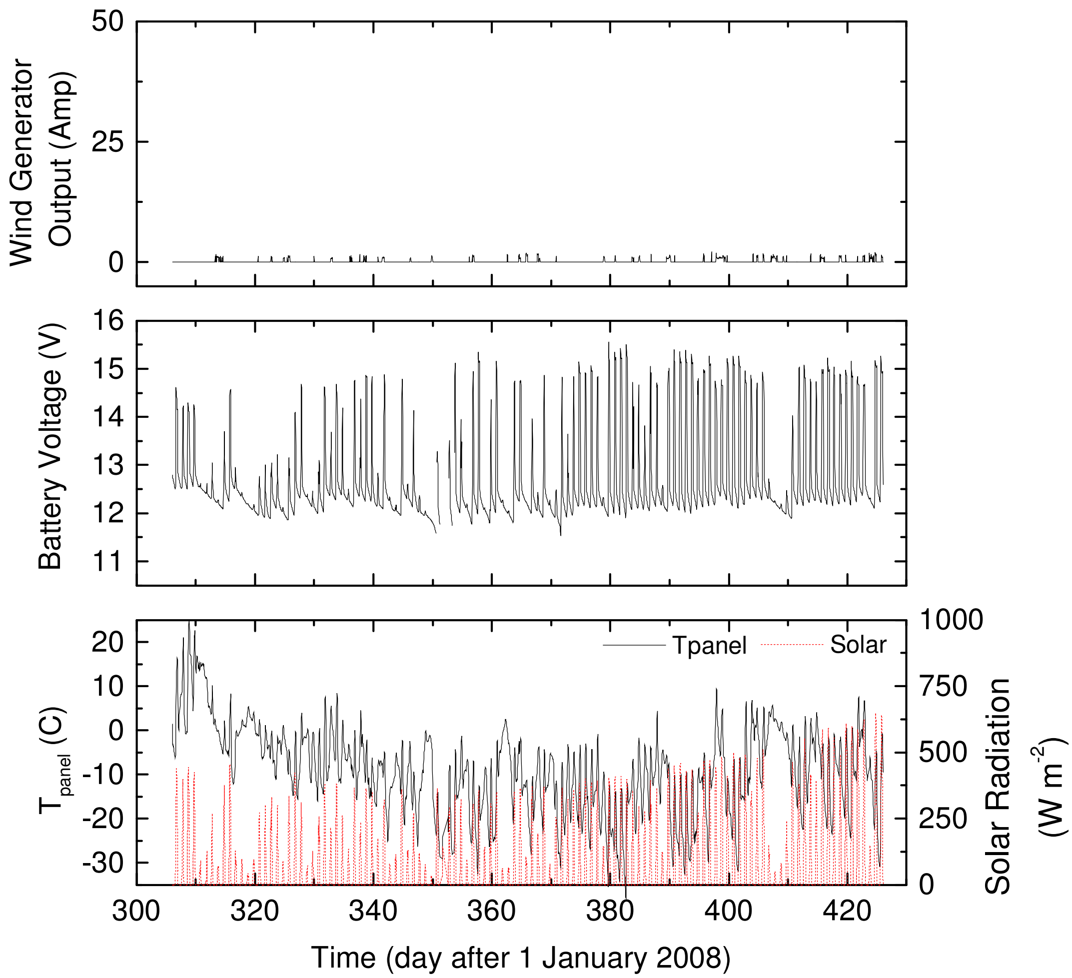

Figure 9. Estimated wind generator output and measured battery voltage, datalogger panel temperature (T_{panel}), and solar radiation from Sandstone throughout the winter of 2008-2009. Wind generator output was estimated from measured wind speed and wind generator manufacturer specifications.

