

IEEE Recommended Practice for Sizing Lead-Acid Batteries for Photovoltaic (PV) Systems

Sponsor

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Abstract: IEEE Std 1013-1990, IEEE Recommended Practice for Sizing Lead-Acid Batteries for Photovoltaic Systems, describes methods for sizing both vented and valve regulated lead-acid batteries used with terrestrial photovoltaic (PV) systems. The purpose of this document is to assist system designers in sizing batteries for residential, commercial, and industrial PV systems. Iterative techniques to optimize battery costs, installation, maintenance, safety, testing procedures, and consideration of battery types other than lead-acid, are beyond the scope of this document. Recommended practices for the remainder of the electrical systems associated with PV installations are also beyond the scope of this document.

Keywords: Battery sizing, photovoltaic power systems, lead-acid batteries, bond determination, battery reserve

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Foreword

(This Foreword is not a part of IEEE Std 1013-1990, IEEE Recommended Practice for Sizing Lead-Acid Batteries for Photovoltaic (PV) Systems.)

This Recommended Practice applies to all terrestrial photovoltaic power systems, regardless of size or application, that contain lead-acid battery storage subsystems.

This document should assist a photovoltaic system designer in sizing lead-acid batteries for a particular installation. A worksheet is included to facilitate the battery sizing process. Examples of its application are found in Appendix B.

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IEEE Recommended Practice for Sizing Lead-Acid Batteries for Photovoltaic (PV) Systems

1. Scope

This Recommended Practice describes methods for sizing both vented and valve regulated lead-acid batteries used with terrestrial photovoltaic (PV) systems. Installation, maintenance, safety, testing procedures, and consideration of battery types other than lead-acid, are beyond the scope of this document. Recommended practices for the remainder of the electrical systems associated with PV installations are also beyond the scope of this document.

The purpose of this Recommended Practice is to assist system designers in sizing batteries for residential, commercial, and industrial PV systems. Sizing examples are given for various representative 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 document.

2. References

This Standard should be used in conjunction with the following publications:

- [1] IEEE Std 100-1984, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).¹
- [2] IEEE Std 485-1983, IEEE Recommended Practice for Sizing Large Lead Storage Batteries for Generating Stations and Substations (ANSI).
- [3] IEEE Std 928-1986, IEEE Recommended Criteria for Terrestrial Photovoltaic Power Systems (ANSI).
- [4] IEEE Std 929-1988, IEEE Recommended Practice for Utility Interface of Residential and Intermediate Photovoltaic (PV) Systems (ANSI).
- [5] IEEE Std 937-1987, IEEE Recommended Practice for the Installation and Maintenance of Lead-Acid Batteries for Photovoltaic (PV) Systems (ANSI).

¹ IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, Piscataway, NJ 08855-1331.

3. Definitions

In general, definitions of technical words and terms used in this document are found in IEEE Std 100-1984 [1]². In addition, the following definitions apply specifically to this Recommended Practice:

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

NOTE — For a lead-acid cell, the nominal voltage is 2.0 V.

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.

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

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.

discharge rate: The rate, in amperes, at which current is delivered by a battery. (See also "hour rate" in this Section).

energy capacity: The energy, usually expressed in watt-hours (Wh), which a fully-charged battery can deliver under specified conditions.

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-discharge voltage:

$$\text{Hour rate} = C/I; \tag{1}$$

where C = rated capacity of the battery at the specified discharge current I.

For example, if a fully-charged battery rated at 100 Ah can be discharged at 5 A for a period of 20 h before reaching the end-of-discharge voltage, discharge of the battery at 5 A is referred to as the 20 h rate ($C/I = 100 \text{ Ah}/5\text{A}$).

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

rated capacity (C): The manufacturer's statement of the number of ampere-hours (Ah) that can be delivered by a fully charged cell at a specific discharge rate and electrolyte temperature, and to a specific end-of-discharge voltage.

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

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

valve-regulated battery: A battery in which the venting of the products of electrolysis is controlled by a reclosing pressure-sensitive valve.

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

²The number in brackets corresponds to those of the references listed in Section 2.

4. Overview

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 should be considered to determine the necessary capacity and the number of cells comprising the battery. These factors, as follows, will be discussed in subsequent sections:

- 1) *Battery Reserve Considerations* (Section 5.). The length of time that the load should be supported solely by the battery is established by system design requirements
- 2) *Load Determination* (Section 6.). 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.
- 3) *Battery Capacity and Functional-Hour Rate Determination* (Section 7.). The battery capacity and its discharge functional-hour rate are determined by the specific application load, days of battery reserve, and battery characteristics (see Appendix A).
- 4) *Determining Number of Series-Connected Cells* (Section 8.). The system's voltage limits (voltage window) determines the required number of cells in series. Several criteria should be examined to assure a workable system.
- 5) *Cell Capacity and Battery Size Determination* (Section 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.

- 6) *Battery Sizing Worksheet* (Section 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.
- 7) *Battery Characteristics* (Appendix A). System performance, life, maintenance, and cost are influenced by the type of battery selected for a PV application. Information regarding lead-acid battery characteristics is presented.
- 8) *Examples* (Appendix 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 unanticipated occurrence, such as unusually poor weather or failure of a system component. The number of days of battery reserve is commonly specified as a system design requirement, and is based on several considerations including the following:

- 1) *System Availability*. System availability is the percentage of the time that the PV system is likely to satisfy the system loads.
- 2) *System Application*. Critical load applications generally require more days of battery reserve than noncritical applications.
- 3) *Solar Irradiance Variability*. Daily and seasonal variations in solar irradiance affect the required number of days of battery reserve.
- 4) *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.
- 5) *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.
- 6) *Accessibility of Site*. The worst-case time required for correction of any problem should be considered.
- 7) *System Cost*. Cost trade-offs associated with array and battery size relationships for the required system availability need to be considered.
- 8) *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 PV array or auxiliary power source. For ac loads supplied through an inverter, these loads should 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. Figure None in Section 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. Figure 2 in Section 10. provides 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 this 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 its thus 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 assure load satisfaction. To make a load profile diagram, do the following:

- 1) Tabulate all the individual loads along with their starting and stopping times,
- 2) Total the coincident loads for their respective periods of time, and
- 3) 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 constitutes the system's load-profile diagram. (See Appendix B for examples.)

6.2 Load Data

The information that should be gathered for each load is discussed below.

6.2.1 Momentary Current

Loads lasting one minute or less are designated momentary loads and are given special consideration. The ampere-hour requirements 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 occur repeatedly during the duty cycle. Typical momentary loads are:

- 1) Motor starting current
- 2) 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. In this case, the running current may be calculated as the current required at 95% of the system voltage.

NOTE —

- 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 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 losses, such as those resulting from tare losses of charge controllers and inverters, blocking diodes, and wiring, should be included as loads.
- 3) Consideration of the battery's 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 which 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 should be determined and tabulated (see 8.2). Voltage drops in cabling and any diodes 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 determined individually for each load device and added to its minimum operating voltage to ensure, that 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 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 one minute and calculate the load accordingly.

