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IEEE Recommended Practice for Sizing of Stand-Alone Photovoltaic (PV) Systems

STANDARDS

IEEE Standards Coordinating Committee 21

Developed by the
IEEE Standards Coordinating Committee 21 on
Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage

IEEE Std 1562™-2021
(Revision of IEEE Std 1562-2007)

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Abstract: Provided in this recommended practice is information to assist in sizing the array and battery of a stand-alone photovoltaic (PV) system. Systems considered in this recommended practice consist of PV as the only power source and a battery for energy storage. These systems also commonly employ controls to protect the battery from being over- or under-charged and may employ a power conversion subsystem (inverter or converter). This recommended practice is applicable to all stand-alone PV systems where PV is the only charging source. This recommended practice does not include PV hybrid systems nor grid-connected systems. This recommended practice covers lead-acid batteries only; nickel-cadmium and other battery types are not included. This recommended practice does not include the sizing of the system controller, inverter, wiring, or other system components.

Keywords: distributed energy resources, energy storage, IEEE Std1562™, photovoltaic systems, PV systems

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Introduction

This introduction is not part of IEEE Std 1562-2021, IEEE Recommended Practice for Sizing Stand-Alone Photovoltaic (PV) Systems.

This recommended practice is intended to assist system designers and end users in sizing stand-alone photovoltaic (PV) systems. This document uses the "Peak Sun-hour" method of sizing. Systems are sized based upon the worst-case month using monthly solar irradiance and load demand. This document is not intended to be used for grid-connected or hybrid systems, where the systems are generally designed for annual values. Refer to IEEE Std 1561™ for hybrid designs.

Two critical pieces of information are required for the proper sizing of the PV array and battery in a standalone PV system: accurate load data and accurate solar radiation data. The performance of the system will be only as good as these data.

A computer sizing program is recommended for critical applications.

The annexes contain information on charge controllers, module tilt angles, and sizing examples using the System Sizing worksheet.

This document should be used in combination with IEEE Std 1361™ and IEEE Std 1013™.[1] Together, these documents will provide the user with a general guide to sizing and designing the PV array storage batteries for stand-alone PV systems.

[1] Information on references can be found in Clause 2.

Contents

IEEE Recommended Practice for Sizing Stand-Alone Photovoltaic (PV) Systems

1. Overview

1.1 Scope

This recommended practice provides a procedure to size a stand-alone photovoltaic (PV) system. Systems considered in this document consist of PV as the only power source and a battery for energy storage. These systems also commonly employ controls to protect the battery from being over- or undercharged and may employ a power conversion subsystem (inverter or converter). The issues of array utilization, battery-charge efficiency, and system losses are also considered in terms of their effect on system sizing. This recommended practice is applicable to all stand-alone PV systems where PV is the only charging source. This document does not include PV hybrid[2] systems or grid-connected systems. This document is normally intended to be used in conjunction with IEEE Std 1013 when the solar/PV array is paired with a lead-acid battery systems.[3] This recommended practice does not include the sizing of the system controller, inverter, wiring, or other system components.

1.2 Purpose

The purpose of this recommended practice is to provide procedures to size the PV system according to accepted methods, to improve the performance, cost-effectiveness, and lifetimes of stand-alone PV systems. These procedures are intended to assist designers, manufacturers, system integrators, users, and laboratories with information necessary for sizing, modeling, and evaluating the performance of stand-alone PV systems.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).[4,5]

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[2] A remote hybrid power system integrates two or more energy generation sources, a battery for energy storage, and necessary controls for the purpose of supplying electricity to remote loads. The generation sources typically include at least one variable power source (typically a renewable source, such as wind or solar) and at least one dispatchable generator. A typical configuration, for example, might integrate a diesel-powered generator and a PV array with a battery and controls.

[3] While IEEE Std 1013 is specific to the sizing of lead-acid batteries in stand-alone PV systems, IEEE Std 1562 can also be used to size the PV array for other battery types/chemistries as well.

[4] The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

[5] The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std 1013™, IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stand-Alone Photovoltaic (PV) Systems.[6,7]

IEEE Std 1361™, IEEE Guide for Selection, Charging, Test and Evaluation of Lead-Acid Batteries Used in Stand-Alone Photovoltaic (PV) Systems.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[8]

array-to-load ratio (A:L): The average daily photovoltaic ampere-hours (Ah) available to charge the battery divided by the average daily load in ampere hours.

NOTE—The average daily PV ampere hours is calculated by taking the average sun-hours for the month of interest times the array current at its maximum power point (I_{mp}) under standard test conditions (STC).

autonomy: The length of time that a photovoltaic (PV) system can provide energy to the load without receiving energy from the PV array.

charge controller: An electrical control device that regulates battery charging by voltage control and/or other means.

loss-of-load probability (LOLP): The probability (typically expressed as a percent) of the photovoltaic (PV) power system to have insufficient energy to support the load due to lack of solar radiation.

plane of array (POA): A plane that is at the same tilt angle and azimuth as the photovoltaic (PV) array.

solar irradiance: The instantaneous power density of sunlight measured in watts per meter squared (W/m^2).

solar radiation: The time integral of solar irradiance.

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NOTE—Solar radiation data for a geographic location is generally reported for each month as the average daily radiation for a specific array tilt angle. A typical range for daily solar radiation is 2 kWh/m^2 to 7 kWh/m^2.

standard test conditions (STC): The accepted conditions under which PV devices are commonly rated: 1000 W/m^2 irradiance at a spectral distribution of air mass (AM) 1.5 and a 25 °C PV cell temperature.

sulfation, excessive or "hard": The abnormal growth of lead sulfate crystals on the plates of a lead-acid battery after an extended time in a fully or partially discharged condition.

sun hours: Length of time in hours at a solar irradiance level of 1 kW/m^2 needed to produce the daily solar radiation obtained from the integration of irradiance over all daylight hours. Sun hours is sometimes referred to as peak sun hours.

system availability: A value equal to 1 minus loss of load probability (LOLP), expressed as a percentage.

