Design and Deployment of Ambient Air Monitors that Utilize a Photovoltaic Power Source

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Introduction

As continual improvements are achieved and new ambient air monitoring methods are implemented, attention should also be given to the deployment of monitors that utilize such methods. Sometimes new monitoring techniques are marginalized by the fact that the monitor cannot be placed in an ideal location. Monitoring programs, especially rural programs, are sometimes bound by mundane (and often times viciously circular) restrictions: a site must be near a suitable power source; but that power source is too near an obstruction; if the monitor is moved away from the obstruction it is no longer near the power source. Installing a new power source can be costly especially in a remote location.

This paper will demonstrate that there is potential for moving to off-grid power sources when deploying Federal Reference Monitors (FRMs). It will also highlight schemes that can be used in conventional monitoring applications to increase energy efficiency. At present, off-grid power is not always cheap, but the flexibility it affords is very desirable in some situations. In addition, the cost of off-grid power is not cost-prohibitive when considering the expense of the equipment it will power.

Background

The small town of Weeping Water is situation in central Cass County in southeastern Nebraska. The Weeping Water valley is rich in limestone deposits and as a result the area is home to six major quarrying and aggregate operations. The Nebraska Department of Environmental Quality (NDEQ) has operated particulate monitors in Weeping Water almost since the Department's creation in the 1970s.

Since 2002, the NDEQ has gone to considerable effort to control emissions of PM_{10} in this area. Part of this effort involved phasing out high-volume samplers in favor of sequential filter-based samplers and continuous analyzers. As the monitoring network expanded outside the town boundaries, locating suitable monitoring sites became more problematic. Since the next monitoring site was to collect wind data, the site would require an unobstructed circle 300 feet in diameter. The Weeping Water valley is full of trees so the search for traditional sites yielded marginal results. Sites near roadways that met criteria for particulate monitoring did not meet criteria for meteorological monitoring. The only wide-open spaces suitable for a meteorological tower were cropland.

An agreement was made with Kenneth Lauritzen, a local landowner, to use a small section of his cropland for monitoring. There was a power company substation near the chosen site that was assumed would provide power for the site. After further research, however, it was discovered that this substation was not suitable for providing the type of power needed to run the monitoring station. The alternative was to run power from the farmhouse about a quarter of a mile to the east at a cost of $8000-$13,000. This was deemed an unacceptable expense and deployment of the monitor at this *ideal* site was halted until another, less ideal, site could be found. In the meantime, the search for an alternate, or off-grid, power source began.

Methodology

Determine Loads

When developing an off-grid power source, it is critical to know the exact electrical load of all devices that are to be run on the power source and the amount of time that the loads will run. In this case it was a relatively simple task. All product literature contains power requirements, usually listed are current (amperage, denoted by *I*) and voltage (*V*). The power (*P*) in watts per hour (*W/h*) required is given by the formula:

$$P = IV$$

Table 1: Power Requirements

Devices requiring electricity	**Current**	**Voltage**	**Power**
	I	V (AC)	P (W/h)
*Air Conditioner	30.00	120	3600.0
TEOM control unit and sensor units	1.00	120	120.0
TEOM pump	1.50	120	180.0
Airlink Redwing CDMA cellular modem	0.10	120	12.0
R.M. Young shelter temperature probe	0.30	120	36.0
R.M. Young anemometer	0.13	120	15.6
Total			**3963.6**
***Total without air conditioner**			**363.6**

As is evident from table 1, an air conditioner, even if not running 24 hours per day, would require and extraordinary amount of power. If the site were to run on off-grid power, an air conditioner simply would not be feasible. An alternate method of temperature control was devised and will be discussed later. At this point the project proceeded without an air conditioner and a power requirement of 363.6 watts per hour.

363.6 watts are required each hour of the day, so the total power requirement for this station, which runs continuously, is:

$$363.6 \times 24 = 8726.4 \text{ watts/day} \qquad \text{eq.1}$$

Determine Power Source

The two primary alternative energy (or off-grid) power sources available are photovoltaic (solar) and wind. There is one major factor to consider for each source when determining how feasible each option is.

Wind

Wind power was considered because it is approximately one quarter the cost of solar power per watt of power generated. However, for most small wind turbines to be effective, an annual average wind speed of 12 mph is required. NDEQ meteorological data collected in the Weeping Water Valley in 2003 indicated an annual average wind speed of 4 mph. A site powered solely by wind power was not an option in here.

Photovoltaic

The major factor to consider when using photovoltaics (solar energy), is latitude. Second to latitude is annual weather patterns; namely, how many sunny days per year a location experiences. Both of these factors determine *solar insolation*. Figure 1 is a solar insolation map, it indicates for any point on the globe the number of hours of sunlight per day that are suitable for generating electricity with photovoltaics. Notice that the insolation value increases toward the equator and that highest values are found in the world's deserts where there is the least cloud cover (the Sahara in northern Africa, the Namib and Kalahari in southern Africa, the Australian Outback, and the America Southwest).