For voltage drop considerations, a full minute duration is used in either case. If the duty cycle does not repeat each day, it is necessary to describe the load over the entire days of battery reserve. Figure 2 in Section 10, is provided for this purpose. If the graphical form of the load description is used, the 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 ($C/20$), the method of IEEE Std 485-1983 [2] should be used to size the 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, battery, 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 Section 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 design depth of discharge and 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.

Appendix 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 Adjustments

The unadjusted capacity should be modified to assure satisfactory battery cycle life. Battery manufacturers rate lead-acid cells for maximum depth of discharge (MDOD), maximum daily depth of discharge (MDDOD) and end-of-life (EOL) capacity. The battery capacity should be adjusted for the following factors:

- 1) The capacity adjusted for MDOD is obtained by dividing the unadjusted capacity by MDOD.
- 2) The capacity adjusted for MDDOD is obtained by dividing the maximum daily ampere-hours by MDDOD.
- 3) The capacity adjusted for life is obtained by dividing the unadjusted capacity by the end-of-life capacity expressed in percent of the rated capacity, commonly 80%.

The largest of these three capacities will satisfy the depth-of-discharge and end-of-life adjustments.

7.3.2 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 increases at temperatures above 25 °C and decreases at temperatures below 25 °C. 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 7.3.1 should be corrected by this factor to yield capacity adjusted for temperature.

7.3.3 Design Margin Adjustment

It is prudent design practice to provide a capacity margin to allow for uncertainties in the load determination, 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 7.3.2.

7.4 Functional-Hour Rate

In order to correctly size the battery, the discharge rate and ampere-hour capacity should 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 applications, 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:

- 1) Compare the sum of all coincident running currents with the highest noncoincident running current and select the larger,
- 2) Divide the adjusted capacity as determined in 7.3.3 by the maximum running current selected in (1).

Example 1:

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 divided by 25, or 6 hours.

Example 2:

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

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

The lead-acid cell delivers approximately 2 V; therefore, the number of cells may be estimated by dividing the nominal system voltage by two. It is common practice to use 6 cells for a 12 V system, 12 cells for a 24 V system, etc., but it is possible that the allowable voltage limits may require adjustment to this general 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 should 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. If a charge controller is used, its setpoints should be within this voltage window (See Section 10, 46.2.5b)

NOTE — The battery may be overcharged by a voltage less than Vmax. It is recommended that a charge controller be used to limit battery charge voltage. The consequences of overcharging are described in 9.5, (1).

8.3 Calculating the Number of Series-Connected Cells

The number of series-connected cells is a 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 a optimal and safe cell recharge voltage. In determining the maximum number of cells allowed by the system, the following calculation is performed:

$$\frac{V \text{ max}}{\text{cell recharge voltage}} = \text{Maximum number of cells (rounded off).}$$

Example:

Assume 2.4 V per cell is recommended for recharging. The maximum allowable system voltage is 58 V dc, then:

$$\frac{58 \text{ V}}{2.4\text{V/cell}} = 24.16\text{cells, therefore, use 24 cells.}$$

$$\frac{58 \text{ V}}{2.4\text{V/cell}} = 24.16\text{cells, therefore, use 24 cells.}$$

8.3.2 Minimum System Voltage Versus End-of-Discharge Voltage

To ensure that the battery manufacturer's recommended end-of-discharge (EOD) voltage is not exceeded, calculate the voltage per cell to which the low limit of the system voltage would allow the cell to be discharged. This calculated EOD cell voltage should not be below the manufacturer's limit at the functional-hour rate. This is determined as:

$$\frac{V \text{ min}}{\text{Number of cells in 8.3.1}} = \text{Calculated EOD cell voltage.}$$

Example:

Assume the minimum system voltage is 42 V dc, then

$$\frac{42\text{V}}{24\text{cells}} = 1.75\text{V per cell}$$

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.

NOTE — 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 Multi-Cell Unit Considerations

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

$$\text{Total number of Multi-Cell Units} = \frac{V \text{ max}}{\text{maximum multi-cell recharge voltage}}$$

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 proper system performance. It may be possible to use fewer series-connected cells and yet maintain proper system performance. See Section 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 (1).

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

9. Battery Size Determination

Battery size is determined by using the results of Section 7. and Section 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 7.3.3 when discharged at the functional-hour rate of 7.4 to an EOD voltage that is greater than or equal to the EOD voltage of 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. A manufacturer may list available capacities by the following:

- 1) The capacity of the cell itself, or
- 2) The capacity of an individual positive plate.

If the manufacturer lists capacity of positive plates, the required number of positive plates may be determined by dividing the capacity requirement as found in 7.3.3 by the positive plate capacity. Fractional results are to be rounded up to the next highest whole number.

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, may (consistent with the manufacturer's recommendations) be connected in parallel to obtain the necessary capacity.

The number of parallel strings is calculated by dividing the capacity found in 7.3.3 by the selected cell capacity of 9.1 (rounded up).

9.3 Final Number of Cells

The total number of cells can then be calculated by multiplying the number of series cells from 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, which may affect battery performance. These are as follows:

- 1) *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. The allowable end-of-charge current is highly dependent upon the battery temperature. For vented batteries, this will result in the generation and release of potentially hazardous quantities of hydrogen and oxygen and accelerate water loss. For valve-regulated batteries this also will result in the generation of potentially hazardous quantities of hydrogen and oxygen that may be released. The quantity and composition depends on the rate and duration of the overcharge, the battery and its valve design, oxygen recombination efficiency (see Appendix A, A2), thermal environment, and previous usage of the battery. Consequences of water loss are different for vented batteries where the liquid can generally be replaced. In valve-regulated batteries, the water lost cannot be replaced and, therefore, life will be shortened. Overcharging valve-regulated batteries can also cause a potentially hazardous condition known as thermal runaway. This results in excess heat, which enables the battery to draw ever more current, a cycle that continues until the battery releases all its water and the battery is destroyed. 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.
- 2) *Undercharging.* Insufficient time at the available charge rate or too low a charging voltage will result in an under-charged 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.
- 3) *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 485-1983 [2] (considering the required days of battery reserve for the load profile diagram); or a reexamination of the worst case loads be made and discussed with the PV system designer. If the method of IEEE Std 485-1983 [2] 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.

- 4) *Freezing of the Electrolyte.* Freezing a battery's electrolyte can cause damage and, therefore, should be prevented. Based on the battery's lowest design state of charge, the freezing point of the electrolyte (refer to the manufacturer's literature) should be less than the lowest anticipated operating temperature. If not, consider thermal insulation for the battery or increasing the battery capacity and minimum system voltage.
- 5) *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-discharge 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

The Worksheet in Fig None may be used to organize the manual applications of the procedures outlined previously. Examples of its use are in Appendix 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 for each load device and calculate the daily load for each device. The worksheet in Fig 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.