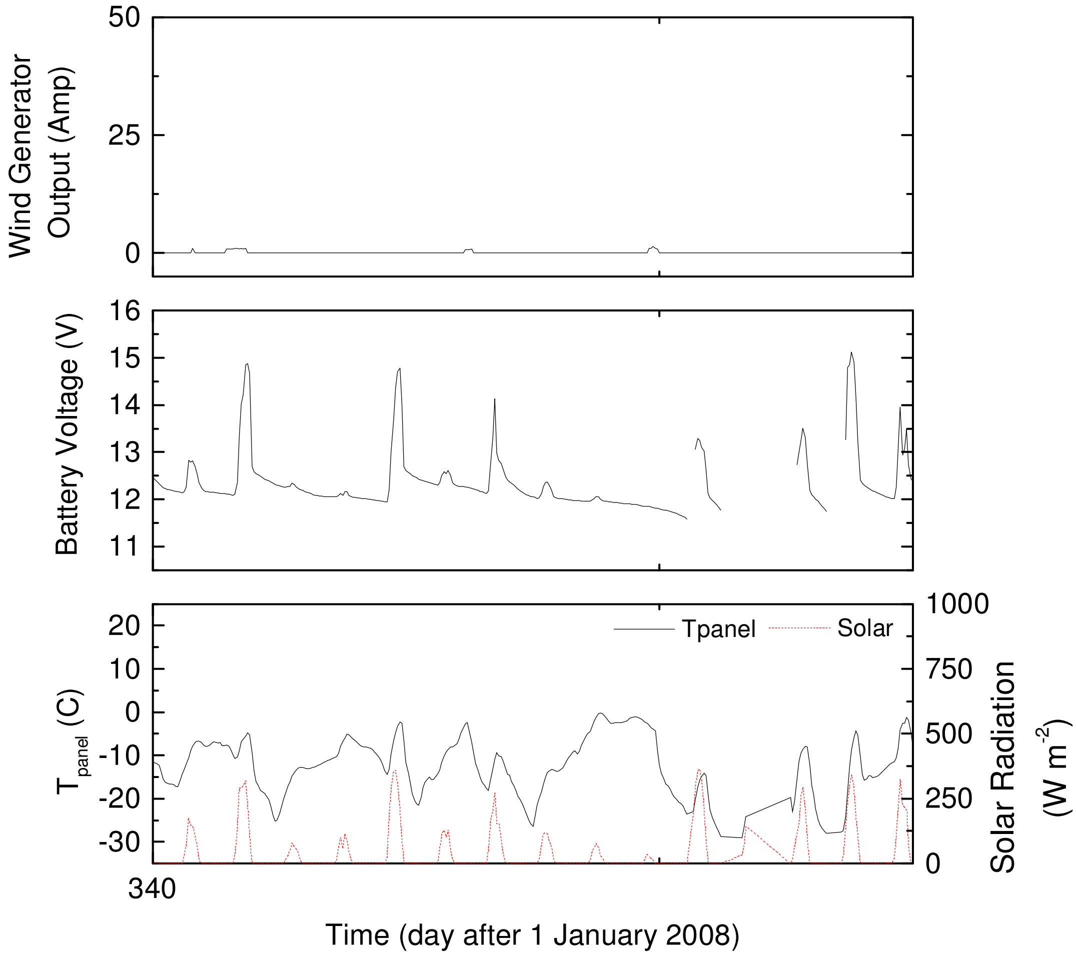

Figure 10. Estimated wind generator output and measured battery voltage, datalogger panel temperature (T_{panel}), and solar radiation from Sandstone throughout a selected period of low battery voltage. Wind generator output was estimated from measured wind speed and wind generator manufacturer specifications.