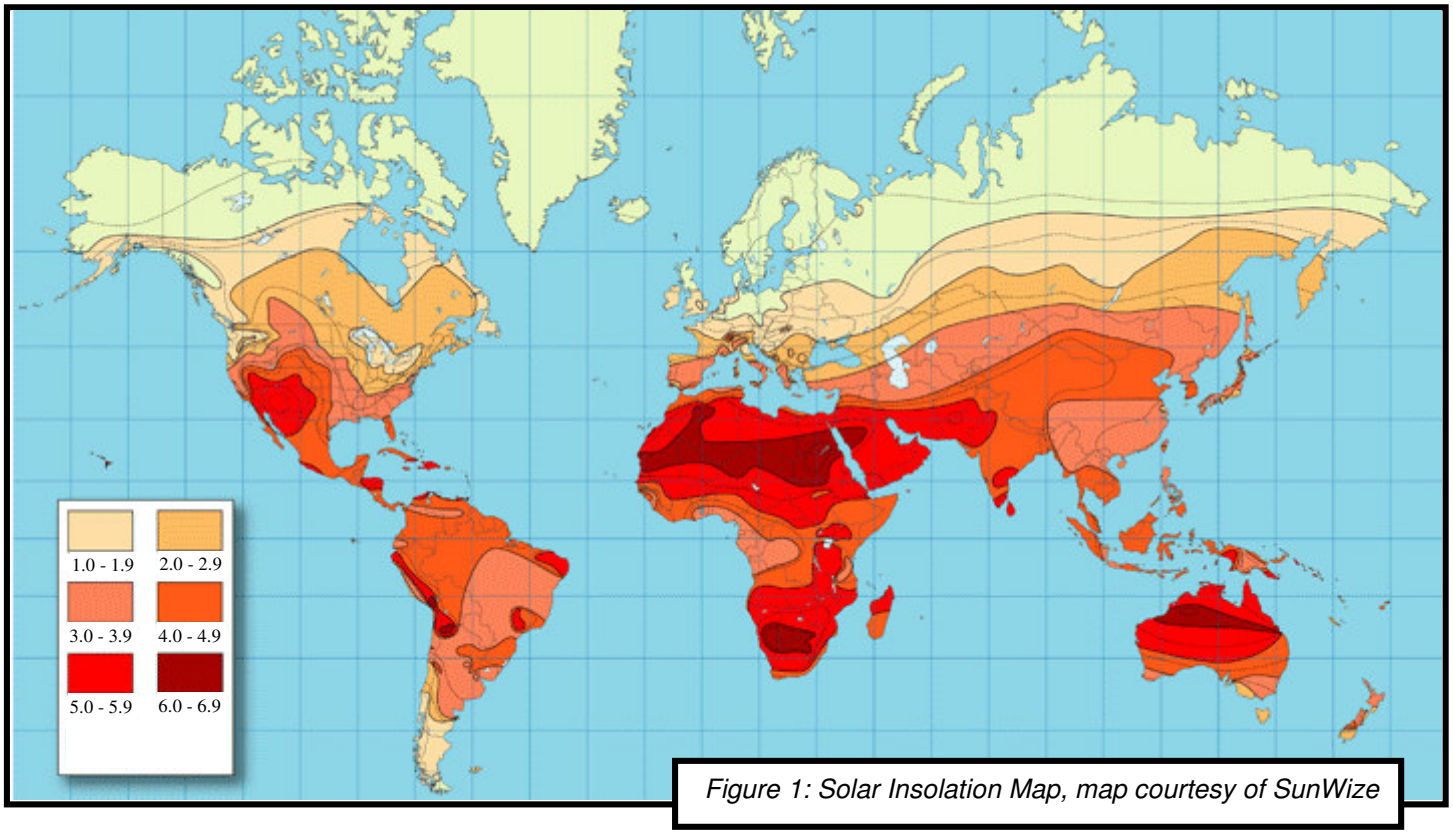

Figure 1: Solar Insolation Map, map courtesy of SunWize

It is important to note that insolation values change with the seasons as the earth tilts towards and away from the sun. The lowest values occur in winter (November, December, and January in the Northern Hemisphere). Figure 1 indicates the winter insolation values, or the lowest values that occur at any given point on the globe. The winter value is the value that should be used if photovoltaics are to be used year round. The December insolation value used for Weeping Water in southeast Nebraska is 3.9.

Basic Components

The basic components and their relationship in a photovoltaic power system are illustrated in figure 2. Each component and its function is briefly discussed below:

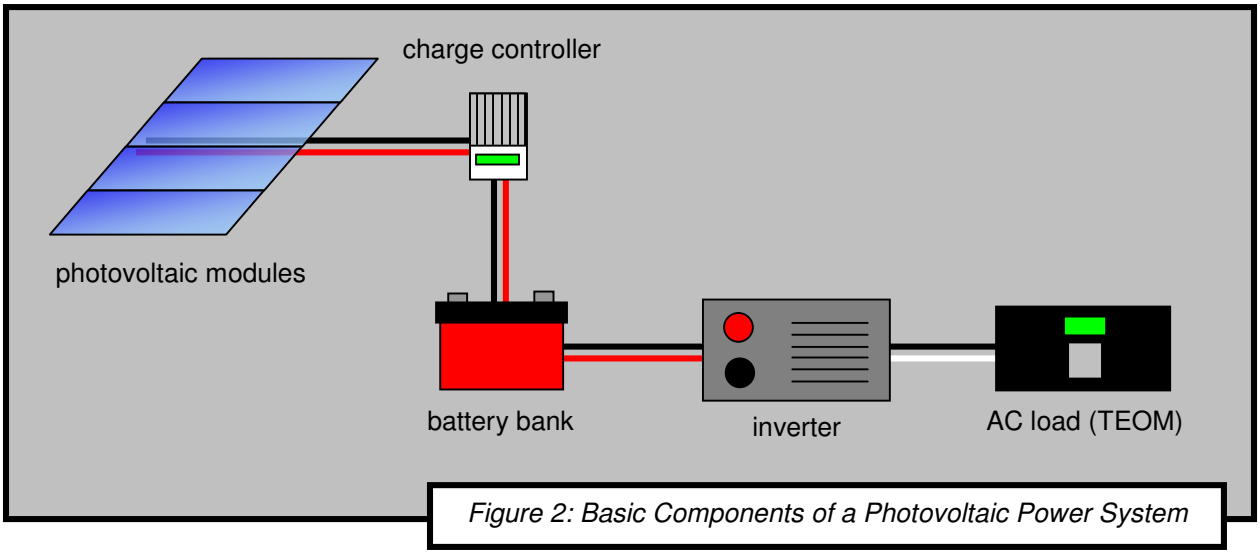

Figure 2: Basic Components of a Photovoltaic Power System

Photovoltaic Modules
The photovoltaic modules use the sun's energy to create electricity. The modules create direct current (DC) electricity. The modules are much like batteries in that they can be arranged in series and parallel to create a desired voltage and current.

Charge Controller
A charge controller regulates the electricity that is generated by the photovoltaic modules. Photovoltaic modules produce different amounts of energy depending on the amount of sunlight available, therefore a controller is required to ensure that the batteries do not receive too much electrical current. The controller is also used to help maintain the batteries: periodically the batteries must be *equalized.* Equalization of the batteries is necessary to extend the life of the batteries. Equalization involves raising the battery voltage in order to stir the fluids within the battery and to breakup any chemical deposition on the negative and positive plates inside the battery.

Battery Bank
The battery bank stores the electricity that is generated by the photovoltaic modules. A battery bank is necessary in order for the system to operate at night and during cloudy conditions.