NOTE — 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 wiring 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, as in 4d. The two columns, I_{coin} and $I_{noncoin}$, refer to the coincidental and noncoincident currents. The $I_{noncoin}$ column is used only for loads which 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 operate in coincidence to generate the maximum running current 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 4f times line 4g or the total time). If the run time varies from day to day, use the work-sheet in Fig 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.)
 - 5a) Enter the Maximum Coincident Momentary Current. (Refer to the load-profile diagrams.)
 - 5b) Enter the Maximum Coincident Running Current. (Refer to the load-profile diagrams.)
 - 5c) Enter the total from the daily load column of Fig 1 or the Average Daily Ampere-Hours from Fig 2.
 - 5d) Enter the maximum daily load from Fig 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 Vmax column.
 - 5k) Enter the highest value from the Voltage Window Vmin column.
- 6) Battery Capacity. To complete this section it is necessary to have the following information:
 - maximum allowable depth of discharge (MDOD),
 - maximum allowable daily depth of discharge (MDDOD),
 - end-of-life (EOL) capacity in percent,
 - minimum temperature at which battery is required to support the load,
 - 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 times line 5c).
 - 6b) Enter MDOD.
 - 6c) Adjust the capacity for MDOD. (line 6a divided by line 6b)
 - 6d) Enter MDDOD.
 - 6e) Adjust the capacity for MDDOD. (line 5c divided by line 6d or line 5d divided by line 6d, if Fig 2 is used.)
 - 6f) Enter EOL.
 - 6g) Adjust the capacity for EOL. (line 6a divided by line 6f)
 - 6h) Enter the largest of the above three capacities.
 - 6i) Enter the minimum operating temperature and indicate use of degrees Fahrenheit (°F) or degrees Celcius (°C).
 - 6j) Enter the appropriate temperature correction factor from the manufacturer's literature.
 - 6k) Adjust the capacity (line 6h) for temperature.
 - 6l) Enter the design margin factor, e.g., for a 10% oversize, enter the number 1.1
 - 6m) Adjust the capacity for the design margin (line 6k times line 6l).
- 7) Functional-Hour Rate. Divide the adjusted capacity (line 6m) 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 setpoints. The controller setpoints should determine the limits of the voltage window and provide as wide a voltage range as possible while protecting the load and battery. (See Note in 8.2.)
 - 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 5i.
 - 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,
 - end-of-discharge (EOD) voltage (at the functional-hour rate): the cell voltage when the fully available capacity to MDOD is reached.
 - 9a) Enter the cell 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 line 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 charge voltage range, proceed to step 9g. If the result is outside the range,
- repeat steps 9e and 9f or,
 - select a different type of cell, e.g. different plate composition or specific gravity, (go back to step 6b) or,
 - adjust the full-charge voltage setpoint on the controller, if used, downward to prevent excessive overcharge (go back to step 8c) or,
 - choose a different controller (go back to step 8a)
- 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 6m divided by line 10a). Round up to the next higher whole number.
- 10c) The final capacity of the battery is the capacity of each cell multiplied by the number of parallel strings (line 10a times line 10b).
- 11) Checks/Considerations. This section serves as a cross check 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 recommended charge current for the battery during recharge (line 11a),
 - maximum available charging current within the voltage window (line 11b),
 - maximum recommended charge current for the battery after reaching gassing voltage (line 11c), (This current is highly dependent on the battery's operating temperature.)
 - maximum available charging current at battery's full-charge voltage (line 11d), electrolyte freezing temperature at the lowest state of charge (line 11e),
 - battery's self-discharge rate (line 11f),
 - electrolyte reserve capacity (for vented cells),
 - battery's physical characteristics.
- 11a) Maximum Charge Rate—The available charging current should be checked against the battery's allowable charging current to ensure that the battery is not damaged from excessive current.
- 11b) Overcharging—For systems without disconnecting charge controllers, the array current equivalent to the battery's full-charge voltage should be checked against the battery's allowable float current to assure that the battery is not damaged by overcharging. [See 9.5(1)]
- 11c) Undercharging—The ampere-hour output of the array should be sufficient to recharge the battery while supplying the daily load.
- 11d) High-Rate Discharge—Momentary or short-duration loads occurring near the end of the days of battery reserve will cause voltage decay. Refer to 9.5 (3) if (line 10c+line 5i) < 20 h.
- 11e) Freezing of Electrolyte—To prevent damage to the battery, the freezing point of the electrolyte at MDOD should be lower than the minimum operating temperature. (line 11e should be less than line 6i)
- 11f) Battery's Self-Discharge—The battery self-discharge may be a significant part of the overall load, particularly for a 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 wiring and diode losses, charge controller consumption and losses, etc. should be included in the load data.)
- 11g) 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.
- 11h) 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.

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 Max. Running Currents	4f. No. 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 per day	h/occurrence	h/day	Ah/day
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____

Total Daily Load _____ Ah

5. Load Data Summary

5a. Maximum Momentary current I_{coin} (refer to load profile diagram): _____ A

5b. Maximum Running current I_{coin} (refer to load profile diagram): _____ A

5c. Total Daily Load (from above table or line 5c of Fig 2.2): _____ Ah/day

Figure 1 – Battery Sizing Worksheet

- 5d. Maximum Daily Load from Fig 2.1 if used: _____ Ah/day
- 5e. Greatest value of I_{noncoin} for Momentary Currents from above table (or Fig 2.2): _____ 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 Fig 2.2): _____ 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 Fig 2.2): _____ V
- 5k. Greatest value of V_{min} from above table (or Fig 2.2): _____ V
- 6. Battery Capacity**
- 6a. Unadjusted battery capacity (line 3 x line 5c): _____ Ah
- 6b. Maximum allowable depth of discharge (MDOD): _____ %
- 6c. Capacity adjusted for MDOD (line 6a+line 6b): _____ Ah
- 6d. Maximum daily depth of discharge (MDDOD): _____ %
- 6e. Capacity adjusted for MDDOD (line 5c+line 6d) [or (line 5d+line 6d) if Fig 2 is used]: _____ Ah
- 6f. Percent of capacity at end of life: _____ %
- 6g. Capacity adjusted for end of life (line 6a+line 6f): _____ Ah
- 6h. Capacity adjusted for depth of discharge (greatest of line 6c, line 6e, or line 6g): _____ Ah
- 6i. Minimum operating temperature: _____ °C or °F
- 6j. Associated temperature correction factor: _____
- 6k. Capacity adjusted for temperature: _____ Ah
- 6l. Design Margin Factor (≥ 1): _____
- 6m. Capacity adjusted for design margin (line 6k x line 6l): _____ Ah
- 7. Functional-Hour Rate (line 6m+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, round down (line 8d+line 9a): _____
- 9c. Recommended EOD voltage for selected cell: _____ V
- 9d. Calculated EOD voltage for cell (line 8b+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+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 should 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 6m, or, largest practical cell less than line 6m., when discharged to voltage line 9d, at functional-hour rate, line 7: _____ Ah
- 10b. Number of parallel strings, round up (line 6m+line 10a): _____
- 10c. Final battery capacity (line 10a x line 10b): _____ Ah

11. Checks/Considerations

Checks:

- 11a. Recommended maximum charge current during recharge: _____ A
- 11b. Maximum available charging current during recharge: _____ A
 NOTE: If line 11b > line 11a, the battery may be damaged
- 11c. Recommended maximum charge current after reaching full-charge voltage at the battery's average temperature of _____ °C/°F. _____ A
- 11d. Maximum available charging current after reaching full-charge voltage: _____ A
 NOTE: If line 11d > line 11c, the battery may be damaged

11e. Freezing temperature of electrolyte at MDOD _____ °C or °F

NOTE: If line 6i < line 11e, the battery may freeze

11f. Battery's self discharge: _____ Ah/month

Considerations resolved:

- (a) Maximum Charge Rate []
- (b) Overcharging []
- (c) Undercharging []
- (d) High-Rate Discharge []
- (e) Freezing of Electrolyte []
- (f) Battery Self Discharge []
- (g) Electrolyte Reserve []
- (h) Battery's 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 _____ h functional-hour rate.