3.2 Acronyms and abbreviations

Ah	ampere-hour
A:L	array-to-load ratio
AM	air mass
a-Si	amorphous silicon
I_{mp}	maximum power current
I_{sc}	short circuit current
LOLP	loss of load probability
MPPT	maximum power point tracker
P_{max}	power at maximum power point
POA	plane of array
ppm	parts per million
PV	photovoltaic
PWM	pulse-width modulation
SOC	state of charge
STC	standard test conditions
Vdc	volts direct current
V_{mp}	maximum power voltage
V_{oc}	open circuit voltage
VLA	vented lead-acid

VRLA valve-regulated lead-acid

4. Outline of sizing methodology

4.1 General

Part of the process of sizing of a stand-alone photovoltaic (PV) system is to determine the required number of PV modules and the capacity of the battery. Other sizing aspects include wire, charge controllers, inverters, etc., which are beyond the scope of this document. The sizing is based on a combination of worst-case solar radiation, load consumption, and system losses. (Ambient temperature is also used when sizing maximum power point tracker (MPPT) charge controllers.) This is different than sizing hybrid or grid-connected systems, where the PV array may be sized to help maximize solar energy production on an annual basis.

The PV array is sized to replace the ampere-hours (Ah) in the battery consumed by the load and to provide sufficient energy to overcome system losses and inefficiencies. Any additional over-sizing of the PV array is used to recharge the battery faster after periods of low solar radiation.

Two different sizing methodologies are used in this recommended practice, both based on the average daily load in Ah. The methodology used depends on the type of charge controller in the system. (Refer to Annex C for more information on charge controller types.)

Module temperature deratings are considered for determining the required number of series modules and Wh production from PV arrays using MPPT charge controllers, as the temperature has a great effect on the operating voltage (and therefore power output) of a PV module.

Shading of the PV array is not addressed, and it is assumed that the PV array will not be shaded throughout the day. If the PV array is shaded, a computer model may be needed to determine the effect of shading on the output of the PV array.

The performance of PV systems is directly dependent on the accuracy of the solar radiation data and the load consumption data used. Inaccuracies in either of these pieces of information will cause the system to be over- or under-designed.

The criticality of the application or load availability is also important. If the load is not critical and a loss of load can be tolerated, then the system can be designed more cost effectively than a critical system that requires extremely high system availability.

4.2 Sun-hour method for PV array sizing

For the purposes of this document, the daily module output is estimated by converting the solar radiation data on the plane of array (POA) into the equivalent number of sun hours of standard full solar irradiance at 1 kW/m^2. For shunt, series, and pulse-width modulation (PWM) regulators, multiplying the number of sun hours times the rated module peak power current (from the PV module datasheet) gives an estimate of the average available Ah/day production from the PV array. For MPPT controllers, multiplying the number of sun hours times the module peak power after temperature derate gives an estimate of the average available Wh/day production from the PV array. The sun-hour method for PV array sizing is used in this document for sizing the PV array.

5. Load calculation

One of the most critical factors in properly sizing a stand-alone PV system is properly determining the load. If the actual load is greater than the estimated load used for sizing, the system will be under-designed. If the actual load is smaller, the system may be over-designed.

The load should be determined as per IEEE Std 1013™.

If the load is not constant for all months, determine the average load for each month. This information will be used in the calculation of monthly array-to-load (A:L) ratios (see Clause 8).

6. Days of autonomy

As the array is sized to replace the Ah used by the load and system losses, the battery is sized to support the load during times of low solar radiation.

Battery capacity has a large effect on system availability. The larger the battery, the more days of backup, and typically the greater the system availability. There is a balance however with lead-acid batteries; the larger the battery, the greater the risk of sulfation. As the battery can operate at a low state of charge (SOC) for long periods of time (also called deficit charge), this risk can be reduced by increasing the A:L so that the PV array can recharge the battery at a higher rate; but this also increases the cost of the system. Conversely, a smaller battery will deep cycle more frequently, reducing availability and battery life.

The following is a general recommendation for determining the number of days of autonomy. For non-critical loads and areas with high solar irradiance, five to seven days of autonomy are recommended.[9] For critical loads or areas with low solar irradiance, seven to 14 days of autonomy or greater should be used.

7. Battery sizing and selection

For battery sizing and selection, refer to IEEE Std 1013™ and IEEE Std 1361™, respectively.

8. Solar radiation

Accurate solar radiation data is as important as accurate load data. Reliable solar radiation data for the site location (or as close as possible), should be used for proper system design. Solar radiation data is available from several public and private sources.

If the load is constant for all months, it is recommended to use the solar radiation for the month with the worst-case solar radiation at the optimum tilt angle (refer to Annex B for tilt-angle selection). The value is usually represented in kWh/m^2, which is equivalent to sun hours. This value will be used later in calculations to size the PV array. If the sun hour data obtained is not in this same single fixed plane of array, the sun-hours must be adjusted for tilt (including potential seasonal adjustments, azimuth, and motorized or passive tracking[10] [the examples in Annex D use single fixed angle arrays that are not seasonally adjusted and use sun hour data (like that found in the NREL Red Book [B3][11]) that is for the plane of array single tilt angle already, so no adjustment is necessary].

If the load is not constant for all months, the array and battery will need to be sized for each month. The month with the lowest A:L and battery autonomy should be used as the worst case for the system design. This will be an iterative process.

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[9] In certain applications with non-critical loads, and high solar irradiation lower autonomies may be used with certain battery technologies. However, this is not recommended. As noted in the text, five to seven days are recommended due to changing this document from a guide to a recommended practice.

[10] Most sun hour data assumes a flat horizontal non-tracking array, with a single permanent fixed tilt angle based on the latitude. While the exact amount of sun-hour energy increase from this value varies by location on the globe for dual and single-axis trackers, and seasonally adjusted fixed angles, conservative estimation would increase the sun hours by 40% for dual-axis tracking arrays, 25% for single-axis tracking arrays, and by 7% for fixed axis arrays adjusted in the spring and fall [B3].

[11] The numbers in brackets correspond to those of the bibliography in Annex E.

9. PV array sizing

9.1 General

The array sizing is determined by the solar radiation, A:L, system losses, and load.

Typical values used for A:L are as follows:

- For non-critical loads and areas with high and consistent solar radiation, an A:L of 1.1 to 1.2 is typical.
- For critical loads or areas with low solar irradiance, an A:L of 1.3 to 1.4 or higher is typical.