3.3.6 Spokane, WA

With battery voltage below 12 V for 22% of the winter, this site clearly needs more energy production. In December and January, conditions were rarely clear for more than 2 or 3 days in a row, and overcast conditions prevailed (Fig. 12). The latitude of the site is 48 deg N, and most of the power issues occurred when the days were shortest (Fig. 11). Either additional solar panels (currently 4 are installed) or a wind generator is needed. Trees are within 75 m of the site in several directions. This makes it difficult to estimate the wind speed at z = 5 m, but the best estimate indicates that this site is moderately well suited for installation of a wind generator. Increasing the height of the generator above 5 m, to 10 to 30 m, would be useful if possible. A wind generator is scheduled to be installed here at a height of 10 m AGL during the 2009 site maintenance visit. Due to the long gaps without sufficient wind and sun, the size of the battery bank should also be increased from its current size of 6 batteries.

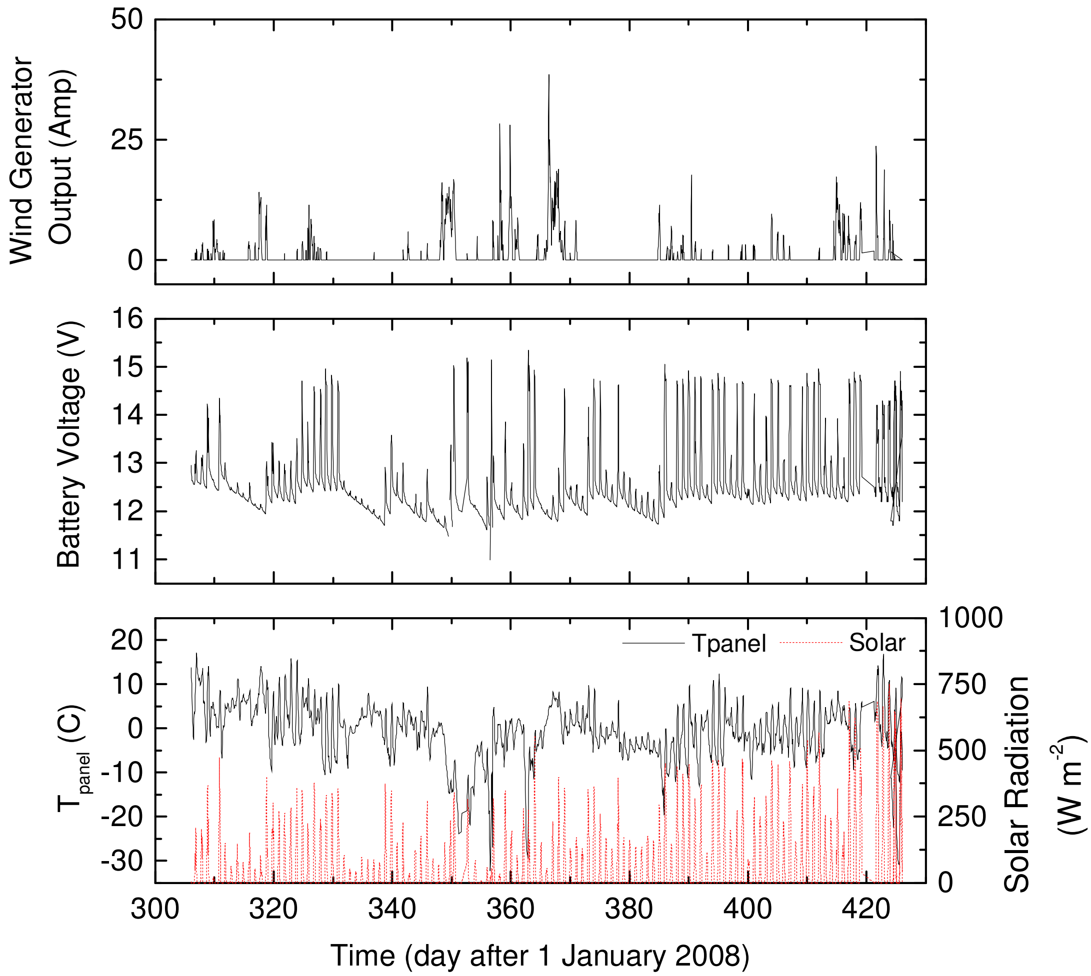

Figure 11. Estimated wind generator output and measured battery voltage, datalogger panel temperature (T_{panel}), and solar radiation from Spokane throughout the winter of 2008-2009. Wind generator output was estimated from measured wind speed and wind generator manufacturer specifications.

