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IEEE Recommended Practice for Sizing Nickel-Cadmium Batteries for Photovoltaic (PV) Systems

Sponsor

Subcommittee on Photovoltaic Energy Storage Systems
of the
IEEE Standards Coordinating Committee on Photovoltaics (SCC21)

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Abstract: A method for sizing nickel-cadmium battery storage subsystems used in residential, commercial, and industrial photovoltaic (PV) systems is described.

Keywords: battery sizing, nickel-cadmium batteries, terrestrial photovoltaic (PV) systems

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Introduction

[This introduction is not part of IEEE Std 1144-1996, IEEE Recommended Practice for Sizing Nickel-Cadmium Batteries for Photovoltaic (PV) Systems.]

This recommended practice applies to terrestrial photovoltaic power systems, regardless of size or application, that contain nickel-cadmium battery storage subsystems.

This recommended practice should assist a photovoltaic system designer in sizing nickel-cadmium batteries for a particular installation. A worksheet is included to facilitate the battery sizing process. Examples of its application are found in annex B.

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CLAUSE PAGE

IEEE Recommended Practice for Sizing Nickel-Cadmium Batteries for Photovoltaic (PV) Systems

1. Overview

1.1 Scope

This recommended practice describes a method for sizing nickel-cadmium batteries used with terrestrial photovoltaic (PV) systems. Installation, maintenance, safety, testing procedures, and consideration of battery types other than nickel-cadmium are beyond the scope of this recommended practice. Recommended practices for the remainder of the electrical systems associated with PV installations are also beyond the scope of this standard.

Sizing examples are given for various representatives system applications. Iterative techniques to optimize battery, costs, which include consideration of the interrelationship between battery size, PV array size, and weather, are beyond the scope of this recommended practice.

1.2 Purpose

This recommended practice is meant to assist system designers in sizing nickel-cadmium batteries for residential, commercial, and industrial PV systems.

2. References

This recommended practice shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms.[1]

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[1] At the time this standard went to press, IEEE Std 100-1996 was approved but not yet published. Anticipated publication is April 1997. IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

IEEE Std 1115-1992, IEEE Recommended Practice for Sizing Nickel-Cadmium Batteries for Stationary Applications (ANSI).

IEEE Std 1145-1990, IEEE Recommended Practice for the Installation and Maintenance of Nickel-Cadmium Batteries for Photovoltaic (PV) Systems (ANSI).

3. Definitions

In general, definitions of technical words and terms used in this document are found in IEEE Std 100-1996. The following definitions apply specifically to this recommended practice:

3.1 cell: The basic electrochemical unit, characterized by an anode, a cathode, and electrolyte, used to receive, store, and deliver electrical energy.

3.2 cycle life: The number of cycles (discharges and recharges), under specified conditions, that a battery can undergo before failing to meet its specified end-of-life capacity.

3.3 days of battery reserve: The number of days fully charged battery can satisfy the load with no contribution from the photovoltaic (PV) array or auxiliary power source.

3.4 depth of discharge (DOD): The ampere-hours removed from a fully charged battery, expressed as a percentage of its rated capacity at the applicable discharge rate.

3.5 discharge rate: The rate, in amperes, at which current is delivered by a battery. *See also:***hour rate**

3.6 energy capacity: The energy, usually expressed in watthours (Wh), that a fully charged battery can deliver under specified conditions.

3.7 hour rate: The discharge rate of a battery expressed in terms of the length of time a fully charged battery can be discharged at a specific current before reaching a specified end-of discharged voltage.

3.8 overcharge: The forcing of current through a battery after it has been fully recharged.

3.9 rated capacity (*C*): The capacity, in ampere hours (Ah), assigned to a nickel-cadmium cell by its manufacturer for a specific constant-current discharge, with a given discharge time, at a specified electrolyte temperature, to a given end-of-discharge voltage.

3.10 self-discharge: The process by which the available capacity of a battery is reduced by internal chemical reactions (local action).

3.11 self-discharge rate: The amount of capacity reduction occurring per unit of time in a battery as the result of self-discharge.

3.12 valve-regulated battery: A battery that is sealed with the exception of a valve that opens to the atmosphere when the internal gas pressure exceeds the atmospheric pressure by a preselected amount. Valve-regulated batteries provide a means for recombination of internally generated oxygen.

3.13 vented battery: A battery in which the products of electrolysis and evaporation are allowed to escape freely to the atmosphere. These batteries have commonly been referred to as "flooded".

4. Outline of sizing methodology

The function of a battery used in a PV system is to supply power when the system load exceeds the output of the PV array. For a satisfactory PV battery system, many factors have to considered to determine the necessary capacity and the number of cells comprising the battery. These factors, as follows, will be discussed in subsequent clauses:

- *Battery reserve considerations (clause 5).* The length of time that the load has to be supported solely by the battery is established by system design requirements.
- *Load determination (clause 6).* The requirements of the application determine the amount of current over a period of time that is to be supplied by the battery. The peak current and the operational voltage window are also determined by the system's load devices.
- *Battery capacity and functional-hour rate determination (clause 7).* The battery capacity and its discharge functional-hour rate are determined by the specific application's load, days of battery reserve, and batter characteristics (see Annex A).
- *Determining number of series-connected cells (clause 8).* The system's voltage limits (voltage window) determines the required number of cells in series. Several criteria have to be examined to ensure a workable system.
- *Cell capacity and battery size determination (clause 9).* Once the overall battery capacity and number of cells in series have been determined, a final selection of a specific cell can be made and the final battery size can be calculated.

  NOTE — Because of the interaction of these factors, an iterative process may be needed to determine the optimum battery for the application.
- *Battery sizing worksheet (clause 10).* A worksheet that provides a systematic approach to the sizing of a battery for a PV system is presented. The application of this worksheet is explained in accompanying textual material.
- *Battery characteristics (Annex A).* System performance, life, maintenance, and cost are influenced by the type of battery selected for a PV application. Information regarding nickel-cadmium battery characteristics is presented.
- *Examples (Annex B).* Examples demonstrating various aspects of battery sizing are presented.

5. Battery reserve considerations

Photovoltaic power systems may require some battery reserve, both for reliability of service and to provide time for intervention in the event of an anticipated occurrence, such as unusually low insulation or failure of a system component. The number of days of battery is commonly specified as a system design requirement and is based on several considerations, including the following:

- *System availability.* System availability is the minimum percentage of the time that the PV system should satisfy the system loads.
- *System application.* Critical load application generally require more days of battery reserve than noncritical applications.
- *Solar irradiance variability.* Daily and seasonal variations in solar irradiance affect the required number of days of battery reserve.
- *Predictability of load.* The load may or may not be predictable; also, there may be the possibility of adjusting the loads, e.g., dropping nonessential loads.
- *Backup power provisions.* If the PV system includes provisions for backup power, the desired frequency and duration of operation of the backup power source needs to be considered.
- *Accessibility of site.* The worst-case time required for correction of any problem needs to be considered.
- *System cost.* Cost trade-offs associated with array and battery size relationships for the required system availability need to be considered.
- *Other costs.* Costs associated with maintenance and the interruption of service should also be considered.

6. Load determination

6.1 General considerations

The overall duty cycle imposed on the battery is the description of the dc load current and its duration within the days of battery reserve, during which it is assumed that no power is provided by the array or auxiliary power source. For ac loads supplied through an inverter, these loads have to be tabulated separately, totaled, and combined with the inverter losses to determine the actual dc load on the battery.

The system's load can be expressed in a tabular or graphical form. As both descriptions start with a tabulation of the individual loads and their durations, the tabular form is more general. The load-profile diagram (the graphical representation) is necessary to visualize the interrelationships of the individual loads. For both load descriptions, all loads expected during a 24-h period are tabulated along with their anticipated durations. Worksheet 1 in clause 10 provides a convenient method of tabulating load data in accordance with the sizing method of this document.

It may be necessary to consider a longer period of time when a 24-h period does not accurately describe the load profile. For those cases where the load profile exceeds 24 h, an average and a maximum daily load should be determined for subsequent battery capacity determinations. Worksheets 2 and 3 in clause 10 provide a convenient method for determining these loads. The average daily load is used in the initial determination of the battery size.

Once the battery has been sized, the maximum daily load is used to determine the ability of the battery to sustain it. If the maximum daily load sequence cannot be established, the days should be arranged in the worst possible order, generally with the maximum load day last. The battery's capacity may need to be increased to satisfy the maximum daily load in this partially discharged state.

A load-profile diagram is a necessary aid in determining those areas where the battery's performance needs to be checked to ensure load satisfaction. A load profile diagram may be made as follows:

a) Tabulate all the individual loads along with their starting and ending times.
b) Total the coincident loads for their respective periods of time.
c) Plot the resulting total load versus time of day.

The resulting curve is the load-profile diagram. If the daily loads vary during the days of battery reserve, the individual daily load-profile diagrams plotted in sequence constitute the system's load-profile diagram. See Annex B for examples.

6.2 Load data

The information that should be gathered for each load is discussed in 6.2.1 through 6.2.5.

6.2.1 Momentary current

Loads lasting 1 min or less are designated as momentary loads and are given special consideration. The ampere-hour requirement of this type of load are usually very low, but their effect on battery terminal voltage may be considerable, and should be taken into account. Momentary loads can be occur repeatedly during the duty cycle. Typical momentary loads are as follows:

a) Motor-starting currents
b) High-inverter surge currents

6.2.2 Running current

Running current is the current required by a load after its starting current has subsided. Certain devices require a constant power, thus the current required will rise as the battery voltage falls. As the battery voltage remains relatively constant until near the end of discharge, the running current for a constant-power device may be approximated as the current required at 95% of the system voltage.