9.2 PV module selection

Selection of the PV modules takes into consideration price, available space, module mounting/dimensions and voltage (nominal, open circuit, and maximum power) ratings. Some PV modules may have advantages over others depending upon the PV array size, performance under various irradiance conditions, and application.

9.3 Charge controller selection

A charge controller (output voltage regulator) is recommended to help ensure the battery is not over-charged during periods of high solar radiation. Refer to Annex C for charge controller technology.

Some charge controllers may have advantages over others depending upon the PV array size, performance under various irradiance conditions, and application. As shunt, series, and PWM regulators cannot adjust the current from the solar array, it is important that the maximum solar array current not exceed the current rating of the controller. While some of these charge controllers can adjust the voltage from input (from the array) to output (to the batteries) by a fair amount, others can only regulate it downward a little bit—it may be important to match array nominal voltage (through proper panel voltage rating selection, and series connection of panels if needed) to battery nominal voltage.

9.4 System losses

System losses need to be estimated and included in the calculation. These losses may include dust or snow on the array, battery coulombic efficiency, parasitic/conversion/dissipation losses (from a charge controller or inverter if not included in the average daily load Ah), etc. These losses are typically expressed as a percentage of the system load. Typical combined values are 10% to 35% (refer to Worksheet 1—System Sizing). Underestimating these losses may lead to reduced system performance. These values can typically be calculated with information obtained from the component suppliers.

9.5 Temperature effect on modules

PV modules are almost always rated at standard test conditions (STC). In reality, modules in systems rarely operate at a cell temperature of 25 °C. Module temperatures may vary from -40 °C to 80 °C, depending on ambient temperature, mounting structure, wind speed, etc. For example, a module mounted in an open rack with air flowing around it will operate cooler versus one mounted directly on a roof. Module operating temperature is important because all PV-module types exhibit reduced voltage and power at elevated module temperatures. In extremely hot climates, like the desert southwest of the U.S., voltage output may decrease to the point that an array cannot charge the system battery.

Photovoltaic-module voltage and power temperature coefficients may range from −0.1%/°C to −0.6%/°C, depending on the specific module and module material. A commonly used rule of thumb for crystalline-silicon is −0.5%/°C. Consult the module literature or manufacturer to determine the temperature coefficients for a particular module. A greater negative value indicates the output of a particular technology will decrease more at higher temperatures. Conversely, at lower temperatures, PV technologies with a greater negative temperature coefficient will have a higher module-output voltage. Maximum module output voltage at the lowest expected temperature needs to be considered when selecting and sizing charge controllers. The National Electrical Code® (NEC®, NFPA® 70 [B1]) contains a sample correction factor Table [690.7(A)], but it is always best to consult the module manufacturer for temperature correction factors.

To calculate the module-output voltage at a temperature other than 25 °C, the translation is calculated [B4] using Equation (1):

$$V_{mp-new^{\circ}} = V_{mp} + (K_{T-V} \times (T_{new} - 25\ ^{\circ}\mathrm{C})) \tag{1}$$

where

$V_{mp-new^{\circ}}$	is the peak-power voltage at the operating temperature
V_{mp}	is the STC rated peak-power voltage of the module
T_{new}	is the operating temperature of the module
K_{T-V}	is the temperature coefficient of voltage

If $K_{T\text{-}V}$ is given in V/°C, then Equation (1) may be used directly. If $K_{T\text{-}V}$ is given in %/°C or parts per million (ppm), Equation 1 may be used if it is converted to V/°C.

As an example, assume a module has a maximum power voltage (V_{mp}) of 17.0 V. The expected operating temperature, T_{new}, is 55 °C. The manufacturer may give the $K_{T\text{-}V}$ as −0.085 V/°C or −0.5%/°C or −5000 ppm/°C.

If $K_{T\text{-}V}$ is given as −0.085 V/°C, then $V_{mp\text{-}new}$ is calculated using Equation (1) directly, as shown below:

$$V_{mp-new^{\circ}} = 17.0\text{ V} + (-0.085\text{ V} \times (55\ ^{\circ}\mathrm{C} - 25\ ^{\circ}\mathrm{C})) = 14.45\text{ V}$$

If $K_{T\text{-}V}$ were given as −0.5%/°C, $K_{T\text{-}V}$ translate it to V/°C before using Equation (1) as shown below:

$$K_{T\text{-}V}\left(\text{V/°C}\right) = K_{T\text{-}V}\ (\text{\%/°C}) \times (V_{mp} \div 100\%) = -0.5\%/°\text{C} \times 17.0\text{ V} \div 100\% = -0.085\text{ V/°C}$$

If $K_{T\text{-}V}$ were given as −5000 ppm/°C, translated it to V/°C before it can be used in Equation (1), as shown below:

$$K_{T-V}\left(\text{V/°C}\right) = K_{T-V}\ (\text{ppm/°C}) \times (V_{mp} \div 1\,000\,000\text{ ppm}) = -5000\text{ ppm/°C} \times (17.0\text{ V} \div 1\,000\,000\text{ ppm}) = -0.085\text{ V/°C}$$

Very similar equations (substituting power or current for voltage) can be used if the temperature coefficients for the power or current are known.

9.6 Module quantity calculations for shunt, series, and PWM charge controllers

9.6.1 Determine the number of series-connected PV modules

To determine the number of series-connected PV modules, the formula is as follows in Equation (2):

$$n_s = \frac{V_{\max}}{V_{mp-new} - V_{losses}} \tag{2}$$

where

n_s	is the number of series-connected PV modules
$V_{\max}$	is the highest battery charging voltage used (typically known as "finish" or "absorption")
V_{losses}	are the voltage losses from wire resistance, charge controllers, etc. from the solar module to the battery

If the result is not a whole number, the result should be rounded up to the nearest whole number, or a different module should be selected, and the calculation repeated with the new nominal module voltage.

When calculating the $V_{mp\text{-}new}$ in 9.5, the T_{new} used should be the highest anticipated to help ensure the module voltage is sufficient in high temperature conditions to charge the battery.

V_{max} should include temperature compensation, equalization, etc.

V_{losses} can be calculated by summing all of the voltage drops through the PV system. Typical voltage drops include wire losses, regulators/charge controllers, shunts, switches, etc.