Inverter
All electricity that is generated using photovoltaics is direct current (DC). The electricity is stored in batteries that are also DC. In order to create alternating current (AC), which is required for traditional regulatory monitoring applications, an inverter is required. If the system is only going to power DC loads then an inverter is not necessary.

Determine Inverter Size

Most inverters accept DC input at 12, 24, or 48 volts. Higher input inverters are usually slightly more efficient at creating AC power and they can output AC power at higher continuous current. This means that more devices can simultaneously use the inverter's output. In fact, during construction of the site, the inverter was able to provide power for several powers tools including a circular saw, a drill, and a vacuum. A higher DC voltage input system also requires lower current to produce AC power; as a result there is less current loss in the wires that tie together the various system components. Although a 12-volt inverter probably would have been sufficient for this application, an Outback FX2548 48-volt inverter was chosen for the added efficiency and flexibility it provided.

Determine System Loses

No electrical system is 100% efficient. When electricity is conducted through a wire, some of the electrical current is lost as heat. This is why, as mentioned above, a lower DC current is preferable. When the wire chosen to connect all the system components is properly sized, a maximum loss of about 3% [(1)] can be expected.

In figure 2 note that there are three sets of wires where line loss will occur:

- between the photovoltaic modules and the charge controller
- between the charge controller and the battery bank
- between the battery bank and the inverter

If a maximum loss of 3% in each set of wires is assumed, then the amount of power, in watts/day (eq. 1), required must be increased by 3% for each set of wires:

$$8726.4 \times 1.03^3 = 9535.6 \text{ watts/day} \qquad \text{eq. 2}$$

Good inverters have an efficiency of 90% or better. In other words, 90% of the DC power created by the photovoltaic modules is inverted to AC power; the rest is lost as heat during the transformation (this is not necessarily a bad thing as will be discussed later). The Outback FX2548 48-volt inverter has a peak efficiency of 93% [(2)], so there is a loss of 7% to compensate:

$$9535.6 \times 1.07 = 10203.1 \text{ watts/day} \qquad \text{eq. 3}$$

Overall, the required power has increased by about 15% in order to compensate for system inefficiencies.

Determine Array to Load Ratio

If a photovoltaic array is only large enough to supply power needs for one day's operations, then no extra power can be generated and stored for later use on cloudy days. For this reason an off-grid array will often be sized to generate more than the amount of power needed on any given day. A commonly used array to load ratio is 1.3 [(3)]. For example, if 10 kilowatt of power are required each day, the array will generate 13 kilowatts each day. On a sunny day when power is generated, 10 kilowatts is used immediately for that day and 3 kilowatts, the reserve power, is stored in the battery bank for use on cloudy days.

$$1.3 \times 10203.1 = 13264.0 \text{ watts/day} \qquad \text{eq. 4}$$

The required power has increased again in order to provide an adequate array to load ratio.

Determine Photovoltaic Modules

Kyocera KC120 120-watt solar modules were chosen for this site. 120-watt solar modules are a common size for large-scale applications such as this one; however, any size module can be used provided there are enough to meet the power demands. The modules were manufactured and provided by Kyocera Solar, Inc. The KC120 is rated at 7.1 amps of current and has a nominal voltage rating of 12 volts. It is has a conversion efficiency of 14% [(4)] (14% of the sunlight that falls on the panel is converted into electricity).

Determine Photovoltaic Array Size

Recall that the insolation value of 3.9 as explained by figure 1 was the value for December—the time during which there is the least sunlight. The system must have an array to load ratio of 1.3 during this time of year when the insolation value is 3.9. During the rest of the year the array to load ratio will be higher since the insolation value is higher. Divide the required power determined in equation 4 by the insolation, 3.9, to determine the power that must be generated during the four hours of most intense sunlight when the sun is overhead in the sky

$$\frac{13264.0}{3.9} = 3401.0 \text{ watts/hour} \qquad \text{eq. 5}$$

Since photovoltaic modules are rated in amps, divide the required load determined in equation 5 by 48 volts (since a 48-volt inverter is being used) to determine the load in terms of amps required per hour rather than watts/hour.

$$\frac{3401.0}{48} = 70.9 \text{ amp/hours} \qquad \text{eq. 6}$$

Divide the required amp/hours by the photovoltaic module's amp rating of 7.1 amps to determine the number of parallel sets of modules required:

$$\frac{70.9}{7.1} = 9.98 \qquad \text{eq. 7}$$

The value of 9.98 must be rounded to 10 in order to determine a whole number of parallels. The photovoltaic modules must be configured so that there are 10 sets of modules each producing 7.1 amps at 48 volts (since a 48-volt inverter is being used). Each single photovoltaic module has a voltage rating of 12 volts, so 4 modules must be combined in series to achieve the required voltage of 48 volts. For the entire system, 40 photovoltaic modules are required: 10 parallels each composed of a series of 4 modules (figure 3).

Series vs. Parallel Wiring

When batteries or (photovoltaic modules) are wired in series the negative terminal of one battery is connected to the positive terminal of its neighbor. When connected in series, the total voltage of the series is the product of the number of batteries and the voltage of an individual battery, but the current of the entire series is the same as the current of a single battery (e.g. four 12-volt/1.5-amp batteries connected in series produces 48 volts at 1.5 amps). When all the negative terminals are connected to each other and all the positive terminals are connected to each other the batteries are wired in parallel. In a parallel configuration, the total current is the product of the number of batteries and the current of an individual battery, but the voltage of the parallel is the same as the voltage of a single battery (e.g. four 12-volt/1.5-amp batteries connected in parallel produces 12 volts at 6.0 amps).