NOTES:

1 — For certain loads, it is necessary to consider both the momentary and running current components of the load. For example, if an electric motor starts during the duty cycle, both the starting (momentary) current and running current need to be considered. The starting current need not to be considered if the load was operating at the beginning of the duty cycle, i.e., at the beginning of the days of battery reserve.

2 — Parasitic power losses, such as those resulting from tare losses of charge controllers and inverters and writing, should be included as currents.

3 — Consideration of the battery self-discharge as a load is recommended as a check (see 9.5) after the battery is selected.

6.2.3 Load duration

The load duration is the time, in hours, of operation of each load. For PV systems, it is very common for load duration to be expressed in terms of a daily cycle that repeats over the days of battery reserve. If the inception time of a load is known but the shutdown time is indefinite, it should be assumed that the load will continue through the remainder of the days of battery reserve.

6.2.4 Load coincidence

Each load current (momentary or running) is classified as to whether or not it is coincident with any other loads and tabulated accordingly. Loads that occur at random are assumed to be coincident loads. This information, portrayed in the load-profile diagram, is later used in battery selection and to check discharge rate (see 6.3).

6.2.5 Maximum and minimum load voltage

The maximum and minimum voltage at which each load operates properly has to be determined and tabulated (see 8.2.). Voltage drops in cabling overcurrent protection and connectors between the battery and the loads are not to be considered as an adjustment to a load's maximum voltage because, at times, the current and resulting voltage drops can be very low, exposing the device to battery terminal voltage. However, these voltage drops should be determinded individually for each load device and added to its minimum operating voltage to ensure the required minimum voltage will be present at the load.

6.3 Data analysis

6.3.1 Ampere hours

It is usually possible to calculate an equivalent daily load by multiplying each load current by its daily duration and then summing the results. If the duration of the momentary load is known, calculate the ampere-hour load by multiplying this duration by the momentary current. If the duration of the momentary load is not known, assume the time to be 1 min and calculate the load accordingly.

If the duty cycle does not repeat each day, it is necessary to describe the load over the entire days of battery reserve. Worksheet 2 in clause 10 is provided for this purpose. If the graphical form of the load descriptions is used, the ampere-hour load is the total area under the load-profile curve.

6.3.2 Currents

The maximum momentary and running currents are determined and used to calculate the battery's maximum discharge current. Since the system loads may operate in various combinations, the maximum current (momentary or running) is the largest summation of the individual loads that can occur simultaneously. If the battery's maximum discharge current is greater than the 20-h discharge rate and the sequence of load is known, the method described in IEEE Std 1115-1992 [2] may result in a less conservatively-sized battery.

7. Battery capacity and functional-hour rate determination

The required battery capacity for a PV application is determined by the number of days of battery reserve and by the characteristics of the load, and installation. A functional-hour rate for the application is determined by capacity and load calculations.

7.1 Unadjusted capacity

The unadjusted capacity, in ampere hours, is calculated by multiplying the days of battery reserve by the average daily load (in ampere hours/day as determined in clause 6). This capacity will be adjusted in 7.3 for battery characteristics and operating conditions.

7.2 Battery type selection

A trial battery type should be selected before proceeding with the sizing process. This is necessary due to characteristics that are different for the various battery types, such as cycle life.

If a vented battery is used, it should be selected for the intended application so that watering intervals, the consequences of hydrogen and oxygen evolution, and wear-out mechanisms are considered.

If a valve-regulated battery is used, it should be selected for the intended application so that recombination is effective, and dry-out, thermal runaway, and the consequences of hydrogen and oxygen evolution are considered.

Annex A provides a more detailed catalog of battery characteristics that should be considered. Reevaluation of the applicability of the trial battery is recommended throughout the sizing process. Refer to manufacturer's literature for specific data on the type of battery selected.

7.3 Capacity adjustment

7.3.1 Discharge adjustment

The battery has to be capable of giving satisfactory cycle in life in the intended application. Nickel-cadmium batteries are characterized by both good deep-cycling capability and ability to be overdischarged. For this reason, maximum depth of discharge (DOD) figures are not published and it is generally necessary only to modify the unadjusted capacity to reflect end-of-life capacity. The aging process for nickel-cadmium batteries is a slow, even loss of capacity with no sharp falloff at the end of life. The user therefore defines the end-of-life for the battery using economic considerations (initial cost versus service life) alone.

Data can be obtained from the manufacturers regarding the number of charge/discharge cycles, relative to the DOD, available from a given battery type for a particular end-of-life capacity. This can be compared with the relationship

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[2] Information on reference can be found in clause 2

between the length of duty cycle and the days of battery reserve. For example, for a daily duty cycle and a ten-day reserve, the average daily DOD is 10% (ignoring cloudy weather capacity deficits and occasional deep discharges). For a battery type capable of providing, for example, 3000 daily cycles of 10% DOD to 80% of rated capacity, this would equate to a service life of 8.2 years. However, the same battery type might provide 5000 cycles of 10% DOD to 60% of rated capacity, which is equal to 13.7 years.

The capacity adjusted for life is obtained by dividing the unadjusted capacity by the end-of-life capacity expressed as a percentage of the rated capacity.

It should be noted that a duty cycle that represents a 10% DOD compared with the unadjusted capacity would equate to only an 8% DOD for a battery adjusted for an 80% end-of-life capacity. This will allow additional margin for the battery to cope with cloudy weather deficits and occasional deep discharges.

7.3.2 Charge adjustment

Nickel-cadmium batteries exhibit high recharge efficiency up to reasonably high (>80%) state of charge (SOC). Beyond this point, the recharge efficiency begins to decline and it becomes progressively more difficult to reach higher states of charge. The point where this effect becomes important varies with the relative amount of overcurrent applied to the battery. For most PV system designs, the charging current will drop with increasing battery voltage, and the influence will not occur until an SOC of 90–95% is achieved. In some applications, for example, where a charge controller is installed to minimize water consumption, the system design may be such that the battery never reaches a 100% SOC. Although the battery is not damaged by being less than fully charged, the low SOC has to be taken into account in the sizing calculations. A common practice is to divide the capacity determined in 7.3.1 by 0.90–0.95.

7.3.3 Temperature adjustment

The available capacity of a battery is affected by its operating temperature. Cell capacity ratings are standardized at 25 °C (77 °F). Capacity increase at temperatures above 25 °C and decreases at temperatures below 25 °C. However, capacity increases above 25 °C are negligible. Therefore, capacity is rarely adjusted for warm temperature operation, but adjustments are routinely made for cold weather applications. Refer to the battery manufacturer's literature for temperature correction factors. The adjusted capacity determined in 7.3.2 has to be corrected by this factor to yield capacity adjusted for temperature.

7.3.4 Design margin adjustment

It is prudent design practice to provide a capacity margin to allow for uncertainties in the load determination, e.g., less-than-optimum conditions, load growth, etc. A common practice to provide this design margin is to add 10–25% to the capacity as determined in 7.3.3.

7.4 Functional-hour rate

In order to correctly size the battery, the discharge rate and ampere-hour capacity have to be considered together. In continuous load applications, the battery should have sufficient capacity to supply the constant discharge rate over the number of days of battery reserve. However, in noncontinuous load application, the discharge rate varies and could include high rates of discharge periodically throughout the days of battery reserve. Using an average rate to size the battery could result in insufficient capacity to supply high currents above the minimum voltage late in the battery discharge. The functional-hour rate conservatively approximates a single discharge rate that is equivalent to the varying discharge rates of a particular duty cycle. The functional-hour rate may be greater than the period of battery reserve.

The functional-hour rate can be calculated as follows:

a) Compare the sum of all coincident running currents with the highest noncoincident running current and select the larger.
b) Divide the adjusted capacity as determined in 7.3.4 by the maximum running current selected in a).

Examples:

The adjusted battery capacity in a system with 5 days of battery reserve is 150 Ah, with a maximum current drain of 25 A. The functional-hour rate is 150 Ah dived by 25 A, or 6 h.

The adjusted battery capacity in a system with 5 days of battery reserve is 150 Ah, with a continuous current drain of 1 A. The functional-hour rate is 150 Ah divided by 1 A, or 150 h.

8. Determining number of series-connected cells

A battery is usually composed of a number of identical cells connected in series. The maximum and minimum system voltages determine the number of series-connected cells of the battery.

8.1 Nominal system voltage

Although the nominal voltage of a nickel-cadmium cell is 1.2 V, dividing the nominal system voltage by 1.2 to arrive at the number of cells will frequently yield an incorrect answer. The number of cells has to be matched to the output characteristics (current-voltage curve) of the array used for its charging. It is common practice to use 9 cells for a 12-V system, 18 cells for a 24-V system, etc., but it is also common that the allowable voltage limits may require adjustment to this rule.

8.2 Voltage window

The system equipment will always have a voltage range within which the equipment will operate at rated capacity and efficiency. If the equipment is exposed to higher- or lower-than-specified voltages, it may be damaged or operate improperly. This high (V_{max}) and low (V_{min}) limit of system voltage is called the voltage window. The magnitude of this window has a direct effect on the number and capacity of battery cells selected. The narrower the window, the larger the cell's capacity needs to be; the wider the window, the smaller the cell's capacity can be.