9.6.2 Determine the number of parallel strings of PV modules

The formula is as follows in Equation (3):

$$N_p = \frac{L_{DA} \times A:L}{(1-\sigma_L)\times I_{mp-new^\circ} \times Sh} \tag{3}$$

where

Np	is the number of parallel strings of PV modules
L_{DA}	is the average daily load in Ampere-hours
$A:L$	is the array-to-load ratio[12]
σ_L	are the system losses
I_{mp-new°	is the module current at maximum power, corrected for the operating temperature[13]
Sh	is the sun hours

As this result will typically not be a whole number, the result should be rounded up to the nearest whole number. Since the number of parallel strings depends on the module selected, an alternative module may result in a more cost-effective solution.

10. Design verification

The battery supplies energy to the loads during periods of low solar radiation. As a general rule, if the A:L is a relatively high value (greater than 1.3), then the availability of the system can be increased by increasing the number of days of autonomy.

The lower the A:L, the greater the time that is required to recharge the battery. Balance of the system availability, system life, and system cost can be achieved by adjusting the array and battery size. A computer-based stand-alone PV system-sizing program can assist the designer in determining this balance.

While it is not technically part of the scope of this document, a loss of load probability (LOLP) calculation is the best way to confirm the design and verify the annual availability of the system and is recommended

[12] When sizing a stand-alone PV system, the month with the lowest A:L should be used for sizing calculations.
[13] Maximum current corrected for the operating temperature should be calculated per 9.5 using the highest expected temperature.

for critical loads. Several publicly- and commercially-available software programs are available to simulate the performance of the system.

Worksheet 1—System sizing

1) Project name and description[14]: ____________________
____
____________________.

2) Nominal system ________ dc voltage.

3) Days of autonomy desired: ________.

4) Total daily load (may be obtained from line 5c of Worksheet 1—Battery Sizing, from IEEE Std 1013-2019): ____ Ah/day.

5) Max battery voltage (may be obtained from line 8d of Worksheet 1—Battery Sizing, from IEEE Std 1013-2019): ____ volts direct current (Vdc).

6) Battery capacity (may be obtained from line 12 of Worksheet 1—Battery Sizing, from IEEE Std 1013-2019): ____ Ah rated at the ____ hour rate.

7) System losses:

7a Description of system loss (percent of system load)	7b Typical % window		7c System loss	7d multiplier[15]
	max %	min %	%	decimal
Parasitic[16] load (losses) of the charge controller	5	1		
Coulombic losses of battery (refer to IEEE Std 1361-2014, Annex A.9)[17]	20	1		
Wire losses	5	0		
Module mismatch losses	5	0		
Module aging[18]	20	0		
Dust	20	0		
Other				
Other				
Other				
7e) Total system losses [multiply all of column 7d, subtract this from 1, then multiply by 100]: ____%				

8) Determine the number of peak sun hours: ____.

9) Decide on an A:L: ____.

10) Choose a PV module (manufacturer and model): ____________________.

   a) Maximum power current (I_{mp}): ____ A.

   b) Short circuit current (I_{sc}): ____ A.

   c) Nominal voltage: ____ Vdc.

[14] Fields in this worksheet highlighted in yellow are provided/decided by the user/designer. Those highlighted in green come from other documents or manufacturer datasheets/manuals. Those highlighted in light blue are calculations.

[15] Calculate each value in column 7d by dividing each value in column 7c by 100, then subtracting that from 1.0.

[16] This is only the losses due to the need to keep the electronics and lights of the charge controller in an operating state, and not the dc-dc conversion losses of an MPPT charge controller (see 18a for those losses). Typical parasitic controller losses are no more than 1%-2%.

[17] Additional information on coulombic conversion losses in batteries can be found in Table B.2 of IEEE Std 1635/ASHRAE 21 [B2].

[18] Modules have an average life of 25 years and lose capacity at a rate of about 1%-1.25 %/yr for the first 2-3 years; after which they age with a capacity loss of about 0.5%-0.88 %/yr, depending on the manufacturer and model.

d) Open circuit voltage (V_{oc}): ______ Vdc.

e) Maximum power point voltage (V_{mp}): ______ Vdc.

f) Maximum power (P_{max}): ______ W.

g) Percentage temperature coefficient of V_{oc}: ______%/°C or %/K.

h) Temperature coefficient of V_{oc} [line 10d × 10g ÷ 100]: ______ V/°C or V/K.

i) Percentage temperature coefficient of P_{max}: ______%/°C or %/K.

j) Temperature coefficient of P_{max} [line 10f × 10i ÷ 100]: ______ W/°C or W/K.

k) Percentage temperature coefficient of I_{sc}: ______%/°C or %/K.

l) Temperature coefficient of I_{sc} [line 10b × 10k ÷ 100]: ______ W/°C or W/K.

m) Maximum operating ambient temperature: ______ °C.

n) Nominal operating cell temperature (NOCT): ______ °C.

o) Maximum operating temperature delta of PV module [line 10m + 10n – 25 °C]: ______ °C.

p) V_{mp} at max. module operating temperature [line 10e + (10h × (10o – 25 °C))]: ______ Vdc.

q) P_{max} at max. module operating temperature [line 10f + (10j × (10o – 25 °C))]: ______ W.

r) I_{mp} at maximum module operating temperature [line 10a + (10ℓ × (10o – 25 °C))]: ______ A.

11) Multiply line 4 times line 9: ______ Ah/day.

12) Divide line 7e by 100 (this converts the percentage to a decimal) and subtract from 1: ______.

Shunt, series, and PWM controller calculations:

13) Multiply line 12 times line 8 times line 10r: ______ Ah/day.

14) Divide line 11 by line 13: ______.

15) Round line 14 up to the nearest whole number: ______. This is the number of parallel PV module strings required.

16) Divide line 5 by line 10p and round up to the nearest whole number: ______. This is the number of modules to be wired in series in each string.

17) Multiply line 15 by line 16: ______. This is the total number of PV modules required for the system.

MPPT controller calculations:

18) Choose a charge controller (manufacturer and model): ______________________.

a) MPPT charge controller (if that is the type used) efficiency[19]: ______%

19) Multiply line 11 times line 2: ______ Wh/day. This is the daily load in Wh.

20) Multiply line 12 times line 8 times line 10q times line 18a divided by 100: ______ Wh/day. This is the individual module daily production.