Battery full-charge voltage is _____ V;

Battery end-of-discharge voltage is _____ V.

Complete a Fig 2.1 for each day (24 h period) for which a distinct daily load exists. Summarize the data in Fig 2.2 and transfer to Fig 1:

Fig 2.1—Daily Load Detail

Load Data

Day: _____

a. dc Load Device	b. Voltage Window		c. Momentary Currents		d. Running Currents		e. Constituents of Max. Running Currents	f. No. of Occurrences	g. Duration h/occurrence	h. Run Time h/day	i. Daily Load Ah/day
	V _{max} V	V _{min} V	I _{coin} A	I _{noncoin} A	I _{coin} A	I _{noncoin} A					
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____

Total Daily Load _____ Ah

Maximum momentary current I_{coin}: (refer to load profile diagram): _____ A

Maximum running current I_{coin}: (refer to load profile diagram): _____ A

Number of repetitions: _____

Figure 2 —Supplemental Battery Sizing Worksheet (For Duty Cycle Periods > 24 h)

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:
- I. Determine the series of repetitions that is going to result in the greatest load, over the period of days of battery reserve.
 - II. 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)

(The following Appendixes are not a part of IEEE Std 1013-1990, IEEE Recommended Practice for Sizing Lead-Acid Batteries for Photovoltaic Systems, but are included for information only.)

This section 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, the amount and concentration of electrolyte (particularly in valve-regulated 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:

- 1) Low temperatures reduce capacity.
- 2) High discharge rates reduce capacity.
- 3) High end-of-discharge voltages reduce capacity.
- 4) Limitations on the depth of discharge reduce capacity.
- 5) Failure to properly recharge a battery limits its capacity.
- 6) Excessive periods of high temperature and/or overcharge may result in dryout and limit capacity of valve-regulated batteries.

A.2 Type

The two generic types of lead-acid batteries are:

- 1) Vented. Vented batteries are characterized by plates immersed in liquid electrolyte. The volume of electrolyte is sufficient to allow for a reasonable 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 gasses with the atmosphere. Catalytic recombiners may be incorporated in each cell vent to reduce water loss. In most of these types of batteries, the lost water can be replaced.
- 2) Valve-regulated. Valve-regulated batteries are characterized by plates in contact with a limited amount of immobilized electrolyte. Water loss is minimized during overcharge by oxygen recombination. As long as the cell's recombination rate is not exceeded, the evolved oxygen is recombined at the cell's negative plates to reform water. Other mechanisms that consume oxygen lead to water loss and the evolution of hydrogen. The cell or multicell container is sealed with the exception of a pressure-relief valve ("valve-regulated") that allows excess pressure (mostly hydrogen) resulting from overcharging to be released. In these types of batteries, the lost water cannot be replaced.

A.3 Cyclability

Lead-acid batteries for PV applications are generally categorized as:

A.3.1 Deep-Cycle Batteries

Deep-cycle batteries may be discharged up to 80% of their rated capacity on a daily basis. Deep-cycle-battery PV applications are those that have a low number of days of battery reserve, or are connected to a backup power source or a utility grid.

A.3.2 Shallow-Cycle Batteries

Usually, shallow-cycle batteries are discharged less than 25% of their rated capacity on a daily basis (MDDOD), and up to 80% over the period of battery reserve (MDOD). Manufacturers can supply the maximum number of permissible 80% discharges per year. Typical shallow-cycle-battery PV applications are those with larger numbers of days of battery reserve where neither a utility grid nor an emergency backup power source is available.

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 operation a battery will provide depends upon the following three factors:

- 1) Cell Design
- 2) Use
- 3) Temperature

A.4.1 Design Factors

Some of the design factors that affect cycle life are:

- 1) Plate thickness,
- 2) Grid alloy and construction,
- 3) Active material density,
- 4) Active material retention systems,
- 5) Electrolyte density and amount,
- 6) Type of separator,
- 7) Pressure setting of valve (valve-regulated batteries).

A.4.2 Use Factors

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

- 1) Depth of discharge
- 2) Stratification of electrolytes
- 3) Excessive overcharge (see A.4.3)
- 4) Insufficient recharge
- 5) End-of-discharge voltage

A.4.3 Operating Temperature

High temperatures increase capacity but decrease cycle life, while low temperatures decrease capacity and increase life. A battery should be sized for operation at its coldest expected operating temperature which, in effect, oversizes the battery for normal warmer operation, resulting in shouldower discharging which increases cycle life.

For valve-regulated batteries, high temperatures can cause excessive overcharge current and result in thermal runaway and dryout. High overcharge current can cause increased cell temperature which can also initiate the conditions leading to thermal runaway. A5. Economic considerations

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

- 1) Initial cost
- 2) Cycle life
- 3) Maintenance costs
- 4) Battery/system reliability
- 5) Economic impact on PV system design including:
 - 1) Charge controller,
 - 2) Structural design including battery support structure and enclosure,
 - 3) Heating, ventilation, and cooling
- 6) Replacement costs
- 7) Salvage value/disposal costs
- 8) Energy efficiency
- 9) Accessory systems required such as for electrolyte agitation and water addition

A6 Physical Characteristics

Physical characteristics that may be important are:

- 1) Size and weight of the smallest transportable unit
- 2) Cell access requirements for maintenance, such as addition of water
- 3) Strength of cell containers for safety and if electrolyte freezing is a possibility
- 4) Terminal connection configuration
- 5) Accessory requirements
- 6) Vent fittings to attach tubing for external venting
- 7) Available enclosure space
- 8) Container flammability

A7 Maintenance

The required maintenance of batteries depends upon the batteries' design and use. Refer to IEEE Std 937-1987 [5].

A8 Safety

Batteries are potentially hazardous for a number of reasons, including generation and release of explosive gasses (see 9.5), stored electrical energy, and presence of corrosive liquids. Installation and maintenance personnel should be qualified in battery operating and safety procedures. Refer to IEEE Std 937-1987 [5] for safety details.

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 Refrigerator/Freezer for Vaccine Storage

The following worksheet describes the battery sizing for a vaccine storage refrigerator intended for remote use. The refrigerator is to be located near the equator in a tropical climate. Vaccines are delivered quarterly. At the same time as deliveries are made, a technician is available for system maintenance. There is a physical size constraint on the size of the battery that can be installed in the refrigerator's battery box.

See Fig B-1 for a simulated load profile diagram for Example Worksheet 1.