From the tabulated maximum and minimum voltages in 6.2.5, the lowest maximum voltage (V_{max}) and the highest minimum voltage (V_{min}) define the voltage window within which all loads in the system will operate properly. Since nickel-cadmium cells are not damaged by overcharging, a charge controller is not normally required unless water loss or damage from system overvoltage is consideration. In such cases, a charge controller is recommended. If a charge controller is used, its set points need to be within this voltage window (see clause 10, 4b).

8.3 Calculating the number of series-connected cells

The number of series-connected cells is function of both the voltage window of the loads and the manufacturer's charging recommendation for the selected cell. An optimum number of cells is determined as a result of iterative calculations.

8.3.1 Maximum number of cells allowed

The most important aspect of calculating the maximum number of series-connected cells is to ensure an optimal and safe cell recharge voltage. In determining the maximum number of cells allowed by the system, the following calculation is performed:

$$\text{Maximum number of cells (round down)} = \frac{V_{max}}{\text{Cell recharge voltage}}$$

Example:

Assume 1.5 V/cell is recommended for recharging. The maximum allowable system voltage is 58 V dc, then

$$\frac{58\,\text{V}}{1.5\,\text{V/cell}} = 38.7 \text{ cells. Therefore, use 38 cells}$$

8.3.2 Minimum system voltage versus end-of-discharge voltage

For a minimum battery voltage, determined by the minimum system voltage, the use of the largest possible number of cells allows the lowest end-of-discharge (EOD) cell voltage. The EOD may vary 1.00–1.20 V per cell. In many PV applications, the average discharge time is 100 h or more, and the average cell discharge voltage is 1.25 V. at the functional-hour rate of 100 h, an EOD of 1.00–1.20 V is recommended. The cell's EOD voltage is determined by

$$\text{Calculated EOD cell voltage} = \frac{V_{min}}{\text{Number of cells calculated by 8.31}}$$

Examples: Assume the minimum system voltage is 42 V dc, then

$$\frac{42\,\text{V}}{38\text{ cells}} = 1.1\text{ V/cell}$$

This cell voltage is within the recommended EOD voltage range.

If the calculated EOD cell voltage is not satisfactory (i.e., is below the manufacturer's recommended EOD voltage at the functional-hour rate), an adjustment should be made to the minimum system voltage, or a smaller number of higher capacity cells should be used, or both.

NOTES:

1 — A nickel-cadmium cell can tolerate complete discharge with almost no permanent deterioration of capacity or life. The EOD cell voltage can, therefore, be allowed to drop to a low voltage if this will result in a more economic system.

2 — If the calculation results in an EOD voltage that is greater than that recommended by the manufacturer, the cell, when discharged to the calculated EOD voltage, will supply less capacity than if it were discharged to the recommended EOD cell voltage.

8.3.3 Multicell unit considerations

If the cell type selected is available only in multicell units, it may be necessary to use a different number of cells than was previously calculated. The conversion from maximum system voltage to number of multicell units is

$$\text{Total number of multicell units} = \frac{V_{max}}{\text{Maximum multicell recharge voltage}}$$

Fractional results are to be rounded down to the next lowest whole number. It is necessary to review the voltage window calculation to ensure that all system requirements are met.

8.3.4 Optimization

The calculation contained in 8.3.1 will provide the maximum number of allowable series-connected cells that should ensure system performance. It may be possible to use fewer series-connected cells and yet maintain proper system performance. See clause 10 for the iterative process that can result in fewer series-connected cells. However, this could result in other problems, including thermal runaway, under certain conditions [see 9.5, a)].

NOTE — Care should be taken to ensure that the chosen number of battery cells can be charged effectively by a commercially available PV charging system. Nonstandard equipment may be expensive and difficult to obtain.

9. Battery size determination

Battery size is determined by using the results of clauses 7 and 8 to select an appropriate battery that meets the load and site requirements.

9.1 Cell size selection

The cell size selection is performed using the same manufacturer's data that was used in 7.2. Choose a cell that meets the capacity requirements of 7.3.4 when discharged at the functional-hour rate determined by 7.4, to an EOD voltage that is greater than or equal to the EOD voltage determinate by 8.3. Where the cell available from the manufacturer does not meet the exact capacity requirement, the next larger capacity cell should be selected. If no single cell has the necessary capacity or its use is not practical for the application, then refer to 9.2

9.2 Number of parallel strings

It is usually preferable to have one string of series-connected cells in a battery rather than a number of parallel-connected strings of series-connected cells. If cells of sufficiently large capacity are not available or practical, then two or more strings of equal numbers of identical series-connected cells (consistent with the manufacturer's recommendations) may be connected in parallel to obtain the necessary capacity.

The number of parallel strings is calculated by dividing the capacity found in 7.3.4 by the selected cell capacity determined by 9.1 (round up).

9.3 Final number of cells

The total number of cells can be calculated by multiplying the number of series cells determined by 8.3 by the number of parallel strings.

9.4 Final battery capacity

The final battery capacity is calculated by multiplying the selected cell capacity by the number of parallel strings.

9.5 Checks/considerations

There are other considerations with respect to the PV system design that may affect battery performance. These are as follows:

a) *Overcharging.* Too high a charge rate at the end of charge, too high an end-of-charge voltage, or no high-limit cut-off voltage at the end of charge will cause overcharging. For vented batteries this will result in the generation and release of potentially hazardous quantities of hydrogen and oxygen and accelerated water loss. For valve-regulated batteries this also will result in the generation of potentially hazardous quantities of hydrogen and oxygen that may be release. The quantity and composition of the vented gases depend on the rate and duration of the overcharge, the battery and its valve design, oxygen recombination efficiency (see

A.2), thermal environment, and previous usage of the battery. Although no damage is generally caused to the battery and the water can be replaced, overcharging valve-regulated batteries can lead to a potentially hazardous conditions known as thermal runaway (see NOTE). This results in excess heat, which enables the battery to draw even more current, a cycle that continues until the battery releases all of its water. If any of the conditions that may lead to overcharging exist, discussion with the PV system designer and the battery manufacturer will be necessary to determine the corrective action required.

NOTE — The valve-regulated batteries currently available allow for water replacement, however, this feature may not exist on future models. Check with the manufacturer.

b) *Undercharging.* Insufficient time at the available charge rate or too low a charging voltage will result in an undercharged battery. If either of these conditions exist, discussion with the PV system designer and the battery manufacturer will be necessary to determine the corrective action.

c) *High-discharge rate.* A momentary load, particularly one occurring at or near the end of the days of battery reserve period, may cause the battery voltage to drop below the minimum system voltage. If such a momentary load is significantly larger than the average load, it is recommended that the battery capacity be sized in accordance with the method of IEEE Std 1115-1992 (considering the required days of battery reserve for the load profile diagram), or that reexamination of the worst-case loads be made an discussed with the PV system designer. If the method of IEEE Std 1115-1992 is used, the resulting battery should be reevaluated using the criteria given in this document. In most cases, if the momentary load is less than the 20-h discharge rate (C/20), then the discharge rate will not cause the battery voltage to drop below the minimum system voltage.

d) *Freezing of the electrolyte.* One of the characteristics of nickel-cadmium batteries is that the electrolyte concentration does not change with SOC. Thus, even a fully discharged battery is no more susceptible to freezing than one that is charged. Also, rather than freezing solid, the electrolyte tends to become slushy at extremely low temperatures (around 50 °C for electrolytes designed for coldweather operation) and the battery is still able to function. Provided that the capacity is adequately compensated for low operating temperatures, no further consideration for cold weather is required.

e) *Self-discharge as a battery load.* All batteries suffer from an internal capacity loss mechanism known as self-discharge. The amount of self-discharge (Ah/month) is a function of battery operating temperature, type, and age. The self-discharged for the battery type selected, within its operating environment, should be obtained and the resulting capacity loss calculated and added as a load if appropriate.

NOTE — Self-discharge generally contributes more to the overall load in systems with large number of days of battery reserve or high battery temperature.

10. Battery sizing worksheet

Worksheet 1 may be used to organize the application of the procedures outlined previously. Examples of its use are in Annex B. Instructions for use follow; the numbering system corresponds to that of the worksheet.

1. *Project name and description.* Enter the necessary information.

2. *Nominal system voltage.* Enter the nominal system voltage (e.g., 12 V, 24 V).

3. *Days of battery reserve.* Enter the number of days of battery reserve.

4. *Load data.* Enter the necessary load information in the table for each load device and calculate the daily load for each device. Worksheet 2 is to be used when the load duty cycle exceeds one day (24 h). The following is an explanation of the terms used:

4a. *dc load device:* The identification of the dc loads.

NOTES:

1 — If the load is an inverter, a separate calculation should be made of the loads run by the inverter plus inverter losses.

2 — If the load device has a momentary current as well as a running current, e.g., a motor, the load device should be treated as two distinct loads-one of which has only a momentary current, the other of which has only a running current.

4b. *Voltage window:* The maximum and minimum voltage V_{max} and V_{min}, acceptable to each load (V_{min} includes writing voltage drops).

4c. *Momentary currents:* The inrush or peak current of each load, e.g., the inrush current required to start a motor. If the momentary current and the running current are the same, enter the running current only (column 4d). The two columns, I_{coin} and $I_{noncoin}$, refer to the coincident and noncoincident currents. The $1_{noncoin}$ column is used only for loads that will never operate at the same time as other loads.