21) Divide line 19 by line 20: ______.

22) Round line 21 up to the nearest whole number: ______. This is the minimum number of PV modules required for the system.

23) Divide line 2 by line 10c: ______. This is the number of PV modules per PV "string."

[19] MPPT converter efficiency on the data sheet is typically the peak/optimal value. Derating this by 1%-2% usually yields a more accurate true efficiency.

24) Divide line 22 by line 23 and round up to the nearest whole number: ________. This is the number of PV "strings."

25) Multiply line 23 by line 24: ________. This is the actual total number of PV modules needed.

Annex A

(informative)

PV module selection

Before choosing the module for a PV system, it is important to know the operation of the load and the site climate. The power required by the loads and the input voltage range are also important for proper design. Common loads include batteries or inverters. The designer should also know the expected solar radiation and ambient temperature for the site. If the solar radiation is typically low during the time of year the load demand is greatest, the array size will have to be increased. With this information, the designer calculates the maximum and minimum expected voltages from the array to verify the array will be able to power the load under all expected climate conditions. The designer should account for all voltage drops in the system wiring (round-trip), fuses, connectors, charge controllers, etc., to determine if the array output will still meet the needs of the load. For example, the voltage output of a crystalline-silicon module with a voltage at P_{max} of 16.90 V, and a temperature coefficient for voltage of −0.43%/°C will drop to 15.40 V at an expected module operating temperature of 46 °C. This may be inadequate to charge a 12 V lead-acid battery.

Annex B

(informative)

Tilt angle selection

B.1 Recommended tilt angle

It is recommended to adjust the array tilt angle for stand-alone PV systems so as to help maximize solar irradiance in the month with the lowest A:L value. This will be an iterative process as described in Clause 8. Generally, for fixed-tilt arrays to optimize performance in the winter, the array tilt angle should be the latitude plus 15° (see NREL/TP-463-5607 [B3][20]). The most accurate way to confirm proper tilt angle is with a computer simulation program.

NOTE—PV array tilt angles for grid-connected and hybrid systems may be different in order to optimize the array output throughout the year.

B.2 PV array orientation

To help maximize the PV array output, typically the array needs to be oriented to face south in the Northern hemisphere and north in the Southern hemisphere. However, this can change within any latitude within 15° of the equator. For sites within 15° of the equator, it is recommended to use a computer simulation program to verify the PV array orientation.

When orienting the PV array on site, the magnetic declination should be considered, as true North can vary by up to 20° versus magnetic North. The orientation is less critical at low latitudes.

B.3 Tracking structures

Single-axis and dual-axis trackers can also be used in the system sizing. A computer simulation program is recommended (if not already included in a solar database) to calculate the monthly average solar radiation in the POA.

Trackers have additional considerations in the system design, such as maintenance, reliability under abusive conditions, and resistance to high winds. The tracker manufacturer should be consulted for considerations to be used in the system design.

[20] This NREL publication is sometimes colloquially referred to as the "Red Book" due to the color of its printed cover.

Annex C

(informative)

Charge controller technologies

C.1 General

The main purpose of a charge controller is to prevent the battery from being under- or overcharged.
Some additional features of charge controllers may include:

- A low-voltage load disconnect to prevent the battery from being over-discharged
- Metering or status indicators
- Over-current protection
- Adjustable settings

There are several different configurations of charge controllers; some may be better for a specific application than others. In general, charge controllers should be voltage-controlled and should include temperature compensation, especially if the battery's temperature deviates significantly from 25 °C.

The charge controller should be sized as per the manufacturer's recommendation and per local electrical codes or standards (e.g., National Electrical Code® (NEC®) (NFPA 70) Article 690 [B1]), as different types of charge controllers have separate sizing requirements.

All charge controllers have a parasitic load on the system. This parasitic load should be included in the system sizing, either as part of the load or in the system losses.

Refer to IEEE Std 1361™ for additional information on charge controller technology, characteristics, and considerations.

C.2 Shunt regulator

Shunt regulators are typically solid-state. Their primary components are a transistor between the array positive and negative lines, and a blocking diode between the battery positive and the array positive. During normal charging, current flows from the array to the battery. When the battery voltage reaches the array disconnect setting, the transistor is activated, shorting the array. The battery is prevented from being shorted by the blocking diode. The blocking diode also prevents the current from flowing back into the PV array from the battery during nighttime. When the battery voltage falls to the array reconnect setting, the transistor is released and the current then flows to the battery again. (See Figure C.1.)

This type of charge controller is typically used on smaller low-voltage systems. Although short circuiting the array does not cause damage, there can be large amounts of current flowing through the transistor. The larger the array, the larger the current flowing through the transistor and the larger the amounts of heat the transistor dissipates. Additionally, voltage drop (loss) occurs across the blocking diode.

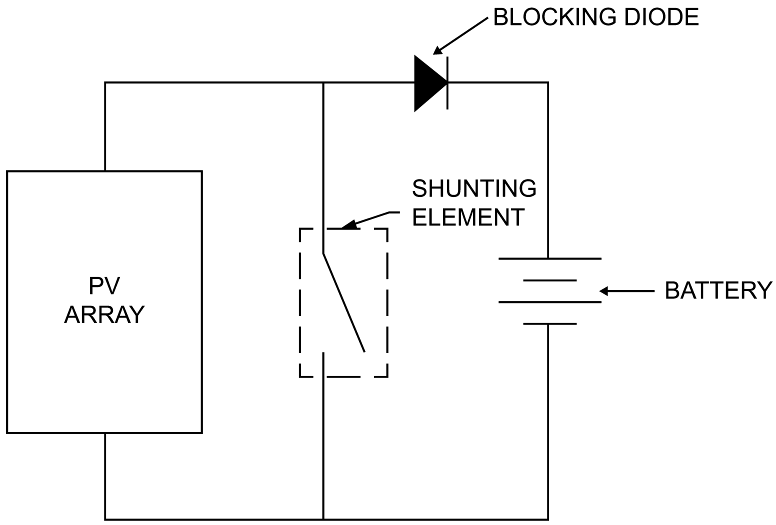

Figure C.1—Typical shunt regulator

C.3 Series regulator

Series regulators come in many variations. The basic series regulator consists of a relay (either mechanical or solid-state) between the battery positive conductor and the array positive conductor (for a negatively grounded system), and a voltage comparator. The negative conductors are used for a positively-grounded system. When the battery voltage reaches the array-disconnect setting, the relay is opened, disconnecting the flow of current to the battery. The PV array becomes open-circuited. When the battery voltage falls to the array-reconnect setting, the relay is closed, allowing the current to flow to the battery again. (See Figure C.2.)