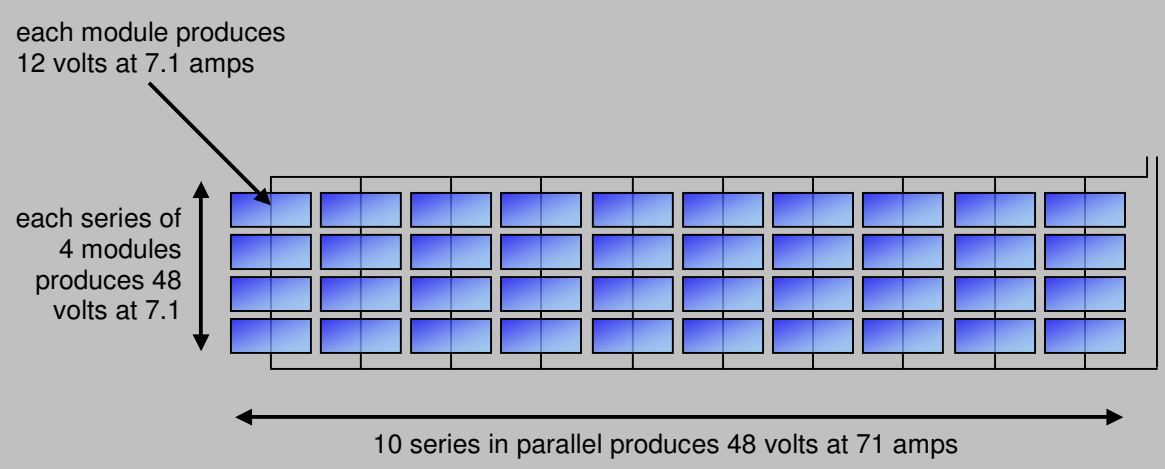

Figure 3: Wiring Schematic of Photovoltaic Array

Determine Battery Bank Size

In order for the monitor to operate at night and on cloudy days a battery bank is required. The size of the battery bank depends on four factors:

- desired days of autonomy
- average wintertime battery temperature
- depth of discharge
- battery capacity

Days of Autonomy
The number of *days of autonomy* refers to how many contiguous days the system can operate in the absence of sunlight. In discussion with monitoring personnel at EPA region VII headquarters, it was decided that four or five days of autonomy would be sufficient. To help keep the cost of the system down, four days was chosen.

Average Wintertime Temperature
The average wintertime temperature is important because batteries operate less efficiently at lower temperatures. One of the requirements of this project was that the shelter housing the monitoring equipment should remain with the range of 2-40ºC; this is the operating range indicated in the operating manual for an R&P TEOM 1400 [(5)]. In the winter, the design assumption was that a temperature well above freezing could be maintained in the shelter (an assumption that was later proven false and will be discussed later). This was to be accomplished by adding extra insulation in the shelter thereby trapping the heat created by the TEOM (a TEOM sensor unit configured for PM_{10} analysis operates at 50ºC). Since it was assumed that the shelter would not approach freezing, there was no adjustment made for colder battery operating temperatures.

Depth of Discharge
Completely draining a battery will cause severe damage so depth of discharge must be considered. The most common depth of discharge is 80% [(6)]; the batteries can be safely discharged up to 80% of their capacity, in other words, they should never be drained to less than 20% of their capacity (in fact, in order to protect the battery bank, the inverter chosen for this system will shutoff if the battery voltage drops to unsafe levels). Although this 20% reserve is never actually used, it must be added to the total capacity of the battery bank to maintain the desired number of days of autonomy and to protect the batteries from damage.

Battery Capacity

Batteries used in photovoltaic systems are typically rated in amp/hours. The most common amp/hour rating is the *20-hour rate*. If a battery has a capacity of 460 amp/hours at the 20-hour rate this means it can deliver 23.0 amps for 20 hours (23.0 x 20 = 460). The 20-hour rate is most often used because that is the amount of time that a battery will be used during any given day. Recall the insolation value of 4.0—4 strong hours of sunlight on an average day. When there is available sunlight, the batteries are not needed so they are simply charged during those 4 hours by the extra power created by the array (determined by the array to load ratio). The other 20 hours during the day, power is drawn from the battery.

As determined above in equation 3 the daily power requirement (taking into account all system losses) was 10203.1 watts. The battery bank size is thus determined by the daily power requirement and the number of days of autonomy:

$$4.0 \times 10203.1 = 40812.4 \text{ watts} \qquad \text{eq. 8}$$

Allow depth of discharge of 80%:

$$\frac{40812.4}{0.80} = 51015.5 \text{ watts} \qquad \text{eq. 9}$$

The battery bank should therefore have a capacity of 51 kilowatts. Once again, since a 48-volt inverter is used, this figure is divided by 48 to determine the number of amp/hours the battery bank must supply:

$$\frac{51015.5}{48} = 1062.8 \text{ amp/hours} \qquad \text{eq. 10}$$

If a battery with a 400 amp/hour capacity is used, this means that 2.7 parallels (which would be rounded up to 3) of 48 volts each would be required:

$$\frac{1062.8}{400} = 2.66 \qquad \text{eq. 11}$$

If a battery with a 350 amp/hour capacity is used, this means that only 3.03 parallels (which would be rounded up to 4) of 48 volts each would be required:

$$\frac{1062.8}{350} = 3.03 \qquad \text{eq. 12}$$

Technically, when sizing photovoltaic systems, numbers of modules or batteries are never rounded down. Thus 3.03 should be rounded to 4. However this would be a substantial increase (33%) in the number of batteries. It was decided that the loss of 12.8 amp/hours (about 1%) was an acceptable concession in order to save a great deal on batteries:

$$350 \times 3.0 = 1050 \text{ amp/hours} \qquad \text{eq.13}$$
$$1062.8 - 1050 = 12.8 \text{ amp/hours}$$

Thus, three 48-volt parallels of 350 amp/hours are required. Batteries for use in photovoltaic system can range anywhere from 2 to 12 volts. Any voltage is adequate provided that 48 volts is the output when the batteries are connected in series. Usually cost is the determining factor and in this system eight 6-volt batteries was the least expensive configuration. Since each battery is 6-volts, 8 are required in each parallel to achieve 48 volts, and since there are three parallels, 24 batteries are required (figure 4).