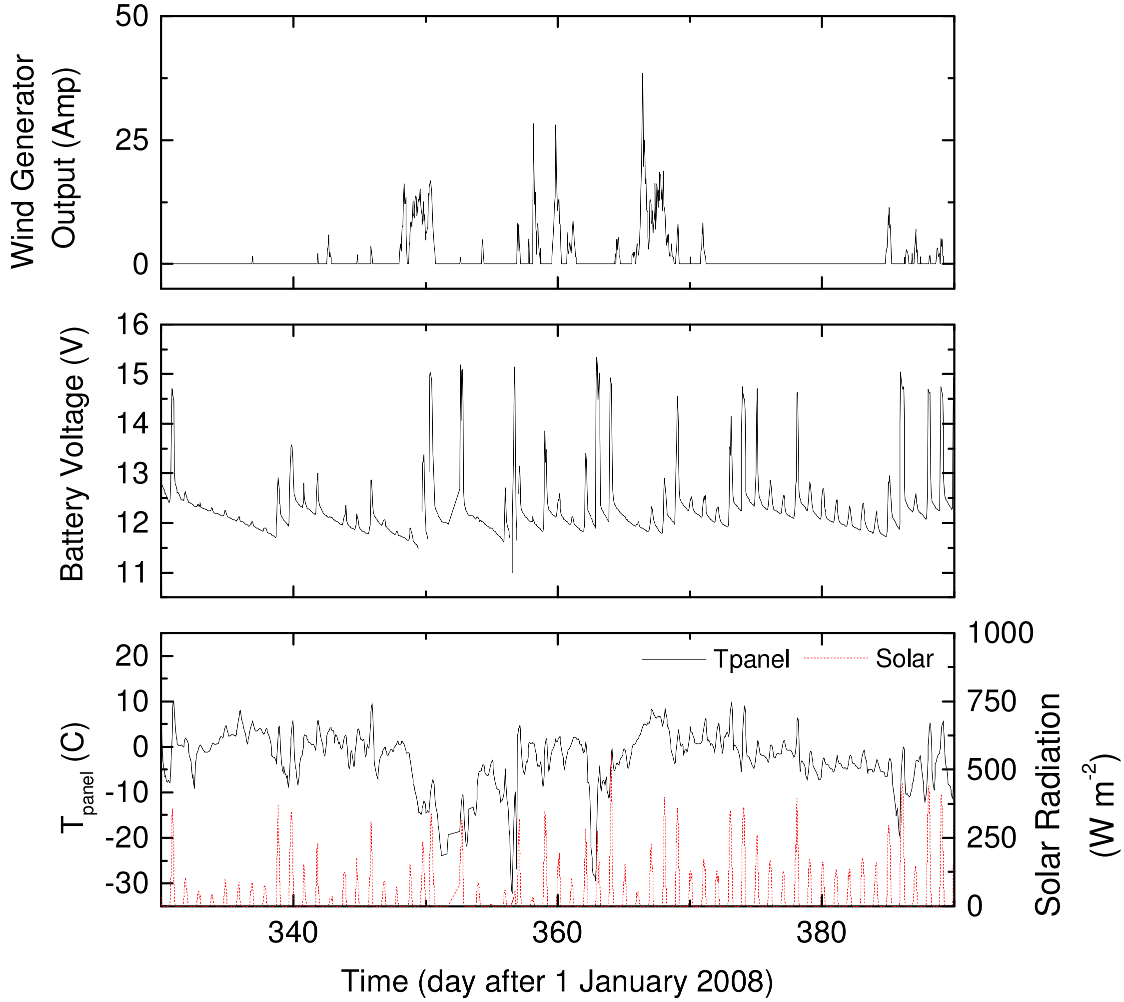

Figure 12. Estimated wind generator output and measured battery voltage, datalogger panel temperature (T_{panel}), and solar radiation from Spokane throughout a selected period of low battery voltage. Wind generator output was estimated from measured wind speed and wind generator manufacturer specifications.

