Paper from: www.RERinfo.ca

Renewable Energy Technologies in Cold Climates '98 (24th SESCI)
May 4-6, 1998 Montréal, Québec, Canada (pp. 273-278)

A CHECKLIST FOR PV SYSTEM MONITORING

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ABSTRACT

Monitoring a photovoltaic system is not conceptually difficult, yet many monitoring projects fail to achieve their objectives: often essential variables are not monitored, improper installation or calibration invalidates results, the budget includes insufficient funds for proper data analysis, or data files are lost. This need not be the case: with proper care monitoring can be done correctly.

This article presents practical guidelines that should improve a monitoring project's chances of success. Emphasis is placed on the planning and design of the monitoring project. Once the desired outcomes of the project have been identified, then the variables to be monitored, the duration of averaging periods, the length of the project, and the budget for the project can be determined. Documentation of the system and all changes made to the system is essential, as is the choice of an appropriate time base and data format. Guidelines for data analysis and error analysis are detailed, and some special considerations for cold climates are listed.

Following these guidelines will require additional time and effort initially, but will greatly increase the reliability of the data and the confidence of the results.

This paper is dedicated to the memory of Prof. Muthu Chandrashekar (1937-1998), director of the Watsun Simulation Laboratory at the University of Waterloo.

1 - INTRODUCTION

Most major photovoltaic (PV) systems undergo some type of monitoring for at least a few years after their installation. Such monitoring can have several goals:

- ensure that the system is operating properly;
- assess the performance of system components, pinpoint faulty devices or devices operating below their nominal performance;
- permit the calibration of design and simulation tools;
- reveal improvements to the design and increase the understanding of the designer.

Despite its usefulness, monitoring is often overlooked. In the past few years, the authors have encountered numerous examples of improper monitoring. For example, in one case, some important variables were simply not monitored. In another case, improper connection of some sensors to the datalogger led to useless numbers. In a third case, improper calibration of an instrument led to the recording of several years of useless data. In yet another case, a data file was inadvertently erased several months after it was recorded – and no backup was available. And in countless cases, the data gathered waits for months –or years –before being properly analyzed.

In fact, proper monitoring of PV systems *does* occur, but it seems to be the exception rather than the rule. There could be many reasons for this:

- in many projects, the focus is on building the PV system itself, rather than assuring that it actually delivers what it is supposed to;
- monitoring is always the last part of a project chronologically, therefore it is more likely to be sacrificed if time constraints or budget overruns occur;
- monitoring extends in time past the completion date, and can require a continuous time commitment over a period of several years –this is often not included in the budgets;
- the personnel in charge of the monitoring (if anyone is in charge) may in some cases be improperly trained or unable to analyze the data;
- additional conditions (harsh climate, remoteness) may exist, which increase the likelihood of monitoring system failure, or render corrective intervention more difficult.

This paper focuses on practical guidelines, encompassing monitoring system design, monitoring system setup, data storage, data analysis, and special considerations for cold climates, which will increase the likelihood that monitoring will lead to useful, valuable information.

2 - MONITORING SYSTEM DESIGN

The first question to ask is not: *what will be measured*, but rather: *what do we want to know*? This usually falls into one of three broad categories:

a) system energy production (most basic information);
b) more detailed engineering information, such as the performance of various components of the system (e.g. array efficiency, inverter efficiency);
c) more specific, research-oriented information (e.g. distribution of diffuse irradiance in the sky, spectral composition of light incident on PV array).

The quality of the information required is related to the use it will be put to (e.g., billing customers; analyzing system performance; doing research on photovoltaics). This needs analysis constrains the minimum monitoring system design, the reporting time interval, and finally the budget. It also helps define the length of the monitoring period. The three broad categories above will lead to different lists of monitored variables, averaging periods, monitoring periods, and budgets:

a) System energy production: It is sufficient to monitor AC power to load (for grid-connected systems), DC power delivered (for stand-alone systems) or water pumped (for water pumping systems), averaged on a daily or monthly basis. If used for billing, monitoring is forever. The instrumentation budget is low.
b) Detailed engineering information: The variables usually include the inputs and outputs of all the components in the system. An indicative list (taken from [1], [3]; see also [10]) is provided in Table 1. Monitoring is usually done for a period from 2 to 5 years, sometimes more if degradation is to be studied (e.g., for amorphous silicon [2]). The data will be averaged on a 15 minutes to one hour period. The instrumentation budget ranges from medium to high.
c) Research: Variables and sampling rate depend on the scientific information required. Monitoring is often for a shorter period of time. The instrumentation budget is usually high.