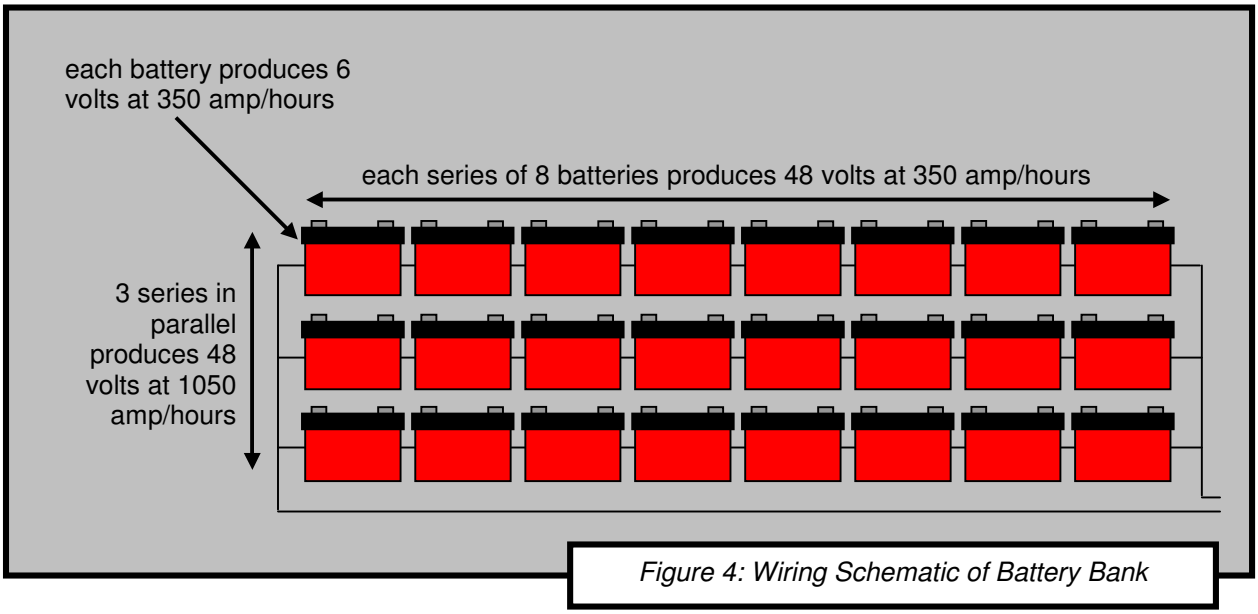

Figure 4: Wiring Schematic of Battery Bank

Alternative Heating and Cooling

When every watt of power required has a dollar figure attached to it in a tangible form such as a photovoltaic module or battery, the cost of electricity becomes much more physical. Needs must be prioritized and it quickly becomes evident what is absolutely necessary and what is not. Such an energy budget forces consideration and implementation of alternative methods and yields results that are practical and more efficient than previous operational mentalities.

Cooling

As discussed above, equipping the shelter with an air condition would have been prohibitively expensive in terms of kilowatts. The previous mindset regarding cooling shelters had always been "just run an air conditioner". This mindset was redefined to the more practical, "don't let the shelter temperature exceed the operational range of the instruments." The operational range of an R&P TEOM 1400 is 2-40ºC (40-104ºF). Meteorological data collected by NDEQ in 2003

and 2004 indicated that ambient summertime temperatures in Weeping Water exceeded 40ºC only once (temperature was 40.6ºC). Thus if the shelter could be maintained at ambient temperature during the summer months, an air conditioner would not be required.

The initial design of the shelter, a 6' x 10' Wells Cargo trailer, called for installation of a vent at the lower rear end of the trailer and a fan, powered by an auxiliary photovoltaic module, at the upper front end of the trailer just above the instruments. In this way the shelter should be cooled by convection and helped along by a fan pulling the warm air out of the trailer (figures 5 & 6).

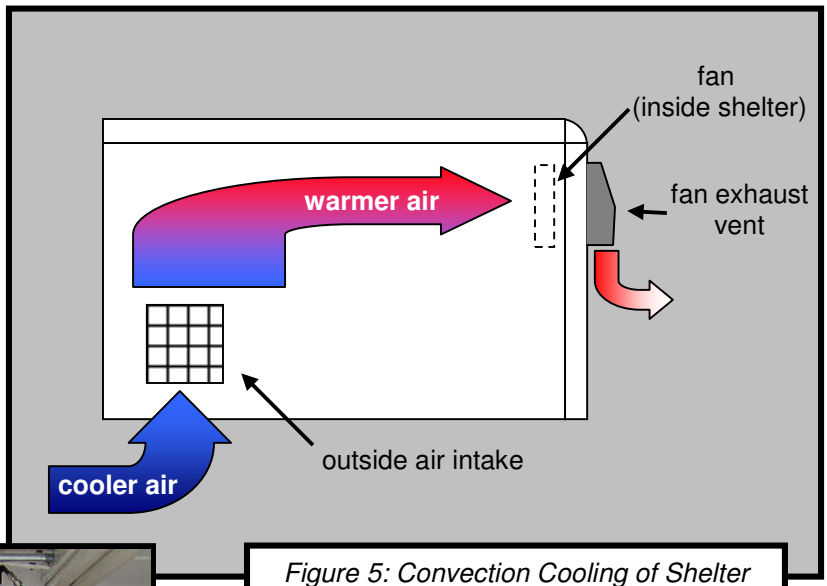

Figure 5: Convection Cooling of Shelter

Figure 6: Interior of shelter, exhaust fan is at upper right

This design worked quite well initially. The shelter usually ran about 5ºC higher than the ambient temperature (figure 7). However, during the hottest summer days there were simply not enough openings in the trailer to allow enough airflow to cool the trailer. The major generator of heat was not the TEOM analyzer as expected but rather the inverter. To correct the problem four more vents were cut in the floor of the trailer and a large exhaust vent with another solar-power fan was put in the roof. Initially, putting any sort of hole in the roof was avoided because of the potential for leaks, but the best way for heat to escape is straight up. Finding an appropriate exhaust vent that would keep out rain and snow was initially problematic until it was realized that some old high-volume particulate samplers were designed to do just that. NDEQ has retired several Anderson 1200 high-volume samplers; the inlet head from one of these was removed and mounted to the shelter roof in order to better vent the warm air inside (figures 9, 10, & 11). This lowered the difference between shelter and ambient temperature from 5ºC to nearly 0ºC (figure 8).