Normally-open or normally-closed relays could be used. If normally-closed relays are used, a blocking diode is needed to prevent the flow of current from the battery to the array at night. The relay can be solid-state or mechanical. Typically, mercury-displacement relays are used because of their high cycle life (over a million cycles) and are available in currents up to 100 A. The frequency with which the relay opens and closes varies greatly and can be hours, minutes, or seconds.

A series charge controller can consist of one relay or several. By placing several relays in parallel and staggering the settings at which the relays open and close, the charge current from the PV array to the battery can be somewhat tapered.

Series charge controllers are used on any size of system. Because of their use of relays, the charge controller can be made larger or smaller by changing the relay.

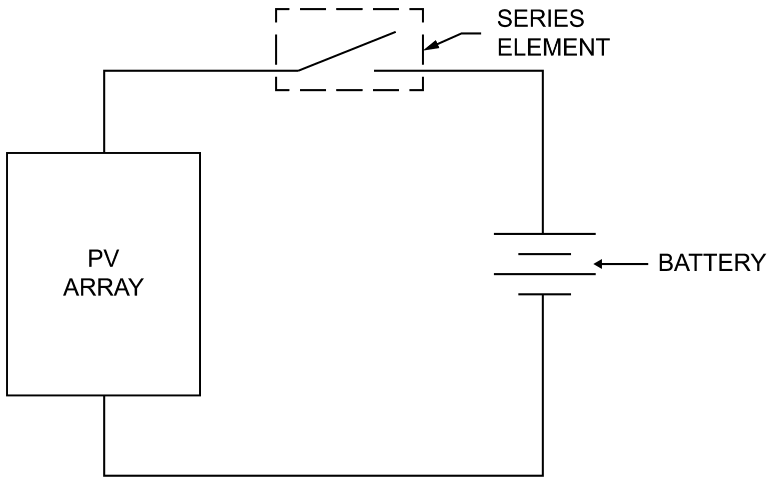

Figure C.2—Typical series regulator

C.4 PWM regulator

A pulse width modulated (PWM) regulator is a variation on the series regulator. The PWM regulator is a series regulator with a solid-state switch instead of a relay. With the solid-state switch replacing the relay, the flow of current from the array to the battery can be switched at high speed (frequencies vary with manufacturers, from a few Hz to kHz). By switching the solid-state switch at high speed, the battery charge voltage can be controlled more accurately. Instead of varying the voltage to control battery charging, the PWM regulator varies the amount of the time the solid-state switch is open or closed by modulating the width of the pulse. (See Figure C.3.)

PWM charge controllers do not require a diode, as the solid-state switch prevents the current from flowing back to the PV array.

PWM charge regulators are used on systems of various sizes; however, they have been known to cause electrical noise on telecommunication systems because of the high-speed switching on the solid-state switch.

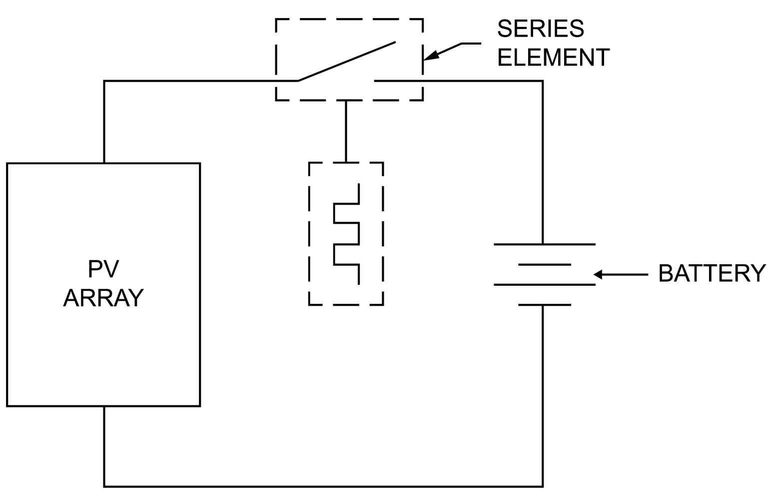

Figure C.3—Typical PWM regulator

C.5 MPPT charge controller

The maximum power point tracker (MPPT) charge controller is a variation of the PWM charge controller. The MPPT charge controller adjusts the PWM to allow the PV array voltage to vary from the battery voltage. Because the MMPT controller allows the array voltage to vary compared to the constant battery charge voltage, the momentary maximum output power from the PV array can be achieved. (See Figure C.4.)

The MPPT charge controller has many advantages over other charge regulators/controllers. In addition to getting more charge current from the PV array, some MPPT controllers allow the array to operate at a much higher voltage than the battery. This feature can be useful to reduce wire size and voltage drop from the PV array to the controller. The PV cell provides the maximum voltage in open circuit (current is zero). It also provides the maximum current when its output is short-circuited. the maximum power (V × I) is somewhere in between these two extremes. Usually, the manufacturer provides the V-I curve, and the maximum power zone, defined as the maximum power point (MPP). The MPP tracker's (MPPT) role is to change the load characteristics (usually the resistance) seen by the PV in order to extract the maximum power at a given sunlight and temperature condition. It does this through the use of PWM technology acting as a dc-dc converter.