4d. *Running currents:* The normal running current of each load, I_{coin} and $I_{noncoin}$. The $I_{noncoin}$ column is used only for loads that never operate at the same time as other loads.

4e. *Constituents of maximum running currents:* The loads that can operated in coincidence to generate the maximum running currents are identified, if known. If the loads are random, the sum of all coincident running currents is used.

NOTE — Columns 4f and 4g are provided to facilitate calculations when the load currents and their duration per occurrence are identical. Otherwise, enter the total run time in column 4h.

4f. *Number of occurrences:* The number of operational periods of each load for the day.

4g. *Duration:* The hours per operational occurrence for each load.

4h. *Run time:* The hours per day of operation of each load (line 4e × line 4f or the total time). If the run time varies from day to day, use Worksheet 2.

4i. *Daily load:* The ampere-hour per day requirements for each load. It is the product of each load current and its respective run time.

5. *Load data summary* (using the *Load data* from 4, columns 4a through 4i)

5a. Enter the maximum coincident momentary current [refer to the load-profile diagram(s)].

5b. Enter the maximum coincident running current [refer to the load-profile diagram(s)].

5c. Enter the total from the daily load column of Worksheet 1, or the average daily ampere-hours from Worksheet 3, if used.

5d. Enter the maximum daily load from Worksheet 2, if used.

5e. Enter the greatest of the values in the momentary currents $I_{noncoin}$ column.

5f. Enter the greater of line 5a or line 5e. This value will be used later when checking the ability of the battery selected to provide the maximum momentary current.

5g. Enter the greatest of the values in the running currents $I_{noncoin}$ column.

5h. Enter the greater of line 5b or line 5g. This will be used later to calculate the appropriate discharge rate for the battery.

5i. Enter the greater of line 5f or line 5h.

5j. Enter the lowest value from the voltage window V_{max} column.

5k. Enter the highest value from the voltage window V_{min} column.

6. *Battery capacity.* To complete this section it is necessary to have the following information:

- End-of-life (EOL) capacity in percent (see 7.3.1)
- State-of-charge (SOC) capacity in percent (see 7.3.2)
- The minimum temperature at which battery has to support the load
- The corresponding temperature correction factor from the manufacturer's literature
- Design margin

6a. An unadjusted battery capacity is calculated. Enter the product of the days of battery reserve and the total daily load (line 3 × line 5c).

6b. Enter EOL.

6c. Adjust the capacity for EOL (line 6a divided by line 6b).

6d. Enter the SOC at the end-of-charge voltage (up to 100%).

6e. Adjust the capacity for SOC (line 6c divided by lined 6d).

6f. Enter the minimum operating temperature and indicate use of degrees Fahrenheit (°F) or degrees Celsius (°C).

6g. Enter the appropriate temperature correction factor from the manufacturer's literature.

6h. Adjust the capacity (line 6e) for temperature.

6i. Enter the design margin factor, e.g., for a 10% oversize, enter the number 1.1.

6j. Adjust the capacity for the design margin (line 6h × line 6i).

7. *Functional-hour rate.* Divide the adjusted capacity (line 6j) by the maximum running current from the battery (line 5h). The functional-hour rate may be greater than the period of battery reserve.

8. *Voltage window adjustment.* This section provides for any adjustment that may be necessary as a result of controller set points (see 8.2). If a charge controller is used, its set points should determine the limits of the voltage window and provide as wide a voltage range as possible while protecting the load and, if possible, minimizing the battery's water consumption.

8a. Enter the setpoint of the low-voltage load disconnect of the controller, if used, which should be greater than or equal to line 5k.

8b. If a charge controller is used, enter line 8a; otherwise enter line 5k.

8c. Enter the setpoint of the full-charge voltage cutout of the controller, if used, which should be less than or equal to line 5j.

8d. If a charge controller is used, enter line 8c; otherwise, enter line 5j.

9. *Number of series-connected cells*. To complete this section, the following information is required from the battery manufacturer:

- Cell's charge voltage: the manufacturer's recommended charging voltage for the type of battery
- EOD voltage (at the functional-hour-rate); the cell voltage when the fully available capacity is reached.

9a. Enter the cell's charge voltage.

9b. Calculate the maximum number of cells connected in series that can be charged within the battery voltage window; round down (line 8d divided by line 9a).

9c. Enter the manufacturer's recommended cell EOD voltage.

9d. Calculate the cell EOD voltage that corresponds to V_{min} (line 8b divided by 9b). If equal to or greater than line 9c, proceed to step 9g; if less than line 9c, proceed to step 9e.

9e. Decrease the number of series cells by 1.

9f. Calculate the cell's charge voltage as determined by the system voltage window (line 8d divided by line 9e). If the result is within the manufacturer's recommended cell's charge voltage range, proceed to step 9g. If the result is outside the range,

i) Repeat steps 9e and 9f, or
ii) Select a different type of cell, e.g., different plate composition (go back to step 6b).

9g. Enter the selected number of series-connected cells (line 9b or line 9e, as appropriate).

10. *Cell selection*

10a. An appropriate cell capacity considering functional-hour rate and calculated EOD (line 9d) is found in the manufacturer's literature and entered.

10b. The number of parallel strings is determined by dividing the required capacity by the capacity of the selected cell (line 6j divided by line 10a); round up to the next higher whole number.

10c. The final capacity of the battery is the capacity of the selected cell multiplied by the number of parallel strings (line 10a x line 10b).

11. *Checks/considerations*. This section serves as a crosscheck between the selected battery and the other aspects of the PV system design, e.g., PV array/controller combination. As each check/consideration is resolved, which may require changes to the system design or the battery selection, the appropriate box is checked off. In order to complete this section, the following information is required:

- Maximum available charging current at the battery's full charge voltage (line 11a)
- Minimum recommended operating temperature for the standard electrolyte used (line 11b)
- Battery self-discharge rate (line 11c)
- Electrolyte reserve capacity (for vented cells)
- Battery's physical characteristics

Considerations resolved

a) *Overcharging.* For systems without disconnecting charge controllers, the array current equivalent to the battery's full-charge voltage should be checked for its impact on water consumption. A general rule of thumb is that every ampere-hour of overcharge consumes one-third of a cubic, centimeter of water per cell. If the anticipated water loss is unacceptable, means to limit the overcharging should be considered. These means include limiting the charging current or its duration while the battery is being overcharged. This may mean reconsidering the use of a charge controller.

b) *Undercharging.* The ampere-hour output of the array should be sufficient to recharge the battery while supplying the daily load.

c) *High-rate discharge.* Momentary or short-duration loads occurring near the end of the days of battery reserve will cause voltage decay if (line 10c divided by line 5i) ≤ 20 h (refer to 9.5c).

d) *Low temperature.* If the minimum operating temperature is below the recommended minimum for the standard electrolyte, then a high-density electrolyte should be used to improve electrical efficiency.

e) *Battery self-discharge.* The battery self-discharged may be a significant part of the overall load, particularly during large number of days of battery reserve, e.g., 10 or more days. This should be checked to determine if the battery size is affected (other parasitic loads, such as writing and diode losses, charge controller consumption and loosed, etc., should be include in the load data).

f) *Electrolyte reserve.* If vented cells are used, they should be selected so that the electrolyte reserve capacity is adequate to sustain the anticipated maintenance interval (see *Considerations resolved,* item a).

g) *Battery size and weight.* The battery size and weight should be compatible with the application requirements and transportation modes.

12. *Summary.* The selected battery and its performance features are specified.

Worksheet 1—Battery sizing

1. *Project name and description*

2. *Nominal system voltage*: _____V

3. *Days of battery reserve*: _____days

4. *Load data*

4a dc load device	**4b** Voltage window		**4c** Momentary currents		**4d** Running currents		**4e** Constituents of maximum running current	**4f** Number of occurences	**4g** Duration	**4h** Run time	**4i** Daily load
	V_{max} V	V_{min} V	I_{coin} A	$I_{noncoin}$ A	I_{coin} A	$I_{noncoin}$ A		Number/ day	hour/ occurrence	hour/ day	Ah/day
								Total Daily Load			Ah

5. *Load data summary*

5a. Maximum momentary current I_{coin} from the above table or line 5a of Worksheet 3 (refer to load-profile diagram): _____A

5b. Maximum running current I_{coin} from the above table or line 5b of Worksheet 3 (refer to load-profile diagram): _____A

5c. Total daily load from above table or line 5c of Worksheet 3: _____Ah/day

5d. Maximum daily load from the load data of Worksheets 2, if used: _____Ah/day

5e. Greatest value of $I_{noncoin}$ momentary currents from above table or line 5d of Worksheet 3: _____A

5f. Maximum momentary current draw from battery (greater of line 5a or line 5e): _____A

5g. Greatest value of $I_{noncoin}$ for running currents from above table or line 5e of Worksheet 3: _____A

5h. Maximum running current draw from battery (greater of line 5b or line 5g): _____A

5i. Maximum current draw from battery (greater of line 5f or line 5h: _____A

5j. Lowest value of V_{max} from above table or line 5f of Worksheet 3: _____V

5k. Greatest value of V_{min} from above table or line 5g of Worksheet 3: _____V

6. *Battery capacity*

6a. Unadjusted battery capacity (line 3 × line 5c): _____Ah

6b. Percent of capacity at end of life: _____%

6c. Capacity adjusted for end of life (line 6a divided by line 6b): _____Ah

6d. Percent of capacity at system end-of-charge voltage (≤100%): _____%

6e. Capacity adjusted for SOC (line 6c divided by line 6d): _____Ah

6f. Minimum operating temperature: _____°C/°F

6g. Associated temperature correction factor: _____

6h. Capacity adjusted for temperature: _____Ah

6i. Design margin factor (≥1): _____

6j. Capacity adjusted for design margin (line 6h × line 6i): _____Ah

7. *Functional-hour rate (line 6j divided by line 5h)*: _____h

8. *Voltage-window adjustment*

8a. Controller low voltage load-disconnect setpoint: _____V

8b. Adjusted V_{min} (greater of line 5k or line 8a): _____V

8c. Controller full-charge voltage setpoint: _____V

8d. Adjusted V_{max} (lesser of line 5j or line 8c): _____V

9. *Number of series-connected cells*

9a. Recommended full-charge voltage for selected cell (limited by line 8d): _____V

9b. Maximum number of cells in series (line 8d divided by line 9a, rounded down): _____

9c. Recommended EOD voltage for selected cell: _____V

9d. Calculated EOD voltage for cell (line 8b divided by line 9b): _____V

NOTE — If 9d > 9c, proceed to 9g; otherwise continue with 9e.