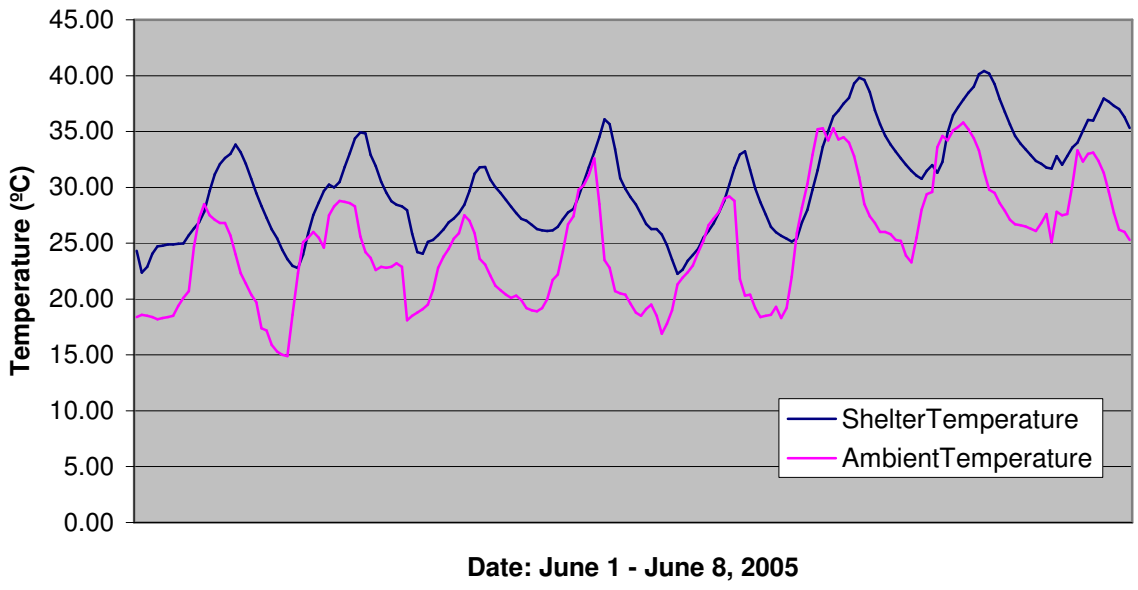

Figure 7: Shelter temperature vs. ambient temperature with minimal venting of inside air

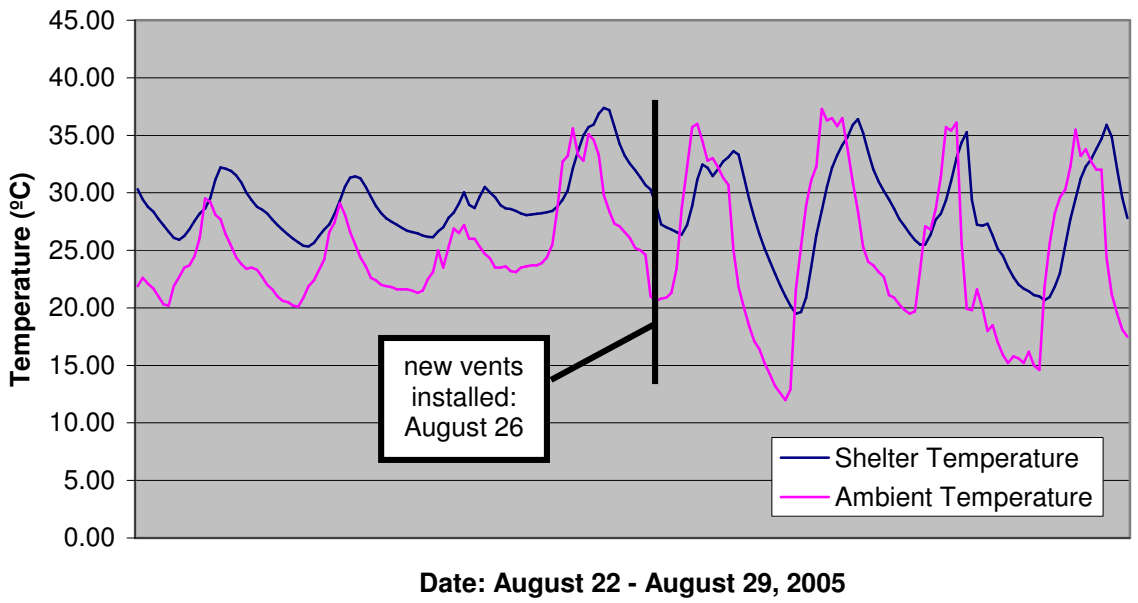

Figure 8: Shelter temperature vs. ambient temperature with increased venting of inside air

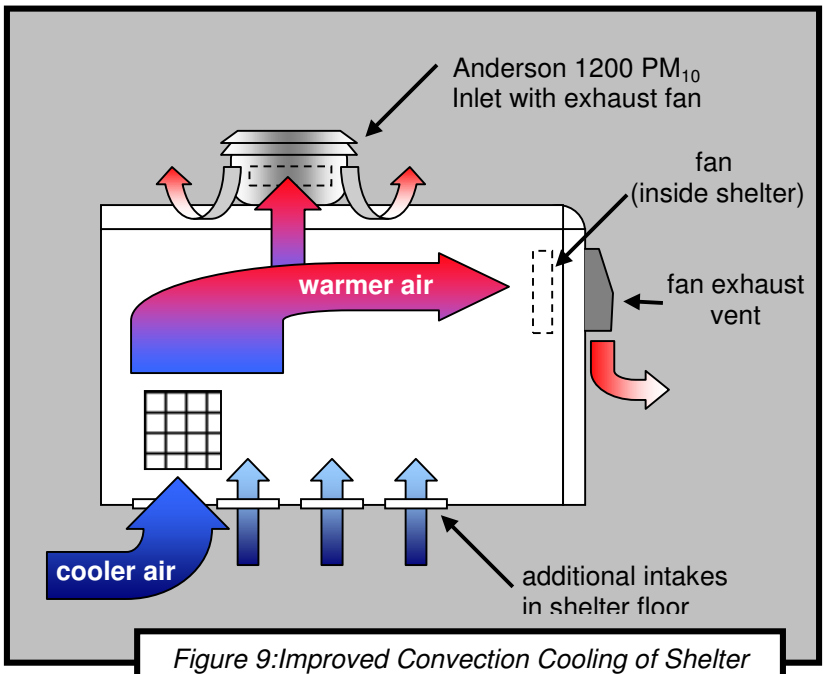

Figure 9:Improved Convection Cooling of Shelter

Figure 10:Vents installed in floor of shelter

Figure 11: Exterior of shelter showing PM_{10} inlet vent and auxiliary photovoltaic modules that power the exhaust fans.