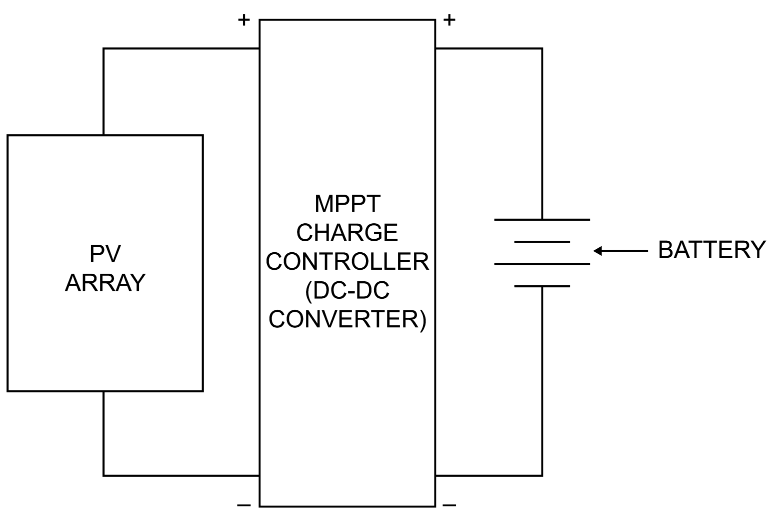

Figure C.4—Typical MPPT charge controller

Annex D

(informative)

Examples

D.1 General

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

D.2 Refrigerator/freezer for vaccine storage

This example describes the system sizing for a remote vaccine storage refrigerator (site is expected to be operational for 15 years) using vented lead-acid (VLA) batteries. The refrigerator is to be located near the equator in a tropical climate. Vaccines are delivered quarterly, and at that time a technician is available for system maintenance. Calculations are run with both a PWM controller and an MPPT controller to show the difference (MPPT controllers sometimes require fewer panels).

Worksheet 1—System sizing

(Refer to Annex B.1 of IEEE Std 1013™-2019)

1) Project name and description: Remote refrigerator/freezer, Brazilian village, tropical climate. High availability required, quarterly maintenance, four starts per day (including one for ice pack freezing).

2) Nominal system voltage: *12* Vdc.

3) Days of autonomy desired: *6* days.

4) Total daily load (may be obtained from line 5c of Worksheet 1—Battery Sizing from IEEE Std 1013-2019): *51.4* Ah/day.

5) Max battery voltage (may be obtained from line 8d of Worksheet 1—Battery Sizing, from IEEE Std 1013-2019): *14.7* Vdc.

6) Battery capacity (may be obtained from line 12 of Worksheet 1—Battery Sizing, from IEEE Std 1013-2019): *440* Ah, rated at the *120-hour* rate.

7) System losses:

7a Description of system loss	7b typical % window		7c system loss	7d multiplier
	max %	min %	%	decimal
Parasitic load (losses) of the charge controller	5	1	*1*	*0.99*
Coulombic effect of battery (refer to IEEE Std 1361™-2014, Annex A.9)	20	1	*17*	*0.83*
Wire losses	5	0	*3*	*0.97*
Module mismatch losses	5	0	*0*	*1.0*
Module aging	20	0	*11*	*0.89*
Dust	20	0	*1*	*0.99*
Other				
Other				
Other				
7e) Total system losses [multiply all of column 7d, subtract this from 1, then multiply by 100]: *30*%				

8) Determine the number of peak sun hours: *4.4*.[21]

9) Decide on an A:L: *1.2*.

10) Choose a PV module: *Brand XYZ, 50 W*.

a) Maximum power current (I_{mp}): *3.0* A.

b) Short circuit current (I_{sc}): *3.2* A.

c) Nominal voltage: *12* Vdc.

d) Open circuit voltage (V_{oc}): *21.8* Vdc.

e) Maximum power point voltage (V_{mp}): *18.3* Vdc.

f) Maximum power (P_{max}): *50* W.

g) Percentage temperature coefficient of V_{oc}: *-0.33*%/°C.

h) Temperature coefficient of V_{oc} [line 10d × 10g ÷ 100]: *-0.072* V/°C.

i) Percentage temperature coefficient of P_{max}: *-0.23*%/°C.

j) Temperature coefficient of P_{max} [line 10f × 10i ÷ 100]: *-0.12* W/°C.

k) Percentage temperature coefficient of I_{sc}: *0.04*%/°C.

l) Temperature coefficient of I_{sc} [line 10b × 10k ÷ 100]: *0.0013* A/°C.

m) Maximum operating ambient temperature: *30*[22] °C.

n) Nominal operating cell temperature (NOCT): *45* °C.

[21] Solar radiation data from RETScreen® Solar Resource and System Load Calculation at www.retscreen.net. (RETScreen® is a registered trademark of the Minister of Natural Resources Canada.) Location: Brasilia, Brazil. The month with the lowest radiation was January with a tilt of 15° (equals latitude).

[22] Maximum expected ambient operating temperature obtained from weather service data for the area.

o) Maximum operating temperature delta of PV module [line 10m + 10n – 25 °C]: *50* °C.

p) V_{mp} at max. module operating temperature [line 10e + (10h × (10o – 25 °C))]: *16.5* Vdc.

q) P_{max} at max module operating temperature [line 10f + (10j × (10o – 25 °C))]: *47* W.

r) I_{mp} at maximum module operating temperature [line 10a + (10l × (10o – 25 °C))]: *3.03* A.

11) Multiply line 4 times line 9: *61.7* Ah/day.

12) Divide line 7e by 100 (this converts the percentage to a decimal) and subtract from 1: *0.70*.

Shunt, series, and PWM controller calculations:

13) Multiply line 12 times line 8 times line 10r: *9.34*.

14) Divide line 11 by line 13: *6.61*.

15) Round line 14 up to the nearest whole number: *7*. This is the number of parallel PV module strings required.

16) Divide line 5 by line 10p and round up to the nearest whole number: *1*. This is the number of modules to be wired in series in each string.

17) Multiply line 15 by line 16: *7*. This is the total number of PV modules required for the system.

MPPT controller calculations:

18) Choose a charge controller (manufacturer and model): Brand LMN, 60 A.

19) MPPT charge controller (if that is the type used) efficiency: 96%.

20) Multiply line 11 times line 2: 740 Wh/day. This is the daily load in Wh.

21) Multiply line 12 times line 8 times line 10q times line 18a divided by 100: 139 Wh/day. This is the individual module daily production.

22) Divide line 19 by line 20: 5.32.

23) Round line 21 up to the nearest whole number: 6. This is the minimum number of PV modules required for the system.

24) Divide line 2 by line 10c: 1. This is the number of PV modules per PV string.

25) Divide line 22 by line 23 and round up to the nearest whole number: 6. This is the number of PV strings.

26) Multiply line 23 by line 24: 6. This is the actual total number of PV modules needed.

D.3 Microwave repeater

This second example describes the system sizing for a telecommunications system near Phoenix, Arizona, where high reliability is required. Calculations are run with both a PWM controller and an MPPT controller to show the difference (if any).

Worksheet 1—System sizing

(Refer to Annex B.2 of IEEE Std 1013™-2019.)

1) Project name and description: *Communications system. High reliability required, six-month interval between servicing, mountaintop location near Phoenix, AZ; valve-regulated lead-acid (VRLA) batteries, MPPT charge controller, 25 year expected life for the panels.*

2) Nominal system voltage: *48* Vdc.

3) Days of autonomy desired: *15* days.

4) Total daily load (may be obtained from line 5c of Worksheet 1—Battery Sizing from IEEE Std 1013-2019): *17.8* Ah/day.

5) Max battery voltage (may be obtained from line 8d of Worksheet 1—Battery Sizing from IEEE Std 1013-2019): *58* Vdc.

6) Battery capacity (may be obtained from line 12 of Worksheet 1—Battery Sizing, from IEEE Std 1013-2019): *660* Ah, rated at the *200-hour* rate.

7) System losses:

7a Description of system loss	7b typical % window		7c system loss	7d multiplier
	max %	min %	%	decimal
Parasitic load (losses) of the charge controller	5	1	*1*	*0.99*
Coulombic effect of battery (refer to IEEE Std 1361™-2014, Annex A.9)	20	1	*9*	*0.91*
Wire losses	10	0	*3*	*0.97*
Module mismatch losses	5	0	*0*	*1.0*
Module aging	20	0	*17*	*0.83*
Dust	20	0	*10*	*0.9*
Other				
Other				
Other				
7e) Total system losses [multiply all of column 7d, subtract this from 1, then multiply by 100]: ***35*** **%**				

8) Determine the number of peak sun hours: *5.3.*[23]

9) Decide on an A:L: *1.3.*

10) Choose a PV module: *Brand XYZ, 120 W.*

a) Maximum power current (I_{mp}): *6.8* A.

b) Short circuit current (I_{sc}): *7.5* A.

c) Nominal voltage: *12* Vdc.

d) Open circuit voltage (V_{oc}): *22.6* Vdc.

[23] Solar radiation data from NREL *Solar Radiation Data Manual*. WBAN No. 23183, Phoenix, AZ [B3]. The month with the lowest radiation was December with a tilt of latitude +15° (http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/sum2/23183.txt).

e) Maximum power point voltage (V_{mp}): 18.1 Vdc.

f) Maximum power (P_{max}): 120 W.

g) Percentage temperature coefficient of V_{oc}: -0.33%/°C.

h) Temperature coefficient of V_{oc} [line 10d × 10g ÷ 100]: -0.075 V/°C.

i) Percentage temperature coefficient of P_{max}: -0.43%/°C.

j) Temperature coefficient of P_{max} [line 10f × 10i ÷ 100]: -0.52 W/°C.

k) Percentage temperature coefficient of I_{sc}: 0.065%/°C.

l) Temperature coefficient of I_{sc} [line 10b × 10k ÷ 100]: 0.0049 A/°C.

m) Maximum operating ambient temperature: 50 °C.

n) Nominal operating cell temperature (NOCT): 45 °C.

o) Maximum operating temperature delta of PV module [line 10m + 10n – 25 °C]: 70 °C.

p) V_{mp} at max module operating temperature [line 10e + (10h × (10o – 25 °C))]: 14.7 Vdc.

q) P_{max} at max module operating temperature [line 10f + (10j × (10o – 25 °C))]: 96.6 W.

r) I_{mp} at maximum module operating temperature [line 10a + (10ℓ × (10o – 25 °C))]: 7.02 A.

11) Multiply line 4 times line 9: 23.1 Ah/day.

12) Divide line 7e by 100 (this converts the percentage to a decimal) and subtract from 1: 0.65.

Shunt, series, and PWM controller calculations:

13) Multiply line 12 times line 8 times line 10r: 24.2.

14) Divide line 11 by line 13: 0.955.

15) Round line 14 up to the nearest whole number: 1. This is the number of parallel PV module strings required.

16) Divide line 5 by line 10p and round up to the nearest whole number: 4. This is the number of modules to be wired in series in each string.

17) Multiply line 15 by line 16: 4. This is the total number of PV modules required for the system.

MPPT controller calculations:

18) Choose a charge controller (manufacturer and model): Brand LMN, 60 A.

a) MPPT charge controller (if that is the type used) efficiency: 96%.

19) Multiply line 11 times line 2: 1110 Wh/day. This is the daily load in Wh.

20) Multiply line 12 times line 8 times line 10q times line 18a divided by 100: 319 Wh/day. This is the individual module daily production.

21) Divide line 19 by line 20: 3.47.

22) Round line 21 up to the nearest whole number: 4. This is the minimum number of PV modules required for the system.

23) Divide line 2 by line 10c: 4. This is the number of PV modules per PV string.

24) Divide line 22 by line 23 and round up to the nearest whole number: 1. This is the number of PV strings.

25) Multiply line 23 by line 24: 4. This is the actual total number of PV modules needed.

Annex E

(informative)

Bibliography

Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this standard. Reference to these resources is made for informational use only.

[B1] ANSI/NFPA 70, National Electrical Code® (NEC®).[24,25]

[B2] IEEE Std 1635™/ASHRAE 21, Guide for the Ventilation and Thermal Management of Batteries for Stationary Applications.[26]

[B3] NREL/TP-463-5607: Marion, William, and Stephen Wilcox, "Solar Radiation Data Manual for Flat-plate and Concentrating Collectors." Apr. 1994. http://rredc.nrel.gov/solar/pubs/redbook/.[27]

[B4] Sivertsen, J.C., and P. Søyland, Masters Thesis, "Design and Installation of a Grid-Connected PV System," University of Agder, 2014.

[24] ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).

[25] The NEC is published by the National Fire Protection Association, Batterymarch Park, Quincy, MA 02269, USA (http://www.nfpa.org/). Copies are also available from The Institute of Electrical and Electronics Engineers (http://standards.ieee.org/).

[26] IEEE publications are available from The Institute of Electrical and Electronics Engineers (https://standards.ieee.org/).

[27] NREL publications are available from the National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, CO 80401 (http://rredc.nrel.gov/).

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