9e. Decrement number of series cells (line 9b – 1): _____

9f. Calculated cell charge voltage (line 8d divided by line 9e): _____V

NOTE — If line 9f is within charge voltage range specified by manufacturer, proceed to line 9g; otherwise, at least one of the following has to be done:

- Decrement number of series cells (repeat 9e and 9f)
- Select different battery type, go to 6b
- Change controller full charge setpoint, go to 8c
- Select different controller, go to 8a

9g. Enter the selected number of series cells (line 9b or line 9e, as appropriate) _____

10. *Cell selection and final capacity determination*

10a. Smallest practical cell capacity available of selected type greater than or equal to line 6j, or largest practical cell less than line 6j when discharged to voltage line 9d at functional-hour rate (line 7): _____Ah

10b. Number of parallel strings (line 6j divided by line 10a), rounded up: _____

10c. Final battery capacity (line 10a × line 10b): _____Ah

11. *Checks/considerations*

Checks:

11a. Maximum available charging current at batter's full charge voltage: _____A

11b. Minimum recommended operating temperature for standard electrolyte used: _____ °C/°F

11c. Battery's self-discharge rate: _____A

Considerations resolved:

a) Overcharging [ ]
b) Undercharging [ ]
c) High-rate discharge [ ]
d) Low temperature [ ]
e) Battery self-discharge [ ]
f) Electrolyte reserve [ ]
g) Battery size and weight [ ]

12. *Summary*

Battery manufacturer and battery model: _______________

Final battery is _____ cells in series by _____ strings in parallel.

Battery capacity is _____ Ah rated at the _____ functional-hour rate.

Battery full-charge voltage is _____ V; battery end-of-discharge voltage is _____ V.

Worksheet 2—Supplemental battery sizing for duty cycle periods greater than 24 h

Complete Worksheet 2 for each day (24-h period) for which a distinct daily load exists. Summarize the data in Worksheet 3, and transfer to Worksheet 1.

Load data: _____

Day: _____

4a **dc load device**	**4b** **Voltage window**		**4c** **Momentary currents**		**4d** **Running currents**		**4e** **Constituents of maximum running current**	**4f** **Number of occurences**	**4g** **Duration**	**4h** **Run time**	**4i** **Daily load**
	V_{max} V	V_{min} V	I_{coin} A	$I_{noncoin}$ A	I_{coin} A	$I_{noncoin}$ A		Number/ day	hour/ occurrence	hour/ day	Ah/ day
								Total Daily Load			Ah

Maximum momentary I_{coin} (refer to load-profile diagram): _____A

Maximum running I_{coin} (refer to load-profile diagram): _____A

Number of repetitions: _____

Worksheet 3—Summary

5. Load data summary

5a. Greatest value of the maximum momentary I_{coin} currents_____A

5b. Greatest value of the maximum running I_{coin} currents:_____A

5c. Average daily load

Determine the series of repetitions that is going to result in the greatest load, over the period of days of battery reserve

Total the load over the period of days of battery reserve and divide by the number of days of battery reserve_____Ah/day

5d. Greatest value of $I_{noncoin}$ for momentary currents for any of the above load devices:_____A

5e. Greatest value of $I_{noncoin}$ for running current for any of the above load devices:_____A

5f. Lowest value of V_{max} for any of the above load devices:_____V

5g. Greatest value of V_{min} for any of the above load devices_____V

Annex A Battery characteristics

(Informative)

This annex summarizes some factors that should be considered in selecting a battery design for a terrestrial photovoltaic (PV) application.

A.1 Capacity

The ampere-hour capacity of a battery depends upon the size and number of plates of the cells, and the number of parallel strings of cells used. The conditions under which a battery is used can change the available capacity of the battery, for example:

a) Low temperatures reduce capacity.
b) High discharge rates reduce available capacity.
c) Limitations on the depth of discharge reduce capacity.
d) Failure to properly recharge a battery limits its capacity.

A.2 Type

The two generic types of nickel-cadmium batteries are as follows:

a) *Vented.* Vented batteries are characterized by plate immersed in liquid electrolyte. The volume of electrolyte is sufficient, if the battery is not routinely overcharged, to allow for several years of service without water addition to compensate the loss of water by evaporation and by the electrolysis associated with overcharging. A vent in the cell's cover allows a free exchange of the resulting gases with atmosphere. Catalytic recombiners may be incorporated in each cell vent to reduce water loss. The lost water can be replaced by "topping" up each cell individually or by a single-point filling device.
b) *Sealed and valve-regulated.* Sealed and valve-regulated cells are characterized by a separator in which all of the electrolyte is absorbed. The cell's plates are in close proximity allowing oxygen formed at the positive plate during charging to recombine at the negative plate. In this way, water loss is minimized. In the sealed cells lost water cannot be replaced, but in valve-regulated cells, manufacturers can recommend water replacement procedures.

Sealed nickel-cadmium cells are normally used in consumer equipment, such as walk lights and radios. They are limited in capacity to approximately 15 Ah. For larger capacities, valve-regulated designs are available.

A.3 Cyclability

Nickel-cadmium batteries are known for their good cyclability. They can be discharge to 100% of their rated capacity over the period of batter reserve. It should be noted that batteries used in PV applications should have lithium hydroxide additives in the electrolyte to improve cycle life. The manufacturers can recommend the right amount of additives.

A.4 Cycle life

The life of a battery can be measured by the number of times it can be cycled before it is no longer able to deliver sufficient energy to satisfy the load requirements of the system. The number of cycles of operational battery will provide depends upon the following factors:

a) Cell design
b) Use
c) Temperature

A.4.1 Design factors

Some of the design factors that affect cycle life are as follows:

a) Plate thickness
b) Active material retention systems
c) Electrolyte density and amount
d) Electrolyte carbonation
e) Amount of lithium hydroxide additive
f) Type of separator

A.4.2 Use factors

How a battery is used has an effect on its cycle life. Some of the considerations are listed below:

a) Depth of discharge
b) Insufficient recharge

A.4.3 Operating temperature

A maximum operating temperature is specified by the battery manufacturer. Extremely high electrolyte temperatures may cause excessive water usage and may damage the battery. Since nickel-cadmium batteries are not damaged by freezing temperatures, special precautions for low temperatures are not required. The battery will give the best performance and maximum service life when operating below the manufacturer's specified temperatures.

A battery should be sized for operation at its coldest expected operating temperature that, in effect, oversizes the battery for normal warmer operation, resulting in shallower discharging that increases cycle life.

A.5 Economic considerations

The optimum battery will be the battery with lowest life-cycle cost. The life-cycle cost, expressed in dollars per kilowatt-hour ($/k Wh) of energy delivered, is a function of a number of variables. These included the following:

a) Initial cost
b) Cycle life
c) Maintenance costs
d) Battery/system reliability
e) Economic impact on PV system design including:
    1) Structural design including battery support structure and enclosure
    2) Heating, ventilation, and cooling
f) Replacement costs
g) Salvage value/disposal costs
h) Energy efficiency
i) Accessory system required such as for charge control and water addition

A.6 Physical characteristics

Physical characteristics that may be important are as follows:

a) Size and weight of the smallest transportable unit
b) Cell access requirements for maintenance, such as addition of water
c) Strength of cell containers for safety
d) Terminal connection configuration
e) Accessory requirements
f) Vent fittings to attach tubing for external venting
g) Available enclosure space
h) Container flammability

A.7 Maintenance

The required maintenance of batteries depends upon the batteries' design and use. Refer to IEEE Std 1145-1990.

A.8 Safety

Batteries are potentially hazardous for a number of reasons, including generation and release of explosive gases (see 9.5), stored electrical energy, and presence of corrosive electrolyte. Installation and maintenance personnel should be qualified in battery operating and safety procedures. Refer to IEEE Std 1145-1990 for safety details.

A.9 Disposal

Local and federal regulations shall be followed for battery disposal. Contract manufacturer for information on how to proceed with respect to treatment, storage, disposal, facility, standards, and applicable permitting procedures.

Annex B Examples

(Informative)

The following examples, including the parameters used, show the application of this sizing method. They are illustrative only and are not intended to cover all possible sizing features.