Heating

Heating the shelter has thus far proven fairly easy. As was stated earlier, the design assumption was that a temperature well above freezing could be maintained in the shelter by adding extra insulation and then allowing the waste heat generated by the instruments to heat the shelter. The unexpected heat given off by the inverter, which was an obstacle in the summer, proved to be a boon in the winter. When temperatures get cooler, all the intake and exhaust vents are sealed (except for a small fan which vents hydrogen from the battery box to the outside) in order to trap the heat generated inside the shelter. From October through December of 2005, the shelter temperature ran 12.6ºC higher on average than the ambient temperature (figure 12).

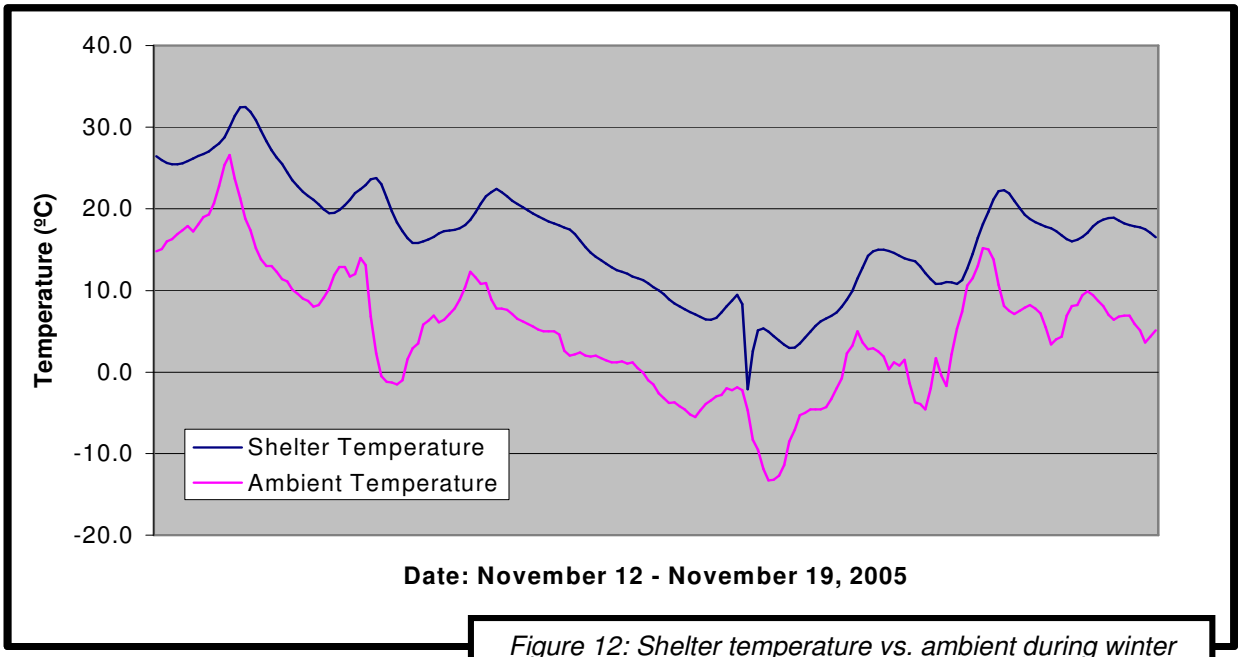

Figure 12: Shelter temperature vs. ambient during winter

As is evident from figure 12, a 12.6ºC differential was not always enough to keep the shelter temperature above 2ºC. With the shelter in this configuration it is estimated that the shelter temperature will remain above 2ºC as long as the ambient temperature does not drop -10.6ºC. Using ambient temperature data collected at other monitors in Weeping Water, a maximum data loss of 15.6% due to an out of range shelter temperature, could be expected (table 2).

Table 2: Percentage of Time that Ambient Temperature is Less than –10.6ºC

Year	Quarter	Site	Percentage of time ambient temp less than –10.6ºC
2004	1	Park	15.3
		Treatment Plant	15.6
	4	Park	2.8
		Treatment Plant	3.1
2005	1	Park	8.1
		Treatment Plant	8.8
	4	Park	6.8
		Treatment Plant	5.8

In the fourth quarter of 2005 at the photovoltaic powered site (dubbed "Lauritzen Farm"), the ambient temperature was less than –10.6ºC 6.1% of the time—note that this is in line with the fourth quarter 2005 values at the other two sites in Weeping Water that recorded values of 6.8% and 5.8% (table 2). However, the shelter temperature dropped below 2ºC only 3.1% of the time; this was less than expected. A temperature differential of 12.6ºC is actually a conservative figure.

With only one quarter of wintertime data thus far, these results are only a starting point. As more data is collected, a more precise value for the temperature differential will undoubtedly emerge. However, the immediate and most important conclusion from these results is that the shelter, in its current configuration, cannot always maintain a temperature of 2ºC or higher. Two solutions are currently in the works to correct this shortcoming:

- addition of more insulation on the shelter ceiling
- installation of a low-wattage heater (135 watts) that is powered by the auxiliary photovoltaic modules that power the exhaust fans in the summer.

Operations to Date

Cost

A major hurdle in the use of photovoltaics and other renewable energy systems is cost. Off-grid systems can be even more costly since large battery banks are required to ensure continuous, uninterrupted operation. The base price of all the system components for this site was about $28,000. Another $1000 was spent modifying the trailer shelter to improve heating and cooling capabilities. While this is a substantial cost, it should be viewed within the context of the cost of instrumentation that environmental agencies routinely deploy. In an undeveloped site in can often cost several thousand dollars just to bring in grid power and then there is still the cost of electricity.

Power Failure

The PM_{10} analyzer sited at the Lauritzen farm became operational on April 8th, 2005. Since that time there has been only one major loss of data due to a power failure. The power failure occurred December 7th and the analyzer was not operational again until December 10th. The failure was not due to a system design flaw but rather to the fact that a heavy snowfall collected on the photovoltaic array preventing it from generating electricity at full capacity. Since no substantial amount of sunlight was able to reach the photovoltaic modules for several days, the system ran on batteries alone for at least three days until the battery voltage finally got so low that the inverter shut down to protect the batteries from being over-discharged. After clearing the snow from the panels, the system was allowed to recharge for two days and then it resumed normal operations.