3.3.7 Sundance, WY

With battery voltage below 12 VDC for 20% of the winter, this site needs more energy production. Most of the problems occurred during two approximately two-week-long periods when incoming solar radiation was low (Fig. 13). The later event is shown in more detail in Fig. 14. This site does have good potential for wind power production, and the solution to its power problems should include a wind generator if feasible. During the period shown in Fig. 14, the average current produced by an AirX at z = 1.5 m would have been 1.7 Amp, which is almost sufficient to power the system without the contribution of the solar array. This site is surrounded by trees, making it difficult to estimate the winds aloft, but the best estimate of the wind speed at z = 5 m (Fig. 13 and 14) resulted in approximately triple the amount of total wind energy available at 1.5 m. A wind generator is scheduled to be installed at this site during the 2009 annual maintenance visit. Currently 4 batteries are installed, and the installation of additional batteries is recommended. No Geonor heating occurred during the problem periods.

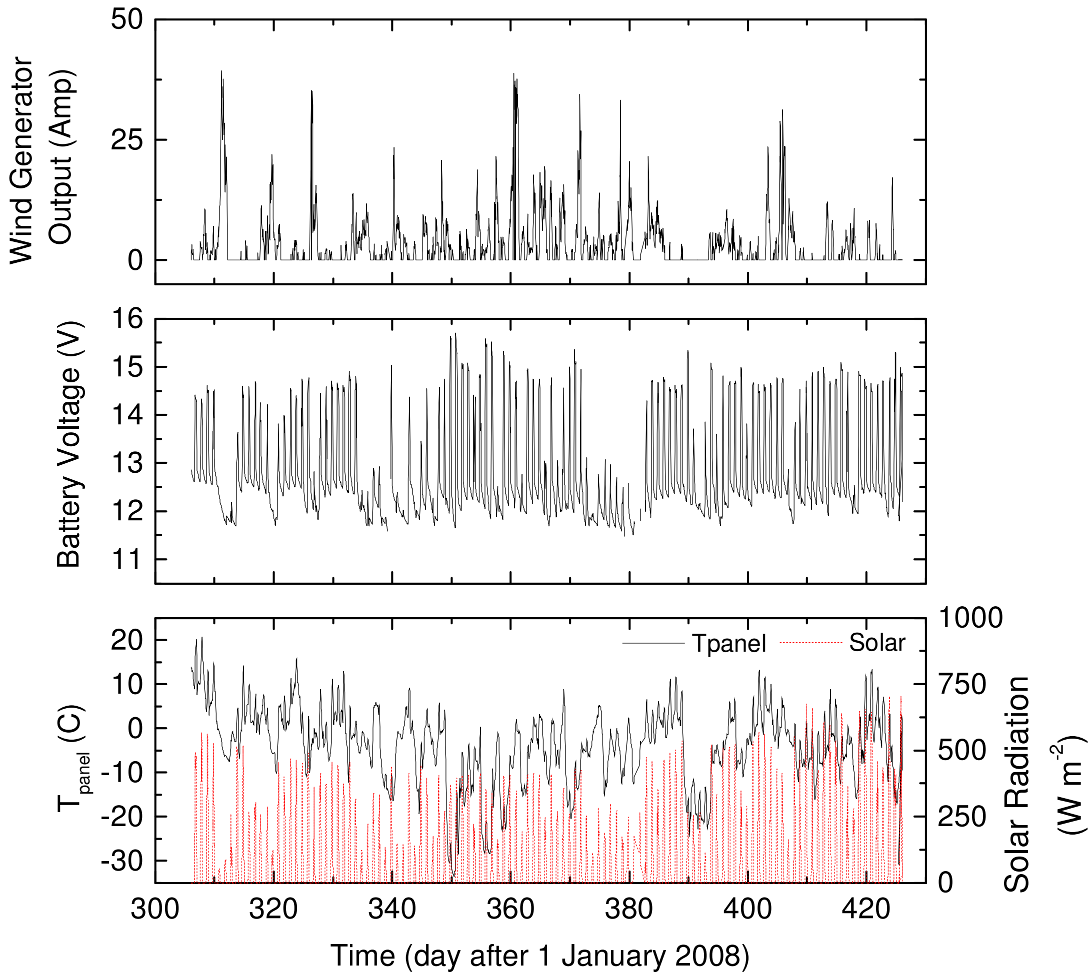

Figure 13. Estimated wind generator output and measured battery voltage, datalogger panel temperature (T_{panel}), and solar radiation from Sundance throughout the winter of 2008-2009. Wind generator output was estimated from measured wind speed and wind generator manufacturer specifications.