1. Date and Time
2. Global irradiation
3. Irradiation in plane of PV array
4. Wind speed
5. Wind direction
6. Ambient temperature
7. Module (cell) temperature
8. Array voltage
9. Array DC current per string of modules
10. Array DC current total
11. Array power
12. DC power to inverter
13. AC voltage (all phases)
14. AC current (all phases)
15. AC power to and from inverter
16. Battery voltage
17. Battery current
18. Energy to each load (DC and AC)
19. Energy to and from grid
20. Energy from backup generator
21. Timing of system switching events
22. Energy used by instrumentation
23. Earth leakage detection on the array field

Table 1 - Examples of variables to monitor
(some variables may not be applicable to some systems)

Before deciding on a final list of variables to monitor, it is imperative to decide how the data will be used: spreadsheet analysis, simulation program, scientific models. Ensure that all *inputs* and *outputs* required by the analysis tool are available, and that the time step is appropriate.

The list of variables to monitor, such as the one shown on Table 1, may contain both 'primary' variables, that are actually measured, and 'derived' ones, calculated from other variables (e.g. power, derived from voltage and current). Also, in some cases, not all the variables included in the list need be monitored; if conditions are favorable, some of them can be obtained from other sources (e.g. meteorological office, local utility).

Redundant variables can be monitored. In this case, if one sensor fails, it will be possible to derive equivalent information from data provided by other sensors. Redundant monitoring has other advantages, such as revealing errors and uncertainties in the measurements. It is not a panacea, however, because monitoring becomes more complex and more time is required for data analysis. The focus should be on monitoring fewer variables, but monitoring them well, rather than being too ambitious and not doing the job properly.

3 - MONITORING SYSTEM SETUP

3.1 - PV system documentation

Monitoring has to be built on strong foundations: prior to designing and installing the monitoring system, one has to make sure that the photovoltaic system itself is properly documented. More specifically, there should be a comprehensive document describing the system in its entirety. That document has to include site information, a complete list of system parameters and setpoints, specification sheets for the various components, accurate blueprints, and possibly photographs of the system.

3.2 - Logbook

A logbook of all events related to the life of the photovoltaic system and to the monitoring system is essential. Examples of entries in the logbook include: maintenance and servicing of the system, major events such as failures, manual interventions (e.g. snow removal), and changes of configuration or components. The logbook can be an electronic document, but the preferred approach is to have a physical (paper) book that is kept next to the experiment itself. A paper book is always readily accessible, even to the computer-illiterate, does not crash, and can receive additional inserts if needed.

Procedures for documenting changes to the system must be defined. Every change, however minor, has to be recorded in the logbook. Also, one has to make sure that *all* the personnel dealing with the PV or the monitoring system are trained to record their actions in the logbook.

3.3 - Monitoring system

Current monitoring technology involves the storing of monitored data in digital form. The monitoring system comprises sensors, a data acquisition unit, and a computer with magnetic mass storage on which the data is stored. There are numerous types of sensors adapted to the measurement of different quantities; discussing the merits of each of them is beyond the scope of this paper. The reader is referred to specialized publications and manufacturers' specification sheets. Use of some particular types of sensors is discussed in Section 7.

The monitoring system must be designed in such a way that it minimally affects the operation of the PV system being monitored. Measuring something invariably changes it, but the change can be made negligible through proper design. If the monitoring system is being powered by the PV system under examination, ensure that the monitoring system consumes less than 5% of the PV systems' output. More subtle influences need to be considered: for example, an AC wattmeter may draw sufficient current that it prevents the inverter it is monitoring from entering "sleep mode".