B.1 Remote subarctic communications system

The following worksheet describes the battery sizing for a 48-V simplex communications system (single-mode operation). The system is located in a northern location near the Arctic circle. Solar insulation is thus limited. This, coupled with the requirement for high reliability, requires a 60-days of battery reserve. The system is inaccessible for several months each year. Although the battery is thermally isolated, it still has to withstand temperatures as low as –20 °C. See figure B.1 for a simulated load-profile diagram for this application.

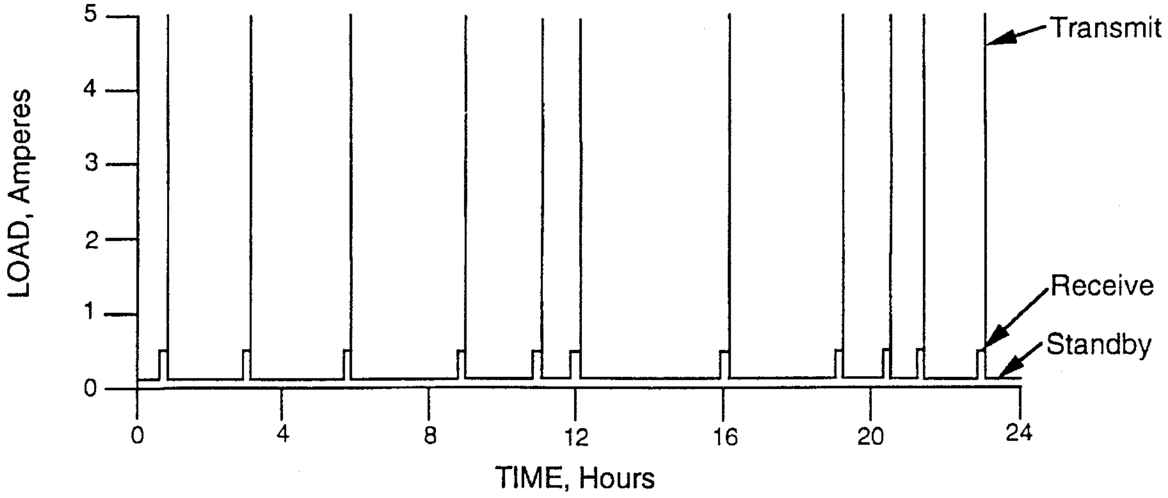

Figure B.1—Remote communications repeater

Worksheet 1—battery sizing

1. *Project name and description*
Communications Systems — High reliability required. Six-month interval between service calls. Northern (near-Arctic) location.

2. *Nominal system voltage*: 48 V

3. *Days of battery reserve:* 60 days

4. *Load data*

4a dc load device	4b Voltage window		4c Momentary currents		4d Running currents		4e Constituents of maximum running current	4f Number of occurrences	4g Duration	4h Run time	4i Daily load
	V_{max} V	V_{min} V	I_{coin} A	$I_{noncoin}$ A	I_{coin} A	$I_{noncoin}$ A		Number / day	hour/ occurrence	hour/ day	Ah/day
Transmitter	64	40				5	✓			0.5	2.5
Receiver	64	40				0.5				2.0	1.0
Standby	64	40				0.1				21.5	2.15
Note: Values are for typical operation.								Total Daily Load			5.65 Ah

self-discharge 0.72

6.37

Sizing including Self-discharge

5. *Load data summary*

5a. Maximum momentary current I_{coin} from the above table or line 5a of Worksheet 3 (refer to load-profile diagram): 0 A

5b. Maximum running current I_{coin} from the above table or line 5b of Worksheet 3 (refer to load-profile diagram): 0 A

5c. Total daily load from the above table or line 5c of Worksheet 3: 5.65 Ah/day

5d. Maximum daily load from Worksheet 2, if used: — Ah/day

5e. Greatest value of $I_{noncoin}$ momentary currents from above table or Worksheet 2: 0 A

5f. Maximum momentary current draw from battery (greater of line 5a or line 5e): 0 A

5g. Greatest value of $I_{noncoin}$ for running currents from above table or Worksheet 2: 5 A

5h. Maximum running current draw from battery (greater of line 5b or line 5g): 5 A

5i. Maximum current draw from battery (greater of line 5f or line 5h): 5 A

5j. Lowest value of V_{max} from above table or Worksheet 2: 64 V

5k. Greatest value of V_{min} from above table or Worksheet 2: 40 V

6. *Battery capacity*

6a. Unadjusted battery capacity (line 3 × line 5c): 339 Ah 382

6b. Percent of capacity at end of life: 60 %

6c. Capacity adjusted for end of life (line 6a divided by line 6b): 565 Ah 637

6d. Percent of capacity at system end-of-charge voltage (≤100%): 95 %

6e. Capacity adjusted for SOC (line 6c divided by line 6d): 595 Ah 670

6f. Minimum operating temperature: -20 °C ~~or °F~~

6g. Associated temperature correction factor: 1.2

6h. Capacity adjusted for temperature: 714 Ah 804

6i. Design margin factor (≥1): 1.2

6j. Capacity adjusted for design margin (line 6h × line 6i): 857 Ah 965

7. *Functional-hour rate* (line 6j divided by line 5h): 171 h 193

8. *Voltage-window adjustment*

8a. Controller low voltage load-disconnect setpoint: 40 V

8b. Adjusted V_{min} (greater of line 5k or line 8a): 40 V

8c. Controller full-charge voltage setpoint: 64 V [Temperature compensated at -0.004 VPC/°
-set at 1.60 VPC at 25°C (57.6V)]

8d. Adjusted V_{max} (lesser of line 5j or line 8c): 64 V

9. *Number of series-connected cells*

9a. Recommended full-charge voltage for selected cell (limited by line 8d): 1.78 V at -20°C

9b. Maximum number of cells in series, round down (line 8d divided by line 9a): 36

9c. Recommended EOD voltage for selected cell: 1.10 V

9d. Calculated EOD voltage for cell (line 8b divided by line 9b): 1.11 V

NOTE—if 9d > 9c, proceed to 9g; otherwise continue with 9e.

9e. Decrement number of series cells (line 9b – 1): —

9f. Calculated cell charge voltage (line 8d divided by line 9e): — V

NOTE—If line 9f is within charge voltage range specified by manufacturer, proceed to line 9g; otherwise, at least one of the following has to be done:

- Decrement number of series cells (repeat 9e and 9f)
- Select different battery type, go to 6b
- Change controller full charge setpoint, go to 8c
- Select different controller, go to 8a

9g. Enter the selected number of series cells (line 9b or line 9e, as appropriate) 36

10. *Cell selection and final capacity determination*

10a. Smallest practical cell capacity available of selected type greater than or equal to line 6j, or largest practical cell less than line 6j when discharged to voltage line 9d at functional-hour rate (line 7): 263 Ah

10b. Number of parallel strings, round up (line 6j divided by line 10a): 4

10c. Final battery capacity (line 10a × line 10b): 1052 Ah

11. *Checks/considerations*

Checks:

11a. Maximum available charging current at battery's full charge voltage: 30 A

11b. Minimum recommended operating temperature for standard electrolyte used: -40 °C~~/°F~~

11c. Battery's self-discharge rate: 0.03 A (2%/month – less in cold periods.)

Considerations resolved:

- a) Overcharging [✓
- b) Undercharging [✓
- c) High-rate discharge [✓
- d) Low temperature [✓
- e) Battery self-discharge [✓
- f) Electrolyte reserve [✓
- g) Battery size and weight [✓

12. *Summary*

Battery manufacturer and battery model: XYZ

Final battery is 36 cells in series by 4 strings in parallel.

Battery capacity is 1052 Ah rated at the 210 functional-hour rate.

Battery full-charge voltage is 64 V; battery end-of-discharge voltage is 40 V.

B.2 Acid rain environmental monitoring station

The following worksheet describes the battery sizing for a 12 V environmental monitor. The monitor is located in a New England wooded area. The monitor measures and records the amount and pH of the local precipitation. The sensors and recorders operate only during showers. The station is in a standby mode (rain and temperature sensors, and timers operational) the rest of the time. During freezing conditions, heaters are required. Such a winter applications is illustrated. The application is readily accessible.

See figure B.2 for a simulated load-profile diagram for this application

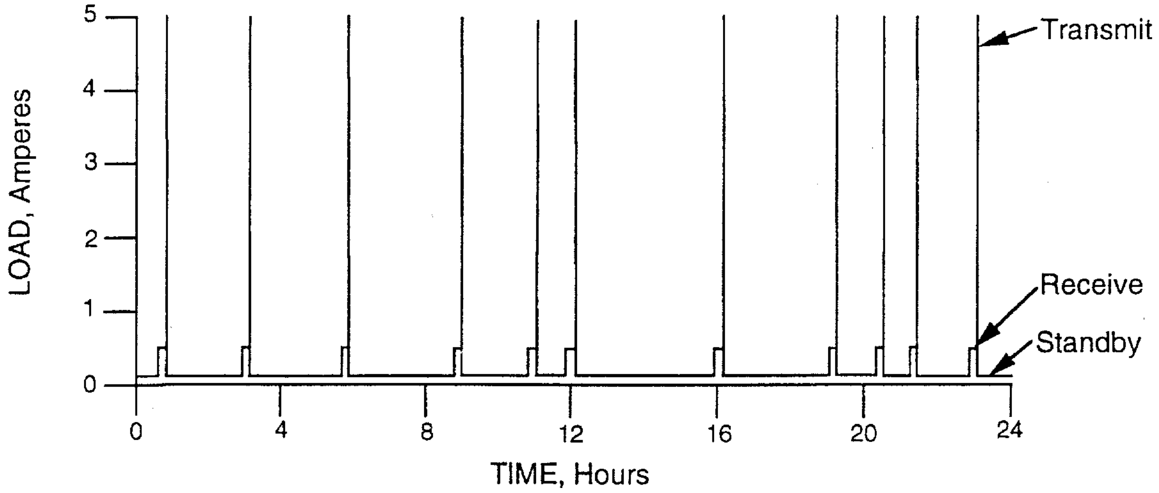

Figure B.2—Acid rain monitoring station-simulated data

Battery sizing worksheet 1

1. *Project name and description*
Environmental monitor – Moderate temperature range – Easy accessibility – noncritical availability – Requires heater for winter operation. (winter operation used for sizing.)