Maintenance

Photovoltaic Array

As is evidenced above, one crucial maintenance task involved in operating a site powered by photovoltaics is keeping the photovoltaic modules clean. However, the incident described above is the exception rather than the rule. It has snowed several times since the site became operational, but only once was the snowfall so heavy that snow actually stuck to the modules and even then the batteries provided enough reserve for the system to operate for several days. Had it been immediately know that the modules were covered with snow, action could have been taken sooner to clear them. As a result NDEQ now coordinates with a volunteer in Weeping Water to check the array after a snowfall and clear it if necessary. Installation of a camera to check for snow cover is also being considered.

A far less daunting task is keeping the photovoltaic array free of dust. The panels are wiped down each time the site operator services the TEOM analyzer. The modules are dusted with a non-abrasive mop and the process only takes about 15 minutes. Occasional rain showers in the spring and summer also help keep the array clean.

In general, the photovoltaic modules require very little maintenance.

Battery Bank

The battery bank is the most maintenance intensive portion of the system. Every 2-3 months the battery bank must be *equalized*. In an equalization cycle, the charge controller raises the battery voltage in order to mix the acid in each battery cell. This keeps the heavier elements in the battery from settling to the bottom and also prevents sulfate deposition on the negative and positive plates inside the battery. After the equalization cycle is complete, the voltage of each battery is equal to all the others—this is optimum for the most efficient operation of the system.

During normal operation, some water in the batteries is broken down into its constituent elements of hydrogen and oxygen (the hydrogen is vented from the battery box and the shelter) and as a result some water is lost. Equalization can cause even more water loss therefore after an equalization cycle each battery cell is topped off with de-ionized water. About five gallons of water are required after each cycle; the total capacity of the entire bank is about 64 gallons.

The specific gravity of each cell in each battery is also measured and recorded after an equalization to ensure that it is an appropriate range. Each battery contains three cells that must be measured. With 24 batteries this means 72 measurements must be taken.

An equalization cycle usually lasts 20-24 hours, but the cycle runs without operator intervention due to the charge controllers. The only labor intensive portion of the equalization process is measuring specific gravity and refilling the battery cells: this can take up to three hours.

Communications

An Airlink Redwing CDMA cellular modem is used to retrieve data from the TEOM analyzer and anemometer at the site. Thus far the modem has proven very reliable. There are plans to eventually report this site's data to the AIRNow network.

Battery Operation in Low Temperatures

As discussed earlier, the one system design aspect that was overlooked was the operational temperature range of the battery bank. It was assumed that the battery box temperature could be kept well above freezing with the added insulation in the shelter as well as the insulation in the box housing the batteries so little account was taken for loss of efficiency in colder temperatures. In reality the shelter temperature did drop to near freezing (and below on a few occasions). This is not detrimental to the batteries; it just makes them less efficient which in turn decrease the number of days of autonomy. At lower temperatures, a multiplier is used to determine the actual capacity of the batteries. Table 3 indicates the capacity the battery bank at various temperatures as well as the expected number of days of autonomy.

Table 3: Battery Capacity and Days of Autonomy at Various Temperatures

Rated capacity of entire bank (from equation 13)	Temperature (ºC/ºF)		Scalar at given [6] temperature	Actual capacity at given temperature (see equation 14)	Days of autonomy at given temperature (see equation 15)
1050	26.7	80	1.00	1050.0	4.1
1050	21.1	70	1.04	1009.6	3.9
1050	15.6	60	1.11	945.9	3.7
1050	10.0	50	1.19	882.4	3.4
1050	4.4	40	1.30	807.7	3.1
1050	-1.1	30	1.40	750.0	2.9
1050	-6.7	20	1.59	660.4	2.6

$$\frac{\text{rated capacity}}{\text{scalar}} = \text{actual capacity} \qquad \text{eq. 14}$$

$$\frac{\text{actual capacity} \times \text{depth of discharge}}{\text{amp/hours required daily}} = \text{expected days of autonomy} \qquad \text{eq. 15}$$

The result of failing to consider battery temperature simply lessens the number of days of autonomy in the winter. Note that the average ambient temperature during the fourth quarter of 2005 was 6.0ºC: this equates to about 3.2 days of autonomy in the winter.

Conclusions

Much work has already been done in the field of photovoltaic power generation. Sizing photovoltaic arrays and battery banks based on known loads is a fairly standardized practice in the industry. This air monitoring application was no different, even though it is the first known air monitoring application of photovoltaic power of this scale. The real challenge at this site was determining what was absolutely essential for monitor operations in order to reduce power consumption. Greatly reduced power consumption meant that photovoltaics would be a viable alternative to grid power.

If shelters are insulated and vented properly then air conditioning, which requires very large amounts of power relative to the monitoring instruments, is not required. Keeping a shelter warm, on the other hand, presents a greater challenge. Additional insulation does help and might possibly even eliminate the need for heaters as well. However, even if additional insulation is not sufficient, adding it still reduces the amount of additional heat required to keep the shelter within operational norms. This type of shelter design can be used to conserve energy even in shelters that use grid power.

The air monitoring instrumentation industry has the ability to help make instruments powered by renewable energy easier to deploy, and many companies are doing so. By focusing efforts on building DC-powered FRM and FEM instruments with low power requirements (since a site that supports DC-powered instruments would not need an inverter), industry can make instruments that are less expensive to operate and give users more options for powering their instruments. Monitors that do not require grid power allow environmental agencies much greater freedom when siting air monitors.

Renewable energy systems do not necessarily have to be completely off-grid like this monitoring site. Hybrid energy systems use grid power but supplement it with photovoltaic or wind power; this reduces energy costs and reduces reliance on traditional power plants.

Environmental agencies should, first and foremost, perform their monitoring duties as required. Nevertheless, a secondary objective should be to set an example. Two lessons that can be gleaned from this project are:

- Renewable energy is a viable alternative in many situations and when a renewable system is properly designed, it is comparable in reliability to grid power
- Reducing energy consumption is good practice all the time, not just when designing renewable energy systems

Several product names as referenced in this paper; mention of these product names does not indicate an endorsement by the Nebraska Department of Environmental Quality of those products.

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