3.4 - Time base

The time recorded with monitored data should normally be Local Standard Time (LST). LST is the time read on the watch, except when daylight savings time is in effect. In Canada, daylight savings time is 1 hour ahead of LST in the summer. No adjustment of the datalogger's clock should be made for daylight savings time.

It is vital to make sure that the clock is accurate. It is equally important that the data is recorded at regular exact intervals, preferably on round times (e.g. on the hour). This simplifies subsequent data analysis

4 - DATA STORAGE

4.1 - Data retrieval

Data can be retrieved from the monitoring equipment several ways. Transfer on site (via disk or laptop connection) is common but it is increasingly practical to transfer data by modem and phone line, especially from remote sites. Data must be retrieved at regular intervals and submitted immediately to quality control and data analysis (see Section 5.2). Immediately after a data set has been retrieved, the file should be made read-only; a backup should be stored in a different place.

4.2 - Data storage and backup

A naming convention for the data sets should be adopted. The name of a data set can, for example, reflect when it was acquired. Data should be stored in ASCII (text) format, rather than in binary or proprietary format. This makes data readily accessible to programs and spreadsheets, ensures that data will be readable far into the future, and facilitates exchange of data with other teams. Experience shows that the preferred format is comma-delimited ASCII with one line per recording, and with a time stamp (date and time) as the first entry in every record.

Flags, or a particular value such as -9999, or no value at all (this would appear as two consecutive commas in a comma-delimited ASCII file) should be used for missing data. The use of zero for missing data should be avoided since zero can for many quantities be a valid measurement.

Monitoring data often turns out to be useful long after it has been recorded. For that reason data should be archived for the long term (20 years). CD-ROMs are preferred to magnetic media such as tape or diskettes, since CD-ROMs have a much longer shelf life (100 years vs. 5 years).

5 - DATA ANALYSIS

5.1 - Quality control

A quality control (QC) procedure has to be put in place to analyze the data. The procedure has to be documented and automated so that it can be repeatedly used on future sets of data. Criteria to reject 'bad' data have to be decided. For example, the QC can reject or set to zero values below a certain threshold. The QC procedure should also draw the attention of the operator to the occurrence of certain bad data, either because they happen often (which may indicate a faulty sensor) or because they lead to unreasonable secondary measurements. A typical example of such a situation is power measurements leading to abnormally low or high efficiencies.

The QC procedure leads to a new set of data. One should always keep an archive copy of the *raw* data along with the quality-controlled sets.

5.2 - Data analysis

Data analysis should start as soon as possible, and no later than a few weeks after the monitoring system starts to operate. Waiting increases the chances that either the PV system or the monitoring system is not operating properly. The whole analysis has to be run, using the tool(s) defined during the monitoring system design phase (see Section 2). Performing this analysis near the beginning of the monitoring session will help find setup mistakes (e.g. improper connection of thermocouples) and even more subtle errors such as improperly calibrated pyranometers.

Data analysis has to be done on a continuous, routine basis. For example every month the data from the system has to be retrieved and thoroughly analyzed. This will make sure that the photovoltaic system and the monitoring system are still operating properly, and enable immediate corrective action if needed. One direct consequence is that appropriate staffing is required on a continuous basis for the whole duration of the monitoring project.

6 - ERROR ANALYSIS

Error analysis refers to an appraisal of how well measured and derived values reflect reality, especially in an attempt to minimize the discrepancy. Error analysis is often ignored in PV system monitoring, possibly because of the relatively difficult mathematical concepts underpinning it. These concepts are outside of the scope of this paper, but some basic considerations are given here, and four "golden rules" of error analysis for PV systems are proposed.

It can be helpful to think of a measured value as equal to the true value plus a certain amount of error. This error includes two types of error: systematic error and random error. Systematic error, also called accuracy error, refers to a persistent difference between the measured and true value that can not be attributed to chance. Random error, also known as precision error, refers to the "noise" of a series of measurements that are scattered around the true reading. When random error is low, an experiment is repeatable: retaking the measurement with the same monitoring system gives a very similar value. When systematic error is low, an experiment is reproducible: if the variable is measured with a completely separate apparatus, the two systems will, on average, agree.