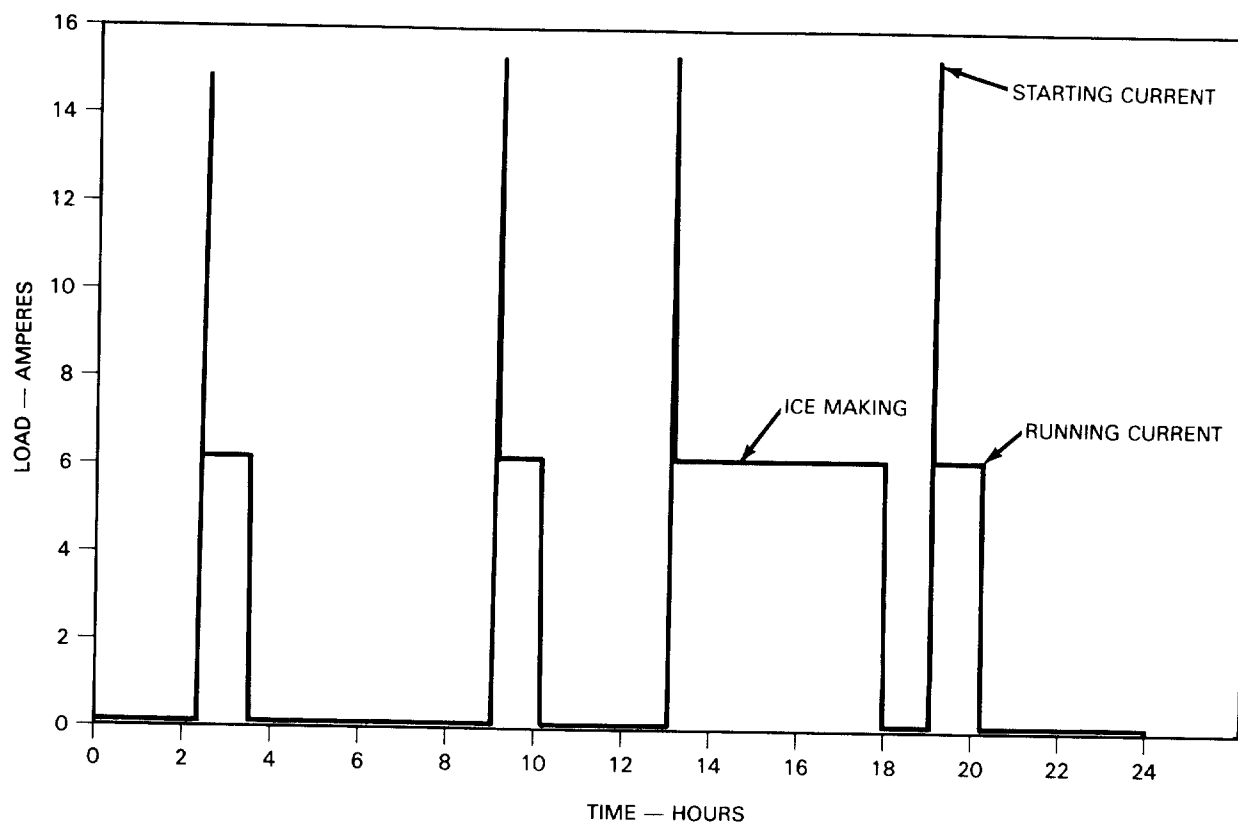


Figure B-1—Simulated Load Profile Diagram for Vaccine Storage Refrigerator/Freezer

**Example Worksheet 1
Battery Sizing**

(Fig 1 of Section 10 worksheet used for this calculation)

1. Project Name and Description: Remote refrigerator/freezer, remote Brazilian village, tropical climate, quarterly maintenance, high reliability, tank starts each 24-h period, including one for ice pack freezing

2. Nominal System Voltage: 12 V

3. Days of Battery Reserve: 6 days

4. Load Data:

4a. dc Load Device	4b. Voltage Window		4c. Momentary Currents		4d. Running Currents		4e. Constituents of Max. Running Currents	4f. No. of Occurrences Number per day	4g. Duration h/occurrence	4h. Run Time h/day	4i. Daily Load Ah/day
	V _{max} V	V _{min} V	I _{coin} A	I _{noncoin} A	I _{coin} A	I _{noncoin} A					
run 1 Compressor	15.0	10.5			6		✓	3	1	3	18
run 2 * Compressor	15.0	10.5			6		✓	1	5	5	30
Start Compressor	15.0	10.5	15					4	0.0167		1
Parasitics					0.1					24	2.4

* For ice freezing.

Total Daily Load 51.4 Ah

5. Load Data Summary

5a. Maximum Momentary current I_{coin} (refer to load profile diagram): 15.1 A

5b. Maximum Running current I_{coin} (refer to load profile diagram): 6.1 A

5c. Total Daily Load (from above table or line 5c of Fig 2.2): 51.4 Ah/day

5d. Maximum Daily Load from Fig 2.1 if used:	<u> </u> Ah/day
5e. Greatest value of $I_{noncoin}$ for Momentary Currents from above table (or Fig 2.2):	<u> 0 </u> A
5f. Maximum momentary current draw from battery (greater of line 5a or line 5e):	<u> 15.1 </u> A
5g. Greatest value of $I_{noncoin}$ for Running Currents from above table (or Fig 2.2):	<u> 0 </u> A
5h. Maximum running current draw from battery (greater of line 5b or line 5g):	<u> 6.1 </u> A
5i. Maximum current draw from battery (greater of line 5f or line 5h.):	<u> 15.1 </u> A
5j. Lowest value of V_{max} from above table (or Fig 2.2):	<u> 15.0 </u> V
5k. Greatest value of V_{min} from above table (or Fig 2.2):	<u> 10.5 </u> V
6. Battery Capacity	
6a. Unadjusted battery capacity (line 3 x line 5c):	<u> 308 </u> Ah
6b. Maximum allowable depth of discharge (MDOD):	<u> 80 </u> %
6c. Capacity adjusted for MDOD (line 6a+line 6b):	<u> 385 </u> Ah
6d. Maximum daily depth of discharge (MDDOD):	<u> 20 </u> %
6e. Capacity adjusted for MDDOD (line 5c+line 6d) [or (line 5d+line 6d) if Fig 2 is used]:	<u> 257 </u> Ah
6f. Percent of capacity at end of life:	<u> 80 </u> %
6g. Capacity adjusted for end of life (line 6a+line 6f):	<u> 385 </u> Ah
6h. Capacity adjusted for depth of discharge (greatest of line 6c, line 6e, or line 6g):	<u> 385 </u> Ah
6i. Minimum operating temperature:	<u> 77 </u> °C or (°F)
6j. Associated temperature correction factor:	<u> 1 </u>
6k. Capacity adjusted for temperature:	<u> 385 </u> Ah
6l. Design Margin Factor (≥ 1):	<u> 1.1 </u>
6m. Capacity adjusted for design margin (line 6k x line 6l):	<u> 424 </u> Ah
7. Functional-Hour Rate (line 6m+line 5h):	<u> 28 </u> h
8. Voltage-Window Adjustment	
8a. Controller low-voltage load, disconnect setpoint:	<u> 10.8 </u> V

- 8b. Adjusted Vmin (greater of line 5k or line 8a): 10.8 V
- 8c. Controller full-charge voltage setpoint: 14.7 V
- 8d. Adjusted Vmax (lesser of line 5j or line 8c): 14.7 V