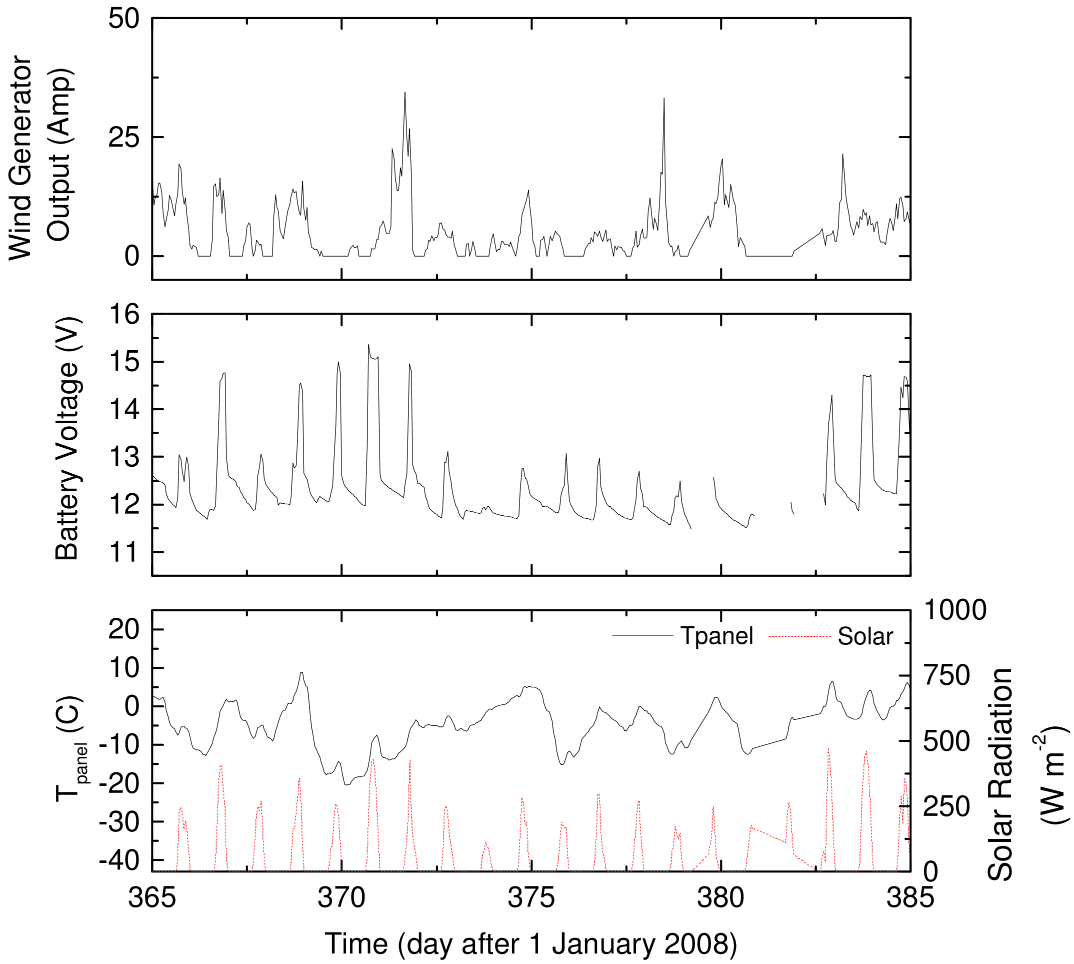

Figure 14. Estimated wind generator output and measured battery voltage, datalogger panel temperature (T_{panel}), and solar radiation from Sundance throughout a selected period of low battery voltage. Wind generator output was estimated from measured wind speed and wind generator manufacturer specifications.

3.4 Site by Site Summaries

Aberdeen, SD: This site experienced persistent power problems throughout the winter. A wind generator will help this site significantly.

Lander, WY: Additional batteries are all that is recommended for the time being, although the potential for wind energy production is very good.

Montrose, CO: Increasing the size of the battery bank is recommended. Installation of a wind generator is justified based on the fact that the surface is very rough, and significantly stronger winds than were locally measured are expected a height of 5 m.

Northgate, ND: Some combination of a wind generator, additional batteries, and possibly additional solar panels are needed at this site.

Sandstone, MN: The size or efficiency of the solar array must be improved. Doubling the size of the solar array is recommended. In addition, the size of the battery bank may need to be increased.

Spokane, WA: More solar panels or a wind generator should be added, and the size of the battery bank should be increased.

Sundance, WY: A wind generator and additional batteries are recommended.

4. DISCUSSION

Increased battery bank capacity will allow all systems to operate through periods of reduced battery capacity caused by low temperatures. Increased battery capacity will also help the systems store power for use during periods when solar power is lacking. Less generated energy will be lost by having more batteries, and indeed batteries will charge more efficiently when their voltage is low. However, more batteries will in some cases cause more energy to be used, such as during periods of low energy production. The Geonor heaters will be activated more frequently, as the batteries will presumably remain above 12 V longer. This indicates that when battery capacity is increased, energy production may also have to increase even when it does not appear necessary from the available data. More significantly however, the quality of the data will improve and less data transmission problems will occur.