Rule #1: Eliminate systematic error by verifying the reproducibility of measurements. Every variable that is being monitored should be checked manually. This is tedious and time-consuming, and it is all too easy to assume that a monitoring system is accurate simply because it operates and the values "seem reasonable" on first inspection. In the authors' opinions, however, there is a simple choice: during installation, spend an extra day or two and check every variable, or, several months or years later, spend an extra week or two trying to figure out why the data does not make sense.

When verifying reproducibility, three considerations are paramount:

1) The apparatus used for validation should be dissimilar to and function independently of the monitoring system. This reduces the chances that the factor(s) that are causing the error in the first instrument cause a similar error in the second instrument.
2) The measurement should be checked over a representative range of values. This reduces the chances that non-linear errors, such as saturation of an amplification circuit, will invalidate readings over a part of their range.
3) The measurement should be checked in its ultimate form, i.e., in the form in which it will be recorded. This reduces the chances of the monitoring system applying an incorrect transformation to the data, which may cause loss of data or precision. This is especially important in the case of non-linear transformations, such as those for thermocouples.

More attention should be paid to systematic error than random error, for two reasons:

1) Human errors, which tend to be common in the design and installation of a complex system, usually result in systematic errors, e.g., the wrong terminals are connected or the wrong multiplicative constant is entered. In contrast, most measuring instruments are fairly precise (i.e., have low random error).
2) Monitoring systems are typically used to find totals or averages, such as average system efficiency or total energy generated. When a large number of

measurements are summed or averaged, the random errors cancel each other out, and the random error of the result is much reduced.

Nevertheless, random error can be important, especially when individual readings are significant (e.g., the battery voltage when a controller disconnects a load) or when a small number of readings are summed or averaged.

Rule #2: Reduce random error where it will lead to improved accuracy in the estimates of quantities of interest — i.e., those quantities identified in response to "what do we want to know?". A lot of money can be wasted buying highly precise instrumentation which will not appreciably reduce error in the final results.

When measured variables are combined to give a derived result (e.g., measurements of current and voltage to give power), their uncertainties are compounded. The absolute error is an indication of the maximum error: it is the error that would result if all the uncertainties were considered independently. In general, however, errors are randomly distributed around the true value: errors in different measurements compensate each other, and the most probable estimate of the resulting error is lower than the absolute error. This "probable error" is related to the square root of the sum of the squared errors, so one measurement with an uncertainty larger than the rest will be responsible for a disproportionate part of the total uncertainty [4], [5]. Efforts to improve precision should focus on this measurement.

Rule #3: Unless they are the sum or average of a large number of measurements, express all results with a confidence interval, i.e., in the form:

$$V = m \pm w \; ; \; p \text{ percent of the time}$$

where V is the measurement or result, m is the best estimate, w is the uncertainty, and p is the confidence level, i.e., how sure one is that the true value will fall within the range $m \pm w$ (methods for calculating this are given in [4], [5]. Perusal of the literature on PV monitoring reveals that this is almost never done. In many cases, such as when the result is an average or sum of a large number of measurements, no harm is done. In other cases, failing to do this can lead to erroneous conclusions, e.g., that one value is greater than another when really the two are equal within the experimental accuracy. In an ideal world, even sums and averages would be expressed with confidence intervals.

Rule #4: Examine the consequences of the natural variation in insolation and ambient temperature. For example, the efficiency of a PV array varies with temperature. Looking at the variation of efficiency from year-to-year has no sense if one does not take into account the year-to-year fluctuations of solar radiation and temperature. This can be done by transforming the data to some standard conditions (e.g., 25ºC and 1000 Wm^{-2}). Alternatively, one can try to determine the uncertainty that results when a finite number of measurements are used to characterize a phenomenon which varies about some "true" mean; the uncertainty is then expressed as a confidence interval, as above. This can be quite complicated, since most methods require that variables have a gaussian distribution and are serially uncorrelated (i.e., in a time series of measurements, one reading implies nothing about the next [7]). Insolation is not gaussian [6], and both insolation and ambient temperature are serially correlated; furthermore, it is questionable whether either of these has a true mean.