9. Number Of Series-Connected Cells

- 9a. Recommended full-charge voltage for selected cell: (limited by line 8d) 2.45 V
- 9b. Maximum number of cells in series, round down (line 8d+line 9a): 6
- 9c. Recommended EOD voltage for selected cell: 1.80 V
- 9d. Calculated EOD voltage for cell (line 8b+line 9b): 1.80 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+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 should be done:

- decrement number of series cells (repeat 9e and 9d);
- 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) 6

10. Cell Selection and Final Capacity Determination

- 10a. Smallest practical cell capacity available of selected type greater than or equal to line 6m, or, largest practical cell less than line 6m., when discharged to voltage line 9d, at functional-hour rate, line 7: 110 Ah
- 10b. Number of parallel strings, round up (line 6m+line 10a): 4
- 10c. Final battery capacity (line 10a x line 10b): 440 Ah

11. Checks/Considerations

Checks:

- 11a. Recommended maximum charge current during recharge: 80 A
- 11b. Maximum available charging current during recharge: 35 A
- NOTE: If line 11b > line 11a, the battery may be damaged
- 11c. Recommended maximum charge current after reaching full-charge voltage at the battery's average temperature of 105 °C/F. 1 * A
- * 4 amperes for four parallel strings.
- 11d. Maximum available charging current after reaching full-charge voltage: 0 * A
- NOTE: If line 11d > line 11c, the battery may be damaged
- * Disconnecting charge controller is used.

11e. Freezing temperature of electrolyte at MDOD

NOTE: If line 6i < line 11e, the battery may freeze

20 °C or ~~F~~

11f. Battery's self discharge:

8 Ah/month

Considerations resolved:

- (a) Maximum Charge Rate
- (b) Overcharging
- (c) Undercharging
- (d) High-Rate Discharge
- (e) Freezing of Electrolyte
- (f) Battery Self Discharge
- (g) Electrolyte Reserve
- (h) Battery's Size and Weight

12. Summary

Battery manufacturer and battery model: XYZ, Co.Final battery is 6 cells in series by 4 strings in parallel.Battery capacity is 440 Ah rated at the 28 h functional-hour rate.Battery full-charge voltage is 14.7 V;Battery end-of-discharge voltage is 10.8 V.

NOTE: Because of this application's enclosed battery container and high ambient temperature, caution should be exercised if a valve-regulated battery is selected to mitigate against the possibility of thermal runaway.

B2 Remote Communications System

The following worksheet describes the battery sizing for a 48 V nominal simplex communications system (single mode operation). A battery reserve of 15 days was selected to ensure high system reliability. The system is not accessible during 6 months of the year. There is a weight limitation on battery transportation.

See Fig B-2 for a simulated load profile diagram for Example Worksheet 2.

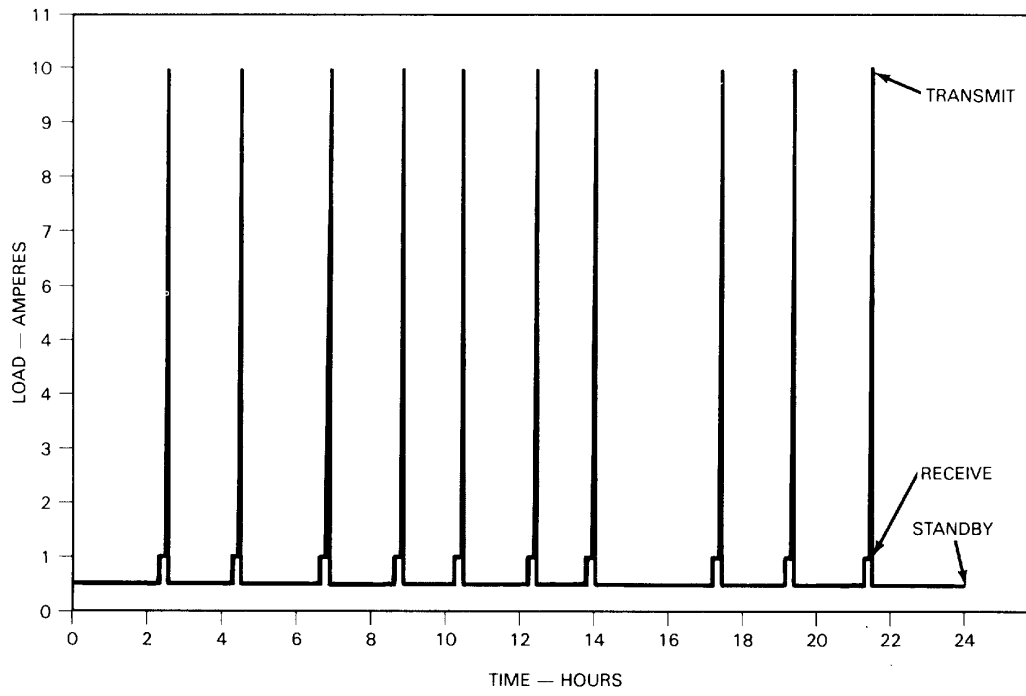


Figure B-2—Simulated Load Profile Diagram for Remote Communications Repeater

1. Project Name and Description: Communications systems, high reliability required, six-month interval between service calls, mountain top location, thermally insulated battery.

2. Nominal System Voltage: 48 V

3. Days of Battery Reserve: 15 days

4. Load Data:

4a. dc Load Device	4b. Voltage Window		4c. Momentary Currents		4d. Running Currents		4e. Constituents of Max. Running Currents	4f. No. of Occurrences Number per day	4g. Duration h/occurrence	4h. Run Time h/day	4i. Daily Load Ah/day
	V _{max} V	V _{min} V	I _{coin} A	I _{noncoin} A	I _{coin} A	I _{noncoin} A					
trans-mitter ϕ	6.4	40			10		✓			0.5	5
Rec'd ϕ	6.4	40			1					2.0	2
standby ϕ	6.4	40			0.5					21.5	10.8
	ϕ		(Battery self-discharge) all include parasitic losses.								

NOTE: Since individual durations are not identical, columns 4e and 4g have not been used. The hours/day have been obtained from the customer's requirements. Total Daily Load 17.8 Ah
18.5 *

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): 0 A

5c. Total Daily Load (from above table or line 5c of Fig 2.2): 17.5 Ah/day
18.5

Example Worksheet 2—Battery Sizing Worksheet (Fig 1 of Section 10 worksheet used for this calculation)