2. *Nominal system voltage:* 12 V

3. *Days of battery reserve:* 5 days

4. *Load data*

4a dc load device	4b Voltage window		4c Momentary currents		4d Running currents		4e Constituents of maximum running current	4f Number of occurrences	4g Duration	4h Run time	4i Daily load
	V_{max} V	V_{min} V	I_{coin} A	$I_{noncoin}$ A	I_{coin} A	$I_{noncoin}$ A		Number / day	hour/ occurrence	hour/ day	Ah/day
Heater	16.0	7.0			0.50		✓			20	10.0
Monitor	14.4	9.6	0.75		0.50		✓			1	0.5
Standby	14.4	7.0				0.05				4	0.2
Note: Values are typical operation.							Total Daily Load			10.7	Ah

Durations depend on temperature and precipitation.

5. *Load data summary*

5a. Maximum momentary current I_{coin} from the above table or line 5a of Worksheet 3 (refer to load-profile diagram): 0.75 A

5b. Maximum running current I_{coin} from the above table or line 5b of Worksheet 3 (refer to load-profile diagram): 1.0 A

5c. Total daily load from the above table or line 5c of Worksheet 3: 10.7 Ah/day

5d. Maximum daily load from Worksheet 2 if used: — Ah/day

5e. Greatest value of $I_{noncoin}$ momentary currents from above table or Worksheet 2: 0 A

5f. Maximum momentary current draw from battery (greater of line 5a or line 5e): 0.75 A

5g. Greatest value of $I_{noncoin}$ for running currents from above table (or Worksheet 2): 0.05 A

5h. Maximum running current draw from battery (greater of line 5b or line 5g): 1.0 A

5i. Maximum current draw from battery (greater of line 5f or line 5h): 1.0 A

5j. Lowest value of V_{max} from above table (or Worksheet 2): 14.4 V

5k. Greatest value of V_{min} from above table (or Worksheet 2): 9.6 V

6. *Battery capacity*

6a. Unadjusted battery capacity (line 3 × line 5c): 53.5 Ah

6b. Percent of capacity at end of life: 80 %

6c. Capacity adjusted for end of life (line 6a divided by line 6b): 66.9 Ah

6d. Percent of capacity at system end-of-charge voltage (≤100%): 90 %

6e. Capacity adjusted for SOC (line 6c divided by line 6d): 74.3 Ah

6f. Minimum operating temperature: −10 °C or °F

6g. Associated temperature correction factor: 1.1

6h. Capacity adjusted for temperature: 81.7 Ah

6i. Design margin factor (≥1): 1.1

6j. Capacity adjusted for design margin (line 6h × line 6i): 89.9 Ah

7. *Functional-hour rate* (line 6j divided by line 5h): 90 h

8. *Voltage-window adjustment*

8a. Controller low voltage load-disconnect setpoint: 9.6 V

8b. Adjusted V_{min} (greater of line 5k or line 8a): 9.6 V

8c. Controller full-charge voltage setpoint: 14.4 V Temperature-compensated controller set at 1.60 VPC at 25 °C.

8d. Adjusted V_{max} (lesser of line 5j or line 8c): 14.4 V

9. *Number of series-connected cells*

9a. Recommended full-charge voltage for selected cell (limited by line 8d): 1.74 V at −10 °C

9b. Maximum number of cells in series, round down (line 8d divided by line 9a): 8

9c. Recommended EOD voltage for selected cell: 1.15 V

9d. Calculated EOD voltage for cell (line 8b divided by line 9b): 1.20 V

NOTE—if 9d > 9c, proceed to 9g; otherwise continue with 9e.

9e. Decrement number of series cells (line 9b – 1): —

9f. Calculated cell charge voltage (line 8d divided by line 9e): — V

NOTE—If line 9f is within charge voltage range specified by manufacturer, proceed to line 9g; otherwise, at least one of the following has to be done:

- Decrement number of series cells (repeat 9e and 9f);
- Select different battery type, go to 6b;
- Change controller full charge setpoint, go to 8c;
- Select different controller, go to 8a.

9g. Enter the selected number of series cells (line 9b or line 9e, as appropriate) 8

10. *Cell selection and final capacity determination*

10a. Smallest practical cell capacity available of selected type greater than or equal to line 6j, or largest practical cell less than line 6j when discharged to voltage line 9d at functional-hour rate (line 7): 110 Ah

10b. Number of parallel strings, round up (line 6j divided by line 10a): 1

10c. Final battery capacity (line 10a × line 10b): 110 Ah

11. *Checks/considerations*

Checks:

11a. Maximum available charging current at battery's full charge voltage: 2 A

11b. Minimum recommended operating temperature for standard electrolyte used: -40 °C~~/°F~~

11c. Battery's self-discharge rate: 0.04 A

0.1%/day max. Negligible – battery is already 20Ah larger than required.

Considerations resolved:

a) Overcharging [✓]
b) Undercharging [✓]
c) High-rate discharge [✓]
d) Low temperature [✓]
e) Battery self-discharge [✓]
f) Electrolyte reserve [✓]
g) Battery size and weight [✓]

12. *Summary*

Battery manufacturer and battery model: abc

Final battery is 8 cells in series by 1 strings in parallel.

Battery capacity is 110 Ah rated at the 110 functional-hour rate.

Battery full-charge voltage is 14.4 V; battery end-of-discharge voltage is 9.6 V.

B.3 Target-range data-gathering bunker

The following worksheet describes the battery sizing for a 24-V data-gathering station for a military target range. The remote bunker is used on an intermittent basis; approximately one shift in four full days. The remainder of the time the bunker is protected by a security alarm and lights. The typical operation consists of radio communications to the range officer and data recording during firing exercises. The duration of each varies, but 1 h of communications and 3 h of recording during a firing operation is typical.

See figures B.3 and B.4 for simulated load-profile diagrams of the unoccupied and occupied days, respectively, for this application.

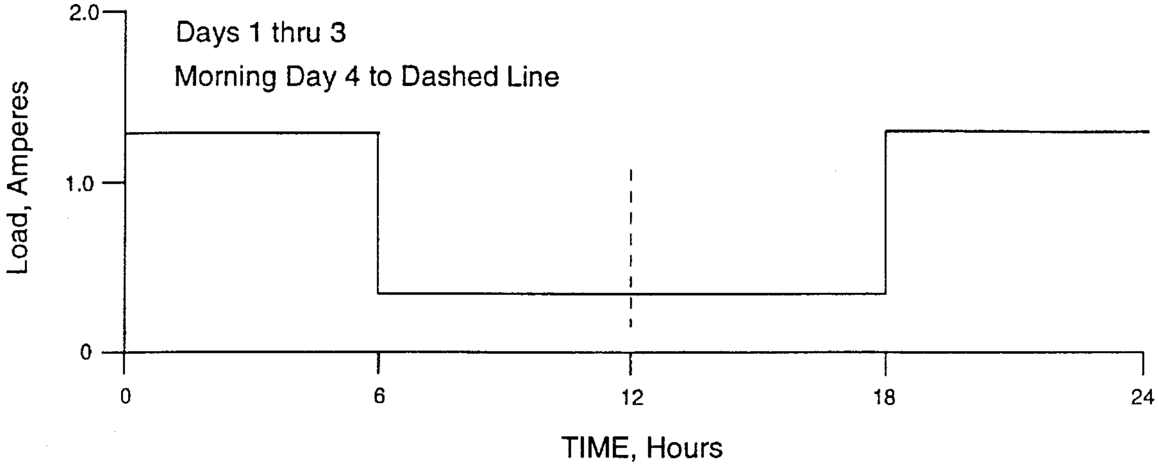

Figure B.3—Data-gathering bunker-unoccupied days

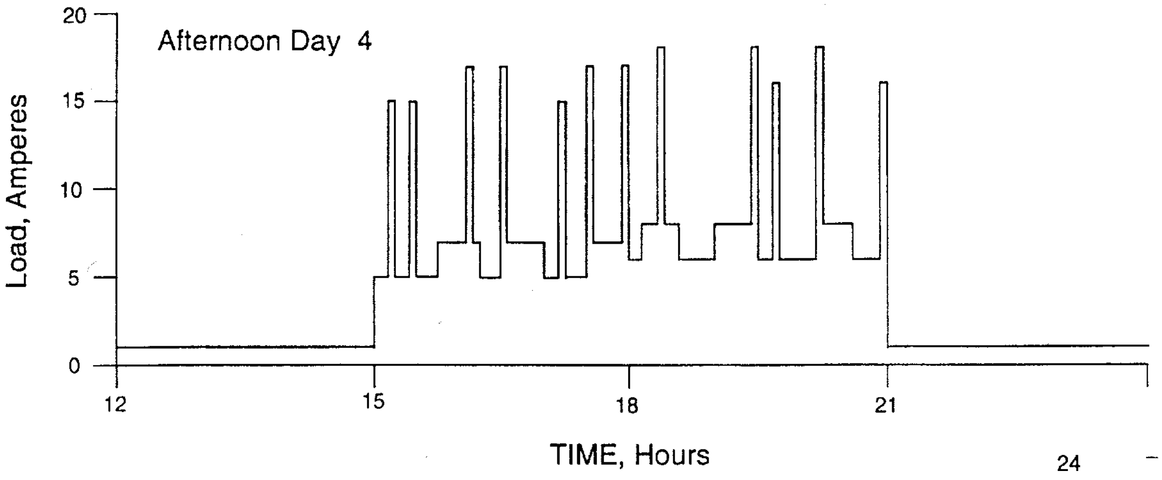

Figure B.4—Data-gathering bunker-occupied days

Worksheet 1—battery sizing

1. *Project name and description*
Data-gathering bunker for target range - Intermittent operation ∼ 1 day out of 4. Moderate temperature range - noncritical application (generator backup). Op time variable - Near worst case conditions selected.