Monitoring hourly power production and power use at one or more test sites would be useful. Data from such test sites could be downloaded during annual visits and used for future analysis of the power requirements of all sites. Such data could be used to remove uncertainties in the estimated current that is generated and required by Climate Reference Network stations in response to changing environmental conditions. Other possible improvements to this analysis would be the inclusion of statistics presented in section 3.1 that quantify the variability of power inputs, such as ‘days with low incoming solar radiation’ or ‘days without wind’. This analysis requires sufficient site years of data to quantify climactic norms and the potential deviations from these norms, allowing for the design of systems able to function through unusually long periods of low levels of incoming radiation and/or wind. That analysis however, is beyond the scope of the present study

5. CONCLUSION

Statistics for solar powered US CRN sites were generated to assess the magnitude of the shortcomings of the available power and to help plan improvements to the sites. A site by site analysis of power related variables was performed, and specific recommendations were made for the sites which experienced significant losses of data transmission during the winter of 2008/2009. The estimated potential for wind power at many of the most problematic sites was good, and wind generators have either been installed or scheduled for installation at these sites.

At other sites additional batteries, solar panels, or a combination of additional power generation equipment and batteries were recommended.

A framework has been created with which to analyze the performance of solar powered CRN sites and recommend improvements where warranted. This work will continue and will aid in the design and maintenance of the installation of future sites. This is particularly true at high latitudes, such as the sites scheduled for installation as part of the Alaska CRN program, where installations at remote locations that receive little or no solar radiation during the winter months demand careful planning and support.

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