- 5d. Maximum Daily Load from Fig 2.1 if used: Ah/day
- 5e. Greatest value of I_{noncoin} for Momentary Currents from above table (or Fig 2.2): 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 Fig 2.2): 10 A
- 5h. Maximum running current draw from battery (greater of line 5b or line 5g): 10 A
- 5i. Maximum current draw from battery (greater of line 5f or line 5h.): 10 A
- 5j. Lowest value of V_{max} from above table (or Fig 2.2): 6.4 V
- 5k. Greatest value of V_{min} from above table (or Fig 2.2): 40 V
- 6. Battery Capacity**
- 6a. Unadjusted battery capacity (line 3 x line 5c): 26.7 Ah 277
- 6b. Maximum allowable depth of discharge (MDOD): 80 %
- 6c. Capacity adjusted for MDOD (line 6a+line 6b): 334 Ah 346
- 6d. Maximum daily depth of discharge (MDDOD): 20 %
- 6e. Capacity adjusted for MDDOD (line 5c+line 6d) [or (line 5d+line 6d) if Fig 2 is used]: 89 Ah 92
- 6f. Percent of capacity at end of life: 8.0 %
- 6g. Capacity adjusted for end of life (line 6a+line 6f): 334 Ah 346
- 6h. Capacity adjusted for depth of discharge (greatest of line 6c, line 6e, or line 6g): 334 Ah 346
- 6i. Minimum operating temperature: 45 °C or °F
- 6j. Associated temperature correction factor: 1.2
- 6k. Capacity adjusted for temperature: 401 Ah 415
- 6l. Design Margin Factor (≥ 1): 1.1
- 6m. Capacity adjusted for design margin (line 6k x line 6l): 441 Ah 457**
- 7. Functional-Hour Rate (line 6m+line 5h):** 44 h 46
- 8. Voltage-Window Adjustment**
- 8a. Controller low-voltage load, disconnect setpoint: 42 V

- 8b. Adjusted Vmin (greater of line 5k or line 8a): 42 V
- 8c. Controller full-charge voltage setpoint: 58 V
- 8d. Adjusted Vmax (lesser of line 5j or line 8c) 58 V

9. Number Of Series-Connected Cells

- 9a. Recommended full-charge voltage for selected cell: (limited by line 8d) 2.40 V
- 9b. Maximum number of cells in series, round down (line 8d+line 9a): 24
- 9c. Recommended EOD voltage for selected cell: 1.75 V
- 9d. Calculated EOD voltage for cell (line 8b+line 9b): 1.75 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+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 should 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) 24

10. Cell Selection and Final Capacity Determination

- 10a. Smallest practical cell capacity available of selected type greater than or equal to line 6m, or, largest practical cell less than line 6m., when discharged to voltage line 9d, at functional-hour rate, line 7: 242 Ah
- 10b. Number of parallel strings, round up (line 6m+line 10a): 2
- 10c. Final battery capacity (line 10a x line 10b): 484 Ah

11. Checks/Considerations

Checks:

- 11a. Recommended maximum charge current during recharge: 97 A
- 11b. Maximum available charging current during recharge: 40 A
NOTE: If line 11b > line 11a, the battery may be damaged
- 11c. Recommended maximum charge current after reaching full-charge voltage at the battery's average temperature of 60 ~~(°F.)~~ (°C) 40 A
- 11d. Maximum available charging current after reaching full-charge voltage: 2 A
NOTE: If line 11d > line 11c, the battery may be damaged

11e. Freezing temperature of electrolyte at MDOD

10 °C or °F

NOTE: If line 6i < line 11e, the battery may freeze

11f. Battery's self discharge:

22 Ah/month*Considerations resolved:*

- (a) Maximum Charge Rate []
- (b) Overcharging []
- (c) Undercharging []
- (d) High-Rate Discharge []
- (e) Freezing of Electrolyte []
- (f) Battery Self Discharge []
- (g) Electrolyte Reserve []
- (h) Battery's Size and Weight []

12. Summary

Battery manufacturer and battery model: xyz, Co.Final battery is 24 cells in series by 2 strings in parallel.Battery capacity is 484 Ah rated at the 4h functional-hour rate.Battery full-charge voltage is 58 V;Battery end-of-discharge voltage is 42 V.

* NOTE: The self-discharge is approximately 5% of the daily load. Resize the battery to include this effect.

** NOTE: Selected battery capacity of 484 Ah is adequate.

B3 Remote Residence

The following worksheet describes the battery sizing for a remote cabin, used only on weekends. Seven days of battery reserve are sought. Although the major load is present on weekends only, the security system operates at all times.

See Fig B-3 for a partial simulated load profile diagram for Example Worksheets 3, 4 and 5.

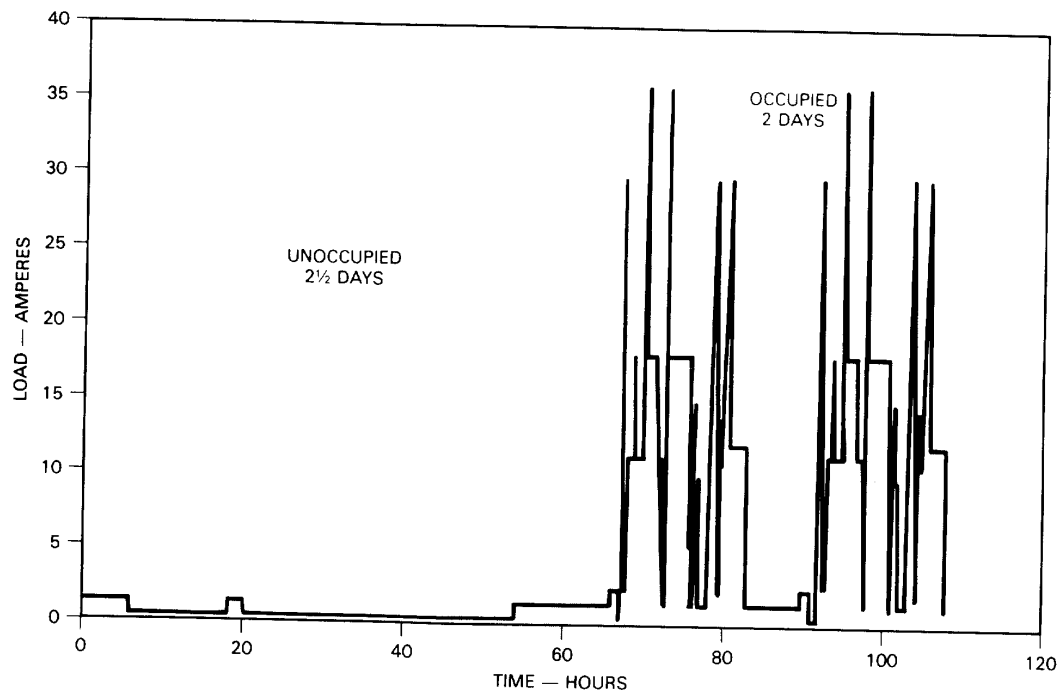


Figure B-3—Simulated Partial Load Profile Diagram for Remote Residence (4 1/2 Days)