2. *Nominal system voltage:* 24 V

3. *Days of battery reserve:* 4 days

4. *Load data*

4a dc load device	**4b** Voltage window		**4c** Momentary currents		**4d** Running currents		**4e** Constituents of maximum running current	**4f** Number of occurrences	**4g** Duration	**4h** Run time	**4i** Daily load
	V_{max} V	V_{min} V	I_{coin} A	$I_{noncoin}$ A	I_{coin} A	$I_{noncoin}$ A		Number / day	hour/ occurrence	hour/ day	Ah/day
							Total Daily Load				Ah

See Worksheets 2

5. *Load data summary*

5a. Maximum momentary current I_{coin} (refer to load-profile diagram): 0 A

5b. Maximum running current I_{coin} (refer to load-profile diagram): 18.1 A

5c. Total daily load from above table or line 5c of Worksheet 3: 32.65 Ah/day

5d. Maximum daily load from Worksheet 2, if used: 65.8 Ah/day

5e. Greatest value of $I_{noncoin}$ momentary currents from above table or Worksheet 2: 0 A

5f. Maximum momentary current draw from battery (greater of line 5a or line 5e): 0 A

5g. Greatest value of $I_{noncoin}$ for running currents from above table or Worksheet 2: 0 A

5h. Maximum running current draw from battery (greater of line 5b or line 5g): 18.1 A

5i. Maximum current draw from battery (greater of line 5f or line 5h): 18.1 A

5j. Lowest value of V_{max} from above table or Worksheet 2: 28 V

5k. Greatest value of V_{min} from above table or Worksheet 2: 22 V

6. *Battery capacity*

6a. Unadjusted battery capacity (line 3 × line 5c): 131 Ah

6b. Percent of capacity at end of life: 75 %

6c. Capacity adjusted for end of life (line 6a divided by line 6b): 175 Ah

6d. Percent of capacity at system end-of-charge voltage (≤100%): 100 %

6e. Capacity adjusted for SOC (line 6c divided by line 6d): 175 Ah

6f. Minimum operating temperature: 0 °C ~~or °F~~

6g. Associated temperature correction factor: 1.05

6h. Capacity adjusted for temperature: 184 Ah

6i. Design margin factor (≥1): 1.2

6j. Capacity adjusted for design margin (line 6h × line 6i): 221 Ah

7. *Functional-hour rate* (line 6j divided by line 5h): 12 h

8. *Voltage-window adjustment*

8a. Controller low voltage load-disconnect setpoint: 22 V

8b. Adjusted V_{min} (greater of line 5k or line 8a): 22 V

8c. Controller full-charge voltage setpoint: 30 V

8d. Adjusted V_{max} (lesser of line 5j or line 8c): 30 V

9. *Number of series-connected cells*

9a. Recommended full-charge voltage for selected cell (limited by line 8d): 1.75 V

9b. Maximum number of cells in series, round down (line 8d divided by line 9a): 17

9c. Recommended EOD voltage for selected cell: 1.15 V

9d. Calculated EOD voltage for cell (line 8b divided by line 9b): 1.29 V

NOTE—if 9d > 9c, proceed to 9g; otherwise continue with 9e.

9e. Decrement number of series cells (line 9b – 1): –

9f. Calculated cell charge voltage (line 8d divided by line 9e): – V

NOTE—If line 9f is within charge voltage range specified by manufacturer, proceed to line 9g; otherwise, at least one of the following has to be done:

- Decrement number of series cells (repeat 9e and 9f)
- Select different battery type, go to 6b
- Change controller full charge setpoint, go to 8c
- Select different controller, go to 8a

9g. Enter the selected number of series cells (line 9b or line 9e, as appropriate) 17

10. *Cell selection and final capacity determination*

10a. Smallest practical cell capacity available of selected type greater than or equal to line 6j, or largest practical cell less than line 6j when discharged to voltage line 9d at functional-hour rate (line 7): 300 Ah

10b. Number of parallel strings, round up (line 6j divided by line 10a): 1

10c. Final battery capacity (line 10a × line 10b): 300 Ah

11. *Checks/considerations*

Checks:

11a. Maximum available charging current at battery's full charge voltage: 15 A

11b. Minimum recommended operating temperature for standard electrolyte used: -40 °C/~~°F~~

11c. Battery's self-discharge rate: 0.1 A

Considerations resolved:

a) Overcharging [✓]
b) Undercharging [✓]
c) High-rate discharge [✓]
d) Low temperature [✓]
e) Battery self-discharge [✓]
f) Electrolyte reserve [✓]
g) Battery size and weight [✓]

12. *Summary*

Battery manufacturer and battery model: pdq

Final battery is 17 cells in series by 1 strings in parallel.

Battery capacity is 300 Ah rated at the 17 functional-hour rate.

Battery full-charge voltage is 30 V; battery end-of-discharge voltage is 12 V.

Worksheet 2—Supplemental battery sizing for duty cycle periods greater than 24 h

Complete Worksheet 2 for each day (24-h period) for which a distinct daily load exists. Summarize the data in Worksheet 3, and transfer to Worksheet 1.

Load data

Day: 1 to 3 (Unoccupied days)

4a dc load device	4b Voltage window		4c Momentary currents		4d Running currents		4e Constituents of maximum running current	4f Number of occurrences	4g Duration	4h Run time	4i Daily load
	V_{max} V	V_{min} V	I_{coin} A	$I_{noncoin}$ A	I_{coin} A	$I_{noncoin}$ A		Number / day	hour/ occurrence	hour/ day	Ah/day
Security Lights	30	21			1.0		✓	2	6	12	12.0
Alarm	30	21			0.3		✓	1	24	24	7.2
Parasitics					0.1		✓		24	24	2.4
							Total Daily Load			21.6	Ah

Maximum momentary I_{coin} (refer to load-profile diagram): 0 A

Maximum running I_{coin} (refer to load-profile diagram): 1.4 A

Number of repetitions: 3

Worksheet 2—Supplemental battery sizing for duty cycle periods greater than 24 h

Complete Worksheet 2 for each day (24-h period) for which a distinct daily load exists. Summarize the data in Worksheet 3, and transfer to Worksheet 1.

Load data

Day: 4 (Occupied day)

4a dc load device	**4b** Voltage window		**4c** Momentary currents		**4d** Running currents		**4e** Constituents of maximum running current	**4f** Number of occurrences	**4g** Duration	**4h** Run time	**4i** Daily load
	V_{max} V	V_{min} V	I_{coin} A	$I_{noncoin}$ A	I_{coin} A	$I_{noncoin}$ A		Number/ day	hour/ occurrence	hour/ day	Ah/day
Security Lights	30	21			1.0		✓	2	6	12	12.0
Alarm	30	21			0.3			1	18 *	18	5.4
Operating Lights	30	21			5.0		✓	1	6	6	30.0
Radio	28	22			10.0		✓	12	0.083	1	10.0
Data Logger	28	22			2.0		✓	6	0.5	3	6.0
Parasitics					0.1		✓		24	24	2.4
								Total Daily Load			65.8 Ah

Maximum momentary I_{coin} (refer to load-profile diagram): 0 A

Maximum running I_{coin} (refer to load-profile diagram): 18.1 A

Number of repetitions: 1

Worksheet 3—Summary

5. Load data summary

5a. The greatest value of the minimum momentary I_{coin} currents_____A

5b. The greatest value of the maximum running I_{coin} currents:_____A

5c. Average daily load

Determine the series of repetitions that is going to result in the greatest load, over the period of days of battery reserve

Total the load over the period of days of battery reserve and divide by the number of days of battery reserve_____Ah/day

5d. Greatest value of $I_{noncoin}$ for momentary currents for any of the above load devices:_____A

5e. Greatest value of $I_{noncoin}$ for running current for any of the above load devices:_____A

5f. Lowest value of V_{max} for any of the above load devices:_____V

5g. Greatest value of V_{min} for any of the above load devices_____V

Annex C Bibliography

(Informative)

IEEE Std 928-1986 (Reaff 1991), IEEE Recommended Criteria for Terrestrial Photovoltaic Power Systems (ANSI).

IEEE Std 929-1988 (Reaff 1991), IEEE Recommended Practice for Utility Interface of Residential and Intermediate Photovoltaic (PV) Systems (ANSI).