7 - COLD CLIMATE CONSIDERATIONS

7.1 – Systematic Errors caused by Snow and Ice on Pyranometers and Anemometers

Snow can accumulate on pyranometers. To avoid this, heating and ventilation units are available for some high-precision thermopile pyranometers. These systems consume from 10 to 80 W of power. For many models of pyranometer and reference cell, no heating system exists off-the-shelf, and the user will have to build one herself.

Ice accumulation can be a much more severe problem, especially in mountainous areas prone to rime icing. There have been few field trials of heating units for pyranometers under these conditions. Ice accumulation on anemometers will greatly affect their measurements of wind speed and direction. Heated anemometers have been developed; unfortunately, field tests suggest that the most reliable and accurate types require around 1500 W for their heaters [8]. These will be practical only at those sites where conventional sources of electricity are available. There have been efforts to develop anemometers requiring only 25 to 50 W for deicing [9].

It is possible that even when a pyranometer or anemometer stays free of ice, rime accumulation on nearby structures will "bridge" towards the instrument and impede its operation. Sometimes good design of support structures can avoid this problem; in other cases it may be necessary to wrap supports in heating cable.

7.2 - Temperature Sensitivity of Pyranometers

Verify that pyranometers and photodiode sensors are either not sensitive to changes in temperature or incorporate temperature compensation circuits. Most high quality thermopile pyranometers are temperature compensated, but some older models are not. The temperature dependence of one photodiode pyranometer is listed as ± 0.15% per C change from 25 ºC; at -5ºC this would introduce a systematic error of magnitude 4.5%.

7.3 – Spectral Sensitivity of Photodiodes and Reference Cells

While thermopile pyranometers are relatively unaffected by changes in the solar spectrum, photodiode pyranometers and reference cells display systematic error when the spectrum shifts. Insolation on a non-horizontal surface will include ground-reflected radiation having an altered spectrum, and therefore photodiodes and reference cells are not recommended for anything but global insolation on the horizontal. Spectral alteration occurs when the sun is low in the sky, causing it to be filtered by a thicker layer of atmosphere. This latter situation is typical during winter at mid-latitude sites and year-round at high latitude sites, and will lead to systematic error in photodiodes and reference cells.

7.4 – Cold Affects Electronics

Cold temperatures, thermal cycling, and condensation can affect the electronic components of a monitoring system. Ensure that the specifications of these components indicate an acceptable range of operating temperatures. Sealed or potted (encased in epoxy) electronics will not fail due to condensation. Contact the manufacturer to discuss the use of their equipment in cold environments.

7.5 – Remote Sites

PV systems are often more economically attractive for remote locations, where the cost of traditional sources of energy is high. For the monitoring system, remoteness will mean additional costs and trouble when problems occur or data is suspect. To avoid this, extra care during design and installation is strongly recommended. It is also advisable that the monitoring system be capable of downloading data through telephone or satellite, and of performing long distance diagnostics on the system.

8 - CONCLUSIONS

PV system monitoring often fails to meet desired objectives. It is speculated that failures are due to poor planning, lack of understanding the importance of monitoring, and insufficient long-term commitment.

Defining the objectives of the monitoring comes first. Listing the questions that the monitoring system will try to answer leads naturally to its specifications in terms of equipment, sampling rate, and budget. The monitoring system and the photovoltaic system itself should be properly documented, and the personnel in charge should be properly trained. Precautions should be taken in the recording and storage of the data. Quality control and data analysis have to be done on a continuous, regular basis. Finally, appropriate error analysis methods should be used, and special considerations for cold climate should be considered when appropriate.

Some of the guidelines listed in this paper are plain common sense; other may seem to impose an undue burden on the monitoring engineer. However, the rewards for following them are substantial, particularly because problems in the monitoring system are caught quickly. This assures that useful data is collected, and it reduces considerably the time needed for subsequent data analysis. In many cases, the procedure will also reveal problems with the PV system itself, and the extra time spent in properly designing, testing, and analyzing the monitoring system will actually pay off in improved efficacy of the whole photovoltaic system.

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