5d. Maximum Daily Load from Fig 2.1 if used:	<u>153</u> Ah/day
5e. Greatest value of I_{noncoin} for Momentary Currents from above table (or Fig 2.2):	<u>0</u> A
5f. Maximum momentary current draw from battery (greater of line 5a or line 5e):	<u>36.1</u> A
5g. Greatest value of I_{noncoin} for Running Currents from above table (or Fig 2.2):	<u>0</u> A
5h. Maximum running current draw from battery (greater of line 5b or line 5g):	<u>35.15</u> A
5i. Maximum current draw from battery (greater of line 5f or line 5h.):	<u>36.1</u> A
5j. Lowest value of V_{max} from above table (or Fig 2.2):	<u>30</u> V
5k. Greatest value of V_{min} from above table (or Fig 2.2):	<u>23</u> V
6. Battery Capacity	
6a. Unadjusted battery capacity (line 3 x line 5c):	<u>414</u> Ah
6b. Maximum allowable depth of discharge (MDOD):	<u>50</u> %
6c. Capacity adjusted for MDOD (line 6a+line 6b):	<u>828</u> Ah
6d. Maximum daily depth of discharge (MDDOD):	<u>20</u> %
6e. Capacity adjusted for MDDOD (line 5c+line 6d) [or (line 5d+line 6d) if Fig 2 is used]:	<u>765</u> Ah
6f. Percent of capacity at end of life:	<u>80</u> %
6g. Capacity adjusted for end of life (line 6a+line 6f):	<u>518</u> Ah
6h. Capacity adjusted for depth of discharge (greatest of line 6c, line 6e, or line 6g):	<u>828</u> Ah
6i. Minimum operating temperature:	<u>0.60</u> or CF
6j. Associated temperature correction factor:	<u>1.35</u>
6k. Capacity adjusted for temperature:	<u>1118</u> Ah
6l. Design Margin Factor (≥ 1):	<u>1.1</u>
6m. Capacity adjusted for design margin (line 6k x line 6l):	<u>1230</u> Ah
7. Functional-Hour Rate (line 6m+line 5h):	<u>34</u> h
8. Voltage-Window Adjustment	
8a. Controller low-voltage load, disconnect setpoint:	<u>24.5</u> V

8b. Adjusted Vmin (greater of line 5k or line 8a):

24.5 V

8c. Controller full-charge voltage setpoint:

28.8 V

8d. Adjusted Vmax (lesser of line 5j or line 8c)

28.8 V

9. Number Of Series-Connected Cells

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

2.4 V

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

12

9c. Recommended EOD voltage for selected cell:

2.0 V

9d. Calculated EOD voltage for cell (line 8b+line 9b):

2.04 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+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 should 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)

12

10. Cell Selection and Final Capacity Determination

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

12.40 Ah

10b. Number of parallel strings, round up (line 6m+line 10a):

1

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

12.40 Ah

11. Checks/Considerations

Checks:

11a. Recommended maximum charge current during recharge:

2.50 A

11b. Maximum available charging current during recharge:

12 A

NOTE: If line 11b > line 11a, the battery may be damaged

11c. Recommended maximum charge current after reaching full-charge voltage at the battery's average temperature of 15 ^{°C} OK.

11 A

11d. Maximum available charging current after reaching full-charge voltage:

2 A

NOTE: If line 11d > line 11c, the battery may be damaged

11e. Freezing temperature of electrolyte at MDOD

NOTE: If line 6i < line 11e, the battery may freeze

-20 °C or °F

11f. Battery's self discharge:

40 Ah/month*Considerations resolved:*

- (a) Maximum Charge Rate []
- (b) Overcharging []
- (c) Undercharging []
- (d) High-Rate Discharge []
- (e) Freezing of Electrolyte []
- (f) Battery Self Discharge []
- (g) Electrolyte Reserve []
- (h) Battery's Size and Weight []

12. Summary

Battery manufacturer and battery model: XYZ, Co.Final battery is 12 cells in series by 1 strings in parallel.Battery capacity is 1240 Ah rated at the 34 h functional-hour rate.Battery full-charge voltage is 28.8 V;Battery end-of-discharge voltage is 24.5 V.

Complete a Fig 2.1 for each day (24 h period) for which a distinct daily load exists. Summarize the data in Fig 2.2 and transfer to Fig 1:

**Fig 2.1—Daily Load Detail
(Unoccupied Days)**

Load Data

Day: 1

a. dc Load Device	b. Voltage Window		c. Momentary Currents		d. Running Currents		e. Constituents of Max. Running Currents	f. No. of Occurrences Number per day	g. Duration h/occurrence	h. Run Time h/day	i. Daily Load Ah/day
	V _{max} V	V _{min} V	I _{coin} A	I _{noncoin} A	I _{coin} A	I _{noncoin} A					
security lights	30	21			1.0		✓		12	12	12.0
security systems	30	21			0.3		✓			24	7.2
Parasitics					0.1		✓			24	2.4

Total Daily Load 21.6 Ah

Maximum momentary current I_{coin}: (refer to load profile diagram): 0 A
 Maximum running current I_{coin}: (refer to load profile diagram): 1.4 A
 Number of repetitions: 5

Example Worksheet 4—Supplemental Battery Sizing Worksheet (For Duty Cycle Periods > 24 h)

Complete a Fig 2.1 for each day (24 h period) for which a distinct daily load exists. Summarize the data in Fig 2.2 and transfer to Fig 1:

**Fig 2.1—Daily Load Detail
(Occupied Days)**

Load Data

Day: 2

a. dc Load Device	b. Voltage Window		c. Momentary Currents		d. Running Currents		e. Constituents of Max. Running Currents	f. No. of Occurrences Number per day	g. Duration h/occurrence	h. Run Time h/day	i. Daily Load Ah/day
	V _{max} V	V _{min} V	I _{coin} A	I _{noncoin} A	I _{coin} A	I _{noncoin} A					
Security lights	30	21	-	-	1.0	-	✓		12	12	12.0
security system	30	21	-	-	0.3	-	✓			24	7.2
lights a.m.	30	23	-	-	1.0	-			1	1	1.0
lights p.m.2	30	23	-	-	10.0	-				2	20.0
lights p.m.1	30	23	-	-	3.0	-	✓			2	6.0
water pump	40	15	15	-	10.0	-		4	0.0675	0.27	2.7
TV	30	23	-	-	0.75	-	✓			2	1.5
Projector	30	22	36	-	18.0	-				5	90.0
Appliance 1	30	22	-	-	30	-		4	0.0175	0.07	2.1
Appliance 2	30	22	-	-	30	-	✓			0.25	7.5
Parasitics				-	0.1	-	✓			24	2.4

Total Daily Load 152.9 Ah

Example Worksheet 5 Supplemental Battery Sizing Worksheet (For Duty Cycle Periods > 24 h) (Fig 2 of Section 10 worksheet used for this calculation)

Maximum momentary current I_{coin} : (refer to load profile diagram):	<u>36.1</u> A
Maximum running current I_{coin} : (refer to load profile diagram):	<u>35.15</u> A
Number of repetitions:	<u>2</u>

Fig 2.2 —Summary

5. Load Data Summary

5a. Greatest value of the maximum momentary I_{coin} currents:	<u>36.1</u> A
5b. Greatest value of the maximum running I_{coin} currents:	<u>35.15</u> A
5c. Average Daily Load:	
I. Determine the series of repetitions that is going to result in the greatest load, over the period of days of battery reserve.	
II. Total the load over the period of days of battery reserve and divide by the number of days of battery reserve:	<u>59.1</u> Ah/day
5d. Greatest value of I_{noncoin} for Momentary currents for any of the above load devices:	<u>0</u> A
5e. Greatest value of I_{noncoin} for Running current for any of the above load devices:	<u>0</u> A
5f. Lowest value of V_{max} for any of the above load devices:	<u>30</u> V
5g. Greatest value of V_{min} for any of the above load devices:	<u>